JIMMA UNIVERSITY
JIMMA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL ENGINEERING

OPTIMUM DESIGN AND ANALYSIS OF SOLAR PV/DIESEL HYBRID POWER GENERATION SYSTEM FOR CHERI ALGA IRRIGATION SITE AND ELECTRIFICATION OF THE NEARBY COMMUNITY AT KOSHA KEBELE

BY

LEMLEM MISGANAW

THESIS SUBMITTED TO JIMMA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN SUSTAINABLE ENERGY ENGINEERING

ADVISOR:

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JIMMA, ETHIOPIA

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Certification

The thesis entitled, optimum design and analysis of solar PV/diesel hybrid power generation system for Cheri Alga irrigation site and Electrification of the nearby community at Kosha Kebele submitted by Lemlem Misganaw to Jimma University in partial fulfillments for the degree of MSc. in Sustainable Energy Engineering is here by recommended for final evaluation and examination.

Advisor : ______________ Date 31/10/2016

Dr.-Ing. Getachew Shunki

Declaration

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

Name: Lemlem Misganaw

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Place: Jimma

Date of submission: 31/10/2016

Acknowledgement

Above all, I would like to give many thanks to God for his greatest support my dream became true. I would like to thank my advisor Dr.-Ing. Getachew Shunki for his invaluable contribution to the successful completion of this thesis work. I would also want to thank my co-advisor Mr. Getnet Zewde for his availability at any time his support is needed for the success of my thesis work. Last but not least I would like to thank NMSA Jimma branch, Jimma Zone Irrigation Development Authority and Limmu Seka Woreda administration office for supporting my thesis work by giving important data.

Abstract

It is highly costly and not feasible to supply power for rural areas which are far from grid and have low population density where their electric consumption is very low. Since currently PV prices are decreasing, it is a better alternative to use solar PV/diesel hybrid systems in order to decrease fuel consumption, operation and maintenance cost and deliver higher quality service than a single diesel generator electric power source.

By this thesis work, optimum design and sensitivity analysis of solar PV/diesel hybrid power supply system with battery bank and converter was done using HOMER for Cheri Alga irrigation site and electrification of nearby rural community in Kosha Kebele.

The services include lighting, school, health center, tea shops, flour mill, radio and television services and water pumping where a diesel generator power supply system is installed only for irrigation water pumping of 70HP.

By designing this hybrid system, additional services/loads of the nearby rural community can be supplied by electric power.

The operational concept of the hybrid system is that solar will be the first choice of supplying load and excess energy produced will be stored in battery. Diesel generator set will be a secondary source of energy.

Electrical load estimation of the area was done by interview, gathering appropriate data from the government administration offices and referring related literatures.

Solar sun shine hour, minimum and maximum temperature of the site was taken from NMSA Jimma Branch and average solar irradiation potential of the site is 5.8kwh/m^2/day. Size, quantity and cost of components was fed to HOMER and the optimum hybrid system is obtained.

Sensitivity analysis also done by considering variation in diesel fuel price, solar radiation and primary load.

In addition, cost and environmental impact comparison was done between diesel generator only and solar PV/diesel hybrid power supply system and cost of the hybrid system was compared with grid extension.

Key words: Optimization, Sensitivity Analysis, Solar PV, Diesel Generator, HOMER.

TABLE OFCONTENTS

Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

HOMER	Hybrid Optimization Model for Energy Renewable
PV	Photo Voltaic
IEA	International Energy Agency
UEAP	Universal Electric Access Program
REF	Rural Electrification Fund
EEPCo	Ethiopian Electric and Power Corporation
TCF	Trillion Cubic Feet
EEU	Ethiopian Electric Utility
HP	Horse Power
PCU	Power Conditioning Unit
RES	Renewable Energy Source
COE	Cost of Energy
NASA	National Aeronautics and Space Administration
GPS	Global Positioning System
AC	Alternating current
DC	Direct Current
KW	Kilo Watt
CPV	Concentrated Photovoltaic
DOE	Department of Energy
NREL	National Renewable Energy Laboratory

SOC State of Charge

SYMBOLS

n-type Negative (electron) type

p-type Positive (proton) type

H Monthly average daily global radiation on a horizontal surface

Ho Monthly average daily extraterrestrial radiation on a horizontal surface

S Monthly average daily hours of bright sunshine

So Monthly average day length

Isc Solar constant (=1367 W/ m^2),

Φ Latitude of the site = 8° 60' 39''

δ Solar declination

Ws Mean sunrise hour angle for the given month

n Number of days of the year starting from the first of January

a Regression coefficient

b Regression coefficient

K_T Clearness index

Y_{pv} The rated capacity of the PV array, meaning its power output under standard test conditions[KW]

f_{pv} PV derating factor[%]

$\bar{G}_T$ Solar radiation incident on the PV array in the current time step[1KW/m^2]

$\bar{G}_{T,STC}$ Incident radiation at standard test conditions[1KW/m^2]

α_P Temperature coefficient of power[%/^{o} C]

T_c PV cell temperature in the current time step[^{o}C

$T_{c,STC}$ PV cell temperature under standard test conditions[25°C]

Rbatt Battery bank life [yr

Nbatt Number of batteries in the battery bank

Qlifetime Lifetime throughput of a single battery [kWh]

Qthrpt Annual battery throughput [KWh/yr]

Rbatt,f Battery float life[yr]

Cann,tot Total annualized cost [$/year]

Eprim,AC AC primary load served [kWh/year],

Edef Deferrable load served [kWh/year].

CRF Capital recovery factor

Rproj Project lifetime

Cnpc Total net present cost of the stand-alone power system [$]

i Interest rate.

Cpower Cost of power from the grid [$/kwh]

Ltot Total primary and deferrable load [kwh/yr]

Ccap Capital cost of grid extension [$/km]

Ccom O & M cost of grid extension [$/yr/km]

CHAPTER ONE

Introduction

1.1Background

Energy is a base for economic growth and social progress of any country. IEA estimates that 1.5 billion people lacked access to electricity in 2008, more than one-fifth of the world's population. Some 85 percent of those without electricity live in rural areas, mainly in Sub-Saharan Africa and South Asia.

Off grid technology options are appropriate to supply populations whose demand is too small to justify the cost of extending grid and far from the existing grid [1].

1.1.1The Energy Sector in Ethiopia

When compared to the African average, overall electric access in Ethiopia is very low. As in most Sub-Saharan Africa countries, urban access and rural access has a huge gap. Urban electricity access is estimated at 80 percent while only two percent of rural households enjoy grid electricity. Of the total number of connected customers, at least 40 percent are concentrated in the capital city of Addis Ababa [2].

The energy sector in Ethiopia is generally categorized in to two: traditional (biomass usage) and modern (fuel usage like electricity and petroleum). Traditional energy sources represent the principal energy source in Ethiopia since more than 80% of the country's population lives in rural areas and engaged in small scale agricultural sector.

Energy requirements for domestic use in urban and rural areas are mostly met from wood, animal dung and agricultural residues. At national level biomass fuel meets 88% of total energy consumption. Access to petroleum and electricity in urban areas enabled significant proportion of population to employ these for cooking and other domestic energy requirements [3].

Ethiopian electrification initiatives can be broadly divided into two groups: 1) Grid Based Extension for which UEAP is an umbrella program executed by EEPCo. to provide grid-based electrification in rural towns and villages over a 10-year horizon. 2) Off-Grid for which REF was established in 2003 to foster private sector participation in the industry and provide flexible and innovative financing for off-grid rural electrification projects.

The off-grid electrification program is progressing at a much slower pace than its grid-based counterpart. To date, there have been only a handful of decentralized projects serving to electrify a few thousand rural households. Presently, only 11,000 households are electrified with support from REF, 10,000 of which are estimated to use diesel generators, reflecting prior emphasis on thermal generation. Currently, however, the emphasis is on renewable energy, particularly solar PV and micro hydropower. Yet it is been noted that the resources available for the off-grid rural electrification component are far less numerous than those available for the grid-based program [2].

1.1.2Status of renewable energy in Ethiopia

Ethiopia has energy resources of Hydropower potential 45,000 MW, Geothermal potential ~ 7,000 MW, Solar energy potential 5.5 kWh /sq. m/day –annual average daily irradiation, Average wind speed > 7 meter/second at 50 m above ground level – 1,350 GW, Natural gas - 4 TCF (113 billion m3),Coal > 300 million tones and Oil shale – 253 million tones.

Current power sector status of Ethiopia in generation capacity in the grid is 2,268 MW. When we see the share of different renewable energy sources: Hydro – 1,978 MW (87%), Wind – 171 MW (0.8%), Geothermal – 7.3 MW (0.003) and from the non-renewable, Diesel – 112 MW (0.05%). Access to electricity grid to Rural Towns and Villages is 54% [4].

1.1.3Solar power as a solution to the Ethiopian power scenario

Solar electricity has advantages in accessibility, cost and reliability when compared to traditional way of rural electrification. Solar electricity will be competitive on grid in the mid to long term period of time. Ethiopia has a large population with rapidly growing economy and very low level of electrification. When compared to traditional alternatives, PV has benefit because of rapidly declining costs, improved quality and reliability and proven models of technology diffusion.

1.1.4Solar PV applications in Ethiopia

In Ethiopia, the first PV systems were installed in 1985 for rural home and school lighting. Out of these 10.5KWp PV system was the largest which was installed in Central Ethiopia and served 300 rural households in a micro grid. In 1989 it was upgraded to 30KWp and provided service for grain mill and water pump. 87% of the total installation of PV systems in Ethiopia is for off-grid telecom systems and the rest for social services such as health, education and water pumping.

Around thirty thousand residential customers in rural areas are electrified with a total capacity of 5.3MWp.

1.1.5 Strategies for a PV industry in Ethiopia

Ethiopia has a large off-grid rural power market, equivalent to the combined off-grid market of countries in East Africa. Ethiopia is singular in the opportunities to address its own as well as regional markets through renewable energy due to good renewable resources, rapidly growing incomes, its green economy strategy, and its growing educated and trained workforce. Solar electricity has the potential to address major development goals in rural areas in the health, education, and information sectors. The size of demand and growing manufacturing capability opens potential to create a domestic solar energy industry.

a) A large dispersed rural population: Eighty percent of the population or 65 million Ethiopians live in rural areas.

b)The fastest growing, non-oil-exporting, economy in Africa: Ethiopia grew at more than 8% annually for the past six years, twice as fast as the African average.

c)One of the few green economy strategies in the world: Ethiopia has one of the few green economy strategies in the world and only the second in Africa.

d) Rapidly growing educated and trained workforce: The pool of engineers and technicians has rapidly increased in Ethiopia over the past decade. This opens the opportunity to engage this workforce in the fast growing solar energy sector in research and development, manufacture and distribution [5].

1.2 Problem Statement and Motivation

Even if there is abundant renewable energy resource in Ethiopia, most of the rural communities did not get electricity supply. This is because there is no enough power generation to support current energy demand and even if generation capacity is there it is difficult to supply rural communities from grid since they live distant from grid and in unfavorable geographical location in a very scattered manner. This needs extension of transmission and distribution lines and construction of substations which requires longer period of time and intensive capital for the connection of rural areas/villages. In addition, the energy demand and exploitation mainly from hydro and other sources is increasing. In addition, connecting rural areas by diesel generators results in large operation and maintenance cost and emission of greenhouse gases. Therefore, it is necessary to use other sources of energy such as off grid power supply in order to fill the gap of power supply from grid and the need of huge capital.

Therefore, this thesis work is intended to supply power for Cheri Alga irrigation site and the nearby community which is 24km far from grid.

Currently, Jimma Zone Irrigation and Development Authority has installed diesel generator to supply power for 70HP water pump which is used only for irrigation. In this research work, it is aimed at optimum design of solar PV/diesel hybrid power system with battery backup to supply power not only for irrigation pump but also for different services that benefits the community living near to the irrigation site

1.3. Objective of the work

1.3.1. General Objective

- Optimum design and analysis of solar PV/diesel hybrid power system with battery backup using HOMER software for Cheri Alga irrigation site and other services which benefits communities at Kosha Kebele.

1.3.2. Specific Objectives

- To assess the solar energy potential of the site and to get preliminary data for the solar power generation system.
- To assess current power demand and forecast the coming three years load growth of the community around the irrigation site.
- To select and size components of the hybrid system.
- To make optimization analysis of the system.
- To make sensitivity analysis of the system.
- To compare cost and environmental impact of solar PV/diesel hybrid power system to that of diesel only power system.
- To compare the hybrid system with grid extension.

1.4. Scope of the present work

In this thesis work, optimum design and sensitivity analysis of solar PV/diesel hybrid system will be done for Cheri Alga irrigation site and nearby community by using HOMER software. The design will be done for irrigation water pumping which requires 70HP and for electrification of the nearby community. Components of the hybrid system will be selected. This design also includes comparison of the diesel only system to that of solar PV/diesel hybrid system in terms of cost, emission reduction and additional power supply in addition to irrigation water pumping.

This thesis work will not cover the practical implementation of the hybrid system.

1.5. Justification of the Study

Jimma Zone Irrigation Development Authority installed diesel generator to supply power for irrigation water pumping at Cheri Alga. But it did not consider supplying power for the nearby community of Kosha Kebele. Considering the fact that power supply is mandatory for the development of a given community, this study focuses on optimum design of solar PV/diesel hybrid system to supply power for the above mentioned community and irrigation water pumping.

1.6. Significance of the study

The Ethiopian government has given a great emphasis to electrify rural areas of the country and devised a mechanism called UEAP in order to make fast the connection of rural areas. In addition, the Ethiopian government has uncompromised policy in generating power from renewable energy sources, this thesis work focuses on replacing diesel generator only power supply for irrigation water pump to solar PV/diesel hybrid power supply system not only for the irrigation site but also to the rural community who are far from the grid.

Policy makers and concerned bodies can use this study as a real problem solving approach for similar and related projects and rural electrification. This study helps in utilizing abundant renewable energy sources like solar energy in solving electrification challenge with regard to long distance grid extensions, power supply shortage and emission reduction.

Even if solar PV power supply has high capital cost, it has very low or insignificant operation and maintenance cost and no greenhouse gas emission, when compared to diesel power supply system.

Furthermore, this study gives answer to the power demand of the community near to the irrigation at Cheri Alga site if there is a concerned body /governmental or non-governmental organizations/ who can work on the practical implementation of the project.

1.7 Limitation of the Study

There is no transportation to the site. So it was difficult to visit the site and to get some information by myself.

1.8 Description of the study area

Cheri Alga Kebele is found in Limmu Seka Woreda and it is 158Km far from Jimma town, capital of Jimma zone. The living condition of the people in this area depends upon agriculture. Currently, Jimma Zone Irrigation Development Authority has installed a diesel generator which supplies power for 70HP water pump for irrigation purpose. The villagers in this area use kerosene for lighting, fire wood, cow dung, agricultural residues for all household activities and primary cells for radio and music player.

904households with 4502 families are available in this village. Since the village is far from the nearby substation at Jimma, 158KM, EEU may not supply power to the village in the near future. The aim of this thesis is to design an off-grid solar PV/diesel hybrid energy system instead of diesel only power system installed for irrigation water pump at Cheri Alga irrigation site and to extend the service to serve communities who live in Kosha Kebele near to the irrigation site. The location of the site is 8° 60' 39" N latitude and 36° 95' 23" E longitude and elevation of 1776 meters above sea level [6, 7].

Figure1.1: Location Map of Jimma Zone

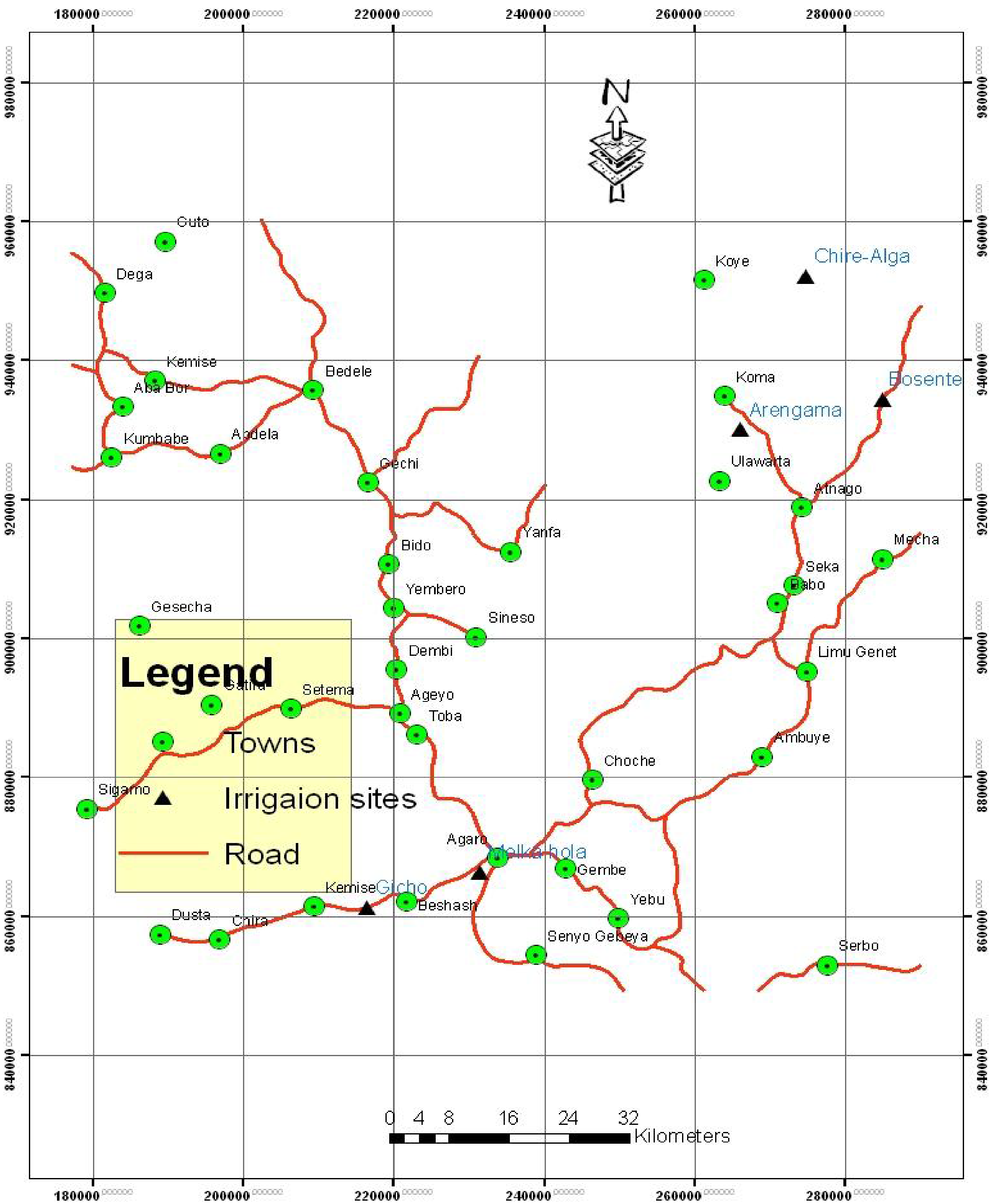


Figure 1.2: Location map of the study area.

Figure1.3: Homes of households around irrigation site

Figure 1.4: Camp shade at Cheri Alga irrigation site.

Figure1.5: Delivery channel, collection chamber and pump house.

Figure1.6: Diesel generator and pump installed at the site.

Figure1.7: Duct for pipes and pipes to transport water from Urgessa river to the pond.

Figure1.8: Pond for water storage and delivery canal to agricultural lands of farmers.

1.9 Literature review

S. Naga Kishore, G. Vinod Kumar, T. V. Rao& M. L. S. Deva Kumar[8]: Designed a solar PV-grid-diesel hybrid power system with battery bank and PCU which consists of charge controller and inverter which was installed in Center for Energy Technology, Osmania University, Hyderabad, India. By their design solar PV is used to charge the battery bank if there is adequate solar radiation and if there is no adequate solar radiation grid supply is used to charge the battery bank. If the two conditions did not met, diesel generator is used to charge the battery bank. The battery bank then feed the inverter and AC loads are supplied from it. In their design they have considered the losses to be 25% which includes battery efficiency losses, the losses of inverter, and losses due to wiring, dust.

They also elaborated by the use of solar PV, diesel fuel consumption was reduced, engine maintenance cost was reduced, the life period of the generator also increased and emission of greenhouse gases were decreased. In this study the design was made for only 2KW electric power supply but in my design much larger load is considered.

J. Muñoz, L. Narvarte and E. Lorenzo[9]: worked on a pilot project of replacement of diesel generators by small PV-Hybrid plants in two remote rural villages, Idboukhtir and Iferd, in the south of Morocco. The two villages were getting electricity supply from diesel generators for four hours per a day, by replacing the generators to solar PV system with generating capacity of 9.24KWp the duration of power supply extended to fourteen hours per a day with limitation in using additional appliances like heaters and cookers. But described above the solar PV system supplies power fourteen hours per a day and using limited type of appliances.

Zelalem G.[10]:has performed techno economic assessment of solar PV/diesel hybrid power system for a hypothetical rural school by using HOMER software to supply peak load of 11kw for 24 hours per day. In his study he has compared only diesel power supply system to that of solar PV/diesel hybrid system with battery bank and he showed that the hybrid system is cost effective and environmentally friendly since the solar PV covers around 95% of power demand and the diesel generator is used to cover only 5% of power demand. In addition he has conducted sensitivity analysis considering uncertainty in two variables: solar radiation and diesel fuel price. Here the study only considered power supply for the school, teachers' resident, barber and mobile charging shops for income generation of the school and the study did not consider the nearby community even if the school is found in rural area.

Baharuddin A., Kamaruzzaman S., MohdazharAbd. R., Mohd Y., Othman, Azami Z. and Ahmad M.[11]: presented the performance of solar PV/diesel hybrid system which is installed and operated successfully at the middle and top stations of the Langkawi Cable Car resort facilities. This hybrid system is installed to supply 16KW electric power for the cable car stations such as water pumps, cable car controller system, air-conditioners and lights. The project is owned by Langkawi Development Authority and operated by Panorama LangkawiSdn. Bhd. During their study, the system had operated for 6 months by supplying power 24 hours per a day where the diesel generator had run for only 300 hours and had been started for 35 times. It only starts once a week with average running hours about 8 hours.

Solomon T.[12]: worked on design and simulation of hybrid wind turbine-PV-diesel generator-battery bank-converter by using Homer for rural communities at Haressaw in Tigray regional state. In his work, primary peak load of 284KW and deferrable peak load of 3.6KW was considered. The community's load was suggested for lighting, water pumping, school and health clinic equipment load, radio, television, flour milling machines and local food (enjera) baking. Solar and wind energy are considered as primary sources to supply electricity directly to the load and to charge battery bank when excess generation is happened however in peak demand times diesel generator could also be engaged. The researcher used two approaches: renewable fraction and low cost of energy to select one power system from the selected options. In this study, utilization of diesel generator source for peak load time is considered and the accurate cost of components of the hybrid system is not included. But in my research work, the exact cost of hybrid components will be considered from the current market price.

M.S. Ismail, M. Moghavvem, and T.M.I. Mahlia[13]:performed solar PV/diesel hybrid system with battery bank for a rural area in Palestine which has around 25KW peak load. They used a simulation program using iterative approach to optimize the sizes of PV system and battery bank. Average daily solar radiation intensity on a horizontal surface is about 5.6 kWh/m^{2}and yearly average daily solar radiation is 6.1 kWh/m^2 at an optimum tilted angle of 30 º.

Three scenarios were analyzed in their paper. The most economic scenario is the one that includes the battery system and the diesel generator in addition to the solar PV panels. The second one is solar PV system and the third is diesel generator system which has additional impact of generating 7 times of CO_2 emission when compared to the hybrid system.

The life cycle period of the project was considered 24 years. It is the life cycle of the component that has maximum life time. But detailed load description is not presented on their paper.

Mutasim Nour, Golbarg Rohani[14]:designed an optimal stand-alone PV-diesel hybrid renewable power system by using HOMER for a rural village Um Azimulin UAE and compared HRES with grid extension economically. The hybrid power system consists of 1500 kW photovoltaic arrays, three500 kW diesel generators, 600 kW battery storages, and 1000 kW converter. It is capable of providing 1000 kW average load and up to 2300 kW peak load.

By their optimum design, the solar PV share is 27%, emission is reduced by 23% and cost of grid extension is greater above 83KM where the village is 143 KM far from the available grid. But in this thesis work the solar PV/RES/ share is only 27%.

SherMohammad Husain, Dinesh Kumar Sharma[15]:presented the most feasible configuration of Solar PV system with diesel generator as back up for the electrification of Nepal Television substation situated in Ilam district having transmitter power of 5 kW and peak energy supply of 9.8 KW 24 hours a day. They had used HOMER software for optimization and sensitivity analysis. The main concern of their thesis was to replace diesel generator power supply to solar PV/diesel hybrid system during grid failure. In addition COE of the hybrid system is less than diesel power supply system the hybrid system reduces CO_2 emission by 44 tons per year when compared to diesel only power supply system.

Bizuayehu Tesfaye [16]: investigated alternative power supply options to replace the existing diesel-only power system for remotely located towns detached from the main electricity grid in Ethiopia with a hybrid PV–wind–battery power systems to meet energy consumption of commercial and residential building. This study conducted comparison of grid extension and diesel only system and sensitivity analysis.

Isaac KwasiYankey, Samuel Kwofie, Godfred Kwame Abledu [17]: worked on techno-economic assessment of installing a reliable renewable energy system for electric power generation at Koforidua Polytechnic in Ghana. 26.7 KW peak was considered in their study and they did not include sensitivity analysis.

Mohammad Shuhrawardy, KaziTanvirAhmmed [18]: they had presented the feasibility study of a grid connected PV system with battery backup in the south-east part of Bangladesh for 69 KW. But they did not include sensitivity analysis in their study.

