# Design and Optimization of Hybrid Photovoltaic /Diesel Storage Battery Mini-Grid System for Rural Electrification
# (Case Study, Albasa Village in Benshangul Gumuz Region, Ethiopia)

By: Amare Gebermedhin Admassu

A Thesis Submitted to

The department of Electrical Power and Control Engineering School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Masters of Science in Electrical Power and Control Engineering

(Specialization in Electrical Power Engineering)

Office of Graduate Studies

Adama Science and Technology University

July, 2021 G.C

Adama, Ethiopia

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# APPROVAL OF BOARD OF EXAMINERS

I, Dr.Tafese Asrat (Assistant Professor), the advisors of the thesis entitled "Design and Optimization of Hybrid Photovoltaic/Diesel Storage Battery Mini-Grid System for Rural Electrification" and developed by **Amare Gebermedhin Id. No. PGE/18896/11** hereby certifies that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

| | | |
|---|---|---|
| Dr.Tafese Asrat (Assistant Professor), | __________________ | _______________ |
| Major Advisor | Signature | Date |

We, the undersigned, members of the Board of Examiners of the thesis by **Amare Gebermedhin Id. No. PGE/18896/11** have read and evaluated the thesis entitled "Design and Optimization of Hybrid Photovoltaic/Diesel Storage Battery Mini-Grid System for Rural Electrification" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in in Electrical Power and Control Engineering (Specialization in Power System Engineering).

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| Office of Postgraduate Studies, Dean | Signature | Date |

## DECLARATION OF STUDENT

I, Amare Gebermedhin, hereby declare that this thesis entitled - Design and Optimization of Hybrid Photovoltaic/Diesel Storage Battery Mini-Grid System for Rural Electrification is entirely my own work and to my knowledge it has not been done or presented by any other person or University. The result of my own work carried out under the supervision of Dr. Tafese Asrat and I swear that all the material used has been properly referenced.

| | | |
|---|---|---|
| Amare Gebermedhin | ____________________ | ____________________ |
| Name of the student | Signature | Date of submission |

# RECOMMENDATION

I, Dr.Tafese Asrat (Assistant Professor),, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "Design and Optimization of Hybrid Photovoltaic/Diesel Storage Battery Mini-Grid System for Rural Electrification" prepared under my/our guidance by Amare Gebermedhin **Id. No. PGE/18896/11**submitted in partial fulfillment of the requirements for the degree of Mater's of Science in in Electrical Power and Control Engineering, the Graduate program of the department of Electrical Power and Control Engineering. Therefore, I recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

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|---|---|---|
| Tafese Asrat (Assistant Professor | ________________ | __________________ |
| Name of Advisor | Signature | Date |

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## LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| Ah | Ampere-hour |
| A-Si | Amorphous or Thin Film Silicon |
| AVR | Automatic Voltage Regulator |
| BESS | Battery Energy Storage System |
| Bcap | Daily Average Battery Capacity Required |
| Bcap.com | Total Commercial Battery Capacity Required |
| CC/CV | Constant Current/Constant Voltage |
| CFL | Compact Fluorescent Lamps |
| COE | Cost of Energy |
| DC | Direct Current |
| DOD | Depth of Discharge |
| FF | Fill Factor |
| EOL | End of Life |
| EPBT | Energy Payback Time |
| EEPCo | Ethiopian Electric Power Corporation |
| FTC | Farmers Training Center |
| HMI | Human Machine Interface |
| HOMER | Hybrid Optimization Model for Electric Renewable |
| HPSs | Hybrid Power Systems |
| HRES | Hybrid Renewable Energy Systems |
| $H_2SO_4$ | Sulfuric Acid |
| $H_2O$ | Water |
| IGBT | Insulated-Gate Bipolar Transistors |
| $I_{sc}$ | Short Circuit Current |
| Kwh | Kilo Watt Hour |
| $Kw/m^2$ | Kilo Watt per Meter Square |
| LCC | Life Cycle Cost |
| LCOE | Levelized Cost of Electricity |
| Li-ion | Lithium Ion |
| MPP | Maximum Power Point |
| MPPT | Maximum Power Point Tracker |

| | |
|---|---|
| MPH | Miles per Hour |
| NASA | National Aeronautics and Space Administration |
| NMSA | National Metrology Service Agency |
| NREL | National Renewable Energy Laboratory |
| NiCad | Nickel Cadmium Battery |
| NiCd | Nickel–Cadmium Cell |
| NiMH | Nickel Metal hydride battery |
| NiO(OH) | Nickel Oxyhy Droxide |
| NiOOH | Nickel Oxide Hydroxide |
| NOCT | Nominal Operating Cell Temperature |
| Nmps | Number Module per String |
| Nsp | Number of String in Parallel |
| NPC | Net Present Cost |
| $PbO_2$ | Lead Dioxide |
| PCS | Power Conversion System |
| PLC | Programmable Logic Controller |
| Pm | Maximum Power |
| PMG | Permanent Magnet Generator |
| Po | Nominal Rated Array Output |
| PV | Photovoltaic |
| PWM | Pulse Width Modulation |
| RES | Renewable Energy System |
| RHS | Renewable Hybrid System |
| RPM | Rotations per Minute |
| SAPS | Stand-Alone Power System |
| Scap | Daily Average System |
| SOC | State Of Charge |
| STC | Standard Test Condition |
| TV | Television |
| UEAP | Universal Electric Access Program |
| $V_{oc}$ | Open Circuit Voltage |
| Vm | Module Design Voltage |
| Vs | System Bus Voltage |

## *ABSTRACT*

*Renewable energies are increasingly seen as the best solution to a growing global population demanding affordable access to electricity while reducing the need for fossil fuels. Country of Ethiopia has vast untapped solar, wind, geothermal, and hydroelectric sources that hold the potential to meet domestic needs. In this thesis, solar PV/Diesel Generator/battery bank/ converter have been simulated and optimized for the rural area of Albasa village among the woreda of Dibate/Metekel Zone in Benshangul Gumuz region of Ethiopia. The optimization software used for this paper is HOMER it determines the optimal architecture. And energy management system is the programmable logic controller (PLC) as a control strategy of the hybrid system. In this applications at remote village with 1110 households with average of five family members per household. Based on the design of hybrid system Primary load demand of the village was 279kWh/day, peak load of 67kW, deferrable energy is about 29kWh/day, and deferrable peak load of 1.9kW were involved during optimization of the power system. Solar PV was considered as primary sources to supply electricity directly to the load and to charge battery bank when there were excess energy generation. However, either in peak load times or low generation of primary sources storage battery bank discharged and Diesel Generator could also be used as a source. The load has been suggested for residential loads and deferrable load (water pumping). During design of this power system set-up, the optimization was done based on the load demand, climatic data, economics of integrated system components and other parameters in which the total NPC and levelized COE have to be minimized to select economically feasible and technically capable hybrid power system. Furthermore; a programmable logic controller (PLC) modeling is also modeled to compare the possible potentials available (only solar energy, only diesel generator or hybrid energy) and take a decision. The decision of programmable logic controller (PLC) modeling is based on the instructional rules written on it.*



***Keywords:*** *Mini-Grid Hybrid System, Rural Electrification, PV, Diesel Generator, Battery Bank, Primary Load, Deferrable Load, HOMER, Programmable Logic Controller (PLC).*

# INTRODUCTION (CHAPTER ONE)

## 1.1 Background of the Thesis

Energy is the fuel for growth of a country or generally growth of the world. An increased access to electricity enhances opportunities for industrial development and improves health and education. But currently still about 37% of the world's population have no access to electricity. Most of rural people depend almost exclusively on biomass for their daily energy need. According to the report of United Nations Food and Agriculture Organization, the numbers of people suffering from shortage of wood fuel were expected to highly increase in the coming years [1, 2].

The Ethiopian Government tried to connect this rural location by using national grid extension for the last two decades. However, still the current electricity access is below 50% and the real connection is less than 14% [2, 3]. Today it is widely accepted that Renewable energy system (RES) have a large potential to contribute to the strengthening and development of national sustainable energy infrastructures in many countries in the world by securing better energy independence through the mobilization of domestic renewable energy resources especially in rural areas [4, 5].

A stand-alone power system (SAPS), also known as remote area power supply (RAPS), is a mini-grid electricity system for locations that are not fitted with an electricity distribution system. Typical SAPS include one or more methods of electricity generation, energy storage, and regulation [6, 7, 8]. Hybrid renewable energy systems (HRES) are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. A hybrid energy system, or hybrid power, usually consists of two or more renewable energy sources as well as a backup is used together to provide increased system efficiency as well as greater balance in energy supply [9, 10, 11].

### 1.1.1 History of Ethiopian Power Sector

The following Figure 1.1 shows that the history of Ethiopian electric power generation starting from the beginning until the current situation.

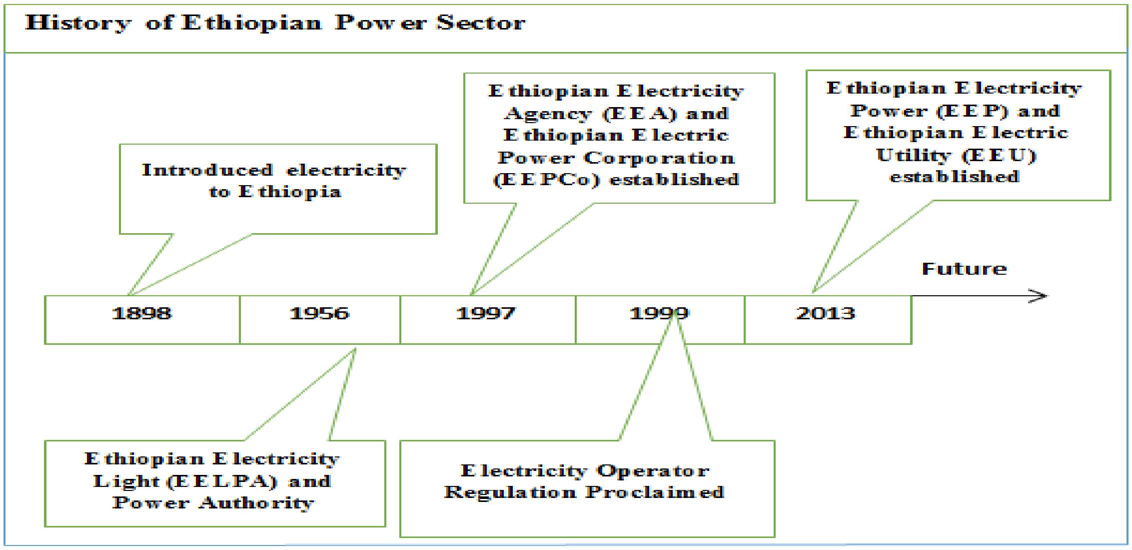



Figure 1. 1: History of Ethiopian Electric Power Sector [1]

## 1.2 Statement of the Problem

Despite of the abundant renewable energy resources, many communities still live without access to electricity either from the utility grid or mini-grid renewable energy generated electricity. Energy consumption involves all energy harnessed from every energy source applied towards activity across all industrial and technological sectors in every country. According to current figures about 30% of the Ethiopian citizens are estimated to have electricity access and the per capital energy consumption is still less than 100 KWh per household, which is the lowest in the world and almost using biomass [12, 13, 14]. This had a direct impact on deforestation. However, energy supply thereby is covered by bio-energy which accounts about 90% of final energy consumption, while a transport sector is predominantly run by imported petroleum; which accounts about 4.5% and the modern energy contributes only about 6% of the overall energy consumption. Nowadays Ethiopia total installed capacity of electric generation is about 4.5 GW (2019) mainly generated by hydro (90%) and followed by wind energy (7.6%). Only few researchers were conducted in Ethiopia to solve problem in rural energy access and empower the development of alternative energy technology. The lack of electricity access causes for social and economic problems such as poverty, poor health services, low quality of education, gender inequity and so on. The feasibility study of the site or the selected area (Albasa) is finished before two years by Ethiopian Electric Utility; Universal Electricity Access Program based on PV/Diesel/Storage Battery mini-grid system [15].Hence, this Thesis prepares the design of hybrid system.

Therefore, this Thesis presents the review of Ethiopia renewable energy potential with current state in a more comprehensive way and provides valuable information for researchers, industrial companies and decision makers to promote investment in renewable energy technology development. During design of hybrid system, it is needed to design efficient control system. If the control system failed to switch to an appropriate power source at desired time, the efficiency of the system will decrease. Hence attentions should be given to the control system during designing of hybrid power system.

## 1.3 Objective of the Thesis

### 1.3.1 General Objective

Design and Optimization of Hybrid Photovoltaic/Diesel Storage Battery Mini-Grid System for Rural Electrification.

### 1.3.2 Specific Objectives

The specific objectives of this thesis are:

- Electricity from the grid is not easily available in this village due to the high cost of transmission lines per km.
- To decrease traditional energy usage i.e., decrease a direct impact on deforestation in this site.
- Alternative options for power generation for rural electrification program as they seek to increase the supply capacity and expand power connections to every household through a solar mini-grid development.
- To determine how designed hybrid system of PV /diesel/battery storage mini-grid system can be used to solve the problem of electricity access in the selected sites.
- To prepare the best optimized hybrid model for providing electricity to the community by considering its overall installation cost, contribution of renewable energy sources and energy cost per kWh for the selected area.

## 1.4 Methodology

Different methodologies have been applied to address each specific objective of this thesis work. First the site should be identified, problems of the community is clearly stated, data required for the thesis work is collected through various data collection mechanisms and different literatures are surveyed to identify the way to do the thesis work, to get data and to enhance academic knowledge and research skills. And following that the data collected from various sources are analyzed using software tool and integrated to give solution for the problems and challenges raised at the start of the thesis work.

### 1.4.1 Site Location

The case study area is identified by directly visiting the site. Site map in Woreda level obtained from Google earth and Google Map were used.


Figure 1. 2: Location of the Site under Woreda Level from Google Earth Map.

### 1.4.2 Problem Identifications

The problem identification involved a literature survey and direct observation in collecting general information about Dibate Woreda, Albasa village community, such as geography, climate, and population, current energy supply sources, current energy utilization mechanism, effects of the current energy supply mechanism, and effects of traditional energy access mechanism. The main focus of the survey was on the renewable energy sources availability, the effect of the current biomass-based energy supply on women health and the effect of fully dependent biomass-based energy supply on the environment.

### 1.4.3 Data Collection and Literature Survey

There are two sources of data collection methods which are primary data gathering and secondary data collections. The primary data gathering conducted through use of questionnaires, site visits and interviews about the selected site. And also, the secondary data gathered from books, journals, newspapers, magazines, conference papers, reports, etc.

### 1.4.4 Analysis and Evaluation of Data

Analysis and evaluation of the collected data in the way to input into the Hybrid optimization model for electric renewable (HOMER) software. The software simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications, using the appropriate and cost-effective power generating technologies. The major applications of HOMER are the design of micro power systems optimization for the efficient evaluation of various renewable energy power generation technologies. It compares a wide range of equipment with different constraints and sensitivities to optimize the system design. And also, Programmable Logic Controller is used to energy management system. Finally based on the findings make conclusion and give recommendation.

## 1.5 Scope of the Thesis

The thesis focuses on selected renewable energy resources such as solar PV/Diesel Generator storage battery bank hybrid system and the selected area. And also, the thesis integrates the HOMER software to optimize the mini-grid hybrid system and Programmable Logic Controller to model and manage the mini-grid hybrid system.

## 1.6 Significant of the Thesis

The main contribution of the thesis is to explore and put forward the appropriate mini-grid PV/Diesel Generator/battery bank hybrid system model and design with energy management. Even though the power consumption of rural community is not so much high, the battery bank system has the possibility to save the electrical power during high generation and discharge to supply the load when low generation of renewable energy. The thesis can also be used as a reference for future studies that can be done on mini-grid solar PV/Diesel Generator/battery bank hybrid system. In addition, anyone who is going to implement mini-grid hybrid system in different urban areas in Ethiopia can use as a procedure.

## 1.7 Organization of the Thesis

The thesis consists of five chapters. The first chapter covers the introduction part which deals with the background, statement of the problem, objectives, scope and significance of the thesis. Chapter two gives the theoretical overviews of solar PV energy, components of Diesel Generator and battery bank and also introduction about programmable logic controller which used for energy management system. Chapter three presents materials and methods which studied about the Potential assessments of renewable energies in Albasa village and the surrounding areas. The assessment was based on the data obtained from primary data and secondary data (Local Source, NMSA and International source, NASA). Estimation of load and also load forecasting requirement per season were presented. Modeling and design of Hybrid power system, overview of HOMER software including energy management system, etc. chapter four were all about the results and discussion of optimization and sensitivity analysis of the system findings of the thesis work and also energy management system. Chapter five presents conclusions and recommendations.

# LITERATURE REVIEW (CHAPTER TWO)

## 2.1 Literature Review

Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat [14]. Worldwide investments in renewable technologies amounted to more than US$286 billion in 2015, with countries like China and the United States heavily investing in wind, hydro, solar and biofuels [16, 17]. Globally, there are an estimated 7.7 million jobs associated with the renewable energy industries, with solar PVs being the largest renewable employer. As of 2015 worldwide, more than half of all new electricity capacity installed was renewable [18, 19, 20].

The thesis investigated by **Berihun G/Yohannes** (2017), A standalone wind/micro hydro/battery hybrid system and only micro hydro system options are considered separately in order to electrify the selected village. HOMER simulation software has been used as the modeling and designing tool. For the first option many feasible hybrid system combinations are listed and sorted according to their net present cost (NPC). Accordingly, levelized cost of energy (COE) and breakeven grid extension distance depend on the selected sensitivity variables. The COE the most favorable wind/micro hydro hybrid system is $0.112/KWh. Likewise, the breakeven grid extension distance of the hybrid system 23.2km. On the other hand, the levelized COE of the micro hydro system is $0.035/KWh which is smaller than that of hybrid system. And it is believed that the standalone micro hydro system is economically feasible and pollution frees to implement for his particular work [21, 22].

The thesis investigated by **Solomon T/Michael** has been design mini-grid hybrid renewable set-up indicates that various combinations based on the renewable sources could be applied simultaneously to cater energy in the form employed in an off-gird supporting with battery storage and diesel generator as backup systems. In this paper wind turbine-photovoltaic-diesel generator-battery bank-converter have been simulated and optimized for the rural community of Haressaw among the sub-districts of Atsbi district in the regional state of Tigray, Ethiopia. Primary load demand of 1505kWh/day, peak load of 284kW, deferrable energy is about 17kWh/day, and deferrable peak load of 3.6kW was involved during optimization of the power system. Well known freeware HOMER modeling tool have been used to design the off-grid system. Wind and solar 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. During the design of this power system set-up, the simulation and optimization was done based on the electricity load, climatic data sources, economics of the power components and other parameters in which the NPC has to be minimized to select an economic feasible power system. Moreover other parameters like capacity shortage, renewable fraction, excess electricity, COE, diesel fuel consumption was also considered to check the technical capability so as to select a system that is sound in techno-economic aspects.