1.10. Methodology and Materials

The methodology to accomplish this thesis work will be as follows:

1.10.1 Literature Review

Published Journals, different energy books, and different literatures related to solar PV/diesel hybrid irrigation and rural electrification, load estimation, potential assessment techniques of solar resources and for optimization of hybrid system components will be reviewed. Related literatures on irrigation water pumping and on rural electrification will be considered.

1.10.2 Data Collection

Primary and secondary data will be collected from the site and concerned bodies.

- Assessment of solar energy potential of the site will be done.
- Primary data collection such as load/power demand of the community by interview of residents and responsible bodies.
- Secondary data collection will be made on the solar energy potentials of the site from NMSA and NASA.

1.10.3 Data Analysis and Feasibility Study

In this research, solar data collected from 2011-2015 by NMSA Jimma branch will be analyzed. The result of this analysis will be compared with the design value of PV-diesel hybrid power supply system.

The sunshine duration & solar radiation will be taken from NMSA and NASA. The solar data from NMSA is sunshine duration data from the nearby station and it will be used to estimate the monthly average solar radiation with angstrom equation. Assessment and estimation of primary loads of the society at the site will be taken. The capital, operating and replacement cost, life time, etc. of components will be searched from local markets, websites and different literatures. Thus monthly average solar radiation, load data and market survey will be prepared in suitable format for input to HOMER software. Optimum design and sensitivity analysis of a solar PV/diesel hybrid system using homer software will be done. The overall design and research report will be written. Finally, conclusion and recommendation will be made based on simulation results.

1.10.4 Materials required for the study:

- Google Earth &Google Map
- Software: HOMER for hybrid optimization and sensitivity analysis tool, and MS Excel for load data estimation processing
- Digital Camera: important photos related to the study will be taken and documented.
- Standard tables and charts: to determine solar irradiation in the study area.
- GPS.

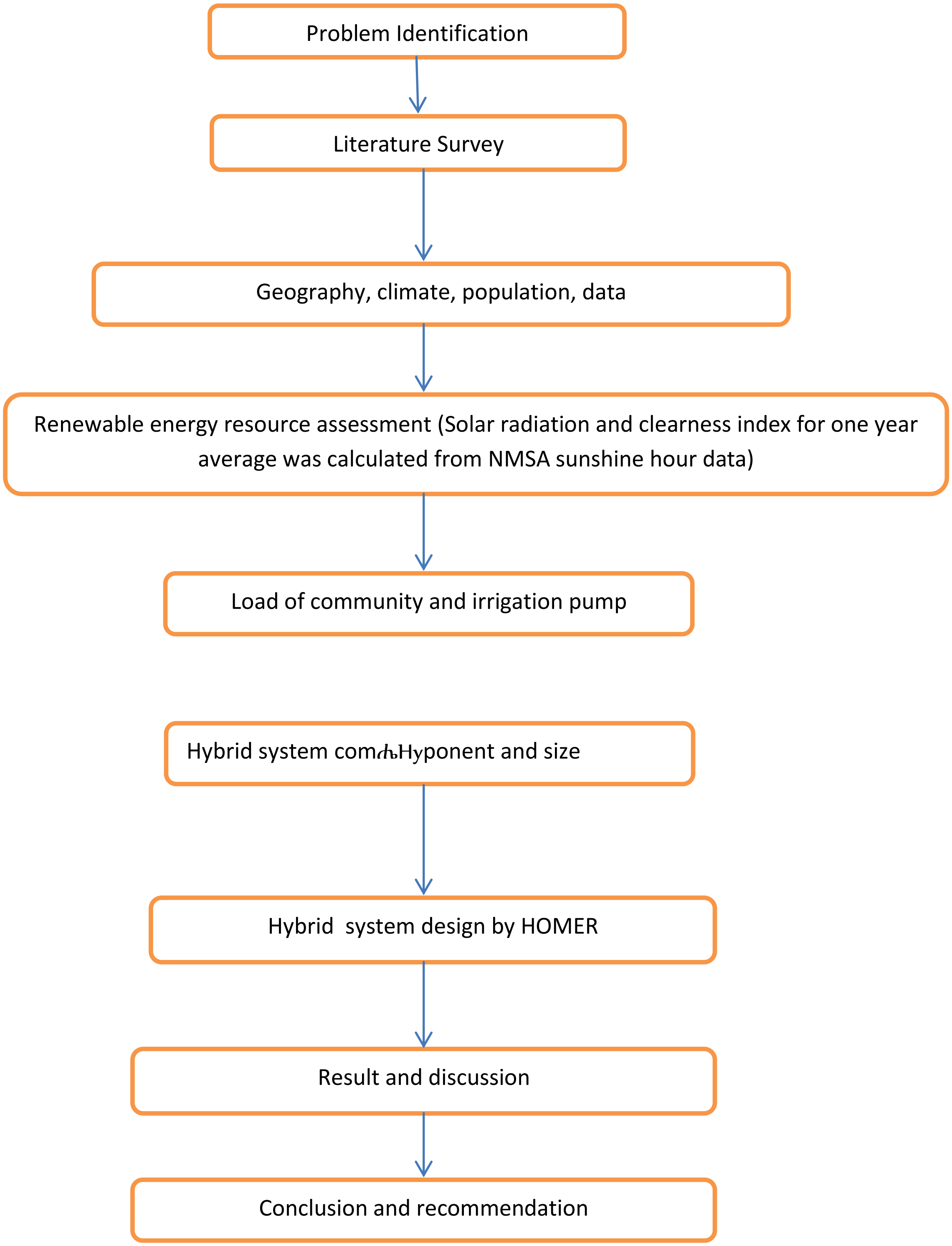

Problem Identification
Literature Survey
Geography, climate, population, data
Renewable energy resource assessment (Solar radiation and clearness index for one year average was calculated from NMSA sunshine hour data)
Load of community and irrigation pump
Hybrid system comሔHyponent and size
Hybrid system design by HOMER
Result and discussion
Conclusion and recommendation

Figure 1.9: General methodology of the study.

1.11. Organization of the Thesis

This thesis report is organized in six chapters. The first chapter discusses the introduction part in which the background, problem statement and motivation, objective, scope, justification, significance, limitations of the study, description of the study area, literature review, methodology and materials are included. The second chapter describes solar PV systems and assessment of solar power potential of the site. The third chapter consists of load estimation of primary and deferrable load and forecast for load growth for the coming three years. The fourth chapter discusses about hybrid systems, sizing of hybrid system components and Homer Tool. The fifth chapter consists of result and discussion. The sixth chapter describes conclusion drawn from the research work and recommendation for future action and further work.

CHAPTER TWO

SOLAR PV SYSTEMS and ASSESSMENT OF SOLAR POWER POTENTIAL OF THE STUDY AREA

Solar energy is available in abundance in most parts of the world. The amount of solar energy incident on the earth's surface is approximately1.5 x 10^{18} kWh/year, which is about 10,000 times the current annual energy consumption of the entire world. The density of power radiated from the sun which is called solar energy constant is 1.373 kW/m^2.

2.1 The photovoltaic effect and how solar cells work

Solar cell is a device which converts photons in Solar rays to direct-current (DC) and voltage by a technology called Solar Photovoltaic (SPV). A typical silicon PV cell is a thin wafer consisting of a very thin layer of phosphorous-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. An electrical field is created near the top surface of the cell where these two materials are in contact (the P-N junction).

When the sunlight hits the semiconductor surface, an electron springs up and is attracted towards the N-type semiconductor material. This will cause more negatives in the n-type and more positives in the P-type semiconductors, generating a higher flow of electricity. This is known as **Photovoltaic effect**[19].

The term photovoltaic means the direct conversion of light into electrical energy using solar cells. Semiconductor materials such as silicon, gallium arsenide, cadmium telluride or copper indium diselenide are used in solar cells. The crystalline solar cell is the most commonly used variety. During 2006, it had a worldwide market share of 95 per cent [17].

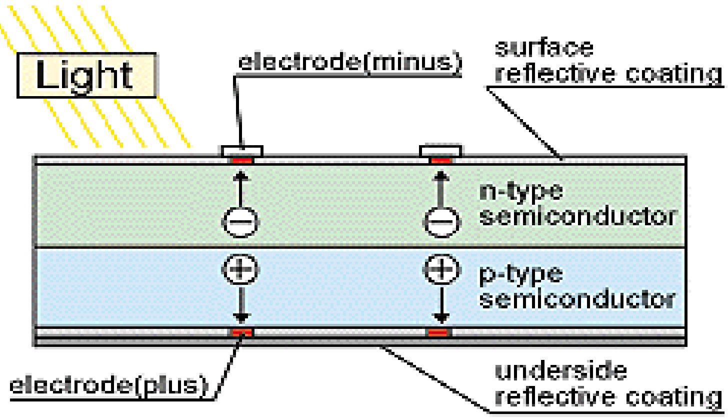


Figure 2.1: Silicon Solar Cell and its working mechanism (Source: [19])

Individual PV cells are assembled in series into PV modules of varying capacity. PV modules are often combined to form PV arrays. They are combined in series to increase supply voltage, and combined in parallel when the application requires an increased current[21].

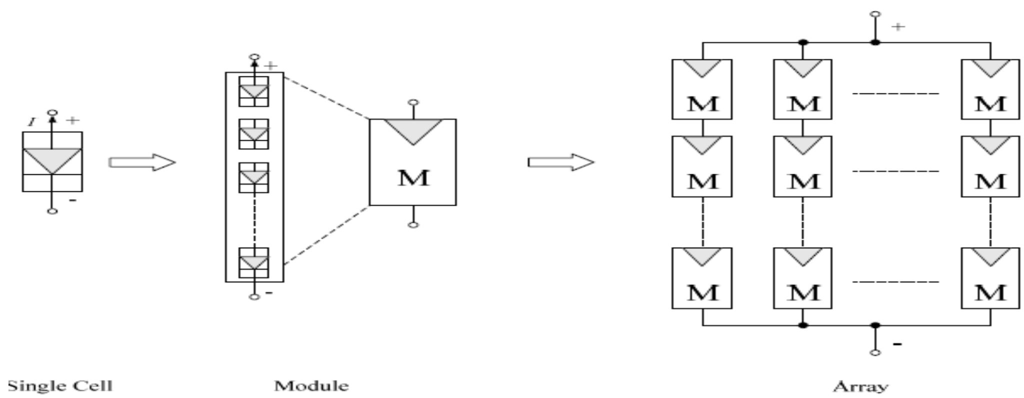


Figure 2.2: Schematic Diagram for Cell, Module and PV Array (Source: [12]**)**

The amount of current generated by a PV cell depends on its efficiency, its size (surface area) and the intensity of sunlight striking the surface [19].

2.2 Classification of Photovoltaic Systems

Photovoltaic (PV) systems can be grouped into stand-alone systems and grid connected systems. In stand-alone systems the solar energy yield is matched to the energy demand. Since the solar energy yield often does not coincide in time with the energy demand from the connected loads, additional storage systems (batteries) are generally used. If the PV system is supported by an additional power source – for example, a wind or diesel generator - this is known as a photovoltaic hybrid system.

Small individual power supplies for homes - known as solar home systems – can provide power for lights, radio, television, or a refrigerator or a pump. And, increasingly, villages are gaming their own power supplies with an alternating current circuit and outputs in the two-digit kilowatt range.

2.2.1 Stand-alone systems

The first cost-effective applications for photovoltaic systems were stand-alone systems. Wherever it was not possible to install electricity supply from the mains utility grid, or where this was not cost-effective or desirable, stand-alone photovoltaic systems could be installed. The range of applications is constantly growing. There is great potential for using stand-alone systems in developing countries where vast areas are still frequently not supplied by an electrical grid. But technological innovations and new lower-cost production methods are opening up potential in industrialized countries as well.

Solar power is also on the advance when it comes to mini-applications: pocket calculators, clocks, battery chargers, flashlights, solar radios, etc., are well known examples of the successful use of solar cells in stand-alone applications.

Other typical applications for stand-alone systems are:

- mobile systems on cars, camper vans, boats, etc.,
- remote mountain cabins, weekend and holiday homes and village electrification in developing countries,
- SOS telephones, parking ticket machines, traffic signals and observation systems, communication stations, buoys and similar applications that are remote from the grid,
- applications in gardening and landscaping,
- solar pump systems for drinking water and irrigation, solar water disinfection and desalination.

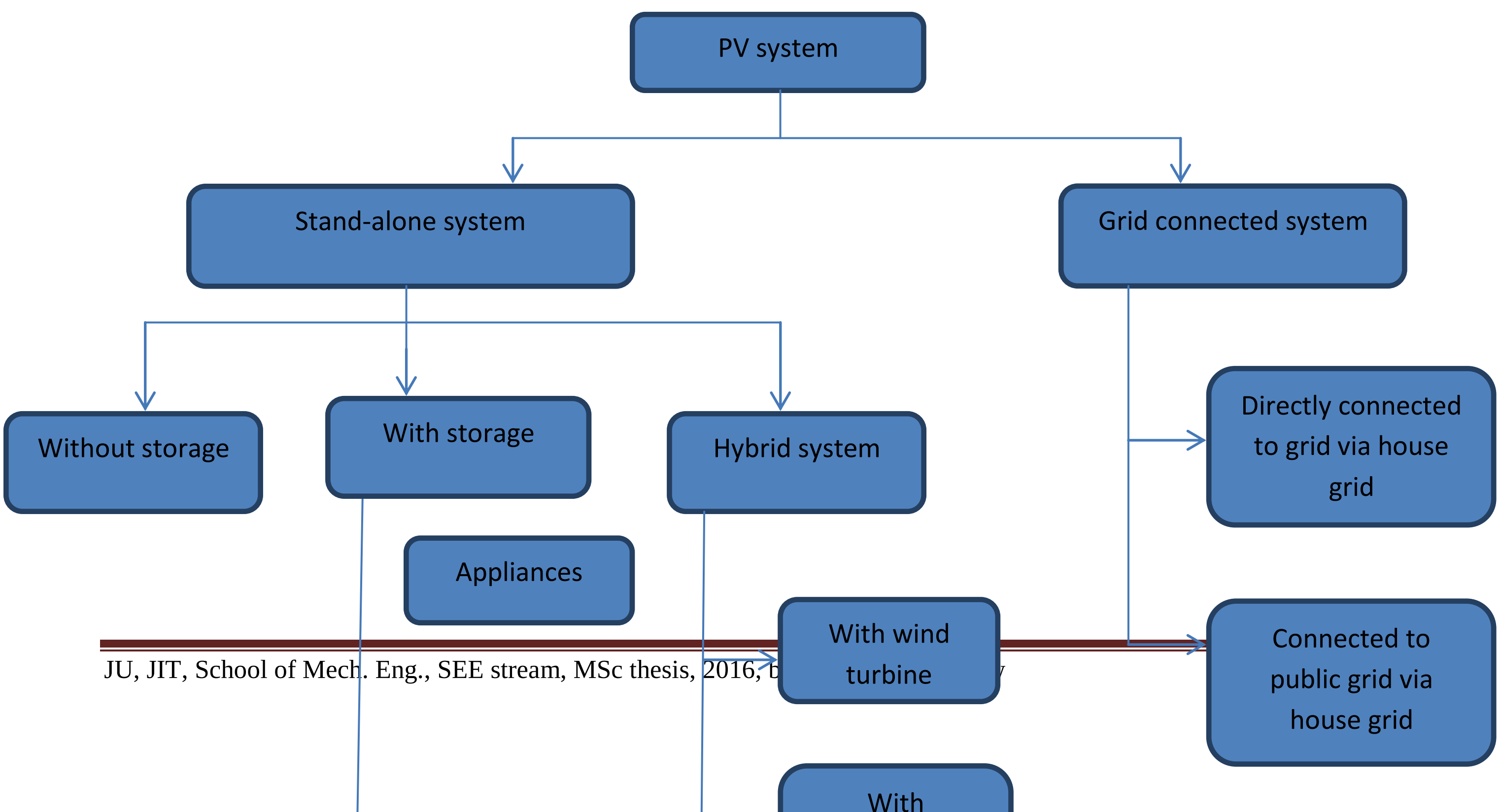
Stand-alone PV systems generally require an energy storage system because the energy generated is not usually (or infrequently) required at the same time as it is generated (i.e. solar energy is available during the day, but the lights in a stand-alone solar lighting system are used at night). Rechargeable batteries are used to store the electricity. However, with batteries, in order to protect them and achieve higher availability and a longer service life it is essential that a suitable charge controller is also used as a power management unit. Hence, a typical stand-alone system comprises the following main components:

1. PV modules usually connected in parallel or series-parallel;
2. charge controller;
3. battery or battery bank;
4. load(s);
5. inverter - in systems providing alternating current (AC) power.

2.2.2 Grid-connected systems

A grid-connected PV system essentially comprises the following components:

1. PV modules/array (multiple PV modules connected in series or parallel with mounting frame),
2. PV array combiner/junction box (with protective equipment),
3. Direct current (DC) cabling,
4. DC main disconnect/isolator switch,
5. Inverter,
6. AC cabling,
7. Meter cupboard with power distribution system, supply and feed meter, andelectricity connection.



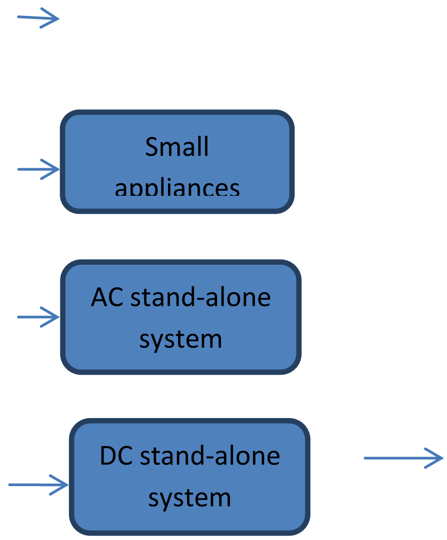


Figure 2.3: Types of PV systems (Source: [20])

2.3 Direct and diffuse radiation

Sunlight on the Earth's surface comprises a direct portion and a diffuse portion. The direct radiation comes from the direction of the sun and casts strong shadows of objects. By contrast, diffuse radiation, which is scattered from the dome of the sky, has no defined direction.

Depending upon the cloud conditions and the time of day (solar altitude), both the radiant power and the proportion of direct and diffuse radiation can vary greatly [20].

2.4. Solar Photovoltaic Technologies

Solar cell is the heart of solar energy generation system. It consists of three major elements, namely:

- The semiconductor material which absorbs light and converts it into electron-hole pairs.
- The junction formed within the semiconductor, which separates the photo-generated carriers(electrons and holes).
- The contacts on the front and back of the cell that allow the current to flow to the external circuit.

Two main streams of technologies have been evolved for the manufacture of Solar Cells/Modules namely: flat plate and concentrated.

2.4.1. Flat plate Technology

Flat Plate Technology is further classified in two ways namely:

- Crystalline Technology and
- Thin Film Technology.

2.4.1.1. Crystalline Technology

Crystalline Silicon (c-Si) was chosen as the first choice for solar cells, since this material formed the foundation for all advances in semiconductor technology. The technology led to development of stable solar cells with efficiency up to 20%.

There are two types of crystalline silicon:

• Mono crystalline Silicon

• Multi crystalline Silicon

2.4.1.1.1.Mono-Crystalline Silicon

Mono-Crystalline Silicon cells are produced by growing high purity, single crystal Si rods and slicing them into thin wafers. Single crystal wafer cells are expensive. They are cut from cylindrical ingot sand do not completely cover a square solar module. This results in substantial waste of refined silicon.

The efficiency of mono-crystalline silicon cells remains between 17-18% because of the purity level.

Figure 2.4: Mono crystalline silicon cell [19]

2.4.1.1.2.Multi/Poly Crystalline Silicon

Poly-crystalline silicon cells are made from sawing a cast block of silicon first into bars and then wafers. Poly-Si cells are less expensive to produce than single crystal silicon cells as the energy intensive process for purification of silicon is not required. They are less efficient than single crystalline cells. The efficiency of polycrystalline silicon cells ranges from13-14%.

2.4.1.2 Thin Film Technology

In Thin Film Solar technology, a very thin layer of chosen semiconductor material ranging from nanometer level to several micrometers in thickness is deposited on to either coated glass or stainless steel or a polymer substrate.

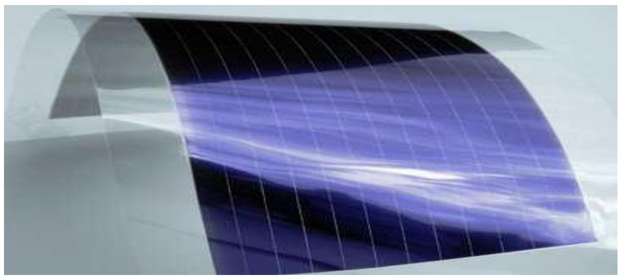


Figure 2.5: Thin film solar cell [19]

2.4.1.2.1Amorphous Silicon Thin Film Technology

Silicon thin-film cells are mainly deposited by chemical vapor deposition (typically plasma-enhanced PE-CVD process) from silane gas and hydrogen gas. Depending on the deposition parameters, this can yield:

- Amorphous silicon (a-Si or a-Si: H)
- Proto crystalline silicon
- Nano crystalline silicon (nc-Si or nc-Si:H), also called microcrystalline silicon.

2.4.1.2.2 Cadmium Telluride Thin Film Technology

A Cadmium Telluride (CdTe) solar cell is a solar cell based on cadmium telluride, an efficient light absorbing material for thin-film cells. Compared to other thin-film materials, CdTe is easier to deposit and more suitable for large-scale production.

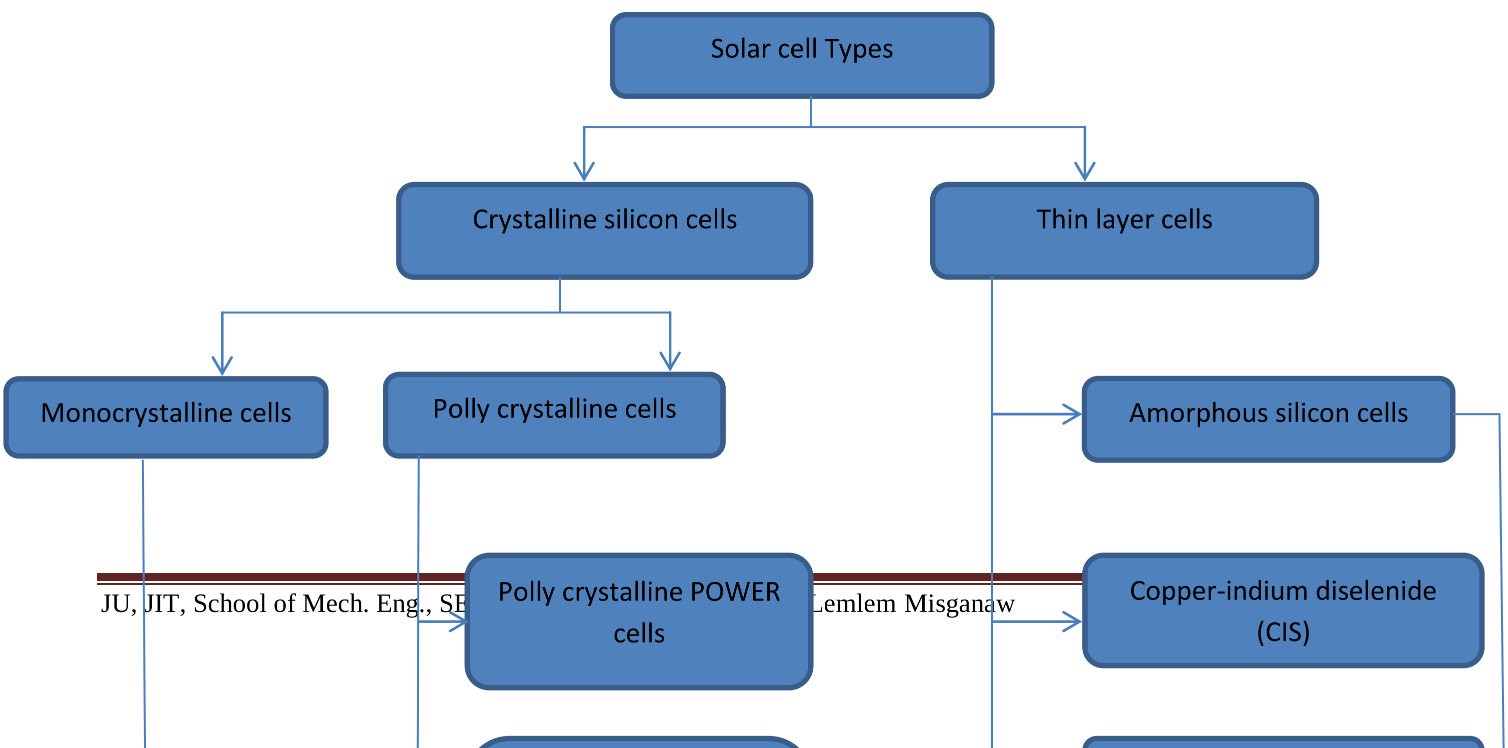
2.4.2 Concentrated Photovoltaic Technology

In Concentrated Photovoltaic (CPV) systems, solar energy collected over large area is focused on each cell having smaller area, to achieve higher power output and improved conversion efficiency.

Thus the expensive semiconductor material required for power generation is reduced giving a substantial cost advantage. Although Si based SPV technology is fairly mature, CPV technology is still evolving and has a huge potential.

Primary reason for using CPV is that, same amount of semiconductor material can produce higher amount of energy thus reducing the cost of power generation significantly [19].

Figure 2.6: Concentrated PV Module (Source: [19])



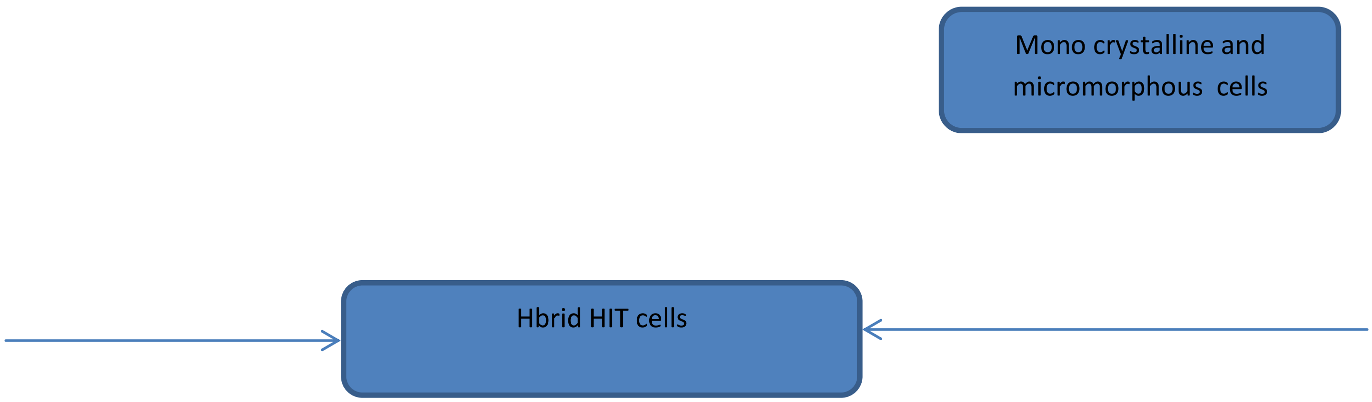


Figure 2.7: Types of solar cells(Source:[20])

2.5. Solar Receiver Technologies

Solar receivers used for collecting solar energy are classified as flat plate arrays, tracking arrays and concentrator arrays.

2.5.1. Flat Plate Arrays

Flat plate arrays use both diffuse and direct sunlight and they can operate in either fixed orientation orin a sun-tracking mode. Fixed orientation is used in most applications. However, with the advent of low-cost passive sun-trackers, flat plate tracking arrays are becoming more popular.

Figure 2.8: Flat plate collector (Source: [19])

2.5.2. Tracking Arrays

In tracking arrays, Solar array follows the path of the sun and maximizes the solar radiation incident on the photovoltaic surface. The two most common orientations of tracking arrays are:

- **One-axis tracking:** In this tracking mechanism, the array tracks the sun east to west. It is used mostly with flat-plate systems and occasionally with concentrator systems.
- **Two-axis tracking:** In this tracking mechanism, the array points directly at the sun at all time. It is used primarily with PV concentrator systems

Figure 2.9: Pole mounted tracking array(Source: [19])

2.5.3. Concentrator Arrays

Concentrator arrays use optical lenses and mirrors to focus sunlight onto high-efficiency cells. The following figure shows three forms of concentrator devices. The major advantage of concentrating device is that they use relatively small areas of expensive photovoltaic material. The larger aperture areas are made up of less expensive plastic lenses or other materials.

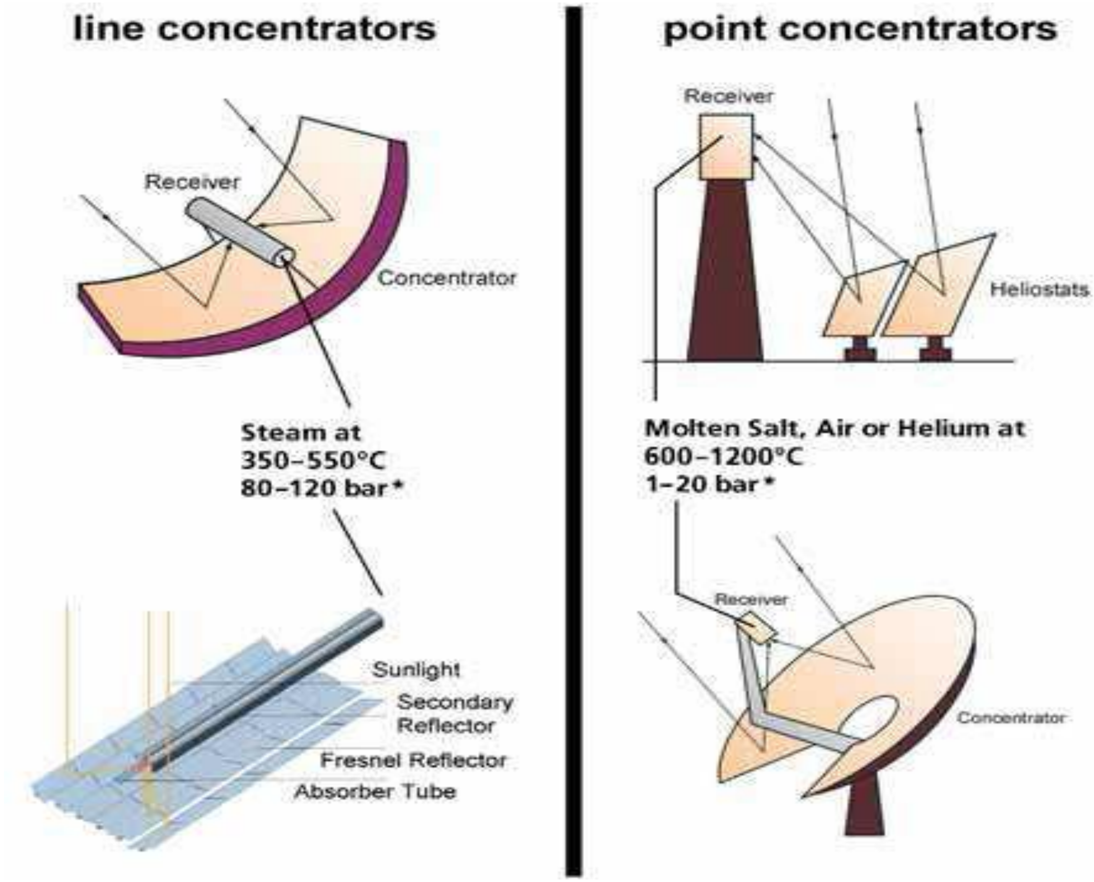


Figure 2.10: Concentrator arrays (Source: [19])

Concentrator arrays must track the sun because they rely on the ability to focus direct sunlight. These arrays are best used in the areas with high direct beam radiation.

2.6. Advantages and Limitations of Solar Energy

Renewable energy sources in general, and Solar Energy source in particular, has the potential to provide energy services with zero or almost zero emission. Among renewable energy sources, solar energy is the most abundant energy source. Every technology has its own advantages and disadvantages. Since solar insolation and atmospheric conditions vary significantly from place to place, efficiency of solar energy generation also differs accordingly.

2.6.1. Advantages

• It is an abundant Renewable Energy Source.

• This technology is Omnipresent and it can be captured for conversion on a daily basis.

• It is a Non-polluting technology it does not release greenhouse gases.

• It is a Noiseless technology as there are no moving parts involved in energy generation.

• This technology requires Low-maintenance cost since there are no moving parts.

• It can be installed on modular basis and expanded over a period of time.

• Most viable alternative for providing electricity in remote/rural areas.

2.6.2. Limitations

• As the technology is in an evolving stage, the efficiency levels of conversion from light to electricity is in the range of 10 to 17%, depending on the technology used.

• The initial investment cost of this technology is high. At present the technology is basically surviving because of subsidy schemes available by the government.

• Solar energy is available only during daytime. Most load profiles indicate peak load in the evening/night time. This necessitates expensive storage devices like battery, which need to be replaced every 3 to 5 years. Generally, the cost of the Battery is 30 to 40% of the system cost.

• As the efficiency levels are low, the space required is relatively high.

• Solar energy is heavily dependent on atmospheric conditions.

• Solar insolation varies from location to location, so there are certain geographic limitations in generating solar power.

• With the existing module and inverter manufacturing technologies, it may not be worthwhile in terms of costs to deploy solar energy for certain loads which require very high starting power (e.g. air conditioners) [19].

2.7. Solar Radiation

Solar radiation is the amount of solar energy available on the ground surface over a specified time, expressed as kwh/m^2/day or MJ/m^2/day. The sum of direct and diffuse solar irradiation is called global irradiation [22].

Solar irradiation incident on the surface of the earth is an important input parameter for many solar energy applications. Thus, the prediction of monthly average of the daily global solar irradiation is necessary to conduct feasibility studies for solar energy systems and their practical implementation [23].

Ethiopia receives an average of 5.5kWh/m^2/day to 6.5kWh/m^2/day of solar insolation. Since there are seasonal variations but not as extreme cases during the year the insolation also varies from4.55kWh/m^2/day in July to a maximum of 5.55kWh/m^2/day in February and March. Moreover, there is also variation in solar energy resource due to geographical location ranging from 4.25kWh/m^2/day in the South-West region to 6.25kWh/m^2/day in the North region of the country.

The most common solar energy resource data collected in many of the meteorological stations throughout the country is the average daily sunshine hours [12].

Sunshine duration or sunshine hours is a climatological indicator, measuring duration of sunshine in a given period for a given location on earth. It is a measure of cloudiness of a location. Bright sunshine hours at a given location vary significantly due to atmospheric components and it is measured by sunshine recorders.

Among the meteorological and atmospheric parameters that affect the amount of global solar radiation reaching a horizontal location, the greatest influence is exerted by sunshine hours [24].

2.7.1 Estimation of Solar Radiation of the Site Using Sunshine Hour

In this work daily sunshine hour data of the site was taken from National Meteorological Service Agency Jimma branch in order to estimate the solar energy potential of the site.

Four years (2012-2015) daily sunshine hour data of the site was considered and monthly sunshine hour was calculated which was shown in table 2.1.

Table 2.1: Four years average monthly sunshine hours of Cheri Alga site.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunshine	8.5	8.8	8.5	8.1	7.3	6.3	4.3	4.4	4.7	8	8.4	8.6

hour												

The monthly average daily hours of bright sunshine from NMSA Jimma branch with Shrink as nearby station for each year and four years average data from 2012 up to 2015is shown in figure 2.10.

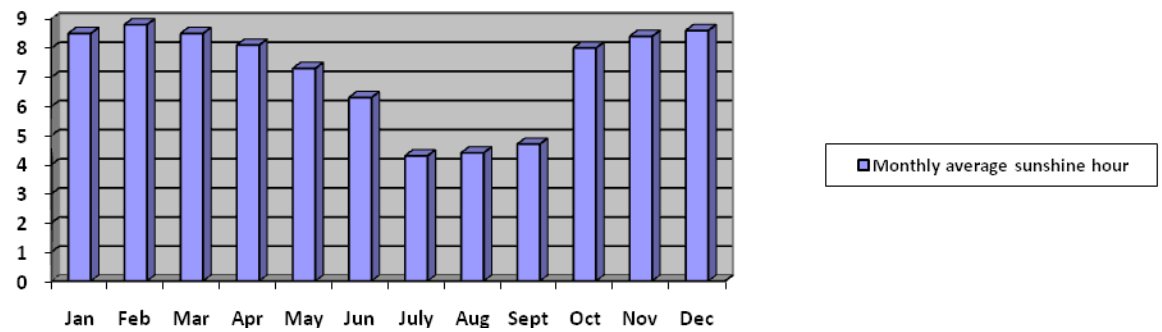


Figure 2.11: Monthly Average daily sunshine hours of the site[Source: NMSA]

The simple model used to estimate monthly average daily global solar radiation on horizontal surface is the modified form of the Angstrom-type equation.

The original Angstrom-type regression equation is related with the monthly average daily radiation to the clear day radiation at the location and the average fraction of possible sunshine hours (Angstrom, 1924). Page (1961) and others have modified the method using the values of extraterrestrial radiation on a horizontal surface rather than that of clear day radiation (Duffie and Beckman, 1991):

The most common model which is used to estimate monthly average daily global solar radiation is the Angstrom – Prescott (1940) model given by:

$$\frac{H}{Ho} = a + b\left(\frac{S}{So}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

Where:

H:is the monthly average daily global radiation on a horizontal surface (MJ/m^2/day), Ho: is the monthly average daily extraterrestrial radiation on a horizontal surface ($MJ/m^2/day$), where $1kWh/m^2/d = 3.6 MJ/m^2/d$

S:is the monthly average daily hours of bright sunshine,

So: is the monthly average day length, and

a and b: are known as Angstrom constants and they are empirical.

The values of the monthly average daily extraterrestrial irradiation (Ho) can be calculated from the following equation (eq. 2.2):

$$Ho = \left(\frac{24}{\pi}\right) * Isc\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] * \left[cos\phi cos\delta sinWs + \left(2 * \pi * \frac{Ws}{360}\right) sin\phi sin\delta\right] \ldots (2.2)$$

Where

Isc:is the solar constant (=1367 W/m^2),

ϕ: is the latitude of the site = 8° 60' 39"

δ:is the solar declination,

Ws: is the mean sunrise hour angle for the given month, and

n:is the number of days of the year starting from the first ofJanuary.

The solar declination (δ) and the mean sunrise hour angle (Ws) can be calculated by the following equations:

$$\delta = 23.45 * \sin\left[360 * \frac{284 + n}{365}\right] \ldots \ldots \ldots (2.3)$$

$$Ws = \cos - 1\ (-tan\phi\tan\delta) \ldots \ldots \ldots (2.4)$$

For a given month, the maximum possible sunshine duration (monthly average day length (So) which is related to Ws, the mean sunrise hour angle can be computed by using the following equation:

$$So = \frac{2}{15} * Ws \ldots \ldots \ldots (2.5)$$

Then, the monthly mean of daily global radiation H was normalized by dividing with monthly mean of daily extraterrestrial radiation Ho. We can define clearness index as the ratio of the observed/measured horizontal terrestrial solar radiation(H),to the calculated/predicted horizontal/extraterrestrial solar radiation(Ho):

$$KT = \frac{H}{Ho} \dots\dots\dots\dots\dots\dots\dots\dots (2.6)$$

[25].

The regression coefficients a and b are expected to improve by adding the effect of latitude, elevation, and ratio of sunshine duration together. Thus the regression coefficients a and b in terms of the latitude, elevation and percentage of possible sunshine for any location around the World (for 5°<*Φ*<54°) are correlated by Gopinathan with equation below [26]:

$$a = -0.309 + 0.539cos\phi - 0.0693h + 0.29\left(\frac{S}{So}\right) \dots\dots\dots\dots\dots (2.7)$$

$$b = 1.529 - 1.027cos\phi + 0.0926h - 0.359\left(\frac{S}{So}\right) \dots\dots\dots\dots\dots (2.8)$$

Where: h is the elevation of the location above sea level in km = 1776 km.

Table 2.2: Solar radiation data analyzed from daily sunshine hour of the site

Month	n(no)	δ(°)	Ws(°)	S(hr)	So(hr)	S/So	a	b	H (kwh/m2/d)	Ho (kwh/m2/d)	KT (H/Ho)
January	17	-21.1	86.56	8.5	11.5	0.74	0.32	0.41	6.68	10.8	0.62
February	47	-14.1	87.7	8.8	11.7	0.75	0.32	0.41	6.48	10.36	0.63
March	75	-2.3	89.43	8.5	11.9	0.71	0.31	0.42	6.38	10.49	0.61
April	105	9.4	88.28	8.1	11.8	0.69	0.30	0.43	6.13	10.28	0.60
May	135	18.8	87.13	7.3	11.6	0.63	0.28	0.45	6.08	10.71	0.57
June	162	23.5	86.56	6.3	11.5	0.55	0.26	0.48	5.30	10.15	0.52
July	198	21.1	86.56	4.3	11.5	0.37	0.21	0.54	4.44	10.77	0.41
August	228	14.1	87.7	4.4	11.7	0.38	0.21	0.54	4.43	10.70	0.41
September	258	2.3	89.43	4.7	11.9	0.39	0.22	0.54	4.31	10.10	0.42
October	288	-9.4	88.28	8.0	11.8	0.68	0.30	0.43	6.35	10.72	0.60
November	318	-18.8	87.13	8.4	11.6	0.72	0.31	0.42	6.68	10.89	0.61
December	344	-23.5	86.56	8.6	11.5	0.75	0.32	0.41	6.36	10.22	0.62
Annual average							0.28	0.46	5.8	10.52	0.55

The solar declination (δ) and the mean sunrise hour angle (Ws) values calculated by equation 2.3 and 2.4 were inserted in equation 2.2 to calculate the monthly average daily extraterrestrial radiation on a horizontal surface (Ho).

The mean sunrise hour angle (Ws) value calculated by equation 2.4 was inserted in equation 2.5 to calculate monthly average day length (So).

The ratio of values of S from table 2.1and the values of So calculated by equation (2.5), latitude and elevation above sea level of the site were inserted in equation 2.7 and 2.8 to calculate the values of regression coefficients "a" and "b".

Annual average values of regression coefficients a and b is obtained as 0.28 and 0.46.

Finally, the monthly average daily horizontal global solar radiation was calculated by equation 2.1 and the maximum solar radiation was obtained on the months of January and November as 6.68 kwh/m^2/d and the minimum value is obtained on the month of September as 4.31 kwh/m^2/d and annual average of 5.8 kwh/m^2/d.

Table 2.3: Monthly average daily horizontal global solar radiations from NMSA and NASA [27].

Month	NMSA	NASA
January	6.68	5.86
February	6.48	6.24
March	6.38	6.21
April	6.13	6.13
May	6.08	5.63
June	5.30	5.11
July	4.44	4.65
August	4.43	4.78
September	4.31	5.43
October	6.35	5.64
November	6.68	5.60
December	6.36	5.76
Average	5.8	5.59

The values ofthe monthly average daily horizontal global solar radiation on a horizontal surface from NMSA and NASA were 5.8 kwh/m^2/d and 5.59 kwh/m^2/d**.** It was observed that there is no significant difference between the above three values.

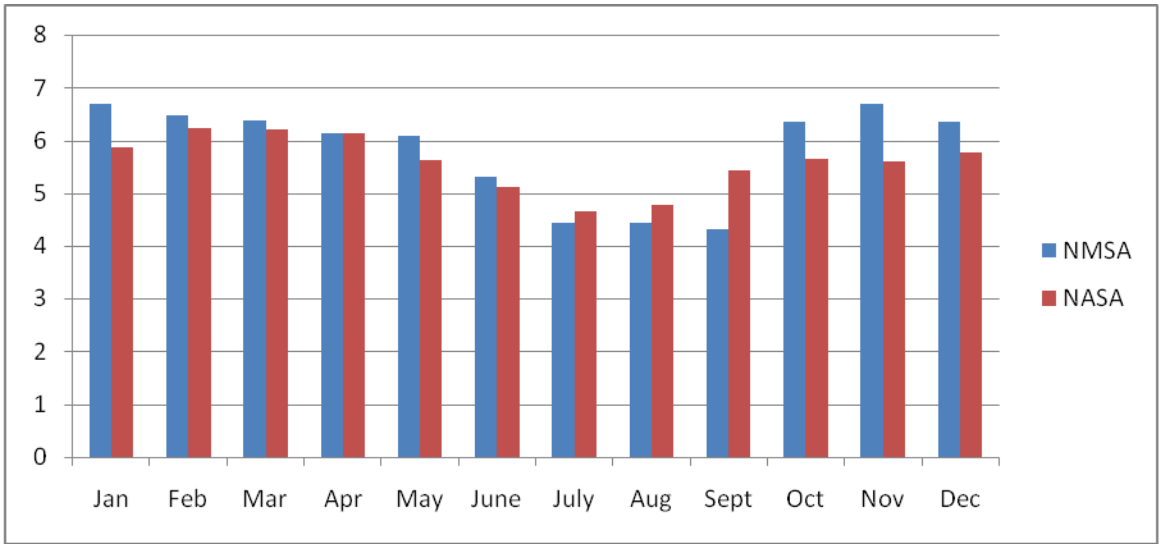


Figure 2:12Monthly average daily horizontal global solar radiations from NMSA and NASA

CHAPTER THREE

ELECTRIC LOAD ESTIMATION

Actual load data for rural populations is not readily available. So load data of the community under this study was obtained by interviewing the rural community to know the type and quantity of household appliances, by obtaining information for number of households, flour mill, education center, health center and small & micro enterprises from Limmu Seka Woreda administration and by referring related literatures.

The electricity consumption does not vary almost the whole year except for May, June, July and August. In this study the electric load demand of the nearby community irrigation water pumping is divided in to the following four major categories. These are: household/domestic load which includes (lighting, Radio, TV, and baking appliances); Commercial loads (flour milling machine, tea shops, small and micro store); Community load which consists of (elementary and satellite school lighting, desktop computer, printer), health clinic which includes (vaccine refrigerator, communication radio, television, microscope, computer and printer) and deferrable load (water supply and irrigation systems). The total electric load estimated for the listed appliances above were summed up to get the required load to be supplied by the system.

Load estimation was done based on the electric appliances to be used by the community. Renewable sources power production systems cannot generate the exact amount sought to meet the load demand, either they produce excess electricity or below the demand. Thus instead of calculating the estimated load of the community by the efficiency factor of each appliances it is better to allow excess electricity production from the system. The initial point to know in calculating the load is deciding which appliance has to be used by the rural family households accounting the current and future situation of the local community.

3.1. Estimation of primary load

Primary load is electrical load that should be met by the energy providing system as it is required immediately. Electrical load demand which includes lighting, baking, different medicine refrigeration, TV, radio, computer, printer, fax, simple laboratory equipments and flour mills typically modeled as primary load. The electricity load consumption in each household is considered to be the same and constant throughout the year. The load estimation of the village was done for 904 households consisting of 2104 males and 2398 females a total population number of 4502.

3.1.1Domestic load

For an individual household, the electricity demand is assumed for compact fluorescent lumps (CFLs), radio or cassette recorder, TV, mobile charger, for Enjera (local food) baking Wot cooking.

The individual household was assumed to use 2 units of 11W compact fluorescent lamps which is to be operational for 6:00 hours, on average from 18:00-00:00 hour. A cassette recorder or a radio of 5W which will be operated for 4 hours from 18:00 to 22:00.

Table 3.1:Common domestic loads of the community

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day
1	Light points	1808	11	6	19.888	119.328
2	Cassette recorder/Radio	904	5	4	4.52	18.08

Street lights were assumed to be used in common by 3 households for 12 hours from 18:00 to 6:00. It is also assumed that Enjera baking machine, stove, Tv sets and Mobile phones will be used by households who can afford them. So a 3KW of Enjera baking machine will be used for 1 hour from 6:00 to 7:00. A stove of 0.5KW will be used for 4 hours from 7:00 to 10:00 and from 19:00 to 20:00.A Tv set of 65W will be on function for 8 hours from 12:00-14:00 and from 18:00-00:00. Refrigerator with a capacity of 200W will be used for 24 hours. A mobile charger will be charged for 2 hours from 12:00 to 13:00 and 21:00 to22:00.

Table 3.2Other domestic loads of the community

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day
1	Enjera baking machine	5	3000	2	15	30
2	Cooking stove	20	500	2	10	20
3	Tv sets	100	65	8	6.5	52
4	Refrigerator	50	200	24	10	240
5	Mobile charger	150	5	2	0.75	1.5
6	Street light	301	11	12	3.311	39.732

3.1.2Health Center Load

There is one governmental health center which is engaged in emergency services, curing minor illnesses and follow up and delivery of pregnant women. The health center has 1 unit of 20W microscope working for 4:00 hours per day from 9:00-12:00 and from 13:00-14:00, 1 unit of 60W vaccine freezer operating for 24:00 hours, 6 compact fluorescent lumps which would work for 8 hours from 8:00-12:00 and from 13:00-17:00 and 2 units of 15W lumps for external lighting from 18:00-6:00 hours, 1 communication radio 5W assumed to work for 8:00 hours of a day from 08:00-12:00 and from 13:00-17:00, 1 unit of 65W 14" television which is expected to work for 9:00 hours per day from 08:00-17:00 hours, 1 unit 60W desktop computer working for 8:00 hours from 8:00-12:00 and 13:00-17:00 hour, 1 unit 50W printer working for 1:00 hour per day from 14:00-15:00.

There is also one private clinic which gives medical services to those who need. 1 unit of 20W microscope working for 4:00 hours per day from 9:00-12:00 and from 13:00-14:00, 4 compact Fluorescent lumps which would work for 8 hours from 8:00-12:00 and from 13:00-17:00 and 1 unit of 15W lump for external lighting which works for 12:00 hours from 18:00-6:00 hours, 1 unit of 60W vaccine freezer operating for 24:00 hours and 1 unit of 65W 14" television which is expected to work for 9:00 hours per day from 08:00-17:00 hours. In addition there is one animal laboratory. 2 compact fluorescent lumps which would work for 8 hours from 8:00-12:00 and from 13:00-17:00 and 1 unit of 15W lump for external lighting which works for 12:00 hours from 18:00-6:00 hours and 1 unit of 60W vaccine freezer operating for 24:00 hours.

Table 3.3: The electric load demand of health centers and animal laboratory.

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day
1	Laboratory Microscope	2	20	4	0.04	0.16
2	Vaccine freezer	2	60	24	0.12	2.88
3	Room lighting	12	11	8	0.132	1.056
4	External-lighting	4	15	12	0.06	0.72
5	Communication radio	1	5	8	0.005	0.04
6	Television	2	65	9	0.13	1.17
7	Computer	1	60	8	0.06	0.48
8	Printer	1	50	1	0.05	0.05

3.1.3 Education/School Load

There is one elementary school from grade 1 up to 8 and one satellite school. It is assumed that there will be no need of light for the class rooms during day time since there will be enough sun light for the class rooms through the windows. It is assumed that electric power supply is required for administration offices, for two night shift classes and for toilet rooms for 3:00 hours from 18:00 to 21:00. 2 lamps for external lighting from 18:00 to 6:00.One 60W computer working for 8 hours a day from 8:00 to 12:00 and from 13:00 to 17:00 hours. One 50W printer working 2 hours per a day from 14:00 to 16:00 hours.