The thesis investigated by **Sisay Fitwi**, feasibility of solar PV-Wind-Biogas hybrid system with battery storage as a backup is studied to electrify the village in Adigrat district. It also compares the cost of the hybrid system against the cost required to electrify the village by extending the grid. The feasibility of his paper is analyzed using HOMER software. The data for biogas energy potential estimation is obtained from the Ministry of Mines and Energy (MME) of Ethiopia. The paper utilized meteorological data obtained from NMSA of Ethiopia, NASA and Solar and Wind Energy Resource Assessment (SWERA) to estimate the solar and wind energy potentials. The data needed for calculating the cost of extending the grid is taken from Ethiopian Electric Power Corporation (EEPCo) and is analyzed using interlinked Microsoft office excel spread sheet prepared by Universal Electric Access Program (UEAP). Electric load estimation and forecasting for the basic needs of the community, such as, for lighting, radio, television, water pumps and flour mills, is done. Primary school and health clinic are also considered for the community. The simulation results show many feasible hybrid system combinations having a cost of energy less than $0.295/KWh which is much lower than diesel generators and previously studied PV/Wind hybrid systems. The hybrid energy system optimized by HOMER for this village is cost effective as compared to the cost required to electrifying the village. The breakeven grid extension distance is found to be

14.9kms, which implies that this hybrid energy system is cost-effective for areas greater than the breakeven distance [23].

The thesis investigated by **Solomon Kiros**, focuses on comparing the economic performance of using various scenarios of stand-alone PV/Wind hybrid system, with battery storage and diesel as a backup, for electrifying Kutur village of Awlio kebele of the Axum district (which is 30kms away from the closest national grid) to the possibility of extending the grid. Axum district which is located at latitude of 14° 07' N and longitude of 38° 43' E is found to have 4.28m/s wind speed at a height of 10m, and 6.19KWh/$m^2$/day solar radiation. Two electric load scenarios are estimated by considering set of incandescent and efficient lamps for lighting for the existing 120 households. The over mentioned solar radiation and wind speed are then used as an input to simulate the hybrid setup for the high and low load estimation using HOMER software. Simulation result shows that the NPC corresponding to high and the cost of energy (COE) low load scenarios were $278,856 and $194,174, respectively [24].

Generally, all the researchers described above was used only HOMER software as a modeling, design and optimization tool to realize their study, the hybrid system set-ups were studied using different load demands and applications, location of studies as well as climatic data's they used were different. Some of the studies were employed in areas that have no electricity at all whereas the others in areas that have already accessed electricity which was provided by using diesel generator.

This thesis has been employed the HOMER software to model, design and optimize the mini-grid hybrid power system. However, it is different from related studies in terms of application, load demand, climatic data and location of the selected area. In addition to this the thesis used Programmable Logic Controller for energy management system. So that no one use Programmable Logic Controller as an energy management in the above studies.

## 2.2 Theories of Renewable Energy

Energy plays an important role in all types of development, including economic development. The world total energy annual consumption generally increases, with the vast majority of energy being produced by fossil fuels such as coal, oil and natural gas. In

2008 fossil fuels provided the three quarters of the total, with the current energy consumption rate, proven coal reserves should last for about 200 years, oil for approximately 40 years and natural gas for around 60 years [25].

With constantly increasing development, diminishing fossil fuel resources and related environmental problems (e.g. emissions), sustainable development and the manner in which energy is produced and consumed is reconsidered. Renewable energy [1], i.e., energy generated from solar, wind, biomass, geo-thermal, hydropower and ocean resources, could increase the diversity of energy supplies and offer "clean"-environmental friendly energy. Although wind and solar energy sources are significantly less productive compared to fossil fuels, the use of PV cells and wind turbines [2] has increased rapidly during the last years, especially in developed countries. PV cells are electronic devices that are based on semiconductor technology and can produce an electric current directly from sunlight [26, 27].

### 2.2.1 Basic Theory of Solar Energy

Solar energy is radiant light and heat from the Sun that is harnessed using a range of ever-evolving technologies such as solar heating, solar PVs, solar thermal energy, solar architecture, molten salt power plants and artificial photosynthesis [19, 28].

It is an important source of renewable energy and its technologies are broadly characterized as either passive solar or active solar depending on how they capture and distribute solar energy or convert it into solar power. Active solar techniques include the use of PV systems, concentrated solar power and solar water heating to harness the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air [18, 29].

Generally, the sun is the largest energy source of life and at the same time it is the ultimate source of most of renewable energy sources that is why sun is considered as the mother or father of all renewable energy sources. Without sun; there is no wind, no water and no biomass energy. Energy from the sun has been used to provide heat and electricity for many years.

### 2.2.2 Solar Photovoltaic (PV) Systems

Solar PVs, by far the most important solar technology for distributed generation of solar power, use solar cells assembled into solar panels to convert sunlight into electricity. It is a fast-growing technology doubling its worldwide installed capacity every couple of years. PV systems range from distributed, residential, and commercial rooftop or building integrated installations, to large, centralized utility-scale solar PV power stations [24, 30].

The predominant PV technology is crystalline silicon, while thin-film solar cell technology accounts for about 10 percent of global PV deployment. In recent years, PV technology has improved its sunlight to electricity conversion efficiency, reduced the installation cost per watt as well as its energy payback time (EPBT) and levelized cost of electricity (LCOE), and has reached grid parity in at least 19 different markets in 2019 [18, 31].

### 2.2.3 Operation of Solar PV

The term PV means the direct conversion of light into electrical energy using solar cells. Solar cells are made up of Semiconductor materials such as silicon, gallium arsenide, cadmium, telluride or copper indium, etc.  Solar PV cells are the devices that are used for converting solar energy into electrical energy by utilizing the PV effect. These cells are used in many real-time applications such as railway signaling systems, street lighting systems, domestic lighting systems, and remote telecommunication systems. Solar PV effect is a process to convert solar energy into direct current (DC) electricity using an array of solar panels. This, DC electricity can be stored in batteries or can be used to feed DC loads directly or can be used to feed alternating current (AC) loads using an inverter that turns DC electricity into 220-volt AC electricity [32].

Solar PV cell consists of a P-type of silicon layer that is placed in contact with an N-type silicon layer. The electrons diffuse from the N-type material to the P-type material. The holes in the P-type material accept the electrons but there are more electrons in the N-type material. So, with the influence of the solar energy, these electrons in the N-type material move from N-type to P-type.

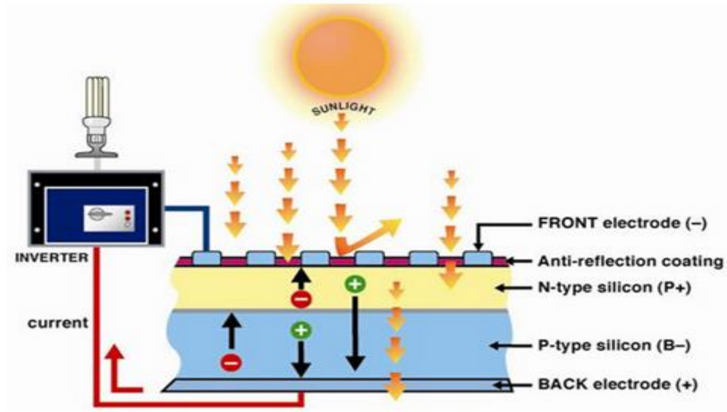



Figure 2. 1: Operation of Solar PV Cells [33]

Thus, these electrons and holes combine in the P-N junction. Due, to this combination a charge on either side of the P-N junction is created and this charge creates an electric field. This formation of electric field results in developing a diode like system that promotes the charge flow. This is called as drift current and the diffusion of electrons and holes is balanced by drift current. This drift current occurs in an area where mobile charge carriers are lacking and is called as the depletion zone or space charge region. Thus, during night time or in the darkness, these solar PV cells behave like reverse bias diodes [33, 34].

### 2.2.4 Solar PV Technologies

When we see physical characteristics of Solar cells for terrestrial applications are typically made from silicon as single-crystal, polycrystalline or amorphous solids.

**Single-crystal or Monocrystalline Silicon Cell.-** is the most efficient because the crystal is free of grain boundaries, which are defects in the crystal structure caused by variations in the lattice that tend to decrease the electrical and thermal conductivity of the material. These cells show efficiencies approximately 17 to 20% depending on the material quality and the specific cell technology [35, 36].

**Polycrystalline or Multicrystalline Silicon**.- has obvious grain boundaries; the portions of single crystals are visible to the naked eye. Slightly bigger solar panel for delivering the same amount of power that of Monocrystalline Silicon Cell. They demonstrate conversion efficiencies slightly lower than those of monocrystalline cells from 14 to 16% [13, 37].

**Amorphous or thin film silicon (A-Si)**.- is the non-crystalline form of silicon where the atoms are arranged in a relatively haphazard way. Due to the disordered nature of the material, some atoms have a dangling bond that disrupts the flow of electrons. It has lowest power conversion efficiencies of the three types but is the least expensive to produce. Additionally, it absorbs light more effectively than crystalline silicon, which leads to thinner cells, also known as a thin film PV technology. The greatest advantage of these cells is that amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible. Their disadvantage is the low efficiency, which is approximately 5 to 7 % [15, 38]. From the above different types of solar cells the best component for this thesis work was monocrystalline silicon.

### 2.2.5 Components of PV Generator

To size the PV generator, the following components are required:

**Solar cells**. - are produced on silicon wafers. It is the oldest and the most popular technology due to high power efficiencies [34, 39].

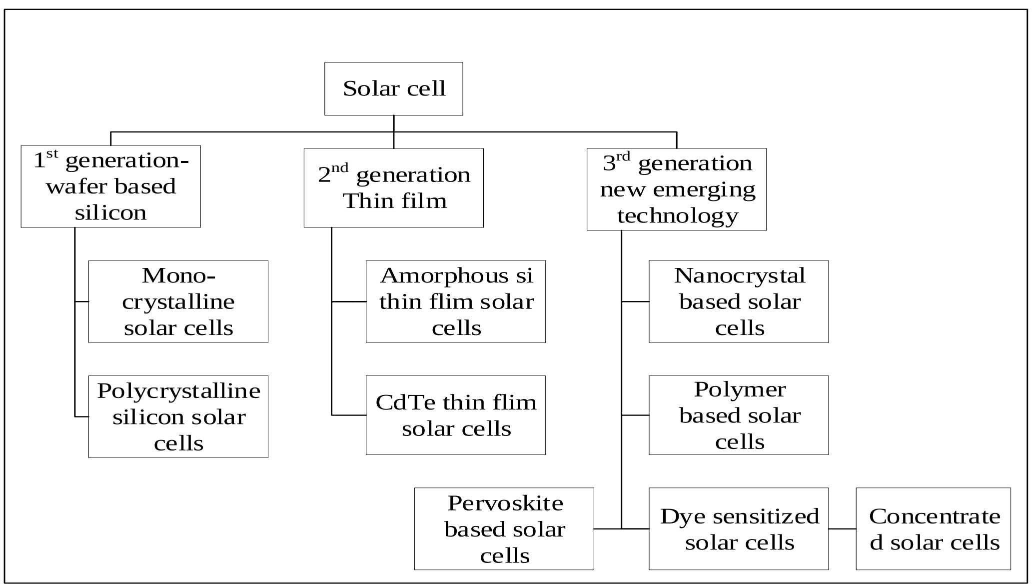



Figure 2. 2: Various Types of Solar Cell Technologies and Current Trends of Development

**PV Modules.-** PV module or panel is a grouping of PV cells. The voltage generated by a single PV cell is inconveniently low. Several cells are always joined in series so that their voltages add up to a more useful value. The series connection of cells forms a unit called a PV module. The front consists of a window of low-iron glass with high transmission characteristic, which protects the surface of the PV material [38,40].

**PV String. -** is a group of modules which are wired either series or parallel. Series string is used to increase the voltage as modern solar electric DC systems operate minimum at 48 volts nominal, and for high-voltage grid-tied systems produce up to 600 volts [17, 21].

**Solar Panels.** - are made up of solar modules or a group of solar modules and is used for converting solar energy into electrical energy. The solar panels utilize Ohmic material for interconnections and external terminals. Thus, the electrons produced in the N-type material are passed to the battery through electrode and wire. From the battery, electrons reach p-type material, where these electrons and holes are combined. Hence, the solar panel connected to the battery behaves like another battery, and hence, is comparable to the two serially connected batteries [35, 41].

**PV Array. -** One of the attractions of PV modules is that connecting modules to form array may increase the power rating of a system. Within a PV array, there are basically two methods of connection between modules. To increase the array voltage, modules are connected in series, known as series string. To increase the generating capacity without changing the array voltage, strings of modules are connected in parallel [36, 42].

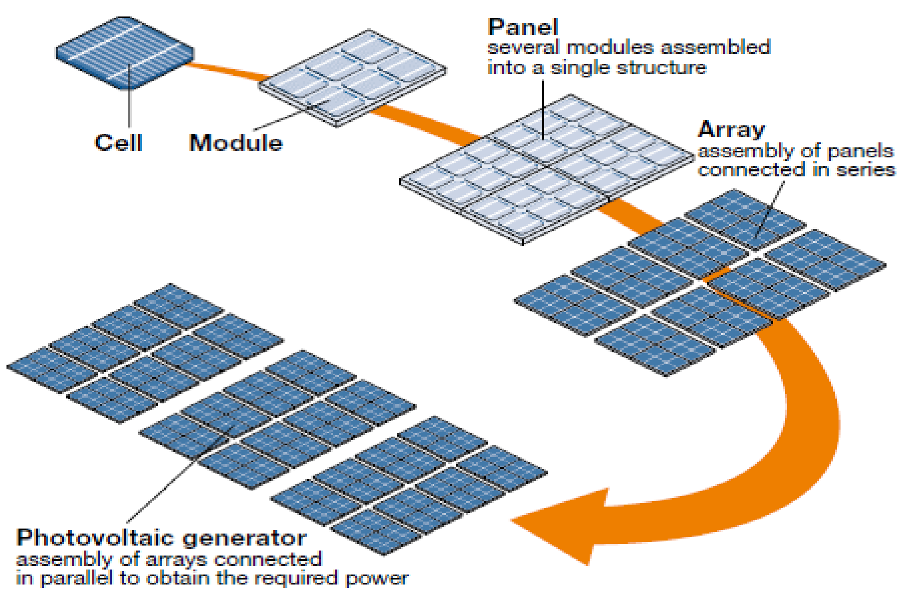
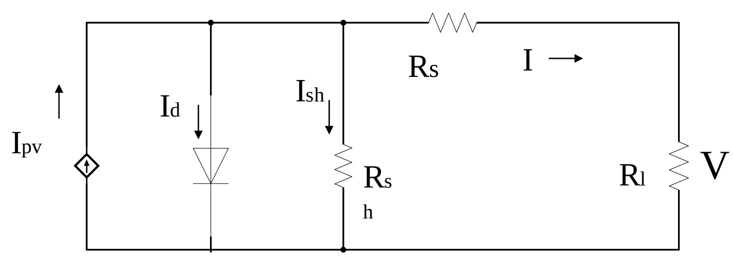



Figure 2. 3: PV Field or Generator [38]

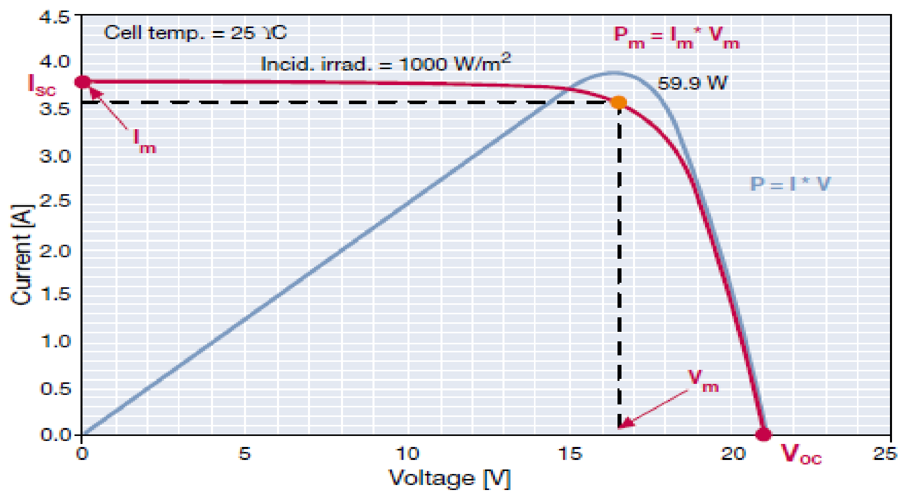
Generally, several panels electrically connected in series constitute an array and several arrays, electrically connected in parallel to generate the required power, constitute the generator or PV field.

### 2.2.6 Equivalent Circuit of PV System

The most popular circuit equivalent to a solar cell/panel is shown in Figure 2.4; it includes a current source, one diode and two resistors: one in series and the other is in parallel. Each element included in the equivalent circuit implies one parameter that has to be determined (two in the case of the diode whose behavior is represented by the Shockley equation). Therefore, five parameters need to be calculated when using this method. These representative points are, together with their variation as a function of the temperature, the normal information included in manufacturers' datasheets [8, 11].




**a)**




**b)**

Figure 2. 4: a) Equivalent Circuit and b) V-I Characteristic of a Solar Panel

The fundamental parameters related to solar cell are short circuit current ($I_{sc}$), open circuit voltage ($V_{oc}$), maximum power point (MPP), efficiency of solar cell and fill factor.

The circuit model formed by one diode and two resistors is defined by the following equation:

$$I = I_{PV} - I_O \left[\exp\left(\frac{V+IR_s}{\alpha V_T}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (2.1)$$

Where, $I_{pv}$ _ the photocurrent delivered by the constant current source;

$I_o$ _ the reverse saturation current corresponding to the diode;

$R_s$ _ Series resistor that takes into account losses in cell solder bonds, interconnection, etc.;

$R_{sh}$ _shunt resistor that takes into account the current leakage through the high conductivity shunts across the p-n junction; and $\alpha$ _ ideality factor

$V_T$ _ Thermal voltage of the diode and depends on the charge of the electron, **q**; the Boltzmann constant, **k**; the number of cells in series, **n**; and the cell temperature, **T**:

$$V_T = n\frac{KT}{q} \quad (2.2)$$

**<u>Short circuit equation</u>. -** $I_{sc}$ is the current corresponds to the short circuit condition when the impedance is low and it is calculated when the voltage equals to zero.

$$I_{SC} = I_{PV} - I_O \left[\exp\left(\frac{I_{sc}R_s}{\alpha V_T}\right) - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \quad (2.3)$$

**<u>Open circuit equation</u>. -** $V_{oc}$ is the voltage when the open circuit occurs and there is no current passing through the cell. The $V_{oc}$ is calculated when the current equals to zero.

$$0 = I_{pv} - I_o \left[exp\left(\frac{V_{0c}}{\alpha V_T}\right) - 1\right] - \frac{V_{0c}}{R_{sh}} \quad (2.4)$$

**<u>Maximum power point circuit equation</u>.-**

$$I_{mp} = I_{PV} - I_O \left[\exp\left(\frac{V_{mp} + I_{mp}R_s}{\alpha V_T}\right) - 1\right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \quad (2.5)$$

## 2.4 Diesel Generator (Backup)

Diesel generators are connected to the mini-grid system to provide back-up during periods of low solar radiation and random nature of renewable energy sources. The generator exists to supply power to the AC bus in case of shortage of production from solar PV array. The generator can also be used to charge the batteries during foggy and rainy days. Without any back-up generator, the battery bank can be damaged because of prolonged deep discharging and insufficient charging during rainy and foggy days. The generator is turned off when the batteries are fully charged.