Table 3.4: Education/school load of the Kebele

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day
1	Class room, administration offices and toilet lighting	7	11	3	0.077	0.231
2	External lighting	2	13	12	0.026	0.312
3	Computer	1	60	8	0.06	0.48
4	Printer	1	50	2	0.05	0.1

3.1.4 Commercial Load

Currently diesel driven flour milling machines are used for flour milling purposes in the study area. But the running cost is high and results in increased price per kilogram of the milled flour as well as environmental pollution. Thus, two flour milling machines were proposed to be installed in the village. It will not only serve the local community but also the nearby communities that do not have electricity access and the owners will get more income. The flour milling motors have power rating of 15KW each and will operate for 8:00 hours a day from 10:00-18:00 hours.

And there are six tea selling/shayi bet/ which will use stoves and have Tv sets. 6 stoves working for 11:00 hours per a day from 7:00 to 18:00 hours and 14" television working for 10:00 hours per a day from 8:00 to 18:00 hours.

In addition there is one store for small and micro services. The store needs 4 compact fluorescent lumps for store lighting working for 8 hours from 8:00 to 12:00 and from 13:00 to 17:00 and two lumps for external lighting working for 12 hours per a day from 18:00 to 6:00 hours.

Table 3.5:Commercial services load of the community

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day
1	Flour mill	2	15000	4	30	120
2	Cooking stove	6	500	11	3	33
3	Tv sets	6	65	10	0.39	3.9
4	Room lighting	4	11	8	0.044	0.352
5	Street light	2	15	12	0.03	0.36

3.2 Deferrable Load

Deferrable load is a load that can be served after the fulfillment of primary load demand except in situations like water tank became empty below the required level. It is also called secondary load. There are two main deferrable loads in the study area:

- Water pump
- Pumped irrigation

Energy storage capacity = No of pumps*Capacity of pumps*running hours per a day*storage days

3.2.1 Water Pump Load

Clean water supply is essential to every community to secure the health condition of a given community. So for the supply of clean water a 7.5KW pump will be operated for 6:00 hours per a day from 9:00 to 14:00. Water storage capacity for three days is preferred.

Table 3.6: Water pump load

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day	Energy storage capacity
1	Water pump	1	7500	6	7.5	45	135

3.2.2 Irrigation Load

Jimma Zone Irrigation Development Authority is currently installing diesel generator to supply power for 70HP/59.5KW/ pump. So the pump works for 8:00 hours a day from 6:00 to 10:00 and from 14:00 to 18:00. Since there will be enough rain water during winter, energy consumption for the months July, August and September considered to be zero.

Table 3.7:Irrigation load

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day	Energy storage capacity
1	Irrigation pump	1	59500	8	59.5	476	1428

Exception to the load profile: for rainy season (months from June to October), irrigation pumps became idle so deferrable load decreases. The power consumption of these pumps is taken to be zero for these months.

3.3.Load forecast for the coming three years

Load forecast was done by taking population growth of the community living in the village. In 2005 number of households in the village were 859 with number of males 2265 and number of females 1987 a total of 4252. And number of households in 2008 is 904. Population growth of the village with three years range is 5.24%. Here it is known that there will not be further extensions in school, health center and irrigation services. And current commercial service and water supply loads can accommodate the coming three years load. So significant load is expected only for domestic purposes.

Domestic load which is expected after three years is shown on the following tables.

Table 3.8:Domestic load growth for common services.

No	Appliances	Quantity	Capacity	Working	Peak load	KWh/day

			(Watts)	(hours/day)	(kW)	
1	Light points	1903	11	6	20.933	125.598
2	Cassette recorder/Radio	951	5	4	4.755	19.02

Table 3.9:Load growth of other domestic loads

No	Appliances	Quantity	Capacity (Watts)	Working (hours/day)	Peak load (kW)	KWh/day
1	Enjera baking machine	5	3000	2	15	30
2	Cooking stove	21	500	2	10.5	21
3	Tv sets	105	65	8	6.825	54.6
4	Refrigerator	52	200	24	10.4	249.6
5	Mobile charger	158	5	2	0.79	1.58
6	Street light	317	11	12	3.487	10.461

Table 3.10: Summary of primary load by service type

Type of Load	Quantity (No)	Capacity(KW)	Total Capacity(KW)
Light points	1903	0.011	20.93
Cassette recorder/Radio	951	0.005	4.8
Enjera baking machine	5	3	15
Cooking stove	21	0.5	10.5
Tv sets	105	0.065	6.8
Refrigerator	52	0.2	10.4
Mobile charger	158	0.005	0.8
Street light	317	0.011	3.5
Flour mill	2	15	30
Water Pump	1	7.5	7.5
Irrigation Pump	1	59.5	59.5

Table 3.11: Summary of primary load

Hour of a day	Power(kw)	Hour of a day	Power(kw)
0:00-1:00	14.227	12:00-13:00	44.950
1:00-2:00	14.227	13:00-14:00	44.620
2:00-3:00	14.227	14:00-15:00	44.550
3:00-4:00	14.227	15:00-16:00	44.500
4:00-5:00	14.227	16:00-17:00	14.450
5:00-6:00	14.227	17:00-18:00	14.020
6:00-7:00	36.120	18:00-19:00	43.420
7:00-8:00	24.120	19:00-20:00	46.920
8:00-9:00	24.950	20:00-21:00	46.920
9:00-10:00	24.990	21:00-22:00	47.640
10:00-11:00	44.490	22:00-23:00	38.540
11:00-12:00	44.490	23:00-24:00	38.540

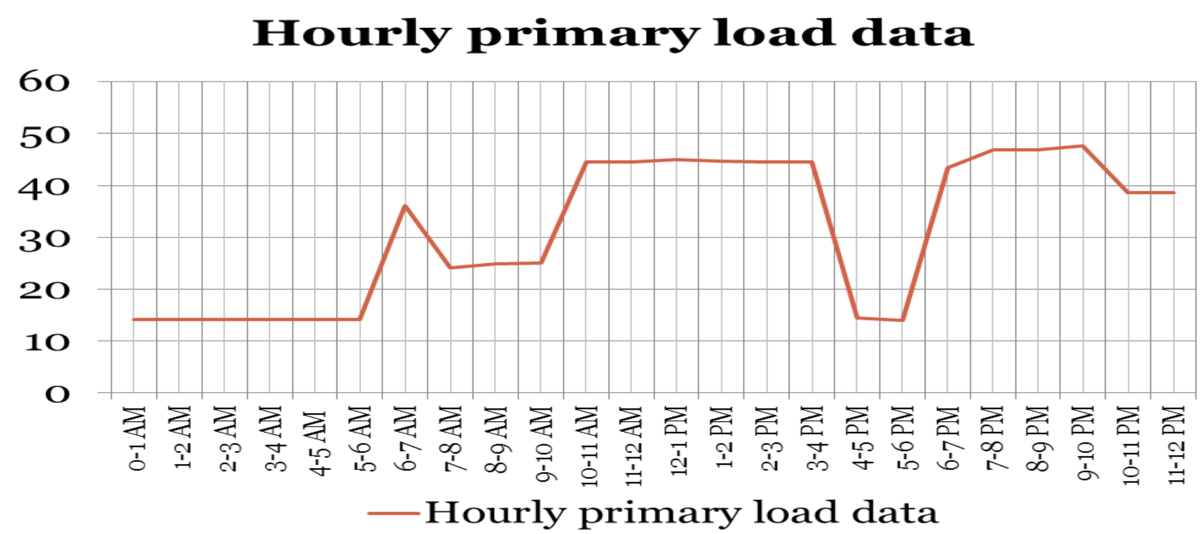


Figure 3:1 Hourly primary load data

CHAPTER FOUR

HYBRID POWER SYSTEM, COMPONENTS AND HOMER TOOL

4.1Hybrid Power Systems

A hybrid system is a system which consists of two or more sources of power generation which is used to obtain higher efficiency than systems which include only one power source and exploitation in the best work point. Since operation of a hybrid power generation system strongly depends on environmental conditions, it is necessary to firstly choose the renewable energy sources which are available in the area of exploitation of the hybrid system. The problem of intermittent nature of renewable energy sources is eliminated by using energy storage elements and non-renewable energy sources in a hybrid system [28].

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

- Diesel generator fuel usage and greenhouse gas emission reduction.
- Use of locally available resources.
- Deducts/avoids power shortfalls, increase sustainable power supply.
- Provides electricity access in short periods than waiting for grid extension and ease to scale-up at any time.

Hybrid standalone systems have merits of environmental protection and power control flexibility than diesel generator alone. A hybrid system can expand its capacity when load demand gets higher in the future, from renewable systems, diesel generator rated power or both of them [12].

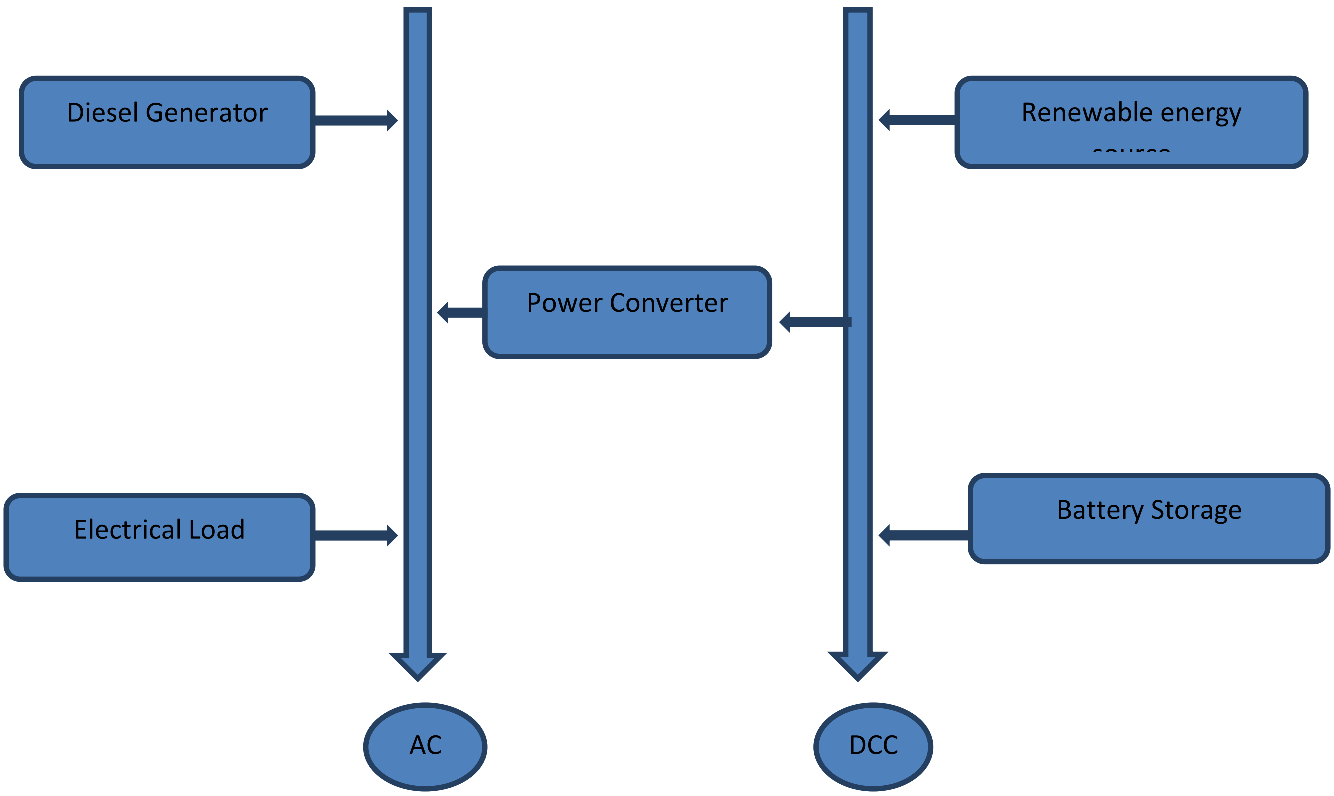


Figure 4.1: Schematic of the hybrid system

Figure 4.1shows the overall schematic of the energy production system independent of grid supply which is considered in this study.

4.2 Components of the Hybrid System

The hybrid system consists of solar PV and diesel generator with battery storage to satisfy the electrical power demand of Cheri Alga Village community and irrigation water pumping.

The hybrid system can be characterized as ac/dc bus hybrid system in which some energy sources connected to the dc bus and others to ac bus. Most of the time PV array is connected to the dc bus via charge controller. AC bus connection of PV is also possible with some systems [29].

Diesel generator power source is connected to the ac bus and charges battery via a bidirectional inverter which will act as rectifier.

This hybrid system consists of solar PV, Diesel Generator, Battery Storage, Charge Controller and Bidirectional Invertor. The DC power supply from PV and Battery is converted to AC by inverter and connected to AC bus. The power supplied by diesel generator is connected to AC bus.

4.3Overview of HOMER Software

Hybrid Optimization Model for Electric Renewable (HOMER) is a free computer model developed originally by the National Renewable Energy Laboratory (NREL)in the United States. This software application is used to design and evaluate technically and financially the

options for off-grid and on-grid power systems for remote, stand-alone and distributed generation applications. It allows considering a large number of technology options to account for energy resource availability and other variables.

HOMER was first developed in 1993 for internal DOE(Department of Energy) use to understand the tradeoffs between different energy production configurations. A few years after the original design NREL made a version publically available for free to serve the growing community of system designers interested in Renewable Energy. Since then HOMER has remained a free software application which has evolved in to a very robust tool for modeling both conventional and renewable energy technologies [30].

It has different energy generating components in its library. The user must select the components from the library to represent the architecture considered. This modeling tool uses time step from 1 minute to several hours. HOMER simplifies or helps the designer to compare various power systems options based on technical and economic aspects. The software answers questions like:

- What type of component to buy (solar PV, wind turbine, either both with battery or only wind and PV)?
- Does the designed system would meet future growing demand?
- What quantity of battery to buy?
- What if fuel and other prices changes?
- How to control the power system?

The software also chooses between the dispatch strategies (cycle charging and load following) by making comparisons. Design and analysis of systems can be challenging task because the large combination of design options and the inclusion of uncertainties. The design complexity and uncertainty increase when renewable sources are included in the system, because they are non-dispatch able and intermittent nature. HOMER developed to overcome these challenges. It does three main tasks as indicated in figure 4.2.

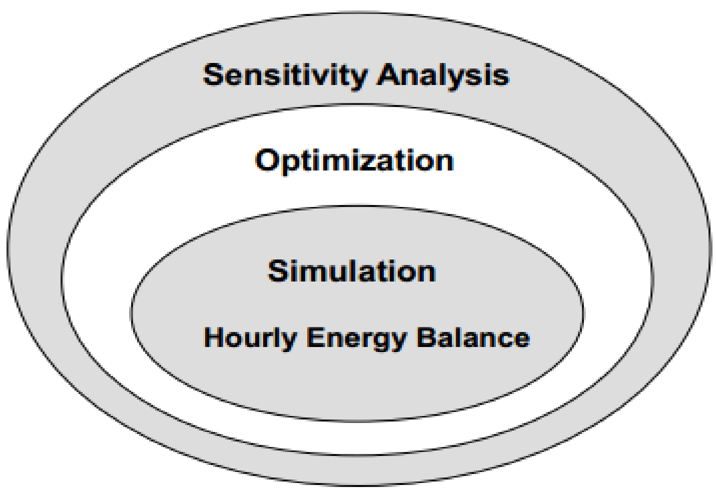


Figure 4.2: Interactions between Simulation, Optimization and Sensitivity Analysis (Source:[12])

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

Optimization: In this process it simulates each different system configurations in search of the lowest NPC and lists each power systems that meet the load demand.

The purpose of optimization is to determine the optimal system based on the decision variables imposed by the designer. Decision variable is a variable that has control by the designer. HOMERs decision variables may include like; PV array size, quantity of wind turbines, generator size, size of converter, quantity of batteries, dispatch strategy, and etc. Searching the optimal system includes deciding the mix of power components like size, quantity at the same time the dispatch strategy.

Sensitivity Analysis: It examines the effect of external parameters and does optimization for each sensitivity variables. But first defining the variables that can affect the system over its entire life is mandatory to input into the software.

The optimization process is repeated after specifying the sensitive parametric variables as an input in to the software. The sensitivity variables can be climatic data variations, components and fuel cost, interest rate, capacity shortages, operating reserves and others. HOMER does multiple optimizations using various sensitive inputs to see how sensitive output of the power system. The sensitivity results from HOMER are displayed in tabular and graphical forms [12].

4.3.1 How does HOMER work?

• HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year.

• For each hour calculates the flows of energy to and from each component of the system.

• HOMER performs these energy balance calculations for each system configuration that you want to consider.

• It then determines whether a configuration is feasible, i.e., whether it can meet the electric demand under the conditions that you specify.

• It estimates the cost of installing and operating the system over the lifetime of the project.

4.3.2 Advantages and Disadvantages

Advantages

Simulates a list of real technologies, as a catalogue of available technologies and components.

Very detailed results for analysis and evaluation.

Determines the possible combinations of a list of different technologies and its size.

It is fast to run many combinations.

It is possible to learn from the results.

Disadvantages

Quality input data needed.

Detailed input data and time needed.

Experienced criteria is needed to converge to the good solutions.

Homer will not guess key values or sizes [32].

4.4 Selection and Sizingof Hybrid System Components by Using Homer Software

4.4.1 Photovoltaic Panels

Solar energy is used as the base-load power source. PV array size is dependent on the solar radiation, load profile and renewable fraction. Renewable fraction is the fraction of energy delivered to the load that originated from renewable power sources, and in this case the renewable fraction is related to the solar PV production [32].

After surveying current price of solar PV from local market, it was observed that the PV cost is \$1.667/Watt. The capital cost of a PV system does not include installation, labor and structure costs. In this paper the replacement cost is taken as 60% of the PV price and the operation and maintenance cost would be 1% per year [33] [34] [35].

Operation and maintenance cost of $1/Watt and maintenance cost $17 per year was fed for Homer software. Aderating factor of 90%was applied to the electric production from each panel. This factor reduces the PV production by 10% to approximate the varying effects of temperature and dust on the panels [36].

The panels were modeled as fixed and tilted south at an angle equal to the latitude of the site.

HOMER uses the following equation to calculate the output of the PV array**[37]**:

$$Ppv = Yfpv\left(\frac{\bar{G}T}{\bar{G}T, STC}\right)[1 + \alpha p(Tc - Tc, STC)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots(4.1)$$

Where:

Y_{pv} is the rated capacity of the PV array, meaning its power output under standard test conditions[KW]

f_{pv} is the PV derating factor[%]

$\bar{G}_T$ is the solar radiation incident on the PV array in the current time step[1KW/m^2]

$\bar{G}_{T,STC}$ is the incident radiation at standard test conditions[1KW/m^2]

α_P is the temperature coefficient of power[%/^{o}C]

T_c is the PV cell temperature in the current time step[^{o}C]

$T_{c,STC}$ is the PV cell temperature under standard test conditions[25^{o}C]

4.4.2 Batteries

A battery is a device that stores Direct Current (DC) electrical energy in electrochemical form for later use. Battery the most widely used device for energy store in a variety of applications.

Most batteries used in the hybrid system are of the depth of the lead –acid types. There are several other appropriate types (nickel-cadmium, nickel-Iron, Iron-air and sodium-sulfur) but these are generally either too expensive or too unreliable for practical application as most of them are still at experimental stage. The lead-acid battery widely used and, although complex, is well known. Its major limitation is that it must be operated within strict boundaries as it is susceptible to damage under a certain condition- such as overcharging, undercharging and remaining for long periods a low state of charge [16].

The type of storage battery chosen is Surret 6CS25P from the manufacturer Rolls/surret, which is given in HOMER tool library. The selected battery has the following characteristics obtained from HOMER modeling tool. The nominal capacity of this battery is 1900Ah (7.4kWh) with nominal voltage of 4V for single battery and the amount of energy stored in a single battery is 7.4kWh, maximum charge current is 67.5A, lifetime throughput of 10569 kWh was considered, minimum state of charge is accounted for 40%, round-trip battery efficiency is taken as 80%.

Capital cost of $1200, replacement cost of $1200 and maintenance cost of $60/yr[39]was fed to HOMER modeling tool.

In HOMER, two independent factors limit the lifetime of the battery bank:

1. The lifetime throughput and
2. The battery float life.

In other words, batteries die either from use or from old age. HOMER calcuates the battery bank life using the following equation[37]:

$$Rbatt = MIN\left(Nbatt * \frac{Qlifetime}{Qthrpt}, Rbatt,f\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

Where:

Rbattis battery bank life [yr]

Nbattis number of batteries in the battery bank

Qlifetimeis lifetime throughput of a single battery [kWh]

Qthrptis annual battery throughput [KWh/yr]

Rbatt,fis battery float life[yr]

4.4.3 Converters

Converter is a device that can convert electrical power from ac to dc in a process called rectification and from dc to ac in a process called inversion. There are two types of converters such as rotary (rectifier or inverter) and solid state which can be sampled by HOMER RE software [40].

A power electronic converter is used to maintain the flow of energy between ac and dc components. The capital cost, replacement costs and maintenance cost for the converter for 1kw is $700, $700 and $50/year respectively [41].

The inverter and rectifier efficiencies were assumed to be 90% and 85% respectively for all sizes considered.

4.4.4 Charge Controller

The charge controller regulates the electric current that is flowing into and out of the battery bank, motor, or pump. By controlling the rate of electric current, charge controllers prevent overcharging and can protect against over-voltage which could damage the battery or motor. A charge controller can also prevent totally draining /deep discharging a battery, or perform controlled discharges, depending on the battery technology, to protect battery life [42].

The solar charge controller is about 3 to 5% of the whole solar system cost. But investing in a quality controller ensures good battery management which extends battery life and reduces associated costs.

This solar charge controller performs crucial system functions such as low voltage disconnection (LVD) to protect the battery from deep discharge, and high voltage disconnection (HVD) to protect the battery from overcharging. A quality solar charge controller should have a good battery state of charge calculation (SOC) to monitor the battery status [43].

4.4.5 Generator

Generators were not allowed to operate at less than 30% capacity. HOMER considered two different types of control strategies. Under the load-following strategy, the generator provides only the power necessary to meet the load at the time.
With the cycle-charging strategy, once the generator is operating, it uses as much power as possible to charge the batteries in addition to meeting the load [44].
In this study cycle-charging strategy is selected, to use the advantage of charging battery for later use and operating the generator under the minimum allowable operating load i.e 30% of its rated capacity.

From local market assessment a diesel generator cost is $400/KW and replacement cost is considered as 80% of capital cost and operation and maintenance cost of $0.015/hr. The life time of diesel generator is taken as 25000hr [41].

In HOMER, the lifetime of generators is specified in terms of operating hours. The number of years that a generator will last is therefore an output variable, which HOMER calculates according to the following equation[39]:

$$Rgen = \frac{Rgen,h}{Ngen} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (4.3)$$

Where:

Rgen is generator lifetime [hr]

Ngen is the number of hours the generator operates during one year [hr/yr]

Table 4.1 Summary of size, cost, quantity and lifetime of hybrid system components input toHOMER for Cheri Alga/Kosha.

No	Component	Size	Capital cost ($)	Replacement cost ($)	O & M cost ($)	Sizes considered	Quantities	Life time
1	PV	1 KW	1667	1000	17	0,1,5,15,25,50,60, 70,80,90,100,120, 140,160,170,180,190 &200	………..	25yrs
2	Generator	1 KW	400	320	0.015/hr	0,30,40,60,80,90,100, 110 &120	…………	25000hrs
3	Battery Surrette 4KS25P	1900 AH	1200	1200	60/yr	…………….	0,4,8,12,16,20,24,28,32,36,40,44,48,52, 56,60,64,70,75,80,85,90,95 & 100	12yrs
4	Converter	1 KW	700	700	50/yr	0,10,20,30,40, 50,60,70,75,80,85,90 &100	…………	25yrs

Table 4.1 shows the values of each optimization variable. The sizes of components of the hybrid system is primarily chosen based on the load of the community and irrigation pump. Homer builds the search space or set of all possible system configurations from this values and then simulates the configurations and sorts them by net present cost. The given costs were obtained from current local and global prices of components.

4.4.6 Connected Electrical Load

Electrical load of the village is calculated based on number of households, their consumption and the load of the irrigation pump. A primary load of 48KW peak and 754kwh/day and Deferrable load of 67KW peak and 402kwh/day is considered in this study.