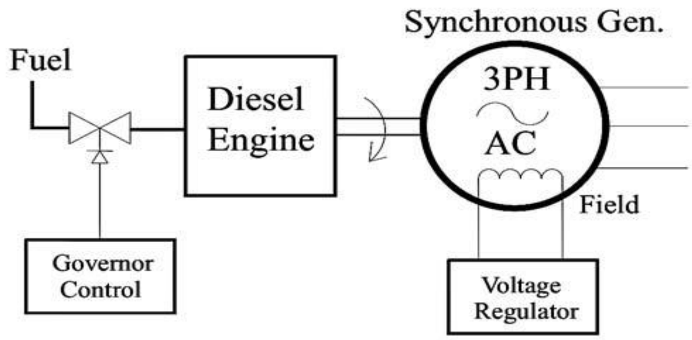



Figure 2. 5: Basic Block Diagram of a Diesel Generator [43]

A diesel generator (diesel engine-generator set) consists of two main components coupled by a common shaft: the diesel prime mover and the electrical generator. Figure 2.5 shows the basic block diagram of a diesel generator. The diesel engine converts chemical energy of the fuel to the kinetic energy of the rotating shaft to drive a synchronous machine. The fuel injection is controlled by a governor to regulate the speed of the engine. Hence, it regulates the output electrical frequency of the generator, since the shaft speed ($\omega$) is related with the electrical frequency (f) and the number of poles (P) of the synchronous machine as,

$$\omega = \frac{120f}{P} \tag{2.6}$$

The synchronous machine has an excitation system to control the output voltage of the genset. The excitation system generates the rotor magnetic field. This field may be provided by means of permanent magnets or by a DC source that feeds the field windings. Normally the diesel genset uses an Automatic Voltage Regulator (AVR) to adjust the generator field voltage and/or the field current according to the variations in the output terminal voltage [43, 44].

Diesel generators are important in renewable energy hybrid systems to improve the quality and the availability of the electricity supply. Since diesel generators are dispatch able they can be used to supply the load when the energy productions from the renewable sources are low or the state of the charge of the battery bank is not sufficient for supplying the load. The following figure 2.6 shows the schematic of a diesel generator.

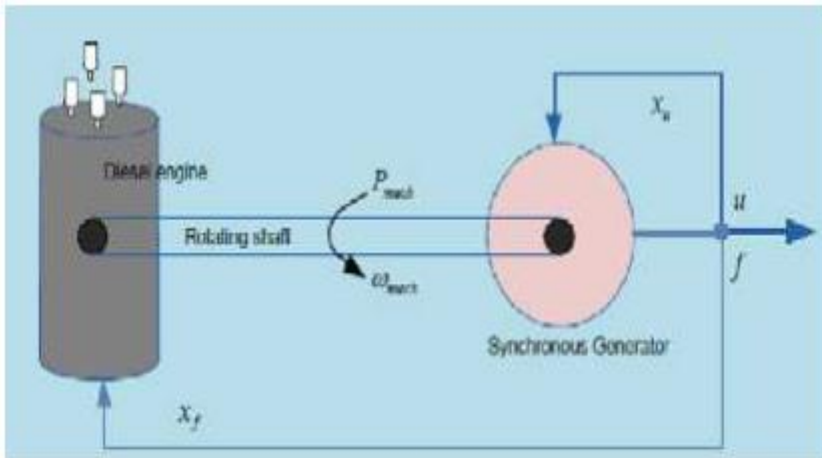



Figure 2. 6: Schematic of Diesel Generator with Constant Engine Speed [35]

The initial investment for installing a diesel generator is relatively small when compared with the initial investment of the PV or wind energy system. However, the operating and maintenance cost of a diesel generator is relatively high as it requires a continuous supply of fuel (diesel), and frequent maintenance of the machine throughout its operating life.

Optimal unit sizing of a diesel generator requires careful consideration of several factors including detailed analysis of daily and seasonal load fluctuations, annual load growth, and incorporation of practical constraints for feasible and reliable diesel operation. If diesel units are only sized based on peak and/or average load values, on an annual base, with some safety margins and additional capacity for future expansion, the diesel plant were generally be very oversized. The reason is that remote community loads are normally characterized as being highly variable, with the peak load as high as many times the average load [45, 46].

Usually diesel generators operate most efficiently near full load. Thus, it is recommended to operate the generator above a certain load factor for maintaining the proper efficiency of the energy conversion hence lowering the fuel cost by reducing the utilization of fuels. The fuel consumption curve of a diesel generator is normally given by the manufacturer in the product specification data sheet and the efficiency curve can be derived. In this study, Cummins diesel generators selected and its fuel consumption curve and the efficiency curve is depicted as below.

**Fuel curve:** It shows the fuel quantity of the generator consumes to generate electricity.

The mathematical expression below is to give the generators fuel consumption in units per hour [2, 10].

$$F = F_o . Y_{gen} + F_1 . P_{gen} \tag{2.7}$$

Where:

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

$Y_{gen}$: Fuel curve slope [units/hr/kW]

$F_1$: Rated capacity in [kW]

$P_{gen}$: Electric output in [kW]

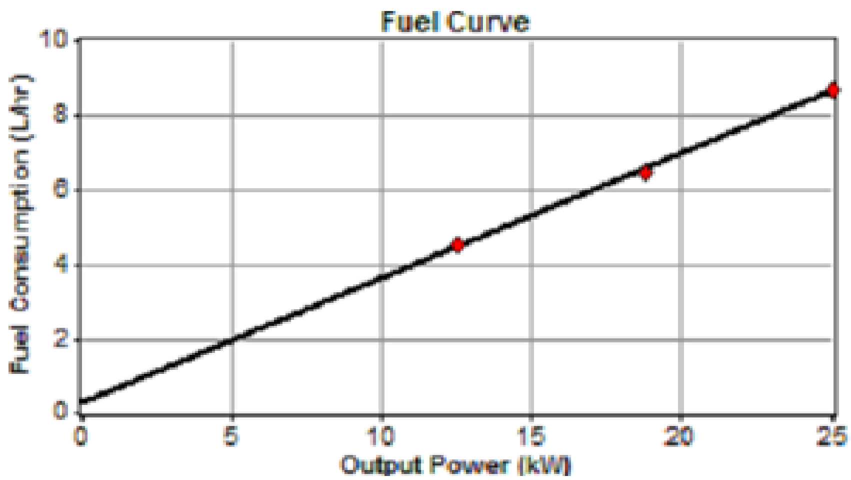



Figure 2. 7: Fuel Consumption Curve [47]

Efficiency curve**:** the efficiency is the ratio of the electrical energy generated to the chemical energy of the fuel consumed by the generator [47].

$$\eta_{gen} = \frac{3.6 * P_{gen}}{m_{fuel} * LHV_{fuel}} \tag{2.8}$$

Where:

$\eta_{gen}$: Generator efficiency

$m_{fuel}$: The mass flow rate of fuel [kg/hr]

$LHV_{fuel}$: The lower heating value [MJ/kg]

$P_{gen}$: The electrical output [kW]

1 kWh = 3.6 MJ

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

$$m_{fuel} = F = F_O.F_{gen} + F_1.P_{gen} \quad (2.9)$$

when litter is the unit of the fuel, the mass flow rate and fuel consumption relation depends on density.

Thus the equation for mass flow is given as below.

$$m_{fuel} = \rho_{fuel}\left(\frac{F}{1000}\right) = \rho_{fuel}\left(\frac{F_o.Y_{gen} + F_1.P_{gen}}{1000}\right) \quad (2.10)$$

Where:

$\rho_{fuel}$: Fuel density [kg/m$^3$]

When m$^3$ the unit of fuel flow, the factor 1000 is omitted from the above equation, so the mass flow equation is now expressed as follows.

$$m_{fuel} = \rho_{fuel} * F = \rho_{fuel}\left(F_O.Y_{gen} + F_1.P_{fuel}\right) \quad (2.11)$$

The efficiency equation when the unit of fuel flow is in litters is given in below.

$$\eta_{gen} = \frac{3600.P_{gen}}{\rho_{fuel}\left(F_O.Y_{gen} + F1.P_{gen}\right).LVH_{fuel}} \quad (2.12)$$

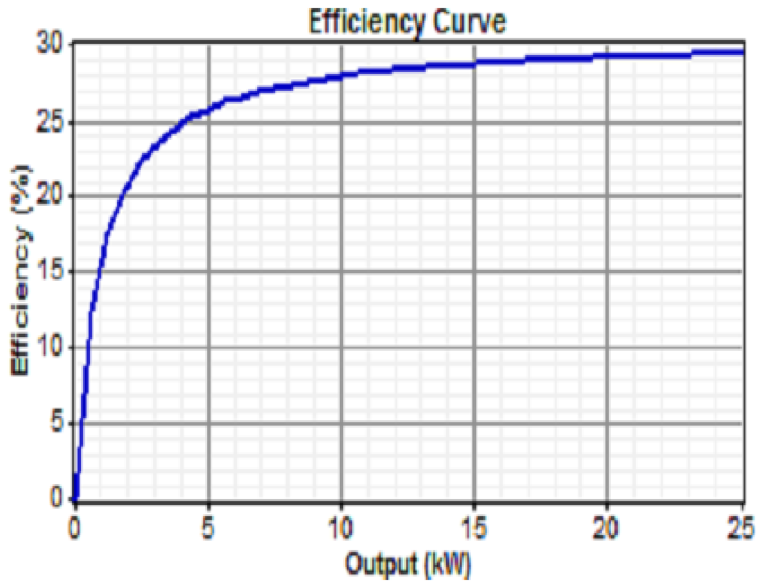



Figure 2. 8: Efficiency Curve

### 2.5 Energy Storage System

The management principle of the Energy Storage System is quite simple: the required power from the batteries is the difference between the load and the power supplied by both the solar power plant and the generator set. The power that can be delivered by the batteries is limited by two factors:

- The maximum charge and discharge power inherent to the battery model.
- The ESS power conversion system (PCS) that limits the output power of the inverter, inherent to the inverter and transformer models.

A wide range of energy storage technologies exist today. In general, energy storage technologies are classified into two categories based on the form of the stored energy: direct energy storage and indirect energy storage technologies [20, 27]. The former store the energy as electrical energy and do not require any conversion to other forms. In contrast, the indirect energy storage technologies require converting electrical energy from/to mechanical energy or chemical energy. The need of energy storage is to transfer the excess power during weak loads or excess supply from RESs to the peak periods [24, 25]. The energy from the RESs has to be transformed into a storable energy form first and then transformed when storing is needed. Technologies of each type are presented in Figure 2.9.

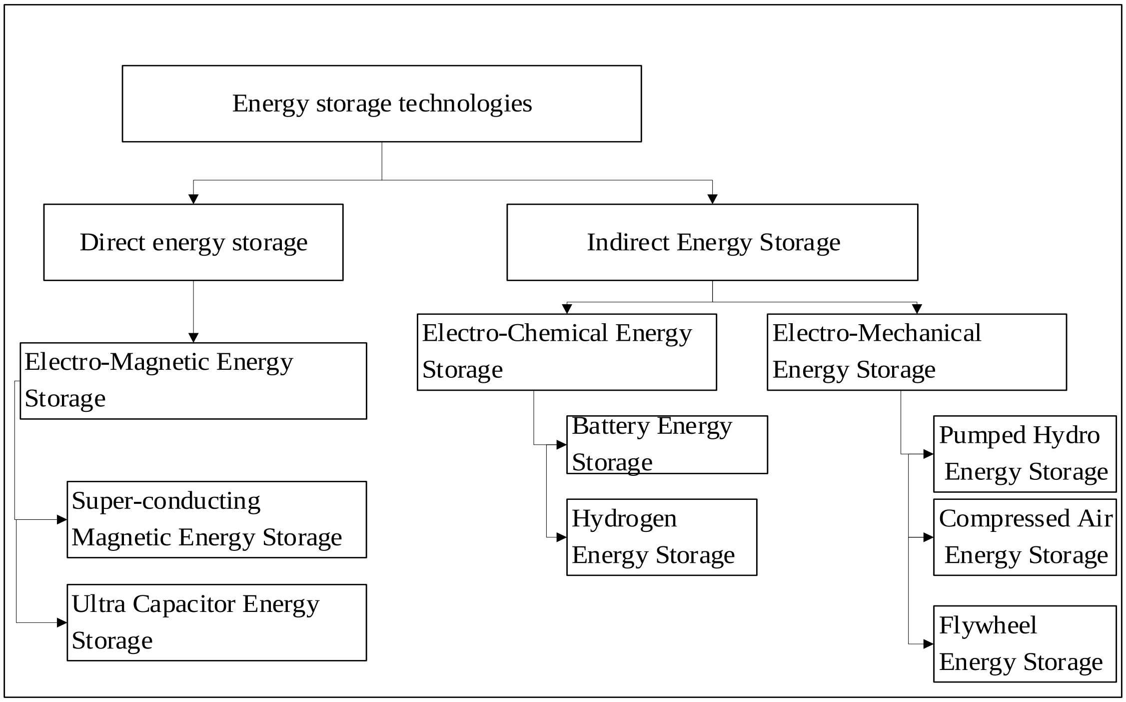



Figure 2. 9: Classification of Energy Storage Technologies [36]

The energy storage element can act as a load or a generator depending on the supply to demand ratio. Ideally, at any instant of time, there should be a zero-net exchange between the energy sources and the energy sinks (both real and reactive power) [16, 18, 21]. If this balance is not achieved, the voltage and frequency of the system changes to maintain equilibrium. In the above Figure 2.9 there are many energy storage techniques from which the good hybrid energy storage system is battery bank.

There are different types of batteries, but the most commonly used rechargeable batteries are:

(a) Lead acid battery

(b) Nickel cadmium (NiCad) battery

(c) Nickel Metal hydride (NiMH) battery

(d) Lithium ion battery

(e) Lithium-polymer battery

(f) Zinc-air battery

**Lead Acid Battery.-**When a lead acid battery is fully or partially discharged, lead sulphate forms at the electrodes. If the battery is allowed to remain for a prolonged period in a discharged state or with a very low state of charge the lead sulphate may form into large crystals which are very difficult to convert back into lead and sulphuric acid by the charging process. The formation of these crystals is called sulphation and causes a permanent loss of capacity of the battery. To avoid this problem, lead acid batteries should therefore only be stored in a fully charged condition and the charge should be topped up from time to time during storage to compensate for the self-discharge of the cells [48, 49].

The electrodes of the cells in a lead storage battery consist of lead grids. The anode is filled with spongy (porous) lead. The cathode is filled with lead dioxide {$PbO_2$}. Dilute sulfuric acid {$H_2SO_4$} serves as the electrolyte. During the battery recharge cycle lead sulfate (sulfation) begins to reconvert to lead and sulfuric acid. During the recharging process as electricity flows through the water portion of the electrolyte and water, ($H_2O$) is converted into its original elements, hydrogen and oxygen [50, 51].

**Nickel Metal Hydride Battery.-** A nickel–metal hydride battery, abbreviated NiMH or Ni–MH, is a type of rechargeable battery. The chemical reaction at the positive electrode is similar to that of the nickel–cadmium cell (NiCd), with both using nickel oxide hydroxide (NiOOH). NiCd batteries use Cadmium, a highly toxic heavy metal that can damage the environment if not disposed of properly. (They should be recycled not discarded). NiMH batteries usually have a higher capacity than NiCd batteries of the same size.

The negative electrode reaction occurring in a NiMH cell is

$$H_2O + M + e^- \rightleftharpoons OH^- + MH$$

The charge reaction is read left-to-right and the discharge reaction is read right-to-left.

On the positive electrode, nickel oxyhy droxide, NiO(OH), is formed:

$$Ni(OH)_2 + OH^- \rightleftharpoons NiO(OH) + H_2O + e^-$$

The metal M in the negative electrode of a NiMH cell is an intermetallic compound. When overcharged at low rates, oxygen produced at the positive electrode passes through the separator and recombines at the surface of the negative electrode. Hydrogen evolution is suppressed, and the charging energy is converted to heat. This process allows NiMH cells to remain sealed in normal operation and to be maintenance-free [9, 18].

**Lithium-ion batteries**.- is a well-established technology for Consumer portable electronics, and is the technology of choice for use in Electric Vehicles.

Lithium-ion batteries has become the dominant rechargeable battery chemistry for consumer electronics devices and is poised to become commonplace for industrial, transportation, and power-storage applications and require relatively complex protection circuitry to protect against a variety of electrical abuse scenarios including over voltage overcharge, over current, discharging at an excessive current (external short circuit), charging outside an acceptable temperature range, over discharge, and imbalance protection for multi-series battery.

Since 2000, they have begun to enter industrial markets, where they feature:

• High energy density

• High energy efficiency

• Maintenance-free design

• Lighter weight

• Excellent charge acceptance

As has been already introduced, Lithium-ion is different from previously popular rechargeable battery chemistries (e.g., nickel metal hydride, nickel cadmium, and lead acid) in a number of ways. From a technology has enabled entire families of portable devices. Hence Lithium iron phosphate (LiFePo4) batteries are used for this thesis work.

Table 2. 1: Equivalent Lead-Acid Battery

| Description | Rating |
|---|---|
| Discharge Time | 4H |
| Battery Cell Capacity (10h rate) | 3600Ah/1800Ah x 2parallel |
| Nominal Cell Voltage | 2.0V |
| Cell End Voltage | 1.81V |
| Battery System Voltage | 125V |
| Minimum Voltage | 105V |
| Maximum Voltage | 140V |
| Number of cells | 116(58x2) |
| Footprint | 19.7$M^2$ |

Table 2. 2: Lithium-Ion Battery Specification

| Description | Rating | Description | Rating |
|---|---|---|---|
| Nominal Cell Voltage | 3.7V | System Nominal Voltage | 125.8V |
| Cell Min. Voltage | 3.0(3.09*)V | System Min. Voltage | 102(105*)V |
| Cell Max. Voltage | 4.2V | System Max. Voltage | 142.8V |
| Cell Capacity | 75Ah | Backup time | 4H |
| Number of Cells per Module | 34(17S x 2P) | Max. Continuous charge C-rate | 1C |
| Number of Modules per Cubicle | 10(2S x 5P) | Max. Continuous Discharge C-rate | 1C |
| Number of Cubicle (Energy) | 3(283kwh) | Peak discharge C-rate | 3C |

Table 2. 3: Comparisons of Secondary Batteries

| Battery Type | Lithium-Ion | Lead-Acid | NiMH |
|---|---|---|---|
| Energy Density (Wh/kg) | 190 ~ 210 | 20 ~ 20 | 50~ 80 |
| Opration Temperature ($^0$C) | -20 ~ 60 | 0 ~ 40 | -20 ~ 50 |
| Self-discharge rate (%/month) | 3 ~ 5 | 20 ~ 90 | 20 ~ 25 |
| Nominal Voltage (V) | 3.7 | 2 | 1.2 |

**Ampere-hour (Ah).**

The current at which a battery can discharge at a constant rate over a fixed interval of time. The measurement of battery capacity is defined in Ampere Hours (Ah). In other words, it is an indication of how much energy can be stored by the battery and integrating discharging current in amperes over specific time. 1Ah equals to the transfer of one ampere over one-hour.

**Reserve capacity.**

The length of time (in minutes) that a battery can produce a specified level of discharge.

**KWh capacity.**

A measure of energy required to fully charge a depleted battery. A depleted battery is not usually a fully discharged battery.

**Autonomy**.

This variable is defined by the ratio of restorable energy capacity to maximum power discharge [52]. It refers to the maximum amount of time the system can continuously release energy. The autonomy of a system depends on the type of storage and the type of application.

$$\alpha = \frac{E_{restore}}{P_{discharge}} \tag{2.13}$$

Where, $E_{restore}$- stored energy (whr), $P_{discharge}$- discharge power (w), and α- Number of days of autonomy (hr).

**Depth Of Discharge (DOD).**

DOD, short for the Depth of Discharge, is used to describe how deeply the battery is discharged. The percentage of battery capacity (Ah) extract from a battery compared to the total charge capacity defined as Depth of Discharge. If a battery is 100% fully charged, it means the DOD of this battery is 0%, If the battery have delivered 30% of its energy, here are 70% energy reserved, we say the DOD of this battery is 30%.

**Durability (cycling capacity).**

Energy storage system is designed to release the energy stored after each recharge in a fixed time. The number of times the energy storage can release the energy level it was designed for after each recharge is referred to as durability or cycling capacity. It is expressed in number of cycles, $N_{cycles}$. The cycling capacity mainly depends on the depth of discharge (DOD).

**State of Charge (SOC).**

The amount of stored energy remaining in the battery defined as State of charge (SOC). The SOC denoted battery fully charged, half charged, and completely discharged. The

SOC of 100% defined as battery fully charged, and 75% of SOC indicated three-fourth (3/4) stored capacity remained for available further requirement.

**<u>Self-discharge</u>.**

This refers to the portion of energy which was initially stored and dissipated in a given non-use period of time. The battery cycles depend on the DOD and End of Life (EOL) [6, 17].

Cycles = f (DOD, EOL) (2.14)

The smaller the DOD, the more cycles can be provided by the battery but not in a linear relationship because of the EOL criterion. The EOL, in general, is a decrease of 80% of its capacity [6, 17]. The normal capacity needed can be given [6] as:

$B_{nom} = 1.25Bcap_{calculated}$ (2.15)

### 2.5.1 Charging and Discharging of Lithium Ion Battery

In the PV system, a battery plays an important role. During the day, the electricity generated from solar is stored in the battery, which is discharged during load demand. During charging state, current flows from PV array or diesel to battery which increases battery terminal voltage and SOC. This current flow is controlled by charge controller. During discharging state, current drifts off from the battery to the loads. As charge decreases instantaneously, the battery voltage is drawn off quickly.

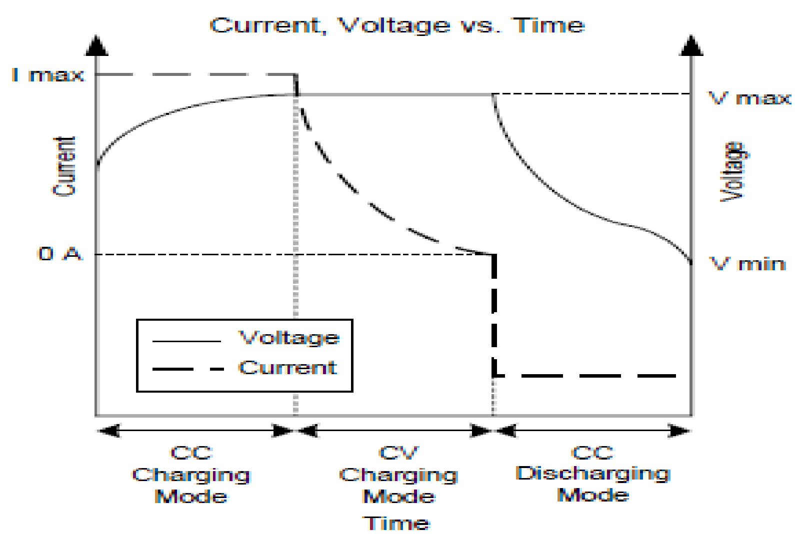



Figure 2. 10: Typical Li-ion Battery Charge/Discharge Profile [52].

The charging method chosen is constant current/constant voltage (CC/CV) method. The CC/CV is the best method in charging the Li-ion battery because it offers the fastest charging time to fully charge the battery. However, it is more complicated to be implemented. Charging starts with constant current (CC) mode until the battery has reached the maximum voltage.

### 2.5.2 Battery Capacity

The measurement of battery capacity can be defined as Ampere Hours (Ah). In other words, it is an indication of how much energy can be stored in a battery and integrating discharging current in amperes over specific time. 1 Ah equals to the transfer of one ampere over one-hour.

Battery capacity can be calculated using equation 2.16 as below:

$$Capacity(kWh) = \frac{Nominal\ Voltage\ of\ Battery * \ Capacity\ of\ Battery\ Storage}{1000} \quad (2.16)$$

## 2.6 Converters

The power conditioning units are electronic devices and grouped into DC - DC/AC, AC/DC. The DC/DC converters are electronic devices used to change DC voltage or current into needed voltage and frequency outputs. This type of converter is required since DC voltage cannot easily be stepped-up or down with transformers. The DC/AC converter uses to switch the DC voltage or current produced by the hybrid system to the AC type voltage output. This type of power converter is called power inverter. The AC/DC power converter functions as an inverse of the inverter and it is called rectifier. It converts the AC input voltage to rectified DC output voltage [5, 9].

### 2.6.1 DC-DC Converter

A DC/DC converter converts a source of direct current (DC) from one voltage level to another level. There are two types of DC/DC converters: linear and switched. A linear DC/DC converter uses a resistive voltage drop to create and regulate a given output voltage, a switched-mode DC/DC converts by storing the input energy periodically and then releasing that energy to the output at a different voltage. There different types of DC/DC converters including buck, boost, buck-boost, bidirectional converter etc.

### *2.6.1.1 Bidirectional Converter*

A bidirectional converter is required to allow the flow of power from and to the batteries in the mini-grid which can be designed by combining the capabilities of the buck and boost converters replacing their diodes with switches as shown in Figure 2.11. The top switch is used to operate the converter as a buck converter, transferring power from the high voltage side to the low voltage side and the bottom switch is used to operate the converter as a boost converter, transferring power from the low voltage side to the high voltage side.

The bidirectional converter will be controlled by a charge controller which will determine whether energy needs to be sent to or from the battery in order to smooth out the fluctuations of renewable energy sources and stabilize the voltage. The same values as the buck converter design were used for the bidirectional converter except for the inductor value.

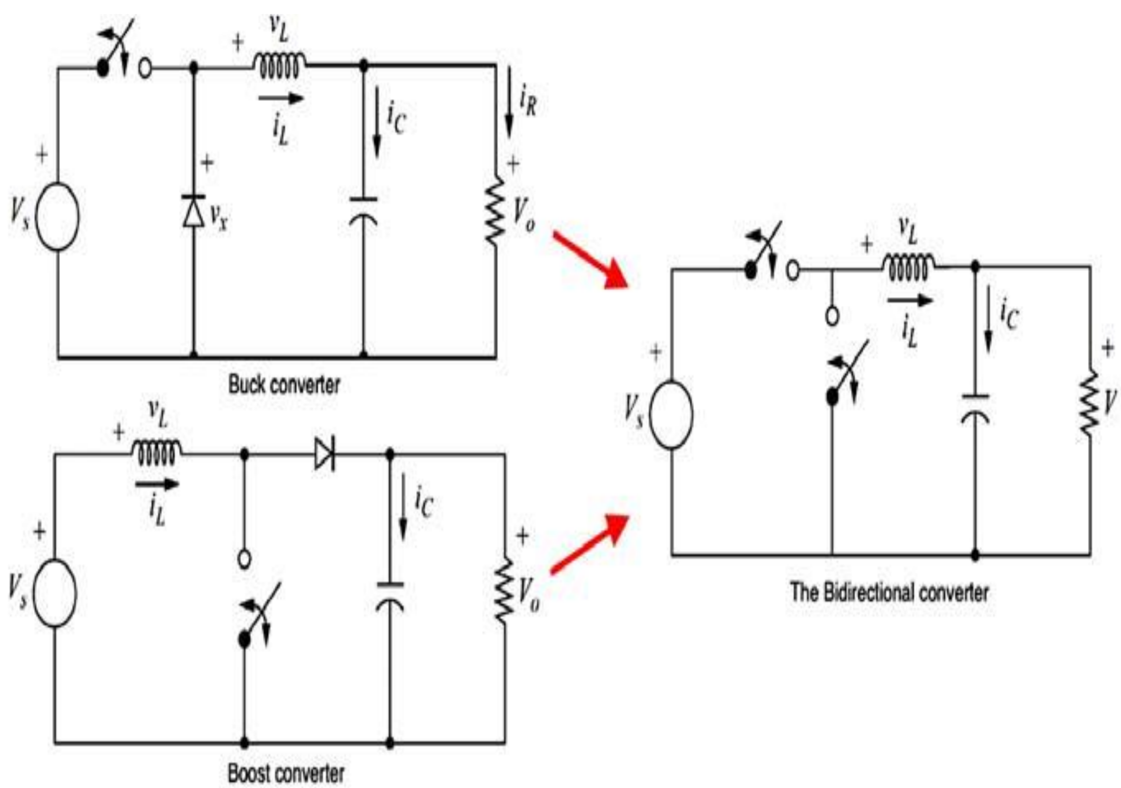



Figure 2. 11: Bidirectional Converter Construction [49].

#### *2.6.1.2 Boost Converter*

Boost converter steps up the input voltage magnitude to a required output voltage magnitude without the use of a transformer. The main components of a boost converter are an inductor, a diode and a high frequency switch. These in a coordinated manner supply power to the load at a voltage greater than the input voltage magnitude. The control strategy lies in the manipulation of the duty cycle of the switch which causes the voltage change.

## 2.7 Charge Controller

**A charge controller (or charge regulator). -** is basically a voltage and/or current regulator to keep batteries from overcharging. It regulates the voltage and current coming from the solar panels and going to the battery. Charge controller is an essential component in hybrid systems where a storage system is required. In other words, the battery charge controller works as a voltage regulator. It protects the battery against both excessive overcharge by a generating unit system and deep discharge by a load. Charge controller shall switch off the load when a certain state of discharge is reached, also shall switch off the battery from the DC bus when it is fully charged [31, 36]. Charge controller can be adjusted to deal with different charging and discharging conditions. The controllers average efficiencies range from 95% to 98% [8].

The main purpose of the controller is to prevent the batteries from over charging. The controller directly reads the battery level, and once the battery is full, it knows to slow down the rate of solar charge to a float; keeping is from charging the batteries past 100%. This is important as overcharging the batteries can potentially ruin them. Another purpose of the controller is to charge the batteries at the correct voltage level. This helps preserve the life and health of the batteries. Also, some controllers have special characteristics which allow you to wire your panels in a special way to achieve your charging goals.

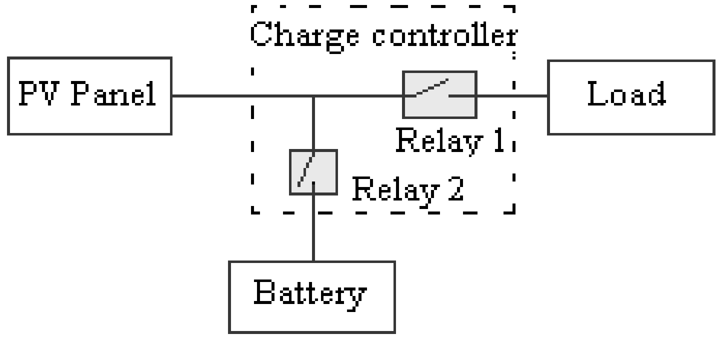



Figure 2. 12: Block Diagram of Charge Controller and PV System

When battery is included in a system, the necessity of charge controller comes forward. A charge controller controls the uncertain voltage build up. In a bright sunny day the solar cells produce more voltage that can lead to battery damage. A charge controller helps to maintain the balance in charging the battery. There are four general types of charge controllers, categorized by the method used to regulate the charge from the solar modules to the batteries: shunt type charge controllers, series type charge controllers, PWM (Pulse Width Modulation) charge controllers and MPPT charge controllers [53][54].

### 2.7.1 PWM Charge Controller

Charge controllers, as the name implies, control the flow of charge from the battery and to the battery. They protect the battery by preventing over-charge or deep discharge of batteries to preserve their life and performance.

PWM stands for Pulse Width Modulation, which stands for the method they use to regulate charge. PWM controllers have the more basic charging feature in the sense that they mainly just drop the voltage coming from the panel to charge the batteries. This drop in voltage equates to a loss in wattage, in the case of the PWM causing 75-80% efficiency.

### 2.7.2 MPPT Charge Controller

**Maximum power point tracking (MPPT)**. - is a technique used with wind turbines and photovoltaic (PV) solar systems to maximize power output. PV solar systems exist in several different configurations.

MPPT charge controllers use this method of charging, which essentially finds out at any given condition, what is the maximum operating point for the panels current and voltage. With this method, MPPT controllers are actually 94-99% efficient.MPPT checks the output of a particular PV panel and after comparing it with battery voltage decides the most efficient voltage i.e. maximum power point voltage. MPPT devices are integrated with power electronics creating an electric power converter system in form of solar inverters which convert DC power to AC power.

A simple MPPT algorithm [55] is implemented as shown in Figure 2.13 Firstly, the load voltage and PV voltages are observed. Depending on these two observations, the controller will generate a suitable duty cycle for the converter

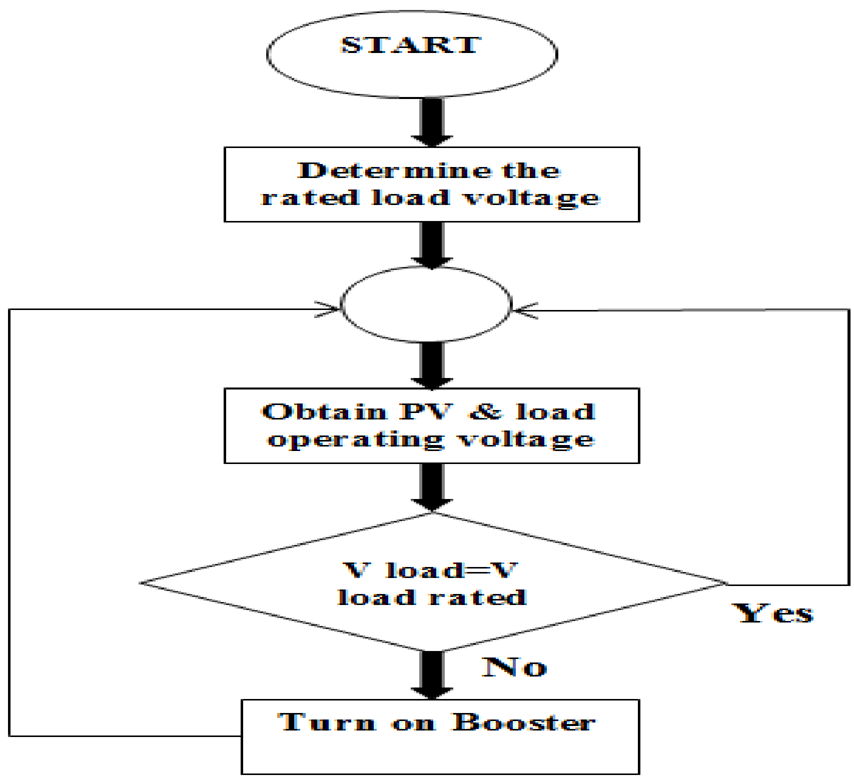



Figure 2.13: Flowchart of Maximum Power Point Tracking

### 2.7.3 Comparison between PWM and MPPT Solar Charge Controllers

**PWM.-** helps to get the batteries charged up, extends the life of the battery, and more of the power generated by the solar panels is stored. Since the batteries store more energy on average, a smaller battery (or less battery in a battery bank) can be used reducing overall system costs [55].

**MPPT solar charge controllers**.- allow users to use PV module with a higher voltage output than operating voltage battery system. Since MPPT units are generally larger in physical size so they are more costly as compared to PWM controllers [56].These controllers also offer the potential ability to have an array with higher input voltage than the battery bank.MPPT controller is at least 30% more efficient than PWM controller i.e. with MPPT weget 30% more output of the solar power system.

### 2.7.4 MPPT Techniques

There are different techniques used to track the maximum power point such as:

1. Perturb and observe (hill climbing method)
2. Incremental Conductance method
3. Current sweep
4. Constant Reference Voltage Algorithm
5. Fuzzy Logic Control
6. Neural network

### 2.7.5 MPPT Algorithm

The output power generated by the solar cell is described as point. Furthermore, the output power curve will increase and fall in between the two points and the highest value of the power on the curve between Isc and Voc is called Maximum Power Point [58]. Thus, it is important to make sure the solar power output is operating near the maximum point for an efficient operation.

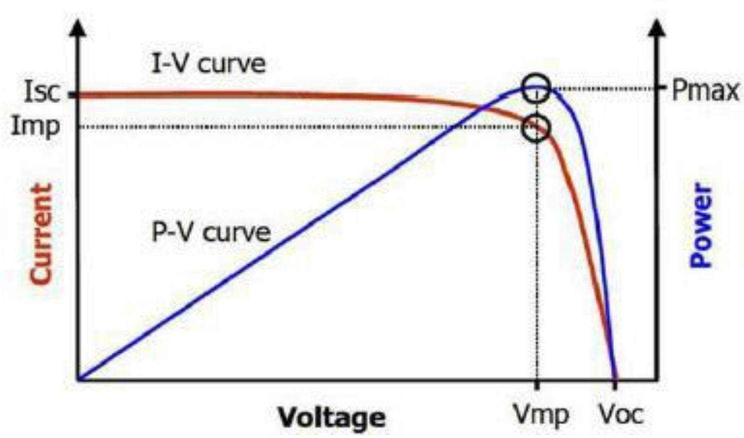



Figure 2. 14: Maximum Power Point (MPP) Curve [58].

However, this I-V curve of PV array relies on irradiance and temperature condition. When the irradiance increases with constant temperature, the PV current also increases in direct proportion with negligible effect on PV voltage. Similarly, if the temperature increases with constant irradiance, the PV voltage decreases substantially while the PV current increases slightly [59]. Hence, a tracking algorithm known as MPPT is needed to regulate the PV panel output that varies non-linearly with irradiance, temperature and load.

**Constant Reference Voltage Algorithm**.- The method used as in this thesis work. The simplest technique to maintain the operation of the PV system near the maximum power point is to control the voltage measured at the PV generator, to its reference voltage corresponding to the optimum voltage [56]. it is widely recognized MPPT algorithms. The PV array voltage is matched to a fixed reference voltage which is chosen to give optimal performance. As the name implies this algorithm operates as a constant voltage value based off of the open circuit voltage.

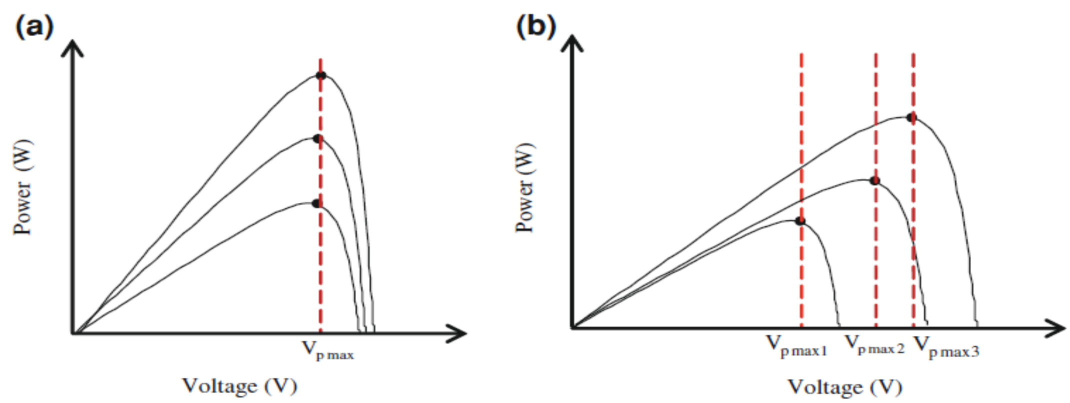



Figure 2. 15: Power–voltage characteristic Ppv (Vpv) of PV generator a-Variable irradiance, constant temperature b-Variable temperature, constant irradiance

This method assumes that the variation of the optimum voltage to climatic factors variations (irradiance, temperature) is negligible as shown in Figure 3.14a. However, when the junction temperature of the PV cell varies as shown in Figure 3.14b, the optimum voltage will be not constant. This method is inherently much less efficient than either the perturb-and-observe method or the incremental conductance algorithm.