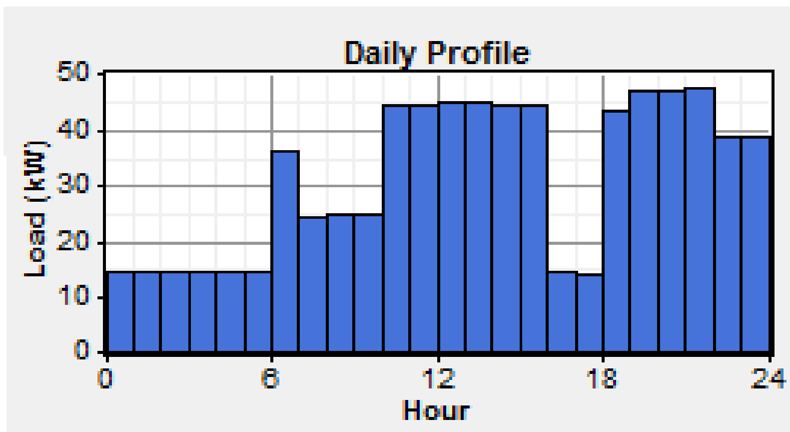


Figure 4.3: Hourly primary load data of Kosha Kebele

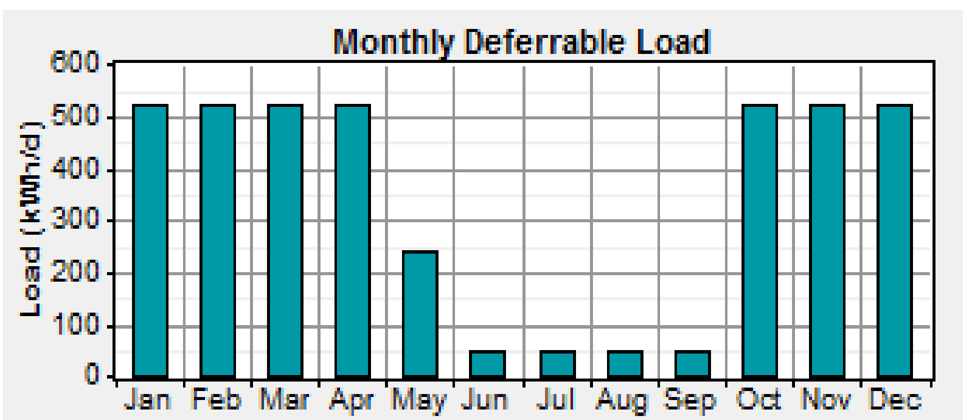


Figure 4.4 Monthly deferrable load data

4.4.7Levelized cost of energy

HOMER defines the levelized cost of energy (COE) as the average cost/kWh of useful electrical energy produced by the system. To calculate the COE, HOMER divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total useful electric energy production. The equation for the COE is as follows [37]:

$$COE = \frac{Cann, tot}{Eprim, AC + Edef} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

Where:

Cann,tot is total annualized cost [$/year]

Eprim,AC is AC primary load served [kWh/year]

Edefis the deferrable load served [kWh/year]

4.4.8 Net present cost (NPC)

The present value of the cost of installing and operating the system over the lifetime of the project (also referred to as lifecycle cost). Project lifetime in this study is considered as 25years. The total net present cost is HOMER's main economic output. All systems are ranked according to net present cost, and all other economic outputs are calculated for the purpose of finding the net present cost. The net present cost is calculated according to the following equation [37]:

$$Cnpc = \frac{Cann, tot}{CRF(i, Rproj)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

Where:

Cann,tot is total annualized cost [$/year]

CRF is capital recovery factor

Rproj is project lifetime

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Simulation results

Equipments considered for solar PV diesel hybrid power generation system were selected from HOMER library and it is shown in the figure 5.1 below.

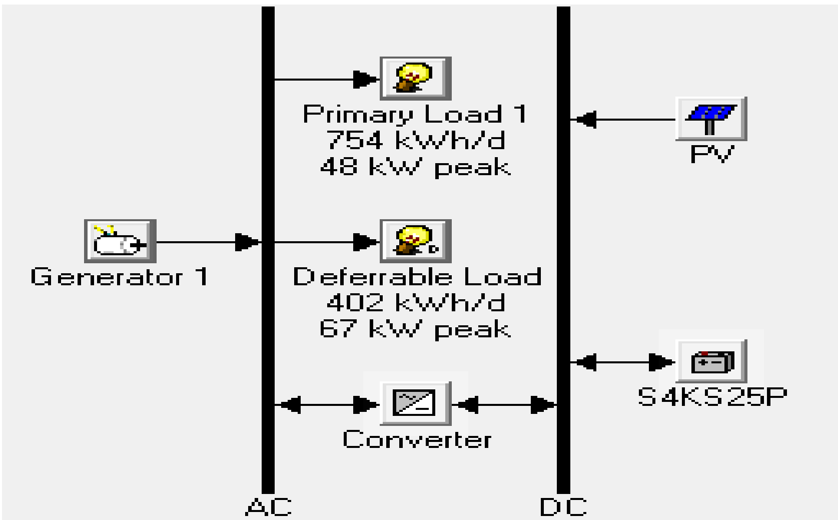


Figure 5.1: Representation of the proposed hybrid system by HOMER tool

Then monthly average global horizontal solar radiation data were fed to HOMER software. The software calculated clearness index values for months of the year.

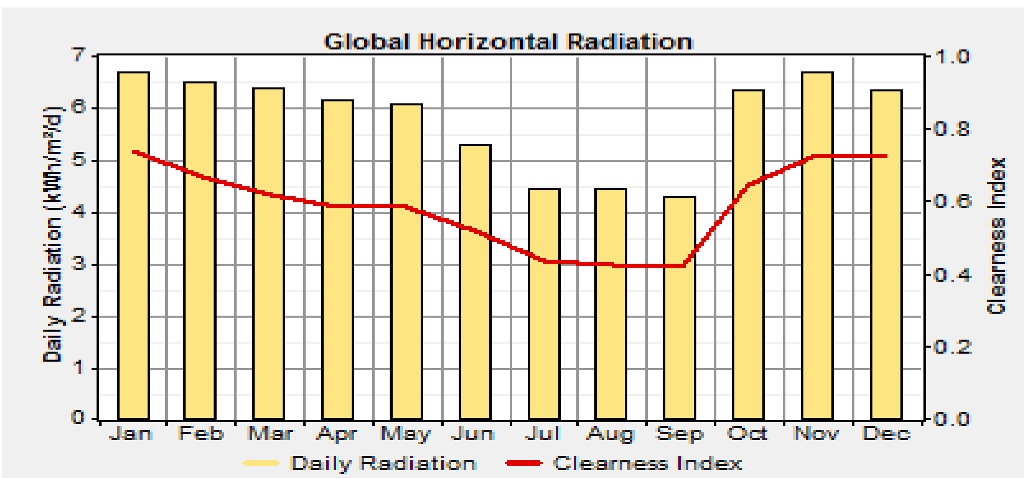


Figure 5.2: Global horizontal radiation and clearness index

The maximum value of clearness index is obtained for the month of January with a value of 7.41 and the minimum value is obtained for the month of September with a value of 0.419.

Maximum annual capacity shortage of 10%, minimum renewable fraction of 50%, diesel fuel price of $0.7/L were considered for simulation of the hybrid system.

The above inputs and inputs described in table 4.1 were fed to HOMER software and the categorized and overall simulation results were obtained and shown below.

Table 5.1: Categorized simulation result for the proposed hybrid system

Sensitivity Results | Optimization Results

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

	PV (kW)	Label (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)	Batt. Lf. (yr)
	170	40		80	$ 355,390	68,044	$ 1,225,219	0.232	0.59	0.04	77,169	6,863	
	160	40	24	80	$ 367,520	68,387	$ 1,241,737	0.231	0.57	0.00	75,137	6,240	12.0

5.2 Optimization Results

HOMER software run50544simulations and out of which 200 are feasible for the proposed hybrid system with a rank of increasing total net present cost /NPC/.

Since HOMER simulated two optimum results in the categorized output, comparison of the two scenarios and selection of the most optimum system was done by the following parameters.

Scenario A (PV, Diesel and Converter)

Scenario B (PV, Diesel, Battery Bank and Converter)

Table 5.2:Extracted values of categorized outputs from HOMER simulation

Scenarios	PV KW	Diesel KW	Battery (No)	Converter KW	Capital cost $	Total NPC $	COE ($/kwh)	Min Ren fraction	Capacity shortage	Unmet load %	CO2 emission	Label life (yr)
Scenario A	170	40	0	80	355,390	1,225,219	0.232	0.59	0.04	0.02	203,212	3.64
Scenario B	160	40	24	80	367,520	1,241,737	0.231	0.57	0	0.00	197,861	4.01

From table 5.2 we observe that Scenario A has lower capital cost and total NPC.COE. Renewable fraction of Scenario A is greater than Scenario B. However, in terms of COE, capacity shortage, unmet load, CO_2 emission and label life, Scenario B is the best alternative. Moreover, battery storage is important to store excess energy produced by solar PV during bright sunshine hours of a day.

Table 5.3: Some simulation results captured from the overall optimization result for Cheri Alga

No	PV (kW)	Diesel (kW)	Battery	Converter (kW)	Initial capital Cost $	Ope& M cost($/yr)	Total NPC($)	COE ($/kWh)	Total elec. Prod (kwh/yr)
1	160	40	24	80	367,520	11,904	1,241,737	0.231	515,170
2	160	40	24	85	371,020	12,135	1,242,764	0.231	513,235
3	140	40	24	80	334,180	11,773	1,244,255	0.231	489,609
4	170	40	24	80	384,190	11,987	1,244,269	0.231	529,089
5	160	40	24	75	364,020	11,676	1,244,652	0.231	518,771
6	140	40	24	75	330,680	11,535	1,245,001	0.231	492,551
7	140	40	24	85	337,680	12,010	1,245,643	0.231	487,659
8	170	40	24	85	387,690	12,221	1,245,723	0.231	527,268
9	170	40	24	75	380,690	11,759	1,246,324	0.232	532,284

10	140	30	48	60	344,980	11,825	1,246,418	0.238	488,068

Table 5.3 shows sizes and quantities of the hybrid system components, capital, operation and maintenance and total NPC. In addition COE and total electric production.

The result shown in the first row is the optimum hybrid system which has 140 KW PV, 40 KW diesel generator, 24 Surrette 4KS25P battery and 80 KW converter. The total NPC is $1,241,737,renewable fraction is 57% and there is no capacity shortage.

The COE is $0.231/kwh and it is less than other similar hybrid off grid systems which are worked in Dagahabur and Kebridahar Townof Somalia Region in Ethiopia for primary load 343, deferrable 150 KW peak and primary 290,deferrable 100KW is 0.441 and $0.422/kwh respectively[16].

And also for 27 KW PV off grid system worked in Ghana, COE is $0.483/kwh[17].

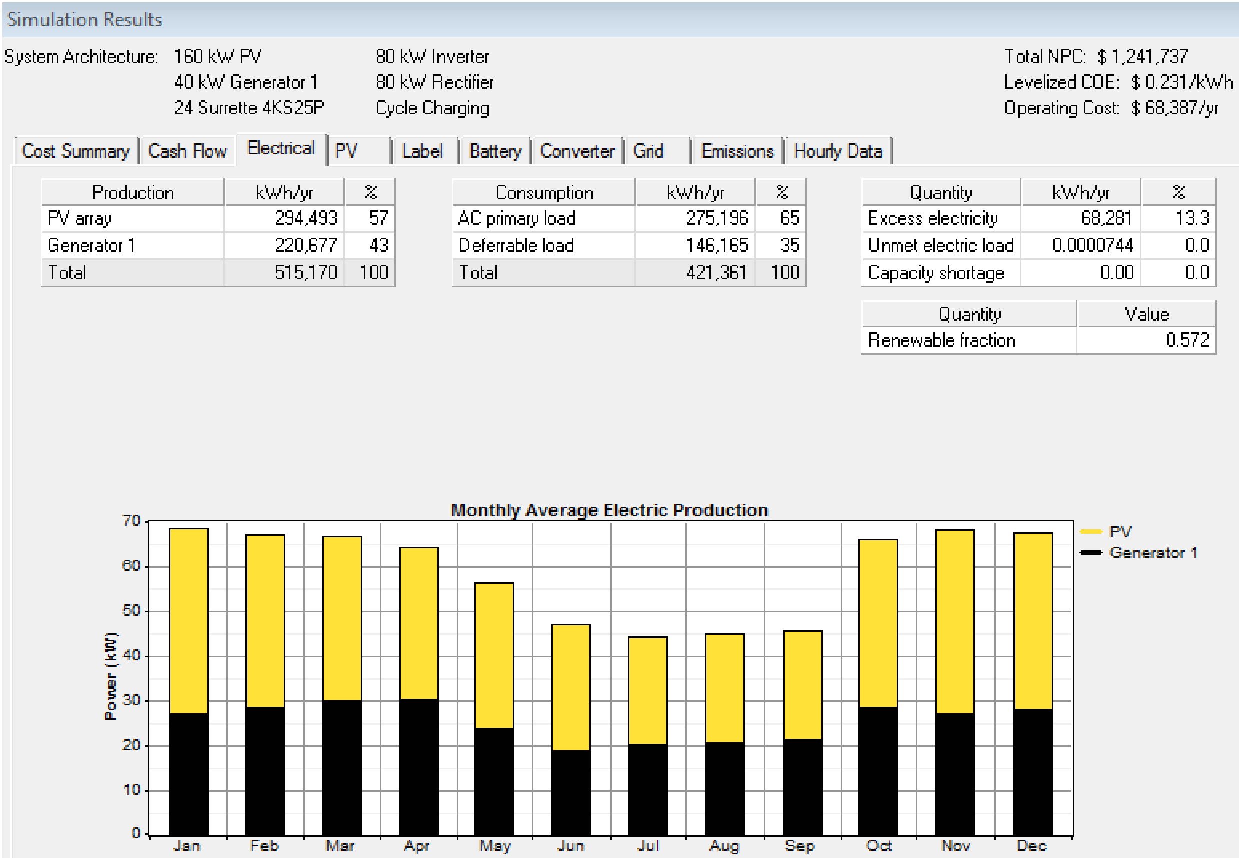
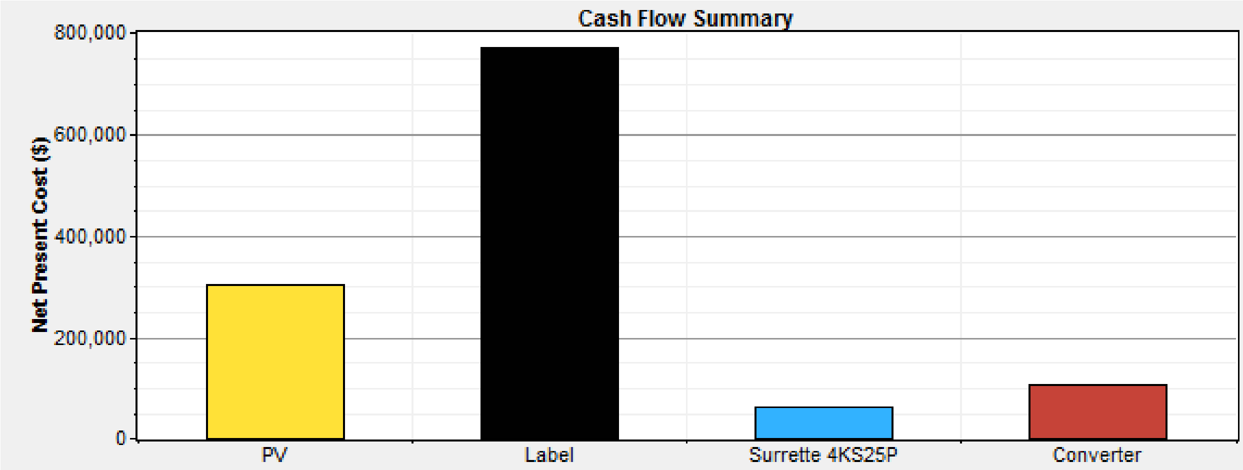


Figure 5.3 Monthly average electric production of the hybrid system

From figure 5.3 above it is observed that a total of 515,170kwh/yr is produced by the hybrid system out of this 294,493 kwh/yr i.e. 57% of the total production is produced by solar PV and 220,677 kwh/yr which is 43 % is produced by diesel generator. Here it is observed that larger share is covered by renewable energy source.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	266,720	0	34,771	0	0	301,491
Generator 1	16,000	36,683	47,861	672,353	-2,267	770,631
Surrette 4KS25P	28,800	21,426	18,408	0	-6,151	62,483
Converter	56,000	0	51,133	0	0	107,133
System	367,520	58,109	152,173	672,353	-8,418	1,241,737

Figure 5.4 Cost summary of hybrid system components

As shown in figure 5.4 the largest capital cost is for PV and the lowest is for generator. The largest total cost is for generator and the lowest is for battery bank.

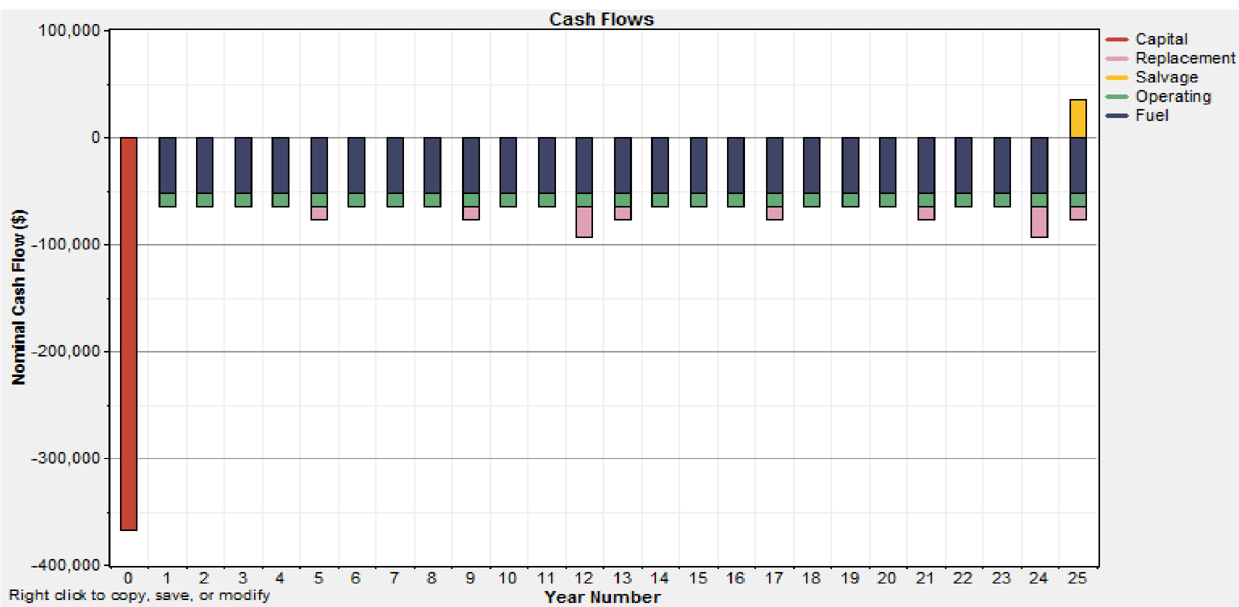


Figure 5.5 Cash flow summary by cost category for project life time

As depicted in figure 5.5 the larger cost is expended in the first year and which is capital cost of the project. Salvage value is calculated at the end of 25th year.

Quantity	Value	Units
Rated capacity	160	kW
Mean output	34	kW
Mean output	807	kWh/d
Capacity factor	21.0	%
Total production	294,493	kWh/yr

Quantity	Value	Units
Minimum output	0	kW
Maximum output	163	kW
PV penetration	107	%
Hours of operation	4,472	hr/yr
Levelized cost	0.0801	$/kWh

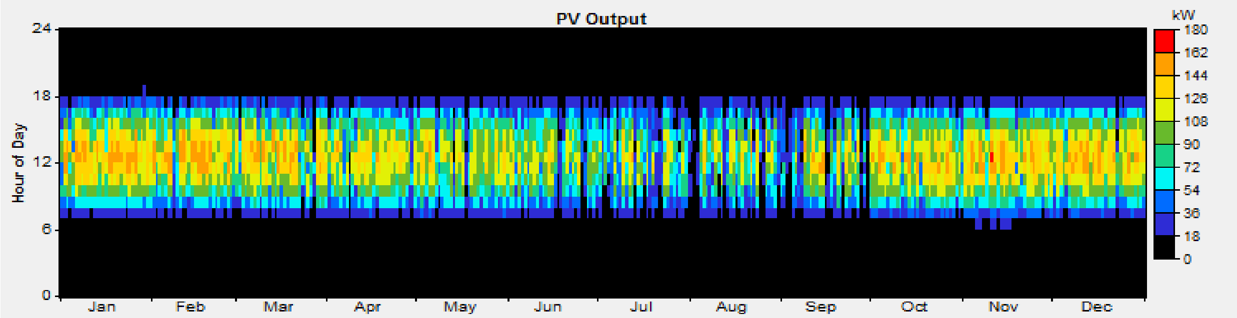


Figure 5.6 Annual electric energy production by PV system

Figure 5.6 depicts the variation of sunlight available throughout the hours of the day, with the lowest values registered in the first and the last hours of the day and the available peak near mid-day. Solar radiation is low during the months from June up to September.

Quantity	Value	Units
Hours of operation	6,240	hr/yr
Number of starts	407	starts/yr
Operational life	4.01	yr
Capacity factor	63.0	%
Fixed generation cost	3.35	$/hr
Marginal generation cost	0.175	$/kWh

Quantity	Value	Units
Electrical production	220,677	kWh/yr
Mean electrical output	35.4	kW
Min. electrical output	12.0	kW
Max. electrical output	40.0	kW

Quantity	Value	Units
Fuel consumption	75,137	L/yr
Specific fuel consumption	0.340	L/kWh
Fuel energy input	739,349	kWh/yr
Mean electrical efficiency	29.8	%

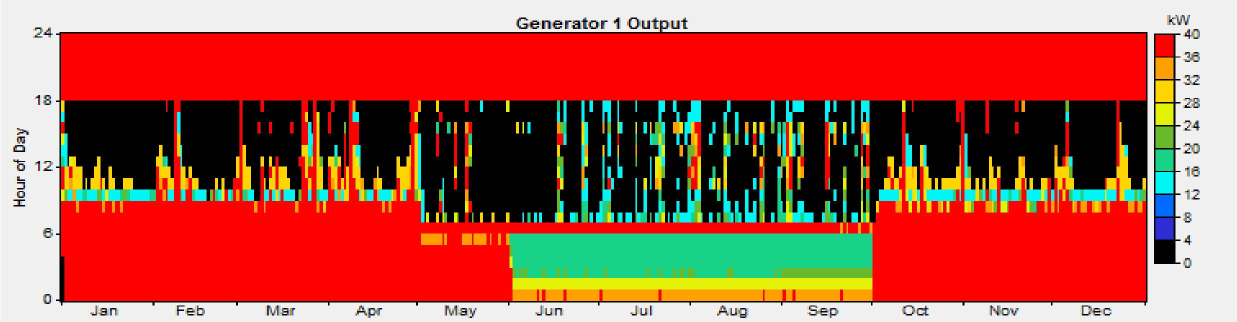


Figure 5.7 Hourly electric energy production by Generator

As shown in figure 5.7 larger amount of energy is produced by the generator in the morning and night time where there is not enough or no sunlight. And during the months June up to September generator production is lower at mid night since irrigation water pumps do not work due to rainy season.

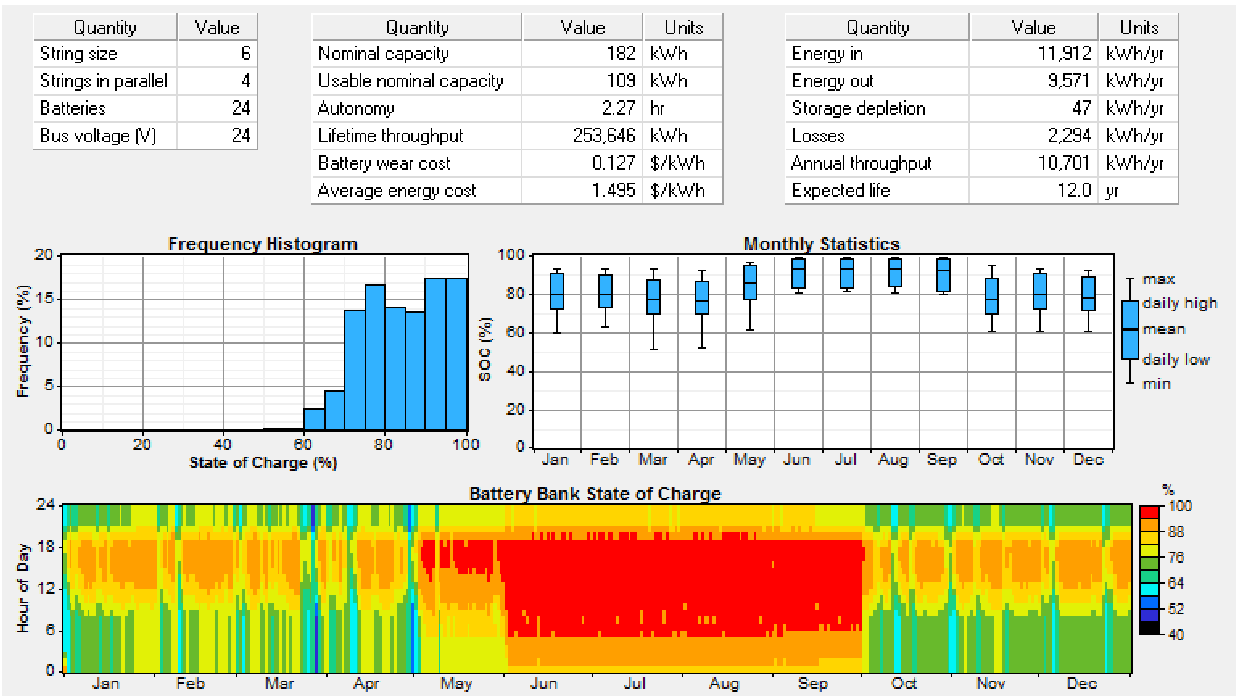


Figure 5.8 State of charge of battery bank

As depicted in figure 5.8 battery bank is more discharged from around 20:00 to 10:00 where there is no sunlight. During the months June up to September from 6:00 to 18:00 the battery bank is not discharged since irrigation pumps do not work since there is enough rain.