Incremental Conductance Method a more complex but typically more accurate procedure is known as the incremental conductance method.

# MATERIALS AND METHODS (CHAPTER THREE)

## 3.1 Data Collection and Assessment

### 3.1.1 Primary and Secondary Data Collection

**Primary data.-** It is a data that are collected by the researcher himself by conducting field survey. During the field survey, the primary data necessary for this thesis were the number of religious institutes and type of community services, such as, one primary school, one health center, one church and one Farmer Training Center (FTC).

**Secondary data.-** It was a data that is not collected by the researcher for him purpose; others collect it for other purpose. For this thesis were solar radiation, Population size and number of households, energy equipment cost related to the proposed RHS configuration and technologies were collected.

Solar radiation is collected from NMSA and NASA Surface metrology; whereas the population size and number of households are taken from Dibate Woreda Administration office. The potential of solar resource for the village was assessed. The solar radiation and clearness index for 22 years average was obtained from NASA surface meteorology and also, the recent actual data for the selected site from 3 to 5 years were obtained from NMSA at Assosa branch.

### 3.1.2 Assessment of Solar Energy Potential in the Case Study

For Ethiopia as a whole, the yearly average daily radiation is 5.26 $kWh/m^2$[1].This varies significantly during the year, ranging from a minimum of 4.55$kWh/m^2$ in July to a maximum of 5.55$kWh/m^2$ in February and March. On a regional basis, the yearly average radiation ranges from values as low as 4.25$kWh/m^2$/day in the areas of Itang in the Gambella Regional State (Western Ethiopia), to as high as 6.25$kWh/m^2$/day around Adigrat in the Tigray Regional State (Northern Ethiopia).

Solar energy was the current source of mini-grid rural applications in homes, rural telecoms and in the social sectors (water pumping, health services, schools). The current total installed PV power in Ethiopia is about 3.5MW (three-quarters installed in telecom stations, mostly in mobile towers but also in other stations).

### 3.1.3 Solar Resource Assessment of the Village

The 22 years' monthly average solar resource of the village varies from 8.20kwh/m$^2$/day in January to 4.38kwh/m$^2$/day in August, which is the winter of Ethiopia, and clearance index are obtained from NASA. An average solar radiation for the village is 6.59kWh/m$^2$/day. The clearance index and daily radiation of the village is obtained from NASA surface metrology at the center latitude 10$^0$.39'N and longitude of 36$^0$.13'E which is a western boundary of 39, northern boundary of 12, eastern boundary of 40 and also southern boundary of 10 in degree. For a PV system to supply sustainable power, the daily radiation should be greater than 4kWh/m$^2$/day. Table 3.1 shows the solar resource profile for Albasa village.

Table 3. 1: Clearance Index and Daily Radiation of the Village (Source: NASA)

| Month | Clearance Index | Daily radiation (kwh/m$^2$/day) | Temperature ($^0$C) | Average daylight hours (Hours) |
|---|---|---|---|---|
| January | 0.68 | 8.20 | 9.61 | 11.5 |
| February | 0.67 | 7.72 | 10.2 | 11.7 |
| March | 0.66 | 6.90 | 9.82 | 12.0 |
| April | 0.66 | 6.43 | 8.80 | 12.3 |
| May | 0.64 | 6.30 | 9.22 | 12.6 |
| June | 0.61 | 5.33 | 8.40 | 12.7 |
| July | 0.60 | 4.42 | 7.69 | 12.7 |
| August | 0.59 | 4.38 | 8.36 | 12.4 |
| September | 0.62 | 5.44 | 10.2 | 12.2 |
| October | 0.66 | 6.90 | 11.3 | 11.8 |
| November | 0.67 | 7.85 | 10.7 | 11.6 |
| December | 0.67 | 8.07 | 9.77 | 11.4 |
| **Annual Average** | - | 6.49 | 9.51 | |

### 3.1.4 Solar Radiation Variation

January is the sunniest month of the year, at which time solar energy resource is 8.20kWh/m$^2$/day, while in August it drops to 4.38kWh/m$^2$/day as shown in Table 3.1. In the months of, January, February, March the clearance index decreases with differences from month to month as (0.68), (0.67) and (0.66) respectively. In these months, the Diesel Generator can compensate. Whereas in the months of September, October and Novembers the clearance index increases from month to month as (0.62), (0.66), and (0.67) respectively.

### 3.1.5 Solar Radiation Potential

For any solar based system design, the most important factors are the position of the sun in the sky, the slope and orientation of a collecting surface, and obstruction and reflection properties of neighboring structures. Figure 3.1 shows below the geometry describing orientation of a collector and position of the sun in the sky.

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

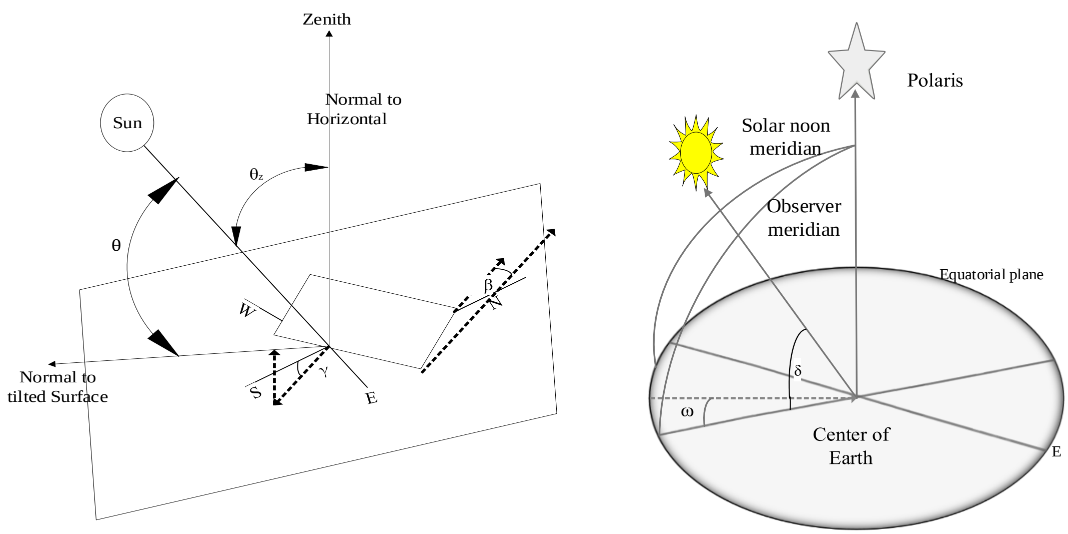



Figure 3. 1: Geometry of Solar Collector and Location of Sun Relative to Earth

Location of the sun in the sky, relative to a point on the ground, can be defined in terms of two angles, the solar altitude, $\alpha_s$ (or its complement the solar zenith angle, $\theta_z$) and the solar azimuth $\gamma_s$. Solar altitude, $\alpha_s$, angle of solar beam to the horizontal. Solar azimuth, $\gamma_s$ is the angle between the solar beam and the longitude meridian projected on the horizontal plane.

Sign convention is the same as for surface azimuth angle (γ). Solar altitude and solar azimuth are functions of location (latitude,∅ ), time of the year (declination angle,δ) and time of the day (hour angle,ω). Solar declination angle (δ) is the angle between the earth's equatorial plane and the earth sun line. Solar hour angle (ω) is the angle Earth has rotated since solar noon. The relation between these angles is given below [Source: HOMER software].

$$\delta = 23.45\sin\left(360^0 \frac{284 + n_d}{365}\right) \tag{3.1}$$

Where: δ is solar declination angle ($^0$)

$n_d$ is day number of the year starting at January 1st as 1

$$\omega = (12 - t_L)15^0) \tag{3.2}$$

Where, $t_L$ = local solar time in hours.

$\omega$ = solar hour angle ($^0$)

$$\sin(\alpha_s) = \sin(\emptyset)\sin(\delta) + \cos(\emptyset)\cos(\delta)\cos(\omega) \tag{3.3}$$

Where, $\alpha_s$ = solar altitude ($^0$), ∅ =latitude ($^0$)

$$\sin(\gamma_s) = \frac{\cos(\delta)\sin(\omega)}{\cos(\alpha_s)} \tag{3.4}$$

Where: $\gamma_s$ = solar azimuth ($^0$)

The sunset/sunrise angle is given by

$$\omega_s = \cos^{-1}\left(-\tan(\emptyset)\tan(\delta)\right) \tag{3.5}$$

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

$$\begin{aligned}\text{Cos}(\theta_i) &= \sin(\delta)\sin(\emptyset)\cos(\beta) - \sin(\delta)\cos(\emptyset)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\emptyset)\cos(\beta)\cos(\omega) \\ &+ \cos(\delta)\sin(\emptyset)\sin(\beta)\cos(\gamma)\cos(\omega) \\ &+ \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)\end{aligned} \tag{3.6}$$

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

$$Gon = G_{sc}\left(1 + 0.033 * \cos\frac{360n_d}{365}\right) \quad (3.7)$$

The extraterrestrial irradiance incident on a horizontal plane at an arbitrary angle of incidence is given by,

$$Go = G_{on}\cos(\theta_z) \quad (3.8)$$

Where, $\theta_z$ = zenith angle (angle between the sun and the vertical line from a point on earth) which equals to the incident angle of a horizontal surface at the point of interest. By integrating the solar constant (extraterrestrial irradiance) over the day length gives us the daily solar radiation on the horizontal surface.

$$Ho = \frac{24 * 3600 * G_{sc}}{\pi}\left(1 + 0.033 * \cos\left(\frac{2\pi n_d}{365}\right)\right) \quad (3.9)$$

Where, $H_o$ is the average extraterrestrial horizontal radiation for the day [kwh/$m^2$/day]

$n_d$ - Day number starting from January 1st as 1,

$G_{SC}$ -1.367KW/$m^2$, the solar constant,

$\emptyset$ -Latitude of the location ($11.35^0$),

$\delta$ -Declination angle ($^0$) given by equation 3.1, $\omega_s$- Sunset hour angle ($^0$)

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

$$H = H_o\left(a + b\frac{n}{N}\right) \quad (3.10)$$

Where, H- monthly average daily radiation on horizontal surface (kwh/$m^2$)

$H_0$ - monthly average daily extraterrestrial radiation on a horizontal surface (kwh/$m^2$)

N - the maximum possible daily hours of bright sunshine given by equation

n - monthly average daily number of hours of bright sunshine

a and b - are regression coefficients having average value of a = 0.33 and b = 0.43.

The day length, N, is the maximum possible daily sunshine hour is given by equation 3.11.

$$N = \frac{2}{15}\omega_s \tag{3.11}$$

### 3.1.6 Estimation of PV Output of the Village

The steps to calculate approximately the output power of solar PV are as follows:

- Determine the radiation at the horizontal surface based on the day of the year and the site latitude and then establish a clearness index.
- The clearness index is then used to calculate the direct, diffuse and random components of the radiation on a horizontal surface.
- The total radiation is then calculated from the direct, diffuse and random values obtained.
- Finally, the radiation on the surface of the panel is determined. It requires monthly average meteorological data at a specific site location as its input for the simulation of the solar radiation process at that site. The necessary data is the monthly average values of solar radiation on the horizontal surface, if temperature effect ignored.

The monthly average values of solar radiation (kWh/$m^2$/day) on the horizontal surface data obtained from NMSA at Assosa branch which is measured one times per day.

Table 3. 2: Monthly Average Solar Radiations [Source: NMSA at Assosa branch]

| Year | 2012 kwh/m$^2$ | 2013 kwh/m$^2$ | 2014 kwh/m$^2$ | 2015 kwh/m$^2$ | 2016 kwh/m$^2$ | **Monthly average** | **Annual average** |
|---|---|---|---|---|---|---|---|
| January | 5.13 | 5.65 | 5.18 | 4.62 | 5.10 | **5.14** | **5.013** |
| February | 6.22 | 6.00 | 5.80 | 5.58 | 5.27 | **5.77** | |
| March | 5.79 | 6.35 | 4.68 | 5.32 | 5.35 | **5.50** | |
| April | 6.16 | 5.29 | 5.95 | 6.01 | 5.44 | **5.77** | |
| May | 5.60 | 5.45 | 5.12 | 5.51 | 5.71 | **5.47** | |
| June | 5.02 | 5.08 | 4.34 | 4.58 | 4.79 | **4.76** | |
| July | 3.97 | 4.25 | 3.90 | 4.64 | 3.86 | **4.12** | |
| August | 4.25 | 3.94 | 3.96 | 4.59 | 4.06 | **4.16** | |
| September | 4.56 | 4.58 | 4.66 | 4.63 | 4.78 | **4.64** | |
| October | 4.15 | 4.54 | 5.18 | 5.56 | 5.63 | **5.01** | |

### 3.2 Load Estimation

The load estimation is mainly concerned with calculating the power and energy demand of the community. The primary and deferrable load estimation is performed for a village with 1110 households by considering the basic needs of the community. The primary load contains lighting, radio receiver, TV and DVD player. In addition to these, the community has school, health clinic, animal clinic, church, farmers training center (FTC), flour mill, etc.

## 3.3 Energy Demand of the Village

### 3.3.1 Energy Demand Assessment and Load Scheduling of the Village

Energy is the oxygen of the economy and the blood live of the growth. To improve the life of the society energy is very important and crucial. Due to the low income of the society, scattered placement, the house hold energy demand of the village is lower than that of in the urban area. The electrical energy produced from the proposed hybrid system is supplied to home appliances, community service, and religious institute and for agricultural activities. In this thesis the electric load demand of the village community is divided into the following four major categories like:

Household/domestic load, Commercial loads, Community load (Primary school load, Health clinic load, Animal clinic load, Church load, FTC load) and Deferrable load. The total electric load estimated for the listed appliances above were summed up to get the required load to be supplied by the system. Despite of the present situation is below the poverty line; Peak operation hours of the appliances have been proposed based on the current living condition of the community and the current growth trend of the country. To design a mini-grid hybrid power system for a specific area community the establishment of information's like the load profile of the community, climatic data of the area, initial cost of the components, etc. are the important parameters to be accounted.

## 3.4 Estimation of Primary Load

Primary load is the load that should meet by the energy providing system as it requires immediately; which includes lighting, baking, vaccine refrigeration, TV, radio, computer, printer, simple laboratory equipment's and others. Here the electricity load consumption in each household is considered to be the same and constant throughout the year. The load determination of the village was performed for 1110 household numbers with average of five family members per household. During load estimation, the nature of load has been thoroughly analyzed to come up with sustainable energy demand satisfaction since electric load is vary hourly, daily and seasonal bases. The rural economic situation of the country is below the poverty line and thus in this energy system design the selection of appliances was reflected for the low wattage for the affordability of the provided electric energy. The electricity load estimation is made according to the following approach.

Annual Energy consumption (KWh) = [(number of appliance used * power rating of each appliance (w) * hours of operation)/1000]

### 3.4.1 Domestic Load

Table 3. 3: Households Electricity Consumption Features

| Appliances | Quantities | Capacity (w) | Operation (hrs) | Total no. of customers (1110) | Time interval (hrs) | Power (kw) | Energy (kwh/day) |
|---|---|---|---|---|---|---|---|
| CFL | 4 | 11 | 4 | 600 | 18:00-21:00 | 26.4 | 105.6 |
| | 2 | 11 | 1 | 100 | 21:00-22:00 | 2.20 | 2.20 |
| | 2 | 11 | 1 | 40 | 22:00-23:00 | 0.88 | 0.88 |
| | 1 | 11 | 6 | 10 | 23:00-5:00 | 0.110 | 0.660 |
| Television | | | | 250 | | | |
| | 1 | 100 | 3 | 50 | 12:00-13:00 | 12 | 12 |
| Radio | | | | 700 | | | |
| | 1 | 10 | 1 | 100 | 7:00-8:00 | 1 | 1 |
| | 1 | 10 | 2 | 120 | 19:00-21:00 | 1.20 | 2.40 |
| Baking machine | | | | 50 | | | |
| | 1 | 2500 | 1 | 13 | 11:00-12:00 | 32.5 | 32.5 |
| | 1 | 2500 | 1 | 15 | 14:00-15:00 | 37.5 | 37.5 |
| | 1 | 2500 | 1 | 10 | 15:00-16:00 | 25 | 25 |
| DVD player | | | | 100 | | | |
| | 1 | 15 | 1 | 50 | 7:00-8:00 | 0.75 | 0.75 |
| | 1 | 15 | 1 | 75 | 12:00-13:00 | 0.375 | 0.375 |
| | 1 | 15 | 2 | 50 | 19:00-21:00 | 0.75 | 1.5 |
| Charger | 1 | 10 | 1 | 300 | | 3 | 3 |
| Total per household per day | | | | | | 143.665 | 225.365 |

### 3.4.2 Commercial Load

Table 3. 4: Electric Load Consumption Characteristics of Commercial Load

| Appliances | Quantities | Capacity (w) | Operation (hrs) | Time interval (hrs) | Power (kw) | Energy (kwh/day) |
|---|---|---|---|---|---|---|
| Flour mill | 1 | 12,500 | 1 | 12:00-14:00 | 12.5 | 12.50 |
| | 1 | 12,500 | 1 | 15:00-16:00 | 12.50 | 12.50 |
| CFL | 2 | 11 | 3 | 18:00-21:00 | 0.022 | 0.066 |
| Fluorescent lamp | 2 | 11 | 3 | 21:00-00:00 | 0.022 | 0.066 |
| Total per commercial per day | | | | | 25.044 | 25.132 |

### 3.4.3 Community Load

**School Load. -** July, August and the semester break were in January. For school total energy requirements for the year computed as daily demand times 160 days per year (8 months per year and 20 days per month). In other words, the total daily electricity consumed by the school except for January, July and August is shown below in Table 3.5.

Table 3. 5 Electric Load Consumption Characteristics of School Load

| Appliances | Quanti-ties | Capacity (w) | Operation (hrs) | Time interval (hrs) | Power (kw) | Energy (kwh/day) |
|---|---|---|---|---|---|---|
| Class-room (CFL) | 10 | 11 | 2 | 18:00-20:00 | 0.11 | 0.22 |
| For staff (CFL) | 4 | 11 | 3 | 18:00-21:00 | 0.044 | 0.132 |
| Fluorescent lamp | 4 | 11 | 6 | 19:00-23:00 | 0.044 | 0.132 |
| Radio | 1 | 10 | 1 | 9:00-10:00 | 0.01 | 0.01 |
| Printer | 1 | 330 | 1 | 10:00-11:00 | 0.330 | 0.330 |
| | 1 | 330 | 1 | 15:00-16:00 | 0.330 | 0.330 |
| Computer | 1 | 300 | 2 | 10:00-12:00 | 0.300 | 0.600 |
| | 1 | 300 | 2 | 14:00-16:00 | 0.300 | 0.600 |
| Copy machine | 1 | 900 | 1 | 10:00-11:00 | 0.900 | 0.900 |
| | 1 | 900 | 1 | 16:00-17:00 | 0.900 | 0.900 |
| Electric stove | 1 | 1500 | 1 | 10:00-11:00 | 1.5 | 1.50 |
| | 1 | 1500 | 1 | 12:00-13:00 | 1.500 | 1.500 |
| Electric siren/bell | 2 | 40 | 1/2 | | 0.080 | 0.040 |
| Total per school per day | | | | | 6.348 | 7.194 |

**Health Clinic Load.-**

Table 3. 6: Electric Load Consumption Characteristics of Health Center Load

| Appliances | Quantity | Capacity (w) | Operation (hrs) | Time interval (hrs) | Power (kw) | Energy (kwh/day) |
|---|---|---|---|---|---|---|
| CFL | 8 | 11 | 2 | 18:00-20:00 | 0.088 | 0.176 |
| | 4 | 11 | 2 | 20:00-22:00 | 0.044 | 0.088 |
| | 2 | 11 | 3 | 22:00-1:00 | 0.022 | 0.066 |
| Vaccine refrigerator | 1 | 100 | 24 | | 0.100 | 2.400 |
| Microscope | 1 | 20 | 1 | | 0.020 | 0.020 |
| Radio | 2 | 10 | 3 | 9:00-12:00 | 0.020 | 0.060 |
| | 1 | 10 | 3 | 14:00-17:00 | 0.010 | 0.030 |
| Computer | 1 | 300 | 1 | 9:00-11:00 | 0.300 | 0.300 |
| | 1 | 300 | 1 | 15:00-16:00 | 0.300 | 0.300 |
| Printer | 1 | 330 | 1 | 11:00-12:00 | 0.330 | 0.330 |
| | 1 | 330 | 1 | 14:00-15:00 | 0.330 | 0.330 |
| Electric siren | 3 | 40 | 2 | | 0.120 | 0.240 |
| Television | 1 | 100 | 10 | | 0.100 | 1.00 |
| Electric stove | 4 | 1500 | 3 | 10:00-14:00 | 6 | 4.5 |
| Total per clinic per day | | | | | 7.784 | 9.832 |

**Animal Clinic Load**.-

Table 3. 7: Electric Load Consumption Characteristics of Animal Clinic Load

| Appliances | Quantity | Capacity (w) | Operation (hrs) | Time interval (hrs) | Power (kw) | Energy (kwh/day) |
|---|---|---|---|---|---|---|
| CFL | 4 | 11 | 2 | 18:00-20:00 | 0.044 | 0.088 |
| | 2 | 11 | 1 | 20:00-21:00 | 0.022 | 0.022 |
| Vaccine refrigerator | 1 | 100 | 24 | | 0.100 | 2.400 |
| Radio | 1 | 10 | 2 | 9:00-11:00 | 0.010 | 0.020 |
| | 1 | 10 | 2 | 14:00-16:00 | 0.010 | 0.020 |
| Computer | 1 | 300 | 1 | 11:00-12:00 | 0.300 | 0.300 |
| | 1 | 300 | 1 | 15:00-16:00 | 0.300 | 0.300 |
| printer | 2 | 330 | 1 | 10:00-11:00 | 0.660 | 0.330 |
| Electric stove | 3 | 1500 | 2 | 10:00-12:00 | 4.5 | 3 |
| Electric siren | 1 | 40 | 1 | | 0.080 | 0.040 |
| Total per clinic per day | | | | | 6.26 | 6.7 |

**Church Load**.-

Table 3. 8: Electric Load Consumption Characteristics of Church Load

| Appliances | Quantity | Capacity (w) | Operation(hrs) | Time interval (hrs) | Power (kw) | Energy(kwh/day) |
|---|---|---|---|---|---|---|
| CFL | 4 | 11 | 2 | 18:00-20:00 | 0.044 | 0.088 |
| Fluorescent lamp | 2 | 11 | 2 | 19:00-21:00 | 0.022 | 0.044 |
| Radio | 1 | 10 | 6 | | 0.01 | 0.06 |
| Microphone | 1 | 15 | 3 | | 0.015 | 0.045 |
| Electric Stove | 1 | 300 | 1 | | 3 | 1.5 |
| Computer | 1 | 330 | 1 | | 0.3 | 0.3 |
| Printer | 1 | 40 | 1 | | 0.66 | 0.23 |
| Electric Siren | 1 | 40 | 1 | | 0.08 | 0.04 |
| Total per Church per day | | | | | 4.131 | 2.307 |

**Farmers Training Center (FTC) Load.-**

Table 3. 9:- Electric Load Consumption Characteristics of FTC load

| Appliances | Quantity | Capacity (w) | Operation (hrs) | Time interval (hrs) | Power (kw) | Energy (kwh/day) |
|---|---|---|---|---|---|---|
| CFL | 4 | 11 | 2 | 18:00-20:00 | 0.044 | 0.088 |
| Fluorescent lamp | 2 | 11 | 4 | 20:00-00:00 | 0.022 | 0.088 |
| Radio | 1 | 10 | 6 | | 0.01 | 0.06 |
| Microphone | 1 | 15 | 2 | | 0.015 | 0.03 |
| Computer | 1 | 300 | 3 | | 0.3 | 0.9 |
| Printer | 1 | 330 | 1 | | 0.33 | 0.33 |
| Electric siren | 1 | 40 | 2 | | 0.04 | 0.08 |
| Total per FTC per day | | | | | 0.761 | 1.576 |

### 3.5 Estimation of Deferrable Load

Deferrable load is electrical load that must be met within some time period, but the exact timing is not important. Loads are normally classified as deferrable because they have some storage associated with them. Water pumping is a common example - there is some flexibility as to when the pump actually operates, provided the water tank does not run dry. Other examples include ice making and battery charging.

**Water pump.-** Water pumping in small communities is used for the following purposes:

- Remove water from the source, such as a river, lake, reservoir, well, spring, etc.
- Move water from the treatment plant to the distribution system or irrigation system.
- Circulate water through a distribution system.
- Maintain pressure in the distribution system.
- Circulate glycol through heat exchanger or heating loop.
- Pump chemicals into the system.

Generally, water pumping system is required for the households, the schools and health care centers. About 125L of water per day per family and 2400L/day for each pair of one health center and one primary school, etc is suggested. During the rainy season (summer) delivery of water to distribution center with the aid of pumps is expected to decrease and to be shared by rain water, moreover, the amount of water to be covered by the rain water was assumed about 30% of the deferrable load. Whereas in June since it is the beginning month to the rainy season only 15% reduction is being suggested. There are no classes in July and August (annual break) and in January (semester break).

The average water requirement in developing country is about 125lit/day. This village has 1110 households total amount of water consumption can be calculated as follows:

1110*125 = 138,750lit/day = 90m$^3$

For considerable depth of 20m**,** the pump average operating time is 6hours/day

The flow rate (Q) = 138.570*1000/ (6*3600) = 6.424lit/sec = 385lit/min

The electric power capacity of pump can be calculated as follows.

$$P = \frac{gQh}{\eta} (\text{watt}) \qquad (3.12)$$

Where, g is Gravitation force of earth [9.81m/s$^2$], Q is flow rate

h is considerable height (depth) and η is efficiency of pump typically 90%.

$$P = \frac{9.81*6.424*20}{0.9} = 1400\text{watt} \cong 1500\text{watt}$$

For this case water storage capacity for 3 - 5 days is also recommended. The energy storage capacity can be calculated as follows:

Energy storage capacity = No. of pumps rating * capacity of pumps storage days * running hours per day.

## 3.6 Modeling of Hybrid Energy System Components

### 3.6.1 Mathematical Modeling of PV System

As the operation and the performance of PV generator is interested to its maximum power, the models describing the PV module's maximum power output behaviors are more practical for PV system assessment. Using the solar radiation available on the tilted surface, the ambient temperature and the manufacturers data for the PV modules as model inputs, the power output of the PV generator, $P_{PV}$, can be calculated according to equa. 3.13

$$P_{pv} = \eta_g N A_m G_t \qquad (3.13)$$

Where, $\eta_g$ **-** is the instantaneous PV generator efficiency, $\mathbf{A_m}$ **-** is the area of a single module (m$^2$), $\mathbf{G_t}$ **-** is the global irradiance incident on the titled plane (KW/m$^2$) and

N - is the number of modules.

All the energy losses in a PV generator, including connection losses, wiring losses and other losses, are assumed to be zero. The instantaneous PV generator efficiency is represented by the following equation:

$$\eta_g = \eta_r \eta_{pt}[1 - \beta_t(T_c - T_r)] \tag{3.14}$$

Where, $\eta_r$ is the PV generator reference efficiency, $\eta_{pt}$ is the efficiency of power tracking equipment which is equal to 1, $T_c$ is the temperature of PV cell (°C), $T_r$ is the PV cell reference temperature and $\beta_t$ is the temperature coefficient of efficiency, ranging from 0.004 to 0.006 per °C for silicon cells.

Based on the energy balance the PV cell temperature can be expressed as follows:

$$T_c = T_a + G_t\left(\frac{\tau\alpha}{U_L}\right) \tag{3.15}$$

Where, $T_a$ is the ambient temperature (°C), $U_L$ is the overall heat loss coefficient (W/m$^2$/°C), τ and α represent the transmittance and absorptance coefficients of PV cells respectively.

The overall heat loss coefficient $\tau\alpha/U_L$ can be estimated from the nominal operating cell temperature (NOCT) as follows:

$$\left(\frac{\tau\alpha}{U_L}\right) = \frac{NOCT - 20}{800} \tag{3.16}$$

Consequently, the instantaneous PV generator efficiency can be expressed as follows:

$$\eta_g = \eta_r \eta_{pt}\left\{1 - \beta_t(T_a - T_r) - \beta_t G_t\left(\frac{NOCT - 20}{800}\right)(1 - \eta_r \eta_{pt})\right\} \tag{3.17}$$

Where, $\boldsymbol{\eta_{pt}}$, $\boldsymbol{\beta_t}$, NOCT, $\mathbf{A_m}$ were parameters that depend on the type of module and given by the manufacturer of the modules. Using the solar radiation available the hourly energy output of the PV generator ($\mathbf{E_{PVG}}$ ) can be calculated according to the following equa. 3.18

$$E_{PVG} = G(t) * A * P_{PV} * \eta_{PVG} \tag{3.18}$$

Where, G (t) is the hourly irradiance in kWh/m$^2$, A is the surface area in m$^2$, $P_{PV}$ is the PV penetration level factor and $\eta_{PVG}$ is the efficiency of PV generator.

### 3.6.2 Mathematical Model of Converter

In the proposed scheme, a converter contains both rectifier and inverter. PV and battery sub-systems are connected with DC bus. At the same time charging the battery. The rectifier model is given below:

$$E_{rec-out}(t) = E_{rec-in}(t) * \eta_{rec} \tag{3.19}$$

$$E_{rec-in}(t) = E_{sur-ac}(t) \tag{3.20}$$

At any time, t,

$$E_{sur-ac}(t) = E_{weg}(t) - E_{load}(t) \tag{3.21}$$

Where, $E_{rec-out}(t)$ is the hourly energy output from rectifier, KWh

$E_{rec-in}(t)$ - is the hourly energy input to rectifier, KWh

$\eta_{rec}$ - is the efficiency of rectifier

$E_{sur-ac}(t)$ - is the amount of surplus energy from AC sources, KWh

Here converter is used which can work both as an inverter and rectifier depending on the direction of flow of power.

### 3.6.3 Mathematical Model of Charge Controller

To prevent overcharging or discharge of a battery, a charge controller is used to sense when the batteries are fully charged and to stop or reduce the amount of energy flowing from the energy source to the batteries. The model of the charge controller rating is given below:

$$\text{solar charge controller rating} = I_{sc} * \text{Total number of modules} * 1.1 \tag{3.22}$$

Where: 1.1 - is charge controller oversizing factor, $I_{sc}$ - Total short circuit current, of PV array.

The energy of the charge controller is also given as:

$$E_{cc-out}(t) = E_{cc-in}(t) * \eta_{cc} \tag{3.23}$$

$$E_{cc-in}(t) = E_{rec-out}(t) + E_{sur-dc}(t) \tag{3.24}$$

Where, $E_{cc-out}(t)$ - is the hourly energy output from charge controller, kWh

$E_{cc-in}(t)$ - is the hourly energy input to charge controller, kWh

$\eta_{cc}$ - is the efficiency of charge controller

$E_{rec-out}(t)$ - is the hourly energy output from rectifier, kWh

($E_{sur-dc}(t)$ - is the amount of surplus energy from DC sources, kWh

### 3.6.4 Mathematical Model of Battery Bank

The battery state of charge, SOC is the cumulative sum of the daily charge/discharge transfers. The battery serves as an energy source entity when discharging and a load when it charging. At any time, t the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from t-1 to t.

Daily Average Battery Capacity Required (Bcap) in Ahrs: The Daily Average System Capacity( Scap) in Whrs can be easily converted into the required battery capacity requires in order providing this amount of energy on a daily basis.

Daily Average Battery Capacity must be:

$$\mathrm{Bcap} = \frac{\mathrm{Scap(Whrs)}}{\mathrm{V_{nom,batt(V)}}} \tag{3.25}$$

Where, Bcap – daily average battery capacity required (Ahrs**)**,

Scap – daily average system capacity (Whrs)

$\mathrm{V_{nom,batt}}$ – Nominal battery voltage (V) i.e 24$\mathrm{V_{DC}}$

To calculate the number of batteries connected in parallel to reach the Ah required by the system.

$$\mathrm{B_P} = \frac{\mathrm{Bcap(Ahrs)}}{\mathrm{B_R}(Ah)} \tag{3.26}$$

Where, $\mathrm{B_P}$ – is batteries connected in parallel, $B_{\mathrm{R}}$ – is required battery rate in Ah

Bcap – is daily average battery capacity required (Ahrs**)**

To calculate the number of batteries to be connected in series to reach the voltage required by the system.

$$\mathrm{B_S} = \frac{\mathrm{V_{nbatt}}}{\mathrm{V_{batt}}} \tag{3.27}$$

Where, $\mathrm{B_S}$ – is number of series connected batteries, $\mathrm{V_{nbatt}}$ – is nominal battery voltage

$\mathrm{V_{batt}}$ – is battery voltage

During the charging process, when the total output energy of all generators exceeds the load demand, the available battery bank capacity at time, t can be described by using:

$$\mathrm{E_{bat}(t)} = \mathrm{E_{bat}(t-1)} - \mathrm{E_{cc-out}(t)} * \eta_{\mathrm{chg}} \tag{3.28}$$

Where, $\mathrm{E_{bat}(t)}$ – is the energy stored in battery at hour t, kWh

$E_{bat}(t-1)$ -is the energy stored in battery at hour t-1, kWh

$\eta_{chg}$ -is the battery charging efficiency

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at time, t, can be expressed as:

$$E_{bat}(t) = E_{bat}(t-1) - E_{needed}(t) \tag{3.29}$$

Where, $E_{needed}(t)$-is the hourly load demand or energy needed at a particular period of time.

Let **d** be the ratio of minimum allowable SOC voltage limit to the maximum SOC voltage across the battery terminals when it is fully charged. So, the Depth of Discharge (DOD)

$$DOD = (1-d) * 100 \tag{3.30}$$

DOD is a measure of how much energy has been withdrawn from a storage device, expressed as a percentage of full capacity. The maximum value of SOC is 1, and the minimum SOC is determined by maximum DOD,

$$SOC_{min} = 1 - \frac{DOD}{100} \tag{3.31}$$

### 3.6.5 Power Generation Model

Total hybrid power generated at any time t, is given by:

$$P(t) = \sum_{pvg=1}^{N_p} P_{pvg} \tag{3.32}$$

Where, $N_p$ is the number of PV cells unit

This generated power will feed to the loads. When this generated power exceeds the load demand then the surplus of energy will be stored in the battery bank. This energy will be used when deficiency of power occurs in order to meet the load demand. The charged quantity of the battery bank has the constraint $SOC_{min} \leq SOC(t) \leq SOC_{max}$. The dump load will draw excess energy produced by the renewable generators but unused when the load does not need all the energy and the battery has reached its maximum capacity and cannot store more energy.

The approach involves the minimization of a cost function subject to a set of equality and inequality constraints.

$$\text{Average Amp h per day load} = \frac{\text{Daily Average System Capacity/inverter efficiency}}{\text{DC System Voltage}} \quad (3.33a)$$

$$\text{Array peak Amps} = \frac{\text{Average Amp h per day load/battery energy efficiency}}{\text{Peak Sun Hours}} \quad (3.33b)$$

$$\text{Modules in Parallel} = \frac{\text{Array peak Amps}}{\text{Peak Amp per module}} \quad (3.33c)$$

Nps= Vs/Vm (3.34)

Nsp= Np/Nps (3.35)

Pm= Isc*Voc*FF (3.36)

Where Nps- Number module per string, Nsp- Number of string in parallel and,

Po-Nominal rated array output, FF -The Fill factor

### 3.6.6 Mathematical Cost Model of Energy Systems

This work developed a mathematical model of a system that could deploy the best renewable energy options available at any base station located in any part of a country in the world; where the term Best represents the integral (total sum) of the minimum economic and environmental (health and safety) costs of the considered options. For this purpose, the thesis adopts the Hybrid Optimization Model for Electric Renewable (HOMER).

**The Annualized Cost of a Component. -** The annualized cost of a component includes annualized capital cost, annualized replacement cost, annual operation and maintenance (O&M) cost and emissions cost. Operation cost is calculated hourly on daily basis.

**Annualized Capital Cost. -** The annualized capital cost of a system component is equal to the total initial capital cost multiplied by the capital recovery factor. Annualized capital cost is calculated by using:

$$C_{acap} = C_{cap} * CRF(i, R_{proj}) \quad (3.37)$$

Where, $C_{acap}$ – is annualized capital cost, $CRF(i, R_{proj})$ – is capital recovery factor, i – is interest rate, $R_{proj}$ – is project lifetime, $C_{cap}$ – is initial capital cost of the component

**Annualized Replacement Cost. -** The annualized replacement cost of a system component is the annualized value of all the replacement costs occurring throughout the lifetime of the project minus the salvage value at the end of the project lifetime.

Annualized replacement cost, $C_{arep}$ is calculated by using:

$$C_{arep} = C_{rep} * f_{rep} * SFF(i, R_{comp}) - S * SFF(i, R_{proj}) \quad (3.38)$$

Where, $C_{rep}$ – is replacement cost of the component, SFF ( ) – is sinking fund factor

$R_{comp}$ – is lifetime of the component, S – is salvaged value of the component

$f_{rep}$ – is replacement factor

$f_{rep}$ , a factor arising because the component lifetime can be different from the project lifetime, is given by:

$$f_{rep} = \begin{cases} \frac{CRF(i,R_{proj})}{CRF(i,R_{rep})}, & R_{rep} > 0 \\ 0 & R_{rep} = 0 \end{cases} \quad (3.39)$$

Where, $R_{rep}$-is replacement cost duration which is given by:

$$R_{rep} = R_{comp} * INT\left(\frac{R_{porj}}{R_{comp}}\right) \quad (3.40)$$

Where, INT () is the integer function, returning the integer portion of a real value.