Quantity	Inverter	Rectifier	Units
Capacity	80.0	80.0	kW
Mean output	23.3	0.3	kW
Minimum output	0.0	0.0	kW
Maximum output	80.0	6.5	kW
Capacity factor	29.1	0.4	%

Quantity	Inverter	Rectifier	Units
Hours of operation	5,652	819	hrs/yr
Energy in	226,768	3,404	kWh/yr
Energy out	204,087	2,894	kWh/yr
Losses	22,681	511	kWh/yr

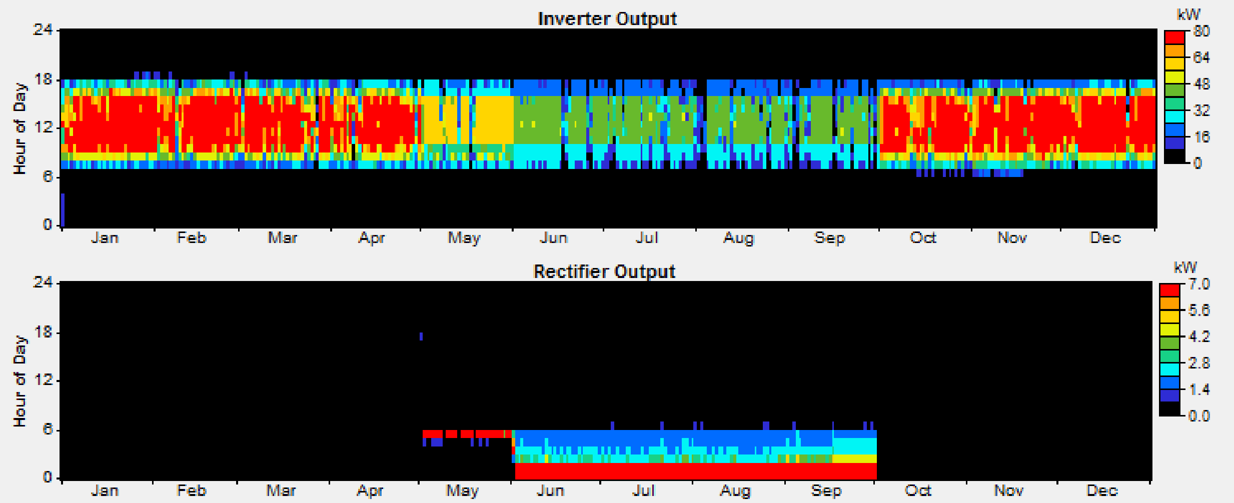


Figure 5.9 Annual statistical result of convertor

As depicted in figure 5.9 the converter is functional from 8:00 to 18:00 to convert DC supply from solar PV and the functionality of converter decreases during months from June up to September since sunlight decreases. The convertor acts as rectifier from 0:00 to 6:00 during the months from June up to September since the diesel generator charges battery bank.

5.3 Sensitivity Analysis

Sensitivity is a measure of how the optimal mix of components changes for any parametric variations in the lifetime of the system. Optimal system design depends on interplay with various necessary input variables. When these input cases change, it is good to know how the optimum system changes with variation of the variables. Three separate sensitivity cases were carried out using variables of sensitivities like, design dependence on primary load, design dependence on solar radiation and design dependence on diesel fuel price.

The optimal system type, surface plot and line graph were used to describe the optimization results.

Table 5.4: Sensitivity variables

Primary load (kwh/d)	**Solar radiation (kwh/m2/d)**	**Diesel fuel price ($/Liter)**
754, 905	4.31, 5.8, 6.68	0.7, 0.8, 1, 1.2

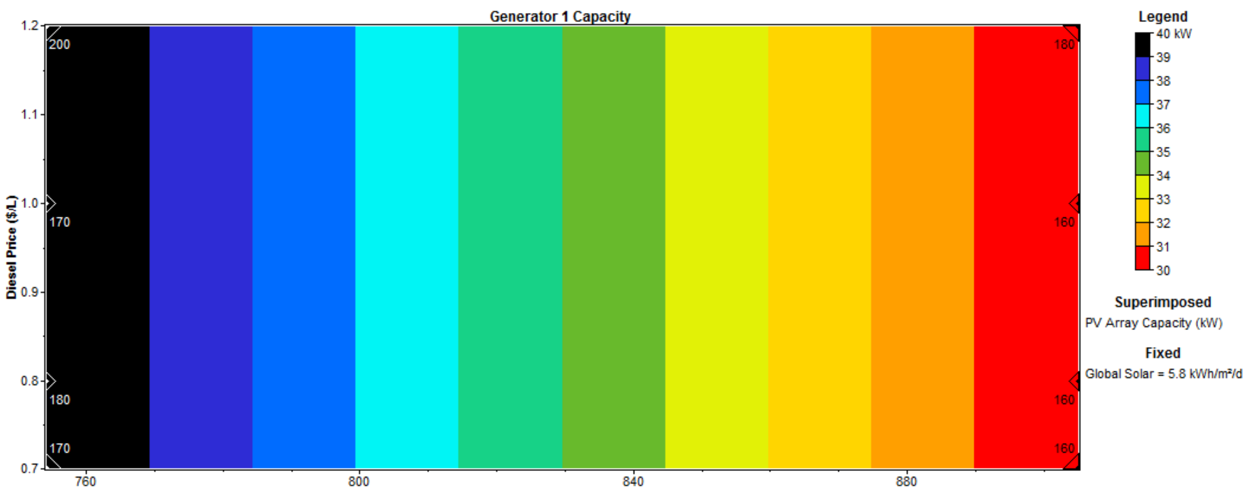


Figure 5.10: PV and diesel Generator Capacity variations

In figure 5.10, surface plot graph showing PV array capacity and Generator capacity variations with primary load and diesel fuel price is displayed. Considering only two of the sensitivity cases (primary load and diesel price) by keeping the other variable fixed (solar radiation at 5.8 kwh/m^2/d).Generator capacity decreases from 40KW to 30 KW as primary load increases from

760 kwh/m^2/d to 900 kwh/m^2/d. For the same value of diesel price and increase in primary load, PV capacity decreases.

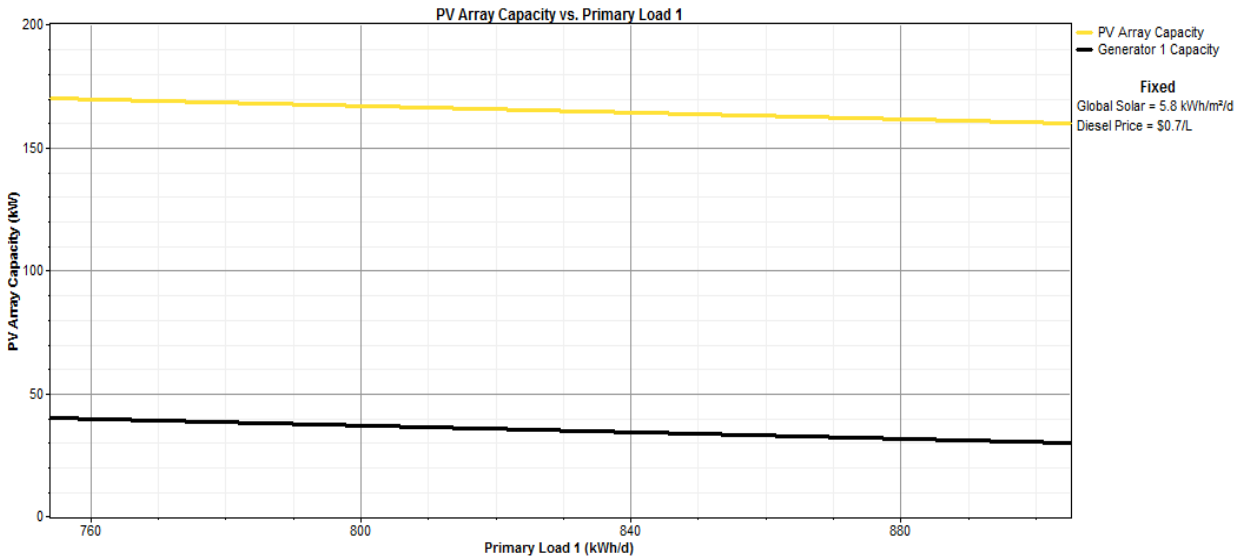


Figure 5.11:PV and diesel Generator Capacity variations by varying primary load only at diesel fuel price $0.7/L

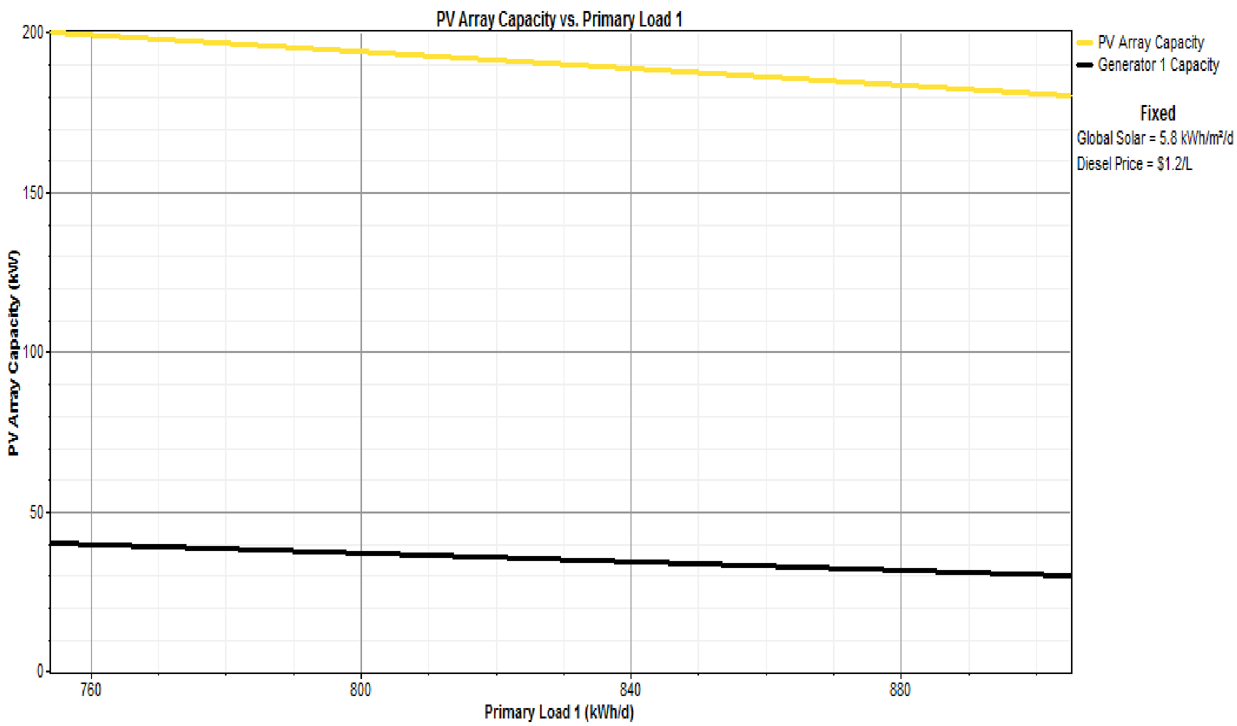


Figure 5.12:PV and diesel Generator Capacity variations by varying primary load only at diesel fuel price $1.2/L

Figure 5.11 and 5.12 show line graph of only one sensitivity parameter variation (primary load) and keeping other sensitivity variables constant.

At diesel fuel price of $0.7/L, PV array capacity increased from 170 KW to 160 KW for increase in primary load whereas diesel Generator capacity decreases from 40 KW to 30 KW. However when diesel fuel price rises from $0.7/L to $1.2/L, solar PV capacity shift from 200KW to 180 KW and diesel Generator capacity varies from 40 KW to 30 KW.

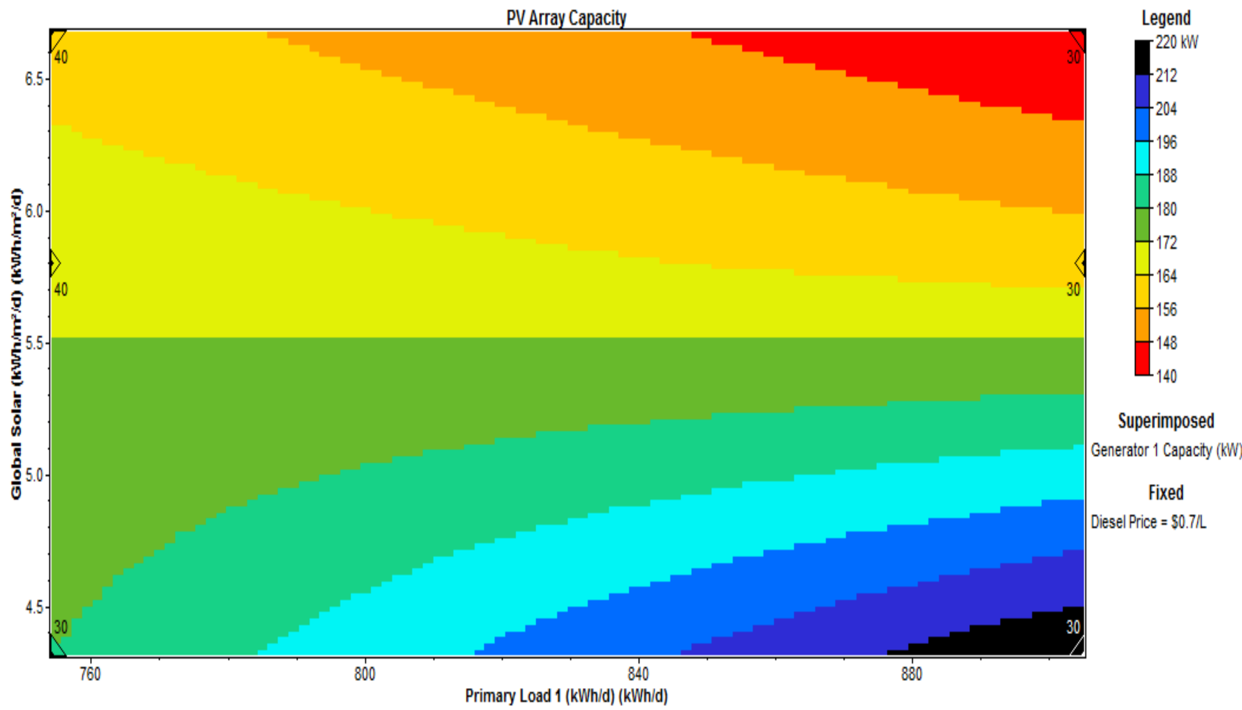


Figure 5.13: PV and diesel Generator Capacity variations

In figure 5.13, surface plot graph showing PV array capacity and Generator capacity variations with primary load and solar radiation is displayed. Considering only two of the sensitivity cases (primary load and solar radiation) and by keeping diesel fuel price at $0.7/L.

PV array capacity increases from 180KW to 220 KW when solar radiation decreases from 5.5 to 4.5 kwh/m^2/d for primary load increase from 760kwh/d to 905 kwh/d however when solar radiation increases from 5.5 to 6.68 kwh/m^2/d PV array capacity decreases from 180KW to 140KW. Whereas diesel capacity remained similar to initial design value of 40KW for solar radiation greater than 5.8 kwh/m^2/d. However, for solar radiation less than 5.8 kwh/m^2/d and increase in primary load, generator capacity decreases to 30 KW.

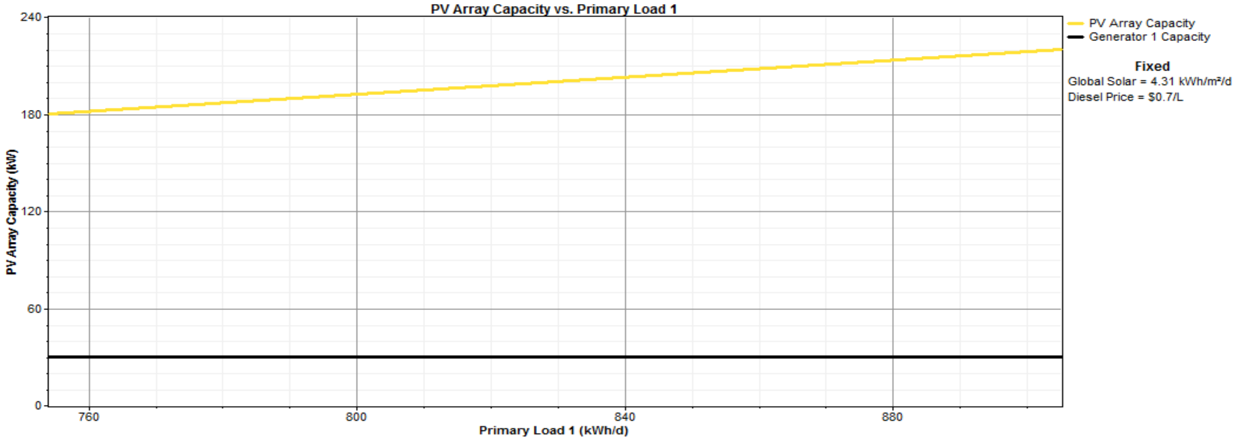


Figure 5.14:PV and diesel Generator Capacity variations by varying primary load only at solar radiation 4.31 kwh/m^2/d

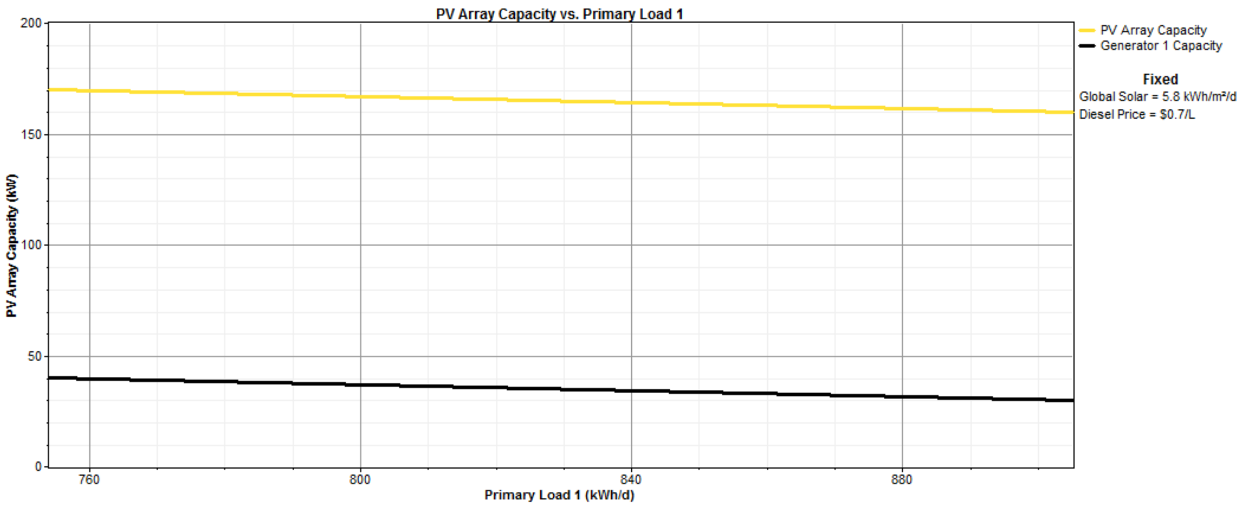


Figure 5.15:PV and diesel Generator Capacity variations by varying primary load only at solar radiation 5.8 kwh/m^2/d

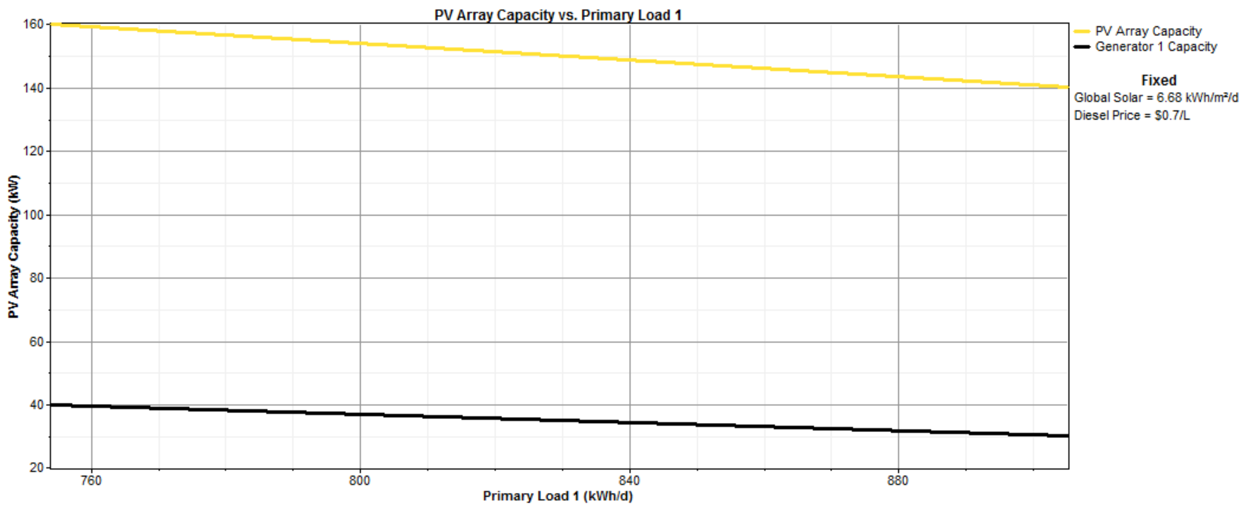


Figure 5.16:PV and diesel Generator Capacity variations by varying primary load only at solar radiation 6.68 kwh/m^2/d

Figure 5.14, 5.15 and 5.16 shows that PV array capacity increases from 180 KW to 220 KW for solar radiation 4.31kwh/m^2/d and increase in primary load. However as the solar radiation increases form 5.8 to 6.68 kwh/m^2/d solar PV capacity decreases from 170 KW to 140 KW. Diesel generator capacity is constant and it is 30 KW for solar radiation value of kwh/m^2/d and for solar radiation greater than 5.8 kwh/m^2/d generator capacity decreases from 40 KW to 30KW.

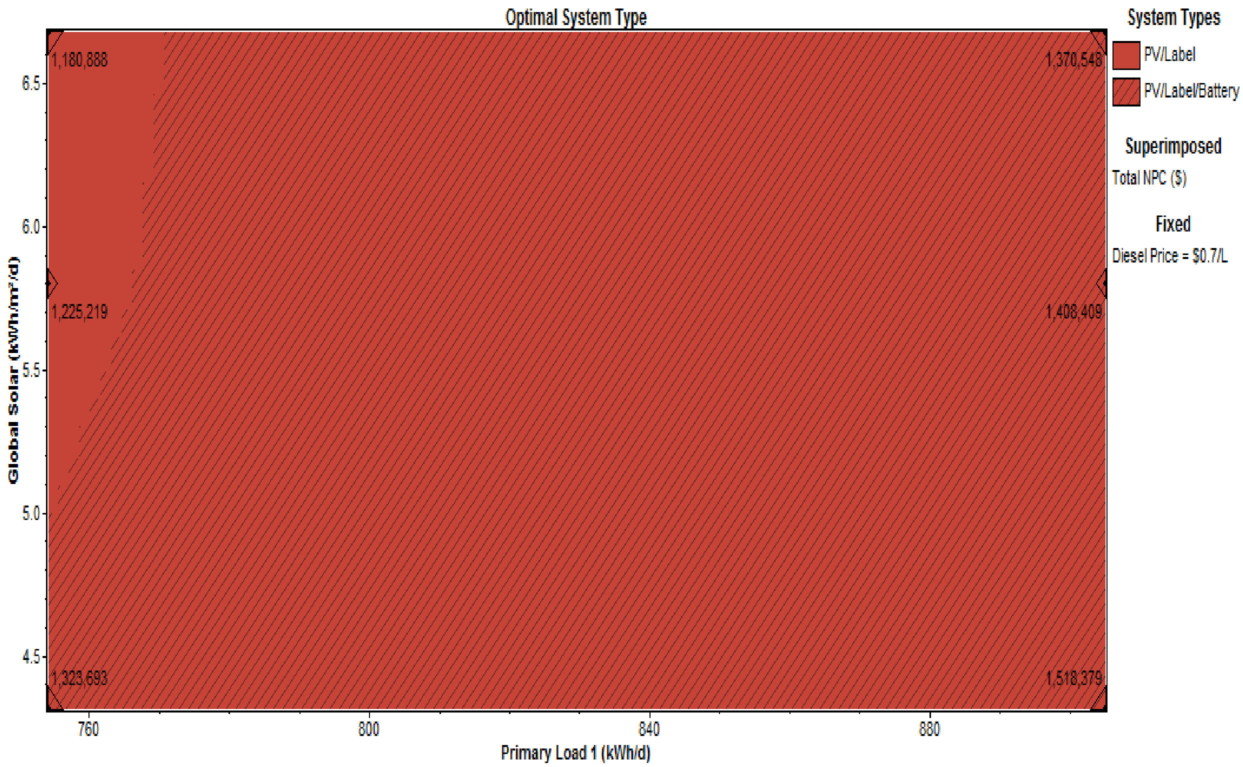


Figure 5.17: Sensitivity result for variable primary load and global solar radiation

As depicted in figure 5.17for primary load less than 770kwh/d and solar radiation greater than 5kwh/m^2/d the solar PV/diesel system is optimum with higher total net present cost. For solar radiation less than 5 kwh/m^2/d, the solar PV/diesel/battery system is optimum with higher total net present cost. As solar radiation becomes greater than 5kwh/m^2/d the solar PV/diesel/battery system is optimum. Here the total net present cost is less for minimum load and high solar radiation. As solar radiation increases, the total net present cost decreases.