SFF (), the sinking fund factor is a ratio used to calculate the future value of a series of equal annual cash flows, is given by:

$$SFF(i, N) = \frac{i}{(1+i)^N - 1} \quad (3.41)$$

Where, *N* = number of years

The salvaged value of the component at the end of the project lifetime is proportional to its remaining life. Therefore, the salvage value *S* is given by:

$$S = C_{rep} * \left(\frac{R_{rem}}{R_{comp}}\right) \quad (3.42)$$

Where, $R_{rem}$ – is remaining life of the component

The remaining life of the component, $R_{rem}$ at the end of the project lifetime is given by:

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \quad (3.43)$$

**<u>Annualized Operating Cost ($C_{aop}$).</u> -** The operating cost is the annualized value of all costs and revenues other than initial capital costs and is calculated by using:

$$C_{aop} \sum_{t=1}^{365} \left\{ \sum_{t=1}^{24} [C_{oc}(t)] \right\} \quad (3.44)$$

Where, $C_{oc}(t)$ – is the Cost of operating component.

Total cost of a component = Economic cost + Environmental cost

Where, Economic cost = Capital cost + Replacement cost + O & M cost

Environmental cost = Emissions cost ≅ 0

Annualized cost of a component is calculated using:

$$C_{ann} = C_{acap} + C_{arep} + C_{aop} + C_{emissions} = C_{acap} + C_{arep} + C_{aop} \quad (3.45)$$

Annualized total cost of a component is calculated using:

$$C_{ann,tot,c} = \sum_{c=1}^{N_c} (C_{acap,c} + C_{arep,c} + C_{aop,c}) \quad (3.46)$$

Where, $C_{ann,tot,c}$ – is Annualized capital cost of a component

$C_{arep,c}$ – is Annualized replacement cost of a component

$C_{aop,c}$ – is Annualized operating cost of a component

From equa. (3.47), the Economic and Environmental cost model through Annualized Total Cost of different Configurations of Power System were derived as follows:

Economic and Environmental cost model of running **Solar Power only** is calculated as:

$$C_{ann,tot,s} = \sum_{s=1}^{N_s} (C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions}) \quad (3.47)$$

Where, $C_{acap,s}$ – is annualized Capital Cost of solar Power

$C_{arep,s}$ – is annualized Replacement Cost of solar Power

$C_{aop,s}$ – is annualized Operating Cost of solar Power

Economic and Environmental cost model of running **Batteries** is calculated as:

$$C_{ann,tot,b} = \sum_{b=1}^{N_b} (C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions}) \quad (3.48)$$

Where, $C_{acap,b}$ – is annualized Capital Cost of batteries Power

$C_{arep,b}$ – is annualized Replacement Cost of batteries Power

$C_{aop,b}$ – is annualized Operating Cost of batteries Power

Economic cost model of **Converter** is calculated as:

$$C_{ann,tot,c} = \sum_{c=1}^{N_c} (C_{acap,c} + C_{arep,c} + C_{aop,c} + C_{emissions}) \qquad (3.49)$$

Where, $C_{acap,c}$ – is annualized Capital Cost of Converter Power

$C_{arep,c}$ – is annualized Replacement Cost of Converter Power

$C_{aop,c}$ – is annualized Operating Cost of Converter Power

Hybridizing the renewable energy generators (PV and Diesel Generator) results in three (3) different topologies as:

Economic and Environmental cost model of running **Solar only + Batteries + Converter** is calculated as:

$$\begin{aligned} C_{ann,tot,s+c+b} &= \sum_{s=1}^{N_s} (C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions}) \\ &+ \sum_{c=1}^{N_c} (C_{acap,c} + C_{rep,c} + C_{aop,c} + C_{emissions}) \\ &+ \sum_{b=1}^{N_b} (C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions}) \end{aligned} \qquad (3.50)$$

Economic and Environmental cost model of running **Diesel Generator only + Batteries + Converter** is calculated as:

$$\begin{aligned} C_{ann,tot,d+c+b} &= \sum_{d=1}^{N_d} (C_{acap,d} + C_{arep,d} + C_{aop,d} + C_{emissions}) \\ &+ \sum_{c=1}^{N_c} (C_{acap,c} + C_{rep,c} + C_{aop,c} + C_{emissions}) \\ &+ \sum_{b=1}^{N_b} (C_{acap,b} + C_{arep,b} + C_{aop,b} \\ &+ C_{emissions}) \end{aligned} \qquad (3.51)$$

Economic and Environmental cost model of running **Hybrid (Diesel Generator and Solar) + Batteries + Converter** is calculated as:

$$C_{ann,tot,s+w+c+b} = \sum_{s=1}^{N_s}(C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions}) + \sum_{d=1}^{N_d}(C_{acap,d} + C_{arep,d} + C_{aop,d} + C_{emissions}) + \sum_{c=1}^{N_c}\left(C_{acap,c} + C_{rep,c} + C_{aop,c} + C_{emissions}\right) + \sum_{b=1}^{N_b}(C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions}) \quad (3.52)$$

The mathematical model derived estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. The output when run with HOMER software will give us the optimal configuration of the energy system that takes into account technical and economic performance of supply options, the 10-year life cycle cost (LCC) of equipment, locally available energy resources (hourly solar insolation data ($KW/m^2$), and system reliability.

## 3.7 The Energy Optimization Model

The process of optimization had been of concern for man for many ages. Previously there were no defined and scientific rules for optimum conditions. But with the passage of time and advancement in science and technology, everything was considered to be based on certain reasons or logics. Mathematical calculations involving process of optimization have become more famous in recent years. True meaning of optimization is to find the best answer for a particular problem. For example, problems dealing with the cost were requiring the best cost to be as less as possible. On the other hand, problems dealing with profit was seen the maximum value as the best answer. So 'Optimum' is the word which is used to demonstrate the meaning of best, and the process of finding the best solution to a particular problem is known as the process of optimization. To solve an optimization problem, we require an optimization algorithm. An optimization algorithm is the algorithm which is used to define an optimized solution for a particular function. Thus, for the stand-alone PV and Diesel Generator hybrid system with constraints under study, I have the following optimization algorithm.

Minimize

$$\text{Cost} = \sum_{i} C_{PVi}N_{PVi} + \sum_{j} C_{DGj}N_{DGj} + \sum_{m} C_{Bm}N_{Bm} + \sum_{n} C_{Cn}N_{Cn} \quad (3.53)$$

Subject to the constraints

$$\text{Load} \leq \sum_{i} E_{PVi}N_{PVi} + \sum_{j} E_{DGj}N_{DGj} \quad (3.54)$$

$$\text{Maximum Power Wattage} \leq \sum_{n} P_{Cn}N_{Cn} \quad (3.55)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (3.56)$$

Where, $C_{PVi}$ – is Cost of a PV module, $C_{DGj}$ – is Cost of Diesel Generator

$C_{Bm}$ – Is Cost of a battery, $C_{Cn}$ – is Cost of a converter, $N_{PVi}$ – is Number of PV modules

$N_{DGj}$ – Is Diesel Generator, $N_{Bm}$ – is Number of battery bank to be use.

$N_{Cn}$ – is Number of converters, $E_{PVi}$ – is kWh generated by PV module i

$E_{DGj}$ – is kWh generated by Diesel Generator j, $P_{Cn}$ – is Maximum output power of converter

$SOC_{min}$ - is State of battery charge at minimum,

$SOC_{max}$ - is State of battery charge at maximum

## 3.8 Population Growth and Load Forecasting

The population of Ethiopia accounts all residents regardless of legal status/citizenship except for refugees not permanently in the country of asylum, which are generally considered part of the population of the country of origin. The average annual population growth rate of Ethiopia was 2.65% from 2005 to 2019 G.C [15].

The formula used for population forecasting is:

$$P_n = P_o(1 + \frac{r}{100})^n \quad (3.57)$$

Where: $P_n$ – is population at the $n^{th}$ year, $P_0$ – is the current population and r – is annual population growth rate in %.

### 3.8.1 Load Forecasting

The load forecasting was done for the two load estimations separately. It was obvious that previously recorded data was required as an input to conduct load forecasting using different techniques. But since the selected area was not electrified so far, the previous data were extracted by using the load forecasting method which was in use by UEAP. This was a governmentally owned company endowed in supplying electric access to rural areas by extending the national grid. The annual load growth rate was about 5% which was calculated by considering the data taken from previously electrified areas [15]. Hence, a primary load forecasting for the first ten years were done using equa. 3.58 given below. The current electric load was taken to be 279kWh/day which was calculated by considering the total primary load of the community.

$$E_n = E_o\left(1 + \frac{r}{100}\right)^n \tag{3.58}$$

Where: $E_n$ - is electric load at the $n^{th}$ year, $E_0$ - is the current electric load and

r - is the annual electric load growth (i.e. 5%)

The result of this analysis was shown in Table 3.10 below. These values are then used as input to forecast for the coming 10 years (2030) using the exponential method of forecasting.

Table 3. 10: Results of Primary Load Forecasting

| Year | 2020(0) | 2021(1) | 2022(2) | 2023(3) | 2024(4) |
|---|---|---|---|---|---|
| Load | 279 kw | 318kw | 375kw | 467kw | 645kw |

Thus, the principle of regression theory was used to forecast the load for the coming ten years by using the results in Table 3.10 as a previous data. Its principle was that any function y = f(x) can be fitted to a set of points (x1, y1), (x2, y2) so as to minimize the sum of errors squared at each point, i.e.

$$\sum_{i=1}^{n}\{y_i - f(x_i)\}^2 = \text{minimum} \tag{3.59}$$

Among the different typical regression curves used in power system forecasting the simple least square line was used for forecasting the load in this thesis. The line $y = a_0 + a_1x$ was fitted to the sets of points $(x_1, y_1), (x_2, y_2) \ldots (x_n, y_n)$.

Where, y - is dependent variable, $a_1$ - is slope, x - is independent variable, $a_0$ - is y-intercept and n are number of years.

$$\varepsilon^2 = \sum_{i=1}^{n}[y_i - (a_0 + a_1 x_i)]^2 = \text{minimum} \tag{3.60}$$

Partial differentiation with respect to the regressions coefficients ($a_0$ and $a_1$) is made and the equations set to zero to obtain the minimum error criterion.

This gives us a set of simultaneous equations in $a_0$ and $a_1$:

$$\text{For} \quad a_0 : 2\sum[y_i - (a_0 + a_1 x_i)] = 0, \text{We get,}$$

$$\sum a_0 + a_1 \sum x_i = \sum y_i$$

$$Na_0 + a_1 \sum x_i = \sum y_i$$

$$\text{For} \quad a_1 : 2\sum[y_i - (a_0 + a_1 x_i)]x_i = 0$$

$$a_0 \sum x_i + a_1 \sum x_i^2 = \sum x_i y_i$$

Which yield

$$a_0 = \frac{(\sum y)(\sum x^2) - [\sum(x)].\sum xy}{N\sum x^2 - (\sum x)^2} \tag{3.61(a)}$$

$$a_1 = \frac{N\sum xy - (\sum x).(\sum y)}{N\sum x^2 - (\sum x)^2} \tag{3.61(b)}$$

Table 3. 11: Results of the Analysis

| Year | Peak Demand (kw) | $x_i$ | $pDi = \frac{peak\,Demand}{10}$ | $Y_i = LnpDi$ | $x_i y_i$ | $x_i^2$ |
|---|---|---|---|---|---|---|
| 2020 | 279 | -2 | 27.9 | 3.32863 | -6.65726 | 4 |
| 2021 | 318 | -1 | 31.8 | 3.45947 | -3.45947 | 1 |
| 2022 | 375 | 0 | 37.5 | 3.62434 | 0 | 0 |
| 2023 | 467 | 1 | 46.7 | 3.84374 | 3.84374 | 1 |
| 2024 | 645 | 2 | 64.5 | 4.16667 | 8.33334 | 4 |
| | | $\sum x_i = 0$ | | $\sum y_i = 18.42285$ | $\sum x_i y_i = 2.06035$ | $\sum x_i^2 = 10$ |

| $a_0$ | $a_1$ | $x_i$ |
|---|---|---|
| 3.62434 | 0.20604 | 5 |

Finally, the values in Table 3.11 are used to determine the load of the selected area in 2030 G.C. The forecasting is then done using equation 3.62 (a) and (b) shown below by considering 2030 as a reference year. Therefore, the load is obtained to be 1050.61kWh/day.

$$Y = a_0 + a_1 . x_i \qquad (3.62(a))$$

$$E_n = 10e^{Y} \qquad (3.62(b))$$

## 3.9 Hybrid System Designing and Sizing

### 3.9.1 Design Methodology

In this thesis the main system design methods based on the daily energy demand assessment of **Albasa** village that is the peak load of 67 kw/day and total energy of 279kwh/day were estimated. The work also dealt with the sizing and specifying of PV array, Diesel Generator, Battery bank, and converter.

### 3.9.2 Designing and Sizing of Solar PV

Based on the above data about 48% of the system at peak time the total power supplied by solar PV(279kWh) to the cluster of villages is 25 kw, neglecting losses in the energy and delivery system. The design requirement was thus for a PV system delivering 400 Vac(0.4kV) ($V_{rms}$) three-phase.

**Selection of PV Module to be used.-**

Module type: Solar Liberty JKM320 watt

Specifications of considered PV system under standard test condition (STC):

**Electrical Data**

| | |
|---|---|
| Maximum Power (Pmax) | 320Wp |
| Maximum Power Voltage (Vmp) | 37.8V |
| Maximum Power Current (Imp) | 8.47A |
| Open Circuit Voltage (Voc) | 46.4V |
| Short Circuit Current (Isc) | 8.98A |
| Module Efficiency | 16.49 |

| | |
|---|---|
| Maximum System Voltage | 1000VDC (IEC) |
| Maximum Series Fuse | |
| Rating | 15A |
| Power tolerance | 0~+3% |

**Mechanical Data**

| | |
|---|---|
| Solar Cell Type | Mono-crystalline 156×156mm (6inch) |
| Number of Cells | 72 (6×12) |

The number of modules in Parallel in the PV System Design is:

$$\text{Average Amp h per day load} = \frac{\text{Daily Average System Capacity/inverter efficiency}}{\text{DC System Voltage}}$$

$$\text{Average Amp h per day load} = \frac{279000\text{watt}/0.94}{24}$$

Average Amp h per day load =12,367.02Ah

$$\text{Array peak Amps} = \frac{\text{Average Amp h per day load/Battery energy efficiency}}{\text{Peak Sun Hours}}$$

$$\text{Array peak Amps} = \frac{12{,}367.02/0.95}{3.86}$$

= 3,372.52A

$$\text{Modules in Parallel} = \frac{\text{Array peak Amps}}{\text{Peak Amp per module}}$$

$$\text{Modules in Parallel} = \frac{3{,}372.52\text{A}}{8.47\text{A}} = 298.172{\sim}399$$

399 modules are connected to in Parallel

Where Nps-Number module per string, Vs - Dividing the system bus voltage,

Vm - Module design voltage, Nsp -Number of string in parallel

Nps= Vs/Vm =24/37.8 =0.64 ~ 1 panel in series

The rounding this figure to the next higher integer determines the number of modules required per string. And dividing the number of modules required to meet energy requirements by the number of module required per string and rounding to the next higher integer determine the number of string in parallel.

Nsp= Np/Nps      =399/1

= 399 panel in parallel, the total number of module is 399*1=399 panels

The Fill factor, **FF** is the ratio of the maximum power (***$P_{Mp}$*** ***)*** generated by the solar cell to the product of the voltage open circuit Voc  and the short circuit current *I sc* .

For the temperature, I'sc, V'oc and FF' are evaluated a FF=320/8.47*46.4=.814

Pm= Isc*Voc*FF =8.98*46.4*0.814  =337.27watt

Nominal rated array output, Po, is determined by multiplying the total number of module by nominal rated module output.

Po= 399*337.27=134,570.73watt

Nominal rated array output is equal to 48% of the total power of the System i.e

48%*279000W=133,920W + loss

### 3.9.3 Battery Sizing and Specifying

The final battery capacity will depend on the following:

1. The total energy that the battery bank must supply to loads.
2. Maximum power demand
3. Maximum depth of discharge
4. System voltage
5. Charge current and recharge time.

**Determining the required battery capacity.-**

Lithium batteries are a great choice of for solar power systems .They are especially for giving when it comes to the level of discharge they will to tolerate.it can safely go up to a 100% depth of discharge (DOD) while maintaining nearly 98% efficiency. They can be wired in 12V, 24V and 48V configuration..Batteries used in all solar systems are sized in Ah under STCs (Temperature: $25^0$C). Battery manufactures usually specify the maximum allowable DOD for their batteries. The nominal battery voltage is 24V. Based on the above equation the net capacity that the battery can store in Ah/day must be:

$$\text{Bcap} = \frac{\text{Scap}}{V_{\text{nom,batt}}} = \frac{279\ \text{kwh/day}}{24V_{DC}} = 11{,}625\text{Ah/day}$$

The net capacity of the battery depends on the DOD of the battery and the DOD determines the life cycle of the battery. They are maintenance free and have 5000 cycle life when discharged to 80% depth of discharge, then total commercial capacity (Bcap.com) of the battery is calculated as:

$$\mathrm{Bcap.com} = \frac{\mathrm{Bcap}}{\mathrm{DOD}} = \frac{11{,}625}{0.8} = 14{,}513.25\ \mathrm{Ah/day}$$

Autonomy is the number of days that a fully charged battery can meet the system loads without any recharge from the PV array.The specified autonomy and maximum allowable depth-of-discharge define the total amount of battery capacity required for a given system load.It is recommended that the battery autonomy is three (3) days autonomy, because of cloudy days, shadows, etc. on solar PV. Benshangul Gumuz Region is six up to seven month rainy Season and it must include in the design.

Therefore, Bcap.com = 14,531.25 Ah/day * 3 = 43,593.75 Ah/day. Hence, the capacity of the battery is taken as 45,000Ah. And also Selected Battery Ah Rating = 1900Ah. To calculate the number of batteries connected in parallel to reach the Ahs required by the system.

$$B_P = \frac{\mathrm{Bcap.com}}{B_R} = \frac{45{,}000}{1900} = 23.68 \sim 24\ \mathrm{batteries}$$

The number of batteries to be connected in series to reach the voltage required by the system.

$$B_S = \frac{V_{nom.batt}}{V_{batt}} = \frac{24V}{12V} = 2\ \mathrm{batteries}$$

24 Batteries are to be connected in parallel and 2 Batteries are to be connected in series, 24*1900 (49,400) Ah Batteries are to be connected in parallel. And 2*1900 (3800) Ah Batteries are to be connected in series.

The total (2*24 = 48) Batteries are to be connected used in the system

### 3.9.4 Charge Controller Sizing and Specifying

An oversize factor of 10% (1.1), to effectively cover the aging of the solar module should be included with systems that include lithium-ion batteries.

The solar charge controller is typically rated against amperage and voltage capacity. The size of the controller depends on the total PV input current which is delivered to the controller and PV panel configuration.

$$\text{solar charge controller rating} = I_{sc} * \text{Total number of modules} * 1.1$$

$$= 8.98 * 399 * 1.1 = 3{,}941.32A \sim 4000A$$

### 3.9.5 Converter Sizing and Specifying

Converter size = maximum Power of Ac loads * 1.1 (oversize factor)

Converter size (kW) = 67 * 1.1 = 73.7kW

For safety, the inverter should be considered 25%- 30% bigger size.

Available converter size were 100, 150, 200, 250kW. The inverter size should be and chosen converter size for this thesis was a capacity of 100 kW and the full load efficiency were greater than 90% (i.e. 95%).