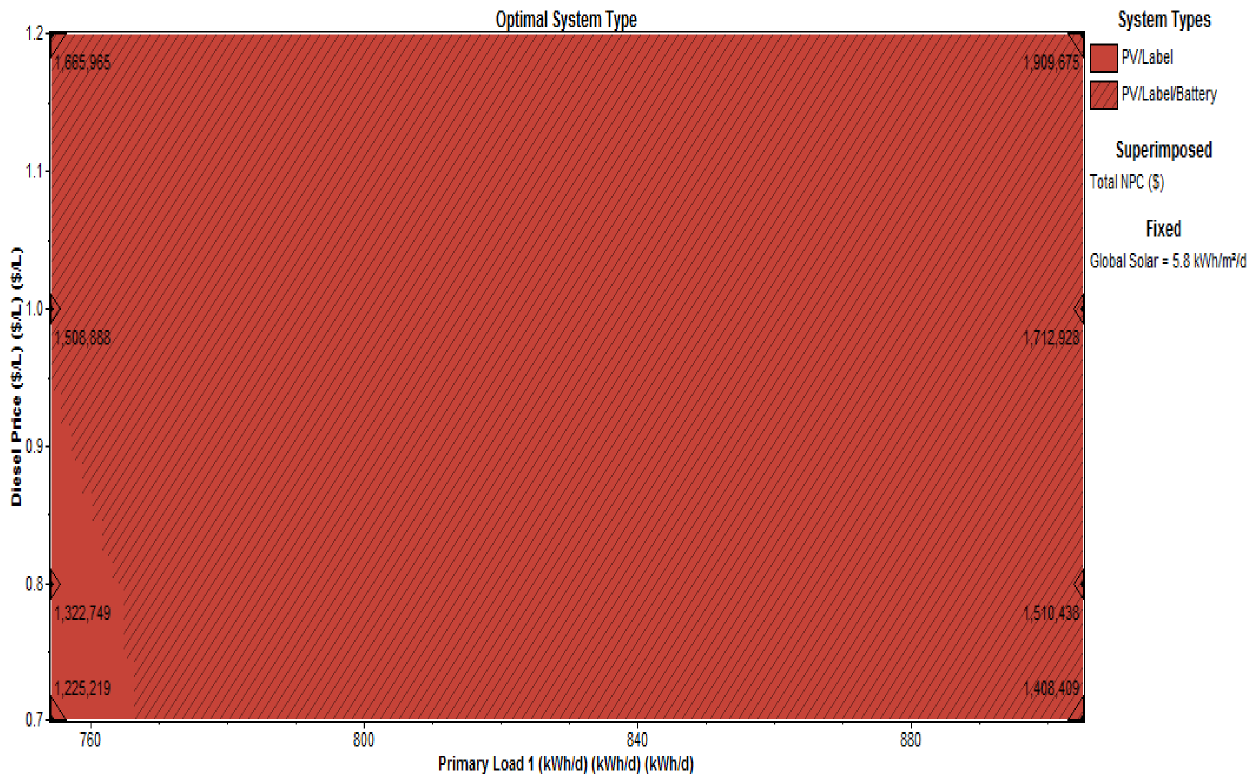


Figure 5.18: Sensitivity result for varying primary load and diesel fuel price.

Figure 5.18showsfor the diesel price from \$0.7/L-\$0.95/L and primary load less than 765 kwh/d, the solar PV/diesel system is optimum. Whereas when the diesel fuel price becomes greater than \$0.95/L the solar PV/diesel/battery system is optimum. The total net present cost rises as the diesel fuel price increases and primary load demand increases.

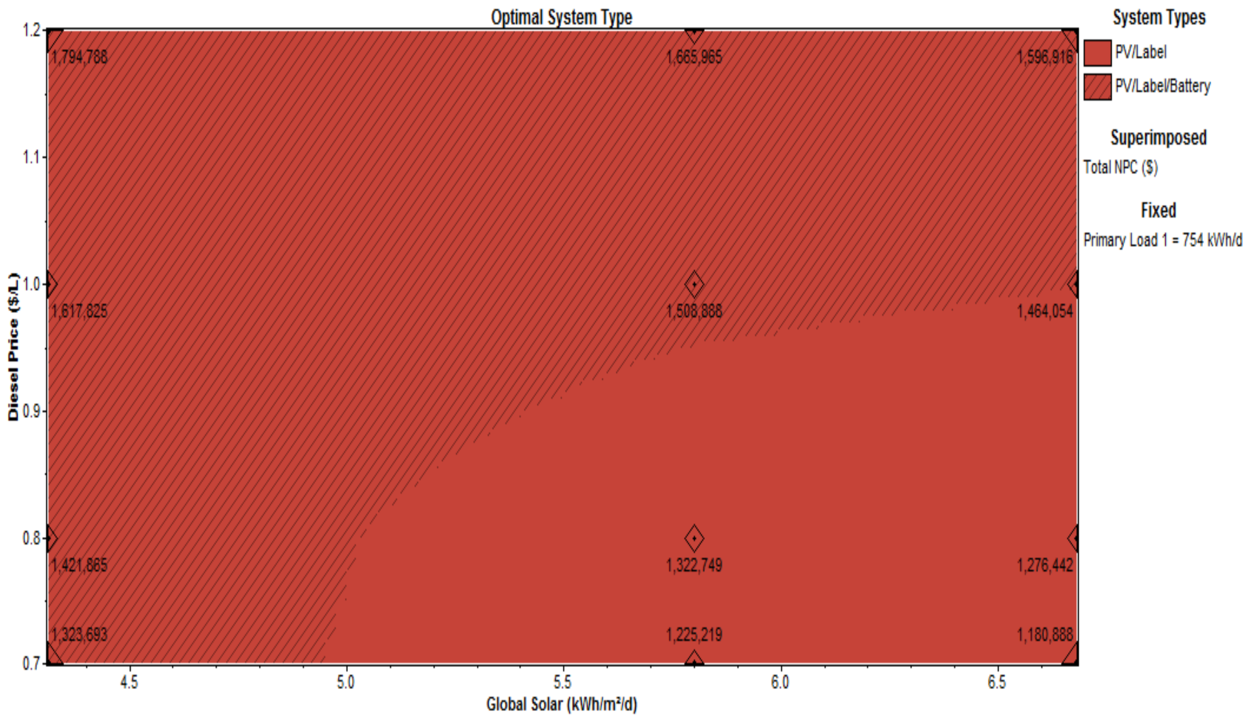


Figure 5.19: Sensitivity result for varying diesel fuel price and global solar radiation.

Figure 5.19 shows as the diesel fuel price decreases from $1/L and solar radiation increases from 4.9 kwh/m^2/d, total net present cost is less for solar PV/Diesel system. For solar radiation less than 4.9 kwh/m^2/d and as diesel fuel price becomes greater than $0.95/L and solar radiation increases the solar PV/diesel/battery system is optimum.

5.4 Comparison of the hybrid system with grid extension

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. Farther away from the grid, the stand-alone system is optimal. Nearer to the grid, grid extension is optimal.

HOMER calculates the breakeven grid extension distance using the following equation:

$$Dgrid = (Cnpc.CRF(i, Rproj) - Cpower.Ltot)/(Ccap.CRF(i, Rproj) + Ccom \ldots \ldots \ldots (5.1)$$

Where:

Cnpn is total net present cost of stand alonesystem[$].

CRF is capital recovery factor.

i is interest rate.

Rproj is project lifetime.

Cpower is cost of power from the grid [$/kwh]

Ltot is total primary and deferrable load[kwh/yr]

Ccap is capital cost of grid extension [$/km]

Ccom is O & M cost of grid extension [$/yr/km] [38].

The proposed stand-alone hybrid system for Cheri Alga is 24 KM far from grid. To compare this hybrid system with grid extension, current cost required to extend 1 KM overhead line which was found from EEP was fed to HOMER to get breakeven distance of grid extension.

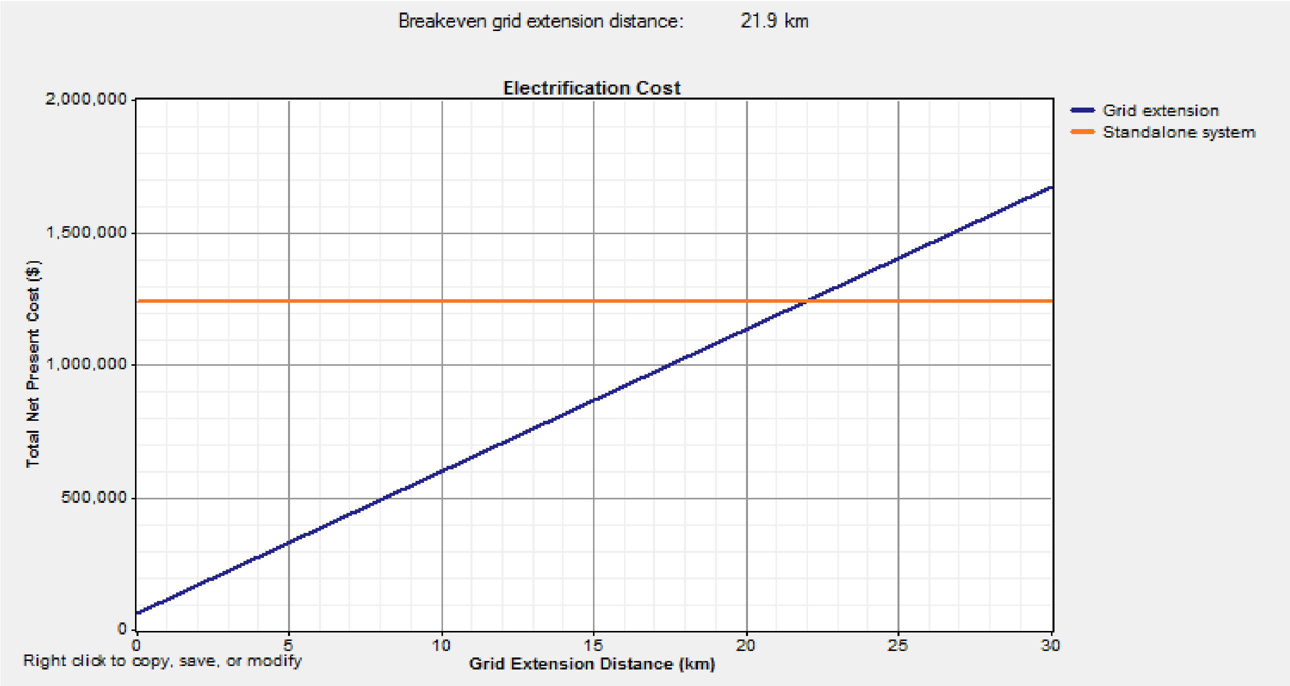


Figure5.20: Breakeven grid extension distance of the hybrid system

As depicted in figure 5.20 above the minimum distance from the grid which makes the stand-alone system cheaper from grid extension is 21.9 KM.

Since Cheri Alga Kebele is 24 KM far from the grid, the stand-alone system is more feasible than grid extension. In addition Jimma Substation is 158 KM far from the study site where the acceptable limit for 33KV line extension is 120 KM. As the distance increases the loss increases and it is difficult to get reliable supply of power.

5.5 Comparison of the hybrid system with diesel generator power supply system

To compare the hybrid system with diesel only system primary and deferrable load data of the proposed area was fed to HOMER. Figure 4.6 shows diesel only system.

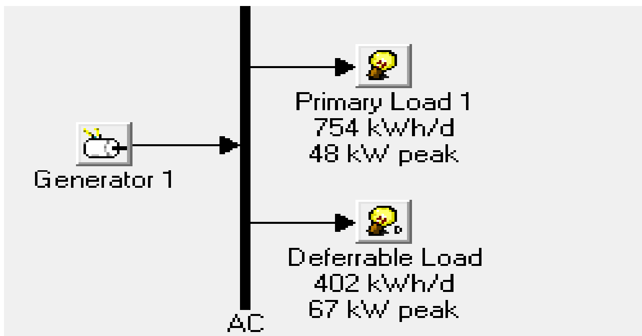


Figure5.21: Diesel only system

Table5.5: Overall simulation result of diesel only system

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

Label (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
60	$ 24,000	117,355	$ 1,524,196	0.283	0.00	0.00	147,784	8,760
80	$ 32,000	132,847	$ 1,730,229	0.321	0.00	0.00	163,292	8,760
90	$ 36,000	140,640	$ 1,833,845	0.340	0.00	0.00	171,113	8,760
100	$ 40,000	148,683	$ 1,940,674	0.360	0.00	0.00	179,293	8,760
110	$ 44,000	156,737	$ 2,047,623	0.380	0.00	0.00	187,487	8,760
120	$ 48,000	164,800	$ 2,154,694	0.400	0.00	0.00	195,694	8,760

As shown above the system with least total NPC costs $1,524,196 and cost of energy $0.283. CO_2 emission of diesel only system is 389,163 kg/yr. Whereas the total NPC of the hybrid system is $1,241,737, COE is $0.231/kwh and CO_2 emission is 197,861 kg/yr. So the hybrid system has lower total NPC, COE and reducesCO_2 emission.

HOMER calculates the emissions of the following six pollutants [38]:

Table 5.6: Pollutants calculated by HOMER

Pollutant	Description
Carbon Dioxide (CO_2)	Nontoxic greenhouse gas.
Carbon Monoxide (CO)	Poisonous gas produced by incomplete burning of carbon in fuels. Prevents delivery of oxygen to the body's organs and tissues, causing headaches, dizziness, and impairment of visual perception, manual dexterity, and learning ability.
Unburned Hydrocarbons (UHC)	Products of incomplete combustion of hydrocarbon fuel, including formaldehyde and alkenes. Lead to atmospheric reactions causing photochemical smog.
Particulate Matter (PM)	A mixture of smoke, soot, and liquid droplets that can cause respiratory problems and form atmospheric haze.
Sulfur Dioxide (SO_2)	A corrosive gas released by the burning of fuels containing sulfur (like coal, oil and diesel fuel). Cause respiratory problems, acid rain, and atmospheric haze.
Nitrogen Oxides (NO_x)	Various nitrogen compounds like nitrogen dioxide (NO_2) and nitric oxide (NO) formed when any fuel is burned at high temperature. These compounds lead to respiratory problems, smog, and acid rain.

Table5.7: Pollutant emission by the proposed and diesel only system.

Type of Pollutant	Emission by hybrid system (kg/yr)	Emission by diesel only system(kg/yr)
CO_2	197,861	389,163
CO	488	961
UHC	54	106
PM	37	72
SO_2	397	782
NO_x	4,358	8,571
Total	**203,195**	**399,655**

Pollutant emission reduction by hybrid system is equal to:

(399655-203195/399655)*100 = 49%.

CO2 emission reduction by hybrid system is equal to:

(389163-197861/389163)*100 = 49%.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This thesis work focused on the design of an off-grid solar PV/diesel hybrid power system for irrigation water pumping and a community of 904 households in the rural village of Cheri Alga. Hourly sunshine hour data of the study area for the period of 2012-2015 was obtained from NMSA Jimma Branch. The average monthly profile for solar energy source was analyzed by using Angstrom Prescott empirical formula and fed to HOMER optimization tool and the result displays solar energy potential of the site is undisputable to exploit for the provision of electricity. The four years global horizontal solar radiation was 5.8kwh/m^2/day.

During the design of the off grid system, an optimization was done based on the electricity load, climatic data sources, and economics of the power components in which the NPC has to be minimized to select an economic feasible power system. HOMER simulation result displayed the most economical feasible system sorted by NPC from top to down, the optimum system has renewable fraction of 57%, 160kW photovoltaic panel, 40kW diesel generator, 24 unit batteries, and 80kW converter.

Sensitivity analysis was also performed for the system and 9 sensitivity cases were considered. It is observed that almost the same configuration was obtained except in some cases there are quantity and size change of the components.

Electrification of rural areas distant from grid and have low energy consumption is challenging for developing countries. So using off grid hybrid energy generation systems can alleviate this problem. For the study area grid power supply is not feasible since it is 24km far from the grid where the grid supply is feasible for 21.9km.

Furthermore this hybrid system has lower total NPC and COE and reduces CO_2emission by49% when compared to diesel only system.

Finally this study shows that off grid hybrid energy system is cost effective and environmentally friendly in delivering power for rural areas far from the grid. Moreover, this study encourages concerned bodies to use renewable energy sources to alleviate power supply problem.The original contribution of this study is to minimize environmental pollution due to diesel generator emission and to help the rural community can get electricity access by using this study.

6.2 Recommendation

Ethiopia has large amount of renewable energy sources which can be used in off grid systems to alleviate or tackle the financial and technical challenges in delivering power from grid systems for rural areas in Ethiopia.

However, there are different challenges in implementing these systems such as lack of awareness and financial capability of the community. Thus the government, non-governmental organizations and the rural communities make efforts to use renewable energy sources for rural electrification and for different services power requirements such as irrigation pumps which is considered in this study.

Furthermore, this study can be used as a benchmark to make similar study activities for other sites and the diesel complimentary for Cheri Alga can be replaced by micro hydro since there is river around this study area.

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APPENDICES

Appendix A: Overall Optimization Result

PV (KW)	Generator (KW)	Battery (No)	Convertor (KW)	Total capital cost ($)	Total O & M cost ($/yr)	Total NPC ($)	COE ($/kwh)	Total ElectrcalProd ucton	Renewable Fracton	Unmet Load	Diesel consumption (L/yr)
170	40	0	80	355,390	11,008	1,225,219	0.232	533,725	0.59	8,401	77,169
170	40	0	85	358,890	11,258	1,225,600	0.232	530,902	0.59	8,401	76,464
180	40	0	80	372,060	11,064	1,226,405	0.232	547,858	0.6	8,388	75,496
160	40	0	80	338,720	10,965	1,226,613	0.232	520,295	0.57	8,417	79,092
160	40	0	85	342,220	11,215	1,226,720	0.232	517,350	0.57	8,417	78,356
180	40	0	85	375,560	11,314	1,227,097	0.232	545,175	0.61	8,388	74,825
170	40	0	75	351,890	10,758	1,228,577	0.233	538,218	0.58	8,401	78,293
180	40	0	75	368,560	10,815	1,228,707	0.233	551,860	0.6	8,438	76,500
180	40	0	70	365,060	10,582	1,229,381	0.235	554,598	0.6	11,048	77,277
170	40	0	90	362,390	11,508	1,229,402	0.233	529,609	0.59	8,401	76,140
160	40	0	75	335,220	10,715	1,229,443	0.233	524,552	0.56	8,417	80,157
160	40	0	90	345,720	11,465	1,230,152	0.233	515,891	0.57	8,417	77,991
190	40	0	80	388,730	11,143	1,230,201	0.233	562,457	0.62	8,377	74,058
170	40	0	70	348,390	10,517	1,230,228	0.234	541,660	0.58	9,458	79,202
180	40	0	90	379,060	11,564	1,231,250	0.233	544,038	0.61	8,388	74,541
190	40	0	85	392,230	11,393	1,231,756	0.233	560,160	0.62	8,377	73,483
160	40	0	70	331,720	10,467	1,232,285	0.234	528,735	0.56	8,665	81,216
190	40	0	75	385,230	10,901	1,232,631	0.234	566,285	0.62	8,593	75,057
190	40	0	70	381,730	10,671	1,232,841	0.237	568,719	0.61	12,355	75,774
200	40	0	80	405,400	11,226	1,235,048	0.234	577,417	0.64	8,368	72,729
190	40	0	90	395,730	11,643	1,236,481	0.234	559,279	0.63	8,377	73,263
200	40	0	75	401,900	10,986	1,237,065	0.235	580,983	0.63	8,791	73,675
200	40	0	85	408,900	11,476	1,237,127	0.234	575,354	0.64	8,368	72,213
170	40	0	100	369,390	12,008	1,241,592	0.235	529,072	0.59	8,401	76,006
140	40	0	80	305,380	10,969	1,241,634	0.235	495,981	0.52	8,459	84,054
160	40	24	80	367,520	11,904	1,241,737	0.231	515,170	0.57	0	75,137

200	40	0	90	412,400	11,726	1,242,079	0.235	574,575	0.64	8,368	72,018
160	40	0	100	352,720	11,965	1,242,153	0.235	515,269	0.57	8,417	77,836
140	40	0	75	301,880	10,719	1,242,610	0.235	499,410	0.52	8,459	84,912
160	40	24	85	371,020	12,135	1,242,764	0.231	513,235	0.57	0	74,554
140	40	0	85	308,880	11,219	1,242,892	0.235	493,551	0.52	8,459	83,447
180	40	0	100	386,060	12,064	1,243,657	0.236	543,598	0.61	8,388	74,431
140	40	24	80	334,180	11,773	1,244,255	0.231	489,609	0.53	0	79,067
170	40	24	80	384,190	11,987	1,244,269	0.231	529,089	0.59	0	73,551
160	40	24	75	364,020	11,676	1,244,652	0.231	518,771	0.57	0	76,153
140	40	24	75	330,680	11,535	1,245,001	0.231	492,551	0.52	0	79,867
140	40	0	70	298,380	10,469	1,245,196	0.236	503,557	0.51	8,459	85,949
140	40	24	85	337,680	12,010	1,245,643	0.231	487,659	0.53	0	78,509
170	40	24	85	387,690	12,221	1,245,723	0.231	527,268	0.59	0	73,009
170	40	24	75	380,690	11,759	1,246,324	0.232	532,284	0.59	344	74,468
140	30	48	60	344,980	11,825	1,246,418	0.238	488,068	0.53	10,994	76,603
160	40	24	90	374,520	12,379	1,246,670	0.231	512,182	0.57	0	74,259
140	40	0	90	312,380	11,469	1,246,711	0.236	492,264	0.52	8,459	83,125
140	40	24	70	327,180	11,301	1,246,988	0.232	495,931	0.52	3	80,796
140	40	0	60	291,380	9,977	1,249,001	0.238	511,011	0.5	10,147	87,852
190	40	0	100	402,730	12,143	1,249,007	0.237	558,892	0.63	8,377	73,166
140	40	24	90	341,180	12,261	1,250,190	0.232	486,679	0.53	0	78,267
170	40	24	90	391,190	12,471	1,250,647	0.232	526,477	0.59	0	72,811
160	40	24	70	360,520	11,466	1,250,854	0.233	523,243	0.56	706	77,485
180	40	24	80	400,860	12,098	1,251,071	0.232	544,010	0.61	0	72,366
180	40	24	85	404,360	12,328	1,252,498	0.233	542,284	0.61	0	71,829
140	30	48	70	351,980	12,329	1,252,569	0.236	484,701	0.53	6,468	75,784
140	30	48	75	355,480	12,579	1,252,856	0.236	481,822	0.53	6,266	75,066
160	40	48	100	410,320	13,923	1,253,213	0.233	493,884	0.6	22	67,568
140	30	48	80	358,980	12,827	1,253,862	0.236	479,364	0.54	6,358	74,437
180	40	24	75	397,360	11,881	1,254,788	0.234	547,599	0.61	602	73,439
200	40	0	100	419,400	12,226	1,254,943	0.238	574,339	0.64	8,368	71,959
170	40	24	70	377,190	11,567	1,255,203	0.234	537,389	0.58	1,495	76,052
170	40	48	100	426,990	14,006	1,255,498	0.233	507,660	0.62	22	65,949
140	30	48	85	362,480	13,077	1,255,549	0.237	477,124	0.54	6,426	73,878
180	40	24	90	407,860	12,577	1,257,447	0.233	541,560	0.61	0	71,638
160	40	24	100	381,520	12,878	1,257,466	0.233	511,079	0.58	0	73,973
160	40	48	90	403,320	13,516	1,257,698	0.234	498,881	0.59	341	69,317
140	30	48	90	365,980	13,327	1,257,731	0.237	475,091	0.54	6,426	73,372
140	40	24	60	320,180	10,878	1,257,740	0.235	504,268	0.51	1,607	83,290

190	40	24	80	417,530	12,209	1,257,958	0.234	558,960	0.63	0	71,185
140	40	0	100	319,380	11,969	1,258,425	0.238	491,515	0.52	8,459	82,938
190	40	24	85	421,030	12,444	1,260,404	0.234	557,519	0.63	0	70,748
170	40	48	90	419,990	13,605	1,260,739	0.235	512,833	0.61	171	67,767
180	40	24	70	393,860	11,679	1,261,546	0.236	552,063	0.6	1,695	74,812
180	40	48	100	443,660	14,112	1,261,585	0.234	522,426	0.63	13	64,696
140	40	24	100	348,180	12,765	1,261,631	0.234	485,673	0.53	0	78,038
190	40	24	75	414,030	11,994	1,261,775	0.235	562,533	0.62	480	72,267
180	40	48	90	436,660	13,681	1,261,850	0.235	526,333	0.63	304	66,038
170	40	24	100	398,190	12,973	1,262,082	0.234	525,525	0.6	0	72,586
160	30	48	50	371,320	11,622	1,262,636	0.246	522,646	0.56	18,732	75,815
190	40	24	90	424,530	12,691	1,265,479	0.235	556,890	0.63	0	70,575
140	30	48	100	372,980	13,825	1,265,504	0.239	472,637	0.55	6,425	72,749
160	40	48	85	399,820	13,340	1,266,541	0.236	503,492	0.58	125	70,860
200	40	24	80	434,200	12,336	1,267,704	0.235	574,656	0.64	0	70,280
190	40	48	90	453,330	13,782	1,267,798	0.236	541,173	0.65	225	64,782
190	40	24	70	410,530	11,790	1,268,124	0.237	566,884	0.62	2,265	73,602
140	40	48	85	366,480	13,193	1,268,575	0.237	478,230	0.54	499	74,782
140	40	48	90	369,980	13,416	1,269,153	0.236	476,366	0.54	521	74,172
170	40	48	85	416,490	13,427	1,269,274	0.237	517,320	0.6	444	69,277
160	40	24	60	353,520	11,094	1,269,294	0.238	533,352	0.55	2,713	80,698
180	40	24	100	414,860	13,084	1,269,599	0.236	540,778	0.61	0	71,481
200	40	24	85	437,700	12,569	1,269,975	0.236	573,234	0.64	0	69,832
190	40	48	100	460,330	14,237	1,272,023	0.236	538,542	0.65	15	63,881
200	40	24	75	430,700	12,127	1,272,284	0.237	578,397	0.64	426	71,433
160	30	48	75	388,820	12,874	1,272,406	0.238	511,974	0.58	3,646	73,159
160	30	48	90	399,320	13,623	1,272,841	0.238	503,230	0.59	3,621	70,967
160	30	48	85	395,820	13,375	1,273,033	0.238	506,238	0.58	3,615	71,731
180	40	48	85	433,160	13,520	1,273,089	0.237	531,483	0.62	490	67,803
160	30	48	80	392,320	13,124	1,273,183	0.238	509,313	0.58	3,611	72,497
140	40	48	80	362,980	12,992	1,273,463	0.237	481,842	0.53	664	75,944
160	30	48	70	385,320	12,624	1,273,988	0.239	515,660	0.57	3,837	74,083
160	40	48	80	396,320	13,153	1,274,140	0.237	507,856	0.58	376	72,290
200	40	24	90	441,200	12,815	1,274,965	0.237	572,605	0.64	0	69,652
160	30	48	60	378,320	12,125	1,275,419	0.241	522,259	0.56	6,439	75,737
160	30	48	100	406,320	14,123	1,276,028	0.239	498,654	0.59	3,622	69,825
170	40	24	60	370,190	11,207	1,276,493	0.24	548,399	0.57	3,259	79,551
190	40	24	100	431,530	13,196	1,277,394	0.237	556,097	0.63	0	70,399
170	30	48	50	387,990	11,777	1,278,086	0.248	540,010	0.58	17,054	75,475

170	40	48	80	412,990	13,252	1,278,190	0.238	521,905	0.6	532	70,823
140	40	48	75	359,480	12,785	1,278,429	0.239	485,665	0.53	750	77,130
200	40	48	90	470,000	13,914	1,278,917	0.238	557,360	0.66	124	64,022
140	40	48	100	376,980	13,901	1,278,971	0.237	475,253	0.54	22	73,813
200	40	24	70	427,200	11,929	1,279,414	0.239	582,936	0.63	2,100	72,843
190	40	48	85	449,830	13,633	1,280,833	0.239	546,755	0.64	224	66,715
140	30	72	50	366,780	12,663	1,281,519	0.25	485,061	0.53	18,321	75,309
160	40	48	75	392,820	12,963	1,282,805	0.239	512,807	0.57	855	73,849
140	40	48	70	355,980	12,578	1,283,485	0.24	489,547	0.53	1,310	78,329
170	30	48	90	415,990	13,778	1,283,777	0.24	518,561	0.6	2,706	70,121
180	40	48	80	429,660	13,349	1,283,787	0.239	536,725	0.62	328	69,536
170	30	48	85	412,490	13,528	1,284,040	0.24	521,686	0.6	2,700	70,900
170	30	48	75	405,490	13,027	1,284,393	0.24	527,860	0.59	2,749	72,438
170	30	48	80	408,990	13,278	1,284,688	0.24	524,956	0.6	2,689	71,720
200	40	48	100	477,000	14,376	1,284,901	0.239	555,267	0.66	15	63,298
170	30	48	100	422,990	14,280	1,285,714	0.24	513,368	0.61	2,719	68,835
170	30	48	70	401,990	12,777	1,286,418	0.24	531,745	0.59	2,882	73,412
170	40	48	75	409,490	13,062	1,286,971	0.24	526,911	0.59	666	72,395
200	40	24	100	448,200	13,316	1,287,009	0.239	571,964	0.64	0	69,498
180	40	24	60	386,860	11,336	1,287,116	0.241	564,420	0.59	3,107	78,740
200	40	48	85	466,500	13,756	1,289,812	0.24	562,253	0.65	206	65,738
170	30	48	60	394,990	12,278	1,289,832	0.242	539,230	0.58	4,644	75,288
160	40	48	70	389,320	12,766	1,289,909	0.241	517,270	0.57	1,183	75,246
190	40	48	80	446,330	13,470	1,292,375	0.241	552,120	0.63	260	68,521
180	30	48	50	404,660	11,931	1,293,847	0.25	557,541	0.59	15,485	75,172
180	40	48	75	426,160	13,175	1,294,783	0.241	542,202	0.61	649	71,312
140	30	72	60	373,780	13,168	1,294,818	0.245	484,875	0.53	7,354	75,287
180	30	48	90	432,660	13,928	1,294,957	0.242	534,188	0.62	1,989	69,319
180	30	48	85	429,160	13,679	1,295,551	0.242	537,418	0.62	1,985	70,131
180	30	48	100	439,660	14,430	1,295,894	0.242	528,563	0.63	1,991	67,922
180	30	48	80	425,660	13,428	1,296,451	0.242	540,843	0.61	2,013	70,982
180	30	48	75	422,160	13,179	1,296,840	0.242	543,982	0.61	2,037	71,771
190	40	24	60	403,530	11,462	1,297,115	0.243	580,299	0.6	3,356	77,872
160	40	24	50	346,520	10,763	1,297,412	0.244	546,516	0.54	4,566	84,889
140	40	48	60	348,980	12,199	1,298,615	0.243	498,408	0.52	2,489	81,191
170	40	48	70	405,990	12,886	1,298,830	0.242	532,869	0.59	952	74,275
180	30	48	70	418,660	12,927	1,298,988	0.242	547,993	0.6	2,136	72,765
140	30	72	75	384,280	13,879	1,299,745	0.243	479,334	0.54	2,792	73,696
140	30	72	80	387,780	14,123	1,300,854	0.243	477,024	0.54	2,871	73,087

140	30	72	70	380,780	13,649	1,301,013	0.243	482,261	0.53	2,762	74,533
170	30	72	90	444,790	14,860	1,301,330	0.242	509,986	0.61	497	66,065
200	40	48	80	463,000	13,594	1,301,436	0.243	567,632	0.65	375	67,551
160	30	72	85	424,620	14,534	1,301,442	0.242	500,002	0.59	775	68,675
160	30	72	80	421,120	14,293	1,301,759	0.242	502,849	0.59	788	69,434
160	30	72	90	428,120	14,780	1,301,948	0.242	497,351	0.59	773	67,993
170	30	72	85	441,290	14,617	1,301,981	0.242	513,038	0.61	495	66,867
160	30	72	75	417,620	14,058	1,302,744	0.242	505,805	0.58	872	70,252
180	30	72	90	461,460	14,944	1,303,193	0.242	523,524	0.63	290	64,393
190	40	48	75	442,830	13,297	1,303,472	0.243	557,600	0.63	426	70,304
170	30	72	80	437,790	14,381	1,303,634	0.242	516,321	0.61	471	67,762
140	30	72	85	391,280	14,375	1,303,667	0.244	475,244	0.54	2,925	72,650
180	30	72	85	457,960	14,702	1,303,935	0.242	526,606	0.63	293	65,203
170	30	72	100	451,790	15,352	1,304,073	0.242	505,454	0.62	505	64,894
180	30	48	60	411,660	12,431	1,304,191	0.244	556,178	0.6	3,202	74,832
180	40	48	70	422,660	12,992	1,305,015	0.244	547,647	0.6	1,033	73,029
180	30	72	100	468,460	15,436	1,305,388	0.243	518,791	0.64	292	63,164
160	40	72	100	439,120	15,310	1,306,069	0.243	491,273	0.6	185	66,633
180	30	72	80	454,460	14,468	1,306,339	0.243	530,143	0.62	280	66,177
160	30	72	100	435,120	15,277	1,306,536	0.243	493,516	0.6	768	67,017
170	30	72	75	434,290	14,156	1,306,546	0.243	519,804	0.6	487	68,766
170	40	24	50	363,190	10,885	1,306,850	0.246	562,250	0.56	4,989	83,965
190	30	48	90	449,330	14,079	1,306,858	0.243	550,109	0.64	1,460	68,594
190	30	48	100	456,330	14,579	1,307,106	0.243	544,218	0.64	1,468	67,124
140	30	72	90	394,780	14,625	1,307,309	0.244	473,864	0.54	2,925	72,307
190	30	72	90	478,130	15,043	1,307,394	0.243	537,669	0.65	158	62,946
190	30	48	85	445,830	13,828	1,307,504	0.244	553,405	0.63	1,460	69,416
200	40	24	60	420,200	11,595	1,307,799	0.246	596,255	0.62	3,680	77,060
160	30	72	70	414,120	13,845	1,307,970	0.243	509,949	0.58	880	71,485
160	30	72	50	400,120	12,950	1,308,462	0.252	518,782	0.57	14,023	74,251
170	40	72	100	455,790	15,396	1,308,627	0.243	505,098	0.62	167	65,039
190	30	48	80	442,330	13,576	1,308,652	0.244	556,970	0.63	1,443	70,297
170	30	72	70	430,790	13,928	1,308,702	0.244	523,051	0.6	877	69,696
190	30	72	85	474,630	14,807	1,308,997	0.243	540,904	0.65	137	63,834
190	30	48	75	438,830	13,326	1,309,104	0.244	560,165	0.62	1,482	71,096
190	30	72	100	485,130	15,535	1,309,634	0.243	532,928	0.66	170	61,720
160	30	72	60	407,120	13,398	1,309,927	0.247	515,107	0.57	4,958	73,057
190	30	48	50	421,330	12,089	1,310,116	0.253	575,184	0.61	14,111	74,917
180	30	72	75	450,960	14,249	1,310,240	0.243	533,891	0.62	305	67,279

160	40	48	60	382,320	12,411	1,310,826	0.246	527,931	0.56	2,963	78,687
190	30	48	70	435,330	13,078	1,311,759	0.244	564,288	0.62	1,579	72,136
160	40	72	90	432,120	14,905	1,312,169	0.245	496,949	0.59	619	68,558
190	30	72	80	471,130	14,577	1,312,191	0.244	544,693	0.64	185	64,886
140	40	48	50	341,980	11,805	1,313,152	0.248	507,514	0.51	5,729	84,031
180	30	72	70	447,460	14,030	1,313,298	0.245	537,264	0.62	782	68,288
190	40	48	70	439,330	13,115	1,313,902	0.245	563,111	0.62	1,080	72,041
170	40	72	90	448,790	14,985	1,313,920	0.245	510,579	0.61	473	66,887
200	30	72	90	494,800	15,155	1,314,612	0.244	552,721	0.67	43	61,800
190	30	72	75	467,630	14,354	1,315,237	0.245	548,186	0.64	183	65,904
200	30	72	85	491,300	14,917	1,315,290	0.244	555,643	0.66	49	62,593
200	40	48	75	459,500	13,438	1,315,394	0.245	573,851	0.64	371	69,608
200	30	72	100	501,800	15,640	1,316,500	0.244	548,054	0.67	54	60,555
170	40	48	60	398,990	12,514	1,316,859	0.247	542,773	0.58	3,088	77,437
140	30	72	100	401,780	15,124	1,317,110	0.246	472,302	0.55	2,926	71,909
180	40	72	100	472,460	15,513	1,317,216	0.245	520,618	0.64	49	64,036
190	30	48	60	428,330	12,581	1,317,401	0.246	572,698	0.61	2,569	74,255
180	40	24	50	379,860	11,013	1,317,439	0.249	578,308	0.57	5,375	83,154

Appendix B : Sensitivity Results

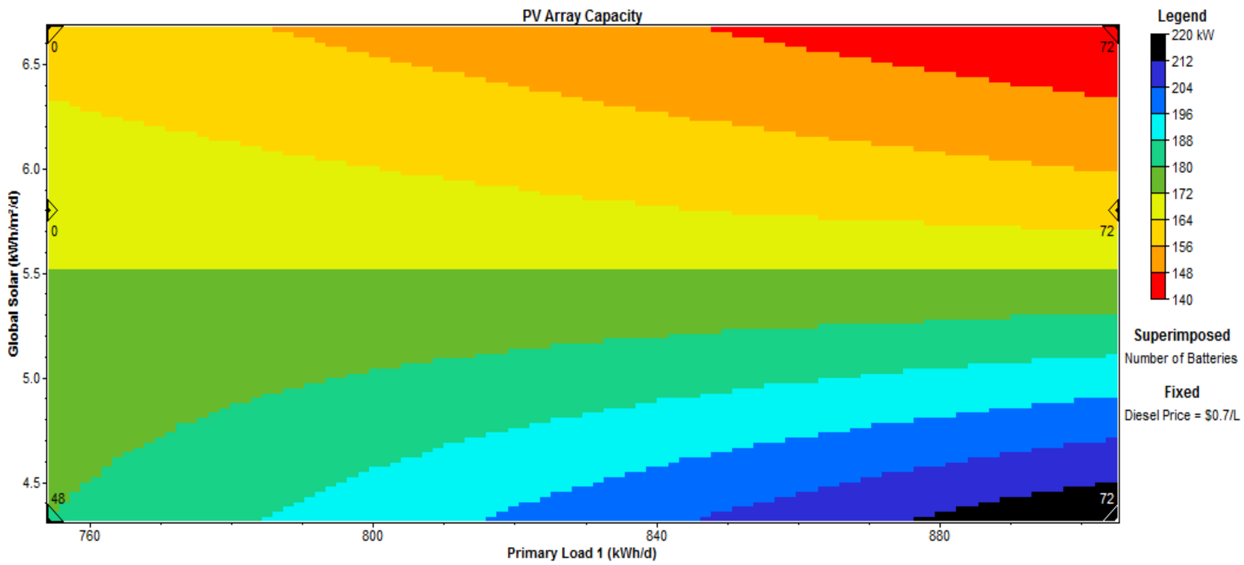

Figure B.1 PV array capacity and battery quantity variation

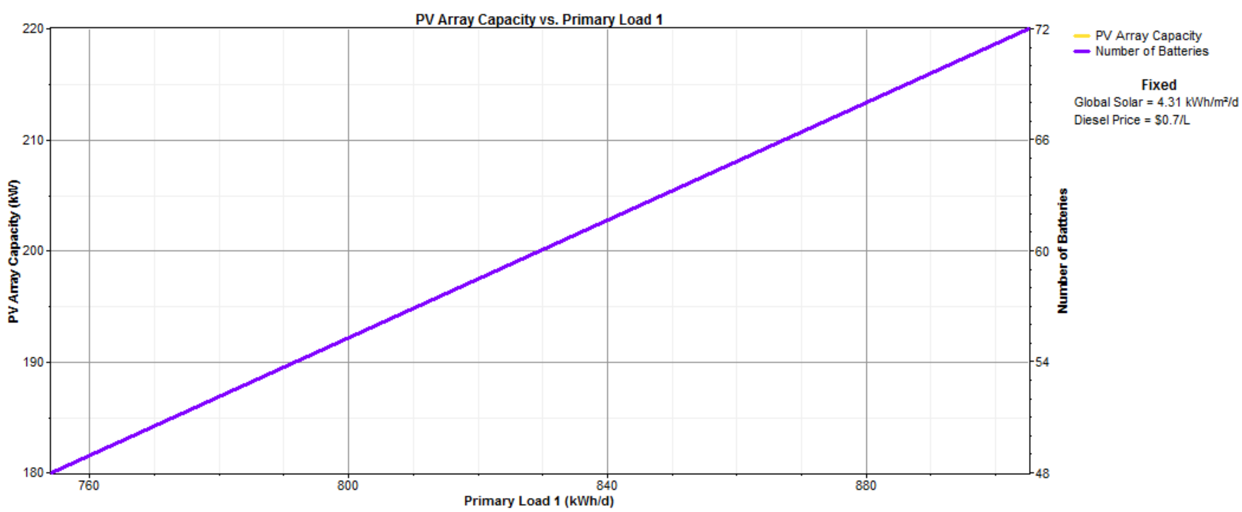

Figure B.2:PV Capacity and battery quantity variations by varying primary load only at solar radiation 4.31 kwh/m^2/d

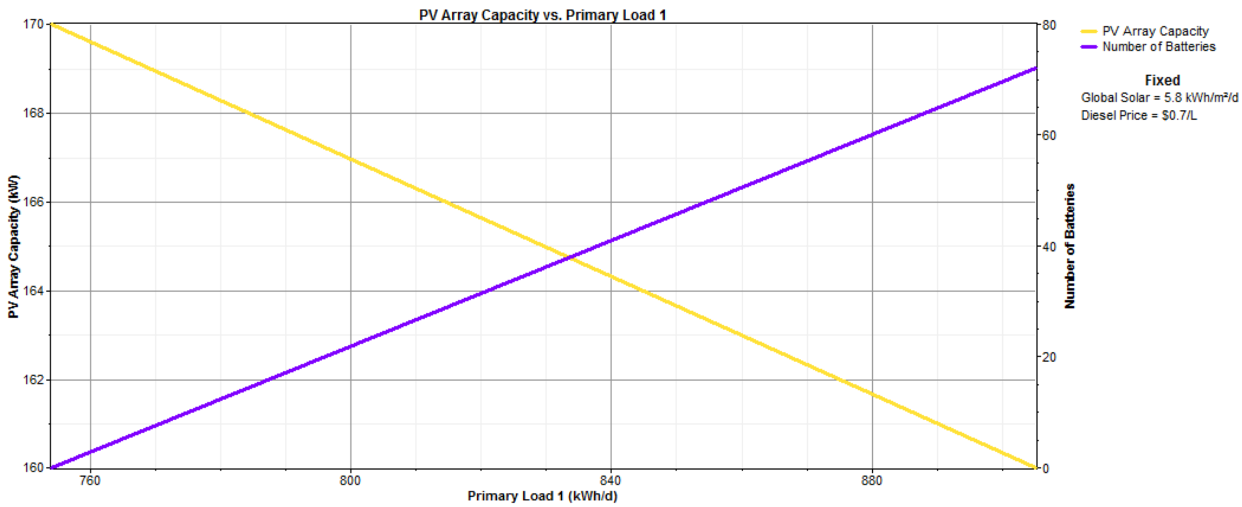

Figure B.3:PV Capacity and battery quantity variations by varying primary load only at solar radiation 5.8 kwh/m^2/d

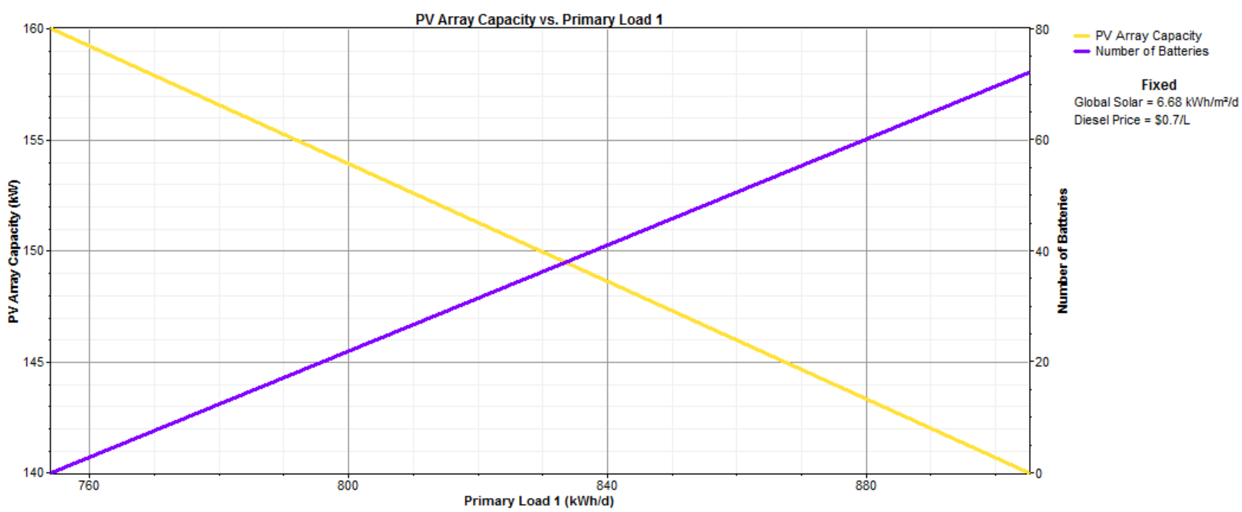

Figure B.4:PV Capacity and battery quantity variations by varying primary load only at solar radiation value of 6.68 kwh/m^2/d.

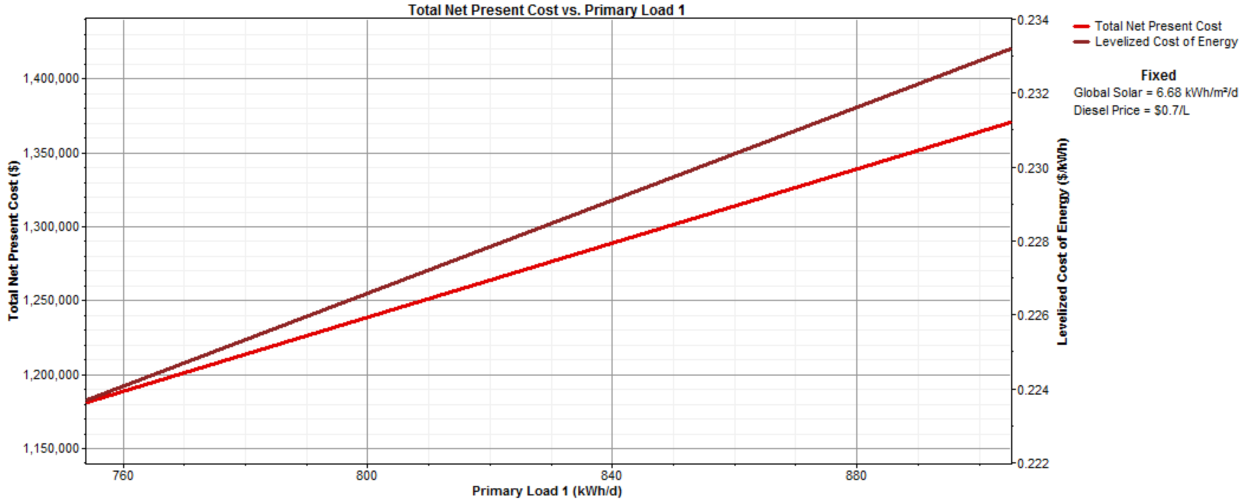

Figure B.5: Total NPC and COE for variation in primary load.

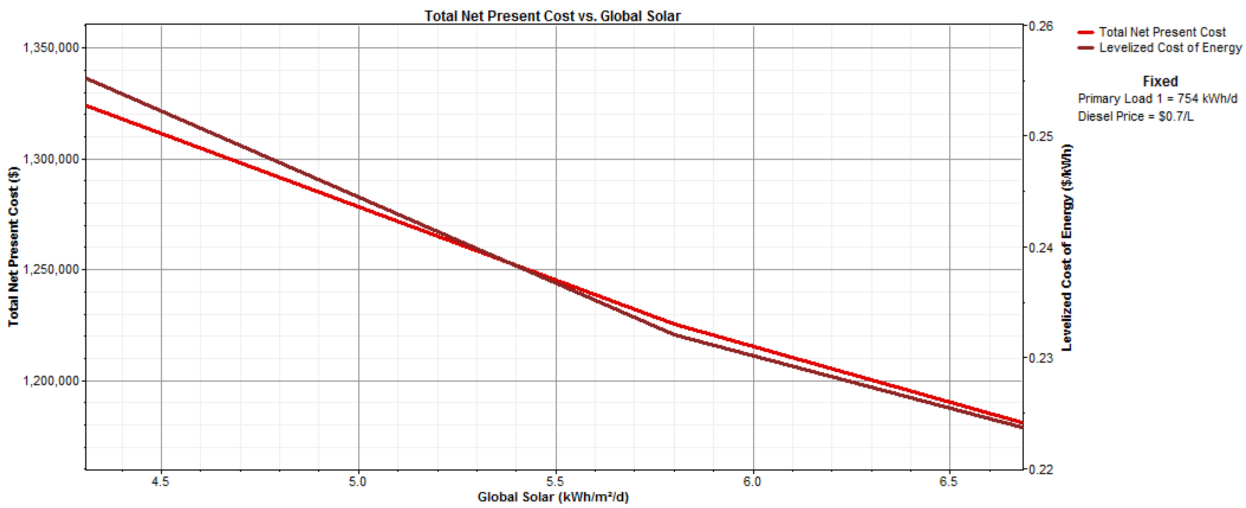

Figure B.6: Total NPC and COE for variation solar radiation.

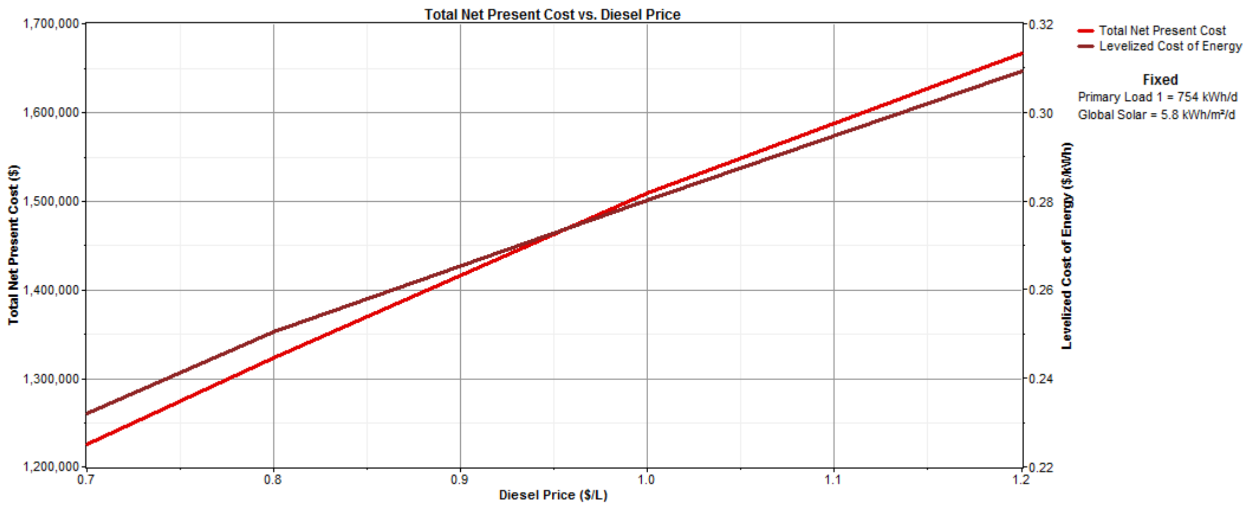

Figure B.7: Total NPC and COE for variation in diesel fuel price.