Table 3. 12: Input Parameters and Costs of different Components

| | |
|---|---|
| **PV System** | |
| Type | JKM320 watt |
| Lifetime | 25 |
| Derating Factor | 97% |
| Capital Cost | $ 237.798/kw |
| Operation and Maintenance Cost | $ 0.5/year |
| **DG** | |
| Size | 88KW |
| Lifetime | 15000hr |
| Capital Cost | $400/kw |
| Replacement Cost | $350/kw |
| Operating and Maintenance Cost | $0.05/hr |
| **Battery** | |
| Type | S4KS25P |
| Lifetime | 10 year |
| Batteries Per String | 2V(24V) |

| | |
|---|---|
| Nominal Voltage | 24V |
| Nominal Capacity | 1900Ah |
| | (1900Ah*3.7V) |
| Nominal Energy Capacity | 7.03kwh |
| Capital Cost | $ 215/quantity |
| Replacement Cost | $ 161/quantity |
| **Converter** | |
| Type | 100kw |
| Lifetime | 10 year |
| Efficiency | 0.94 |
| Capital Cost | $ 3/kw |
| Operating and Maintenance Cost | $0.05/hr |

**Cost of PV System: PV Array and Battery**

The price of the chosen array (made up of 399 modules) for the PV system was computed as follows:

Cost of array = module price × number of modules

= $237.798 × 399 = $94,881.40

The initial cost of the battery bank for this PV system was computed as follows:

Cost of battery = autonomy days × required energy × price = 3 × 7030 × 0.31806 = $6,707.89

The total Cost of the Input parameters and costs of different components is $252,643.6

## 3.10 Homer Software and Programmable Logic Controller

### 3.10.1 Overview of HOMER Software

Hybrid Optimization Model for Electric Renewable (HOMER), is the micro power optimization model, simplifies the task of evaluating designs of both mini-grid and grid-connected power systems for a variety of applications. In designing power systems different decisions can be made about the configuration of the system, such as; what components to include in the system, the size and the quantity of the components and the cost of each components.

Incorrect power system design can lead to shorter life of battery, increase cost of energy production, insufficient supply of electricity demand. HOMER is a computer model developed originally by the National Renewable Energy Laboratory (NREL). It has different energy generating components in its library. The user must select the components from the library to represent the architecture considered. HOMER simplifies or helps the designer to compare various power systems options based on technical and economic aspects.

### 3.10.2 Modeling of Hybrid System with HOMER

HOMER is used to model a power system physical behavior and its life-cycle cost, which is the total cost of installing and operating the system over its life time. HOMER allows the modeler to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs. HOMER was designed to overcome this uncertainty and also the complexity of the renewable energies being intermittent, seasonal, non-dispatch able and having uncertain availability.

The design of mini-grid PV/diesel generator with storage battery hybrid energy system to a community of 1110 households, with average five members per family was carried out based on the theoretical background discussed so far. HOMER software is used as a tool to accomplish the thesis. As earlier, the main objective of the thesis was to design and model hybrid PV/diesel generator with storage battery based mini-grid power generation systems to meet the load requirements of the community specified. A schematic representation of the mini-grid hybrid energy system by HOMER is shown below in Figure 3.2 based on the previous mathematical design.

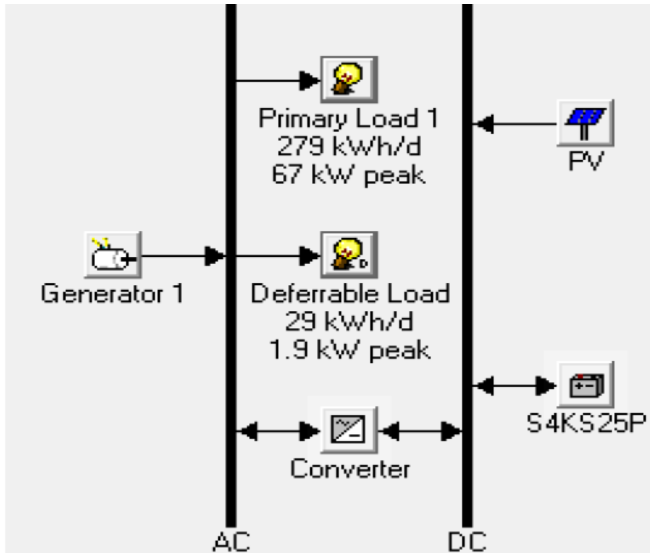



Figure 3. 2: HOMER Diagram for the Hybrid PV/Diesel Generator/Battery-Converter Set-Up

Based on the above primary and deferrable load estimation of the village the HOMER optimization model diagram is given as follows respectively.

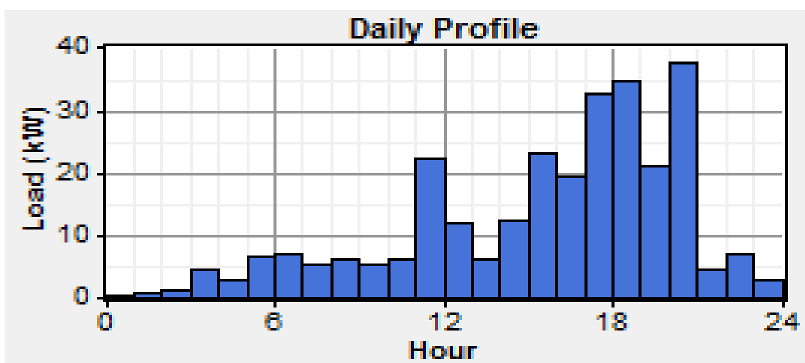



Figure 3. 3: Daily Primary Load

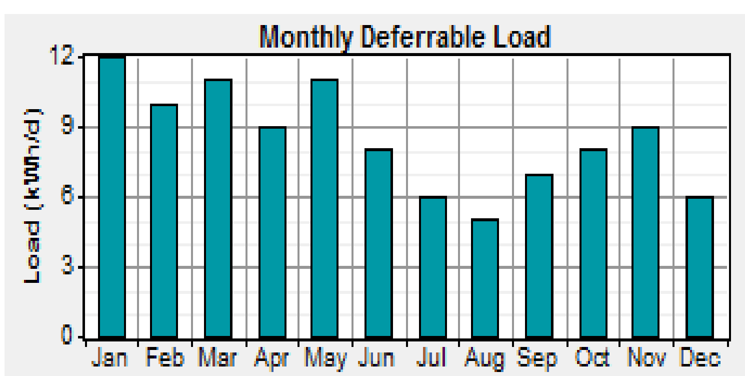



Figure 3. 4: Monthly Deferrable Load Profile

HOMER does three main tasks as indicated in Figure 3.5:

**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 solar PV or diesel generator. For a system that contains battery, solar PV and diesel 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. HOMER decision variables may include like; PV array size, diesel 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 optimization's 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.

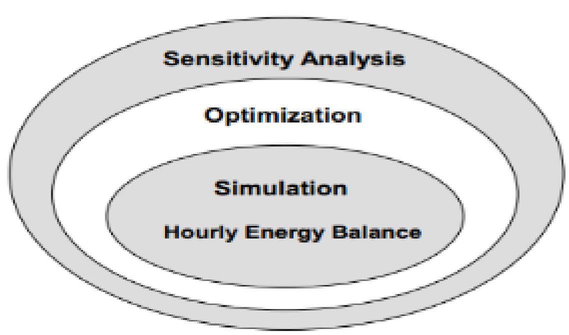



Figure 3. 5: Interactions between Simulation, Optimization and Sensitivity Analysis [8]

### 3.11 Programmable Logic Control System

A Programmable Logic Controller (PLC) is an industrial computer specialized for real time

applications. PLCs are integrated systems containing a processor, main memory, input modules, output modules that are coupled together by a common bus. Input modules interface with plant equipment and convert the field signals to logic levels for the processor to read. The processor uses these inputs to perform control functions based on application software. Output modules transmit the signals via an interface with the plant equipment.

#### 3.11.1 Principle of Operation

A programmable controller, as illustrated in Figure 3.6 consists of three basic sections:

- The central processing unit (CPU)
- Programming device
- The input/output module

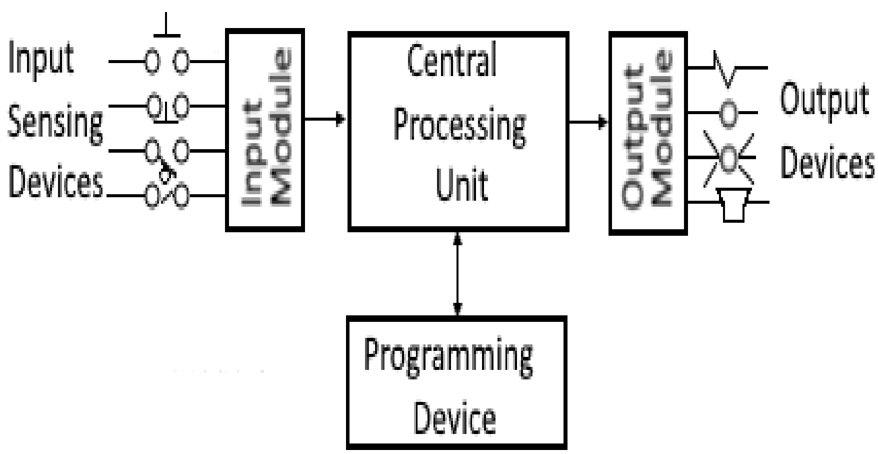



Figure 3. 6: Programmable Controller Block Diagram [28]

The central processing unit (CPU) governs all PLC activities. The following three components, shown in Figure 3.7 form the CPU:

- The processor
- The memory system
- The system power supply

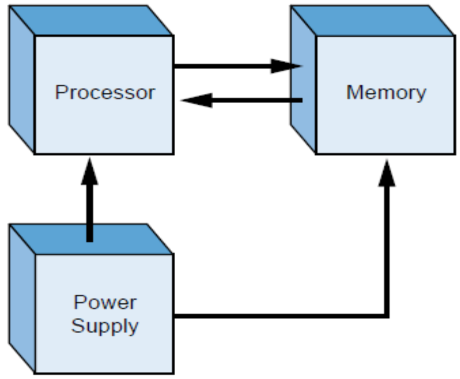



Figure 3. 7: Block Diagram of Major CPU Components [29]

During its operation, the CPU completes three processes: (1) it **reads**, or accepts, the input data from the field devices via the input interfaces, (2) it **executes**, or performs, the control program stored in the memory system, and (3) it **writes**, or updates, the output devices via the output interfaces. This process of sequentially reading the inputs, executing the program in memory, and updating the outputs is known as scanning. Figure 3.8 illustrates a graphic representation of a scan.

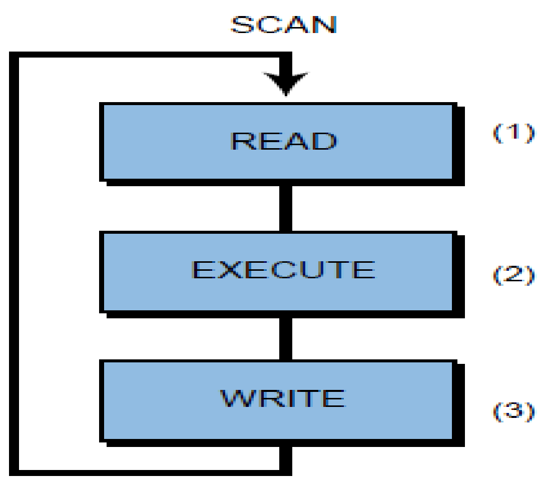



Figure 3. 8: Illustration of a Scan. [25]

The **processor** is the section of the CPU that codes, decodes, and computes data. The **memory system** is the section of the CPU that stores both the control program and data from the equipment connected to the PLC. The **power supply** is the section that provides the PLC with the voltage and current it needs to operate. The operation of a programmable controller is relatively simple. The **input/ output (I/O) system** is physically connected to the field devices that are encountered in the machine or that are used in the control of a process. These field devices may be discrete or analog input/output devices, such as limit switches, pressure transducers, push buttons, motor starters, solenoids, etc. The I/O interfaces provide the connection between the CPU and the information providers (inputs) and controllable devices (outputs) [25]. The input/output system forms the **interface** by which field devices is connected to the controller (see Figure 3.8). The main purpose of the interface is to condition the various signals received from or sent to external field devices. Incoming signals from sensors (e.g., push buttons, limit switches, analog sensors, selector switches, and thumbwheel switches) are wired to terminals on the input interfaces. Devices that were are controlled, like motor starters, solenoid valves, pilot lights, and position valves, are connected to the terminals of the output interfaces.

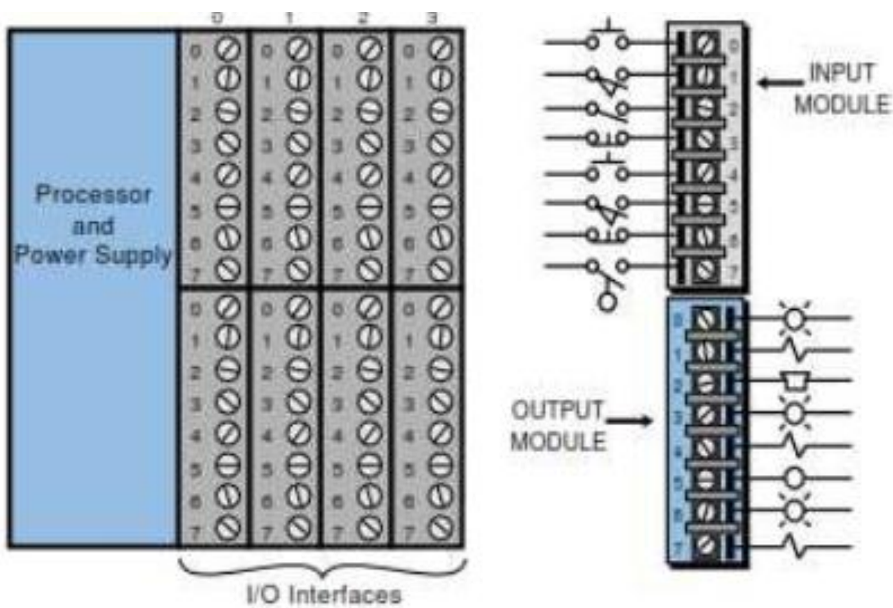



Figure 3. 9: Input/output Interface [29]

## 3.12 PLC in Hybrid System

Table 3.12 below depicts energy management system using plc. When a system has more than two sources it is necessary to have an energy management system which is expected to optimize the power sharing among resources, the cost production and emission. In this thesis, the main purpose of EMS is - Load control (switching) - on/off loads to achieve economic and effective energy use. Source control (switching) which type source at what time (solar, diesel generator and battery) supplies to get continuous and reliable operation at economic level. The PLC SIMATIC manager control makes decision on the output based on the operating state of the input.

Table 3. 13: States of Power Supply Units With Respect to Load Demand and Operating Time

| Operating Time(hr.) | Load (kw) | Solar energy | Diesel generator | Battery (Litum-Ion) |
|---|---|---|---|---|
| 00:00-6:00 | 3.565 | Off | Off | On |
| 6:00-7:00 | 10.825 | Off | On | On |
| 7:00-8:00 | 14.77 | On | Off | Off |
| 8:00-10:00 | 19.18 | On | Off | Off |
| 10:00-11:00 | 14.66 | On | Off | Off |
| 11:00-12:00 | 1.16 | On | Off | Off |
| 12:00-14:00 | 11.3 | On | Off | Off |
| 14:00-15:00 | 13.895 | On | Off | Off |
| 15:00-16:00 | 21.035 | On | Off | Off |
| 16:00-18:00 | 12.43 | On | Off | On |
| 18:00-19:00 | 33.385 | On | On | On |
| 19:00-22:00 | 38.075 | Off | On | On |
| 22:00-23:00 | 10.095 | Off | On | On |
| 23:00-00:00 | 3.75 | Off | Off | On |

## 3.13 Overall Programmable Logic Control Hybrid System

The overall programmable logic control hybrid system consists of the PV system, Diesel Generator and storage battery bank. The separately modeled and simulated PV system, Diesel Generator and storage battery bank are the input parameters. According to the available energy resource solar PV/Diesel Generator or stored energy supplies the power to feed the connected loads. Hence in Figure 3.10, solar indicate the output from solar energy, Diesel Generator indicates electric energy from the Fuel and storage battery bank indicates the battery energy that is stored during high renewable energy generation, minimum load and discharge during low generation of renewable energy. The multiport conditional switch will take an action according to the rules written in programmable logic control system.

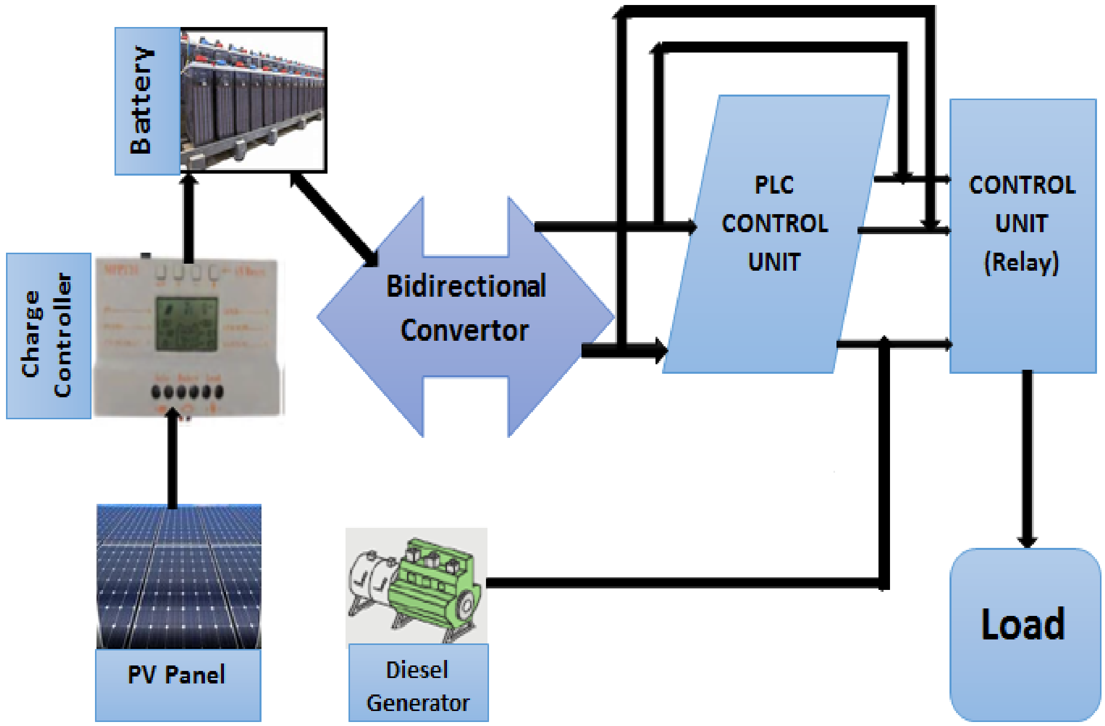



Figure 3. 10: Block Diagram of Hybrid System with PLC Controller

# RESULT AND DESCUSSION (CHAPTER FOUR)

## 4.1 Result

The optimal hybrid system is the one which can supply electricity needs at the lowest price or in other words, the system which is having the lowest total net present value, while supplying the electricity at the required level of availability. In this chapter the results of the designed output of a **PV/Diesel Generator/Storage battery** hybrid power system is presented and discuss the results obtained from the HOMER simulations and the selection of the optimal system based on the simulation results. The chapter also discusses the performance of the optimal hybrid system, hybrid system design, economic viability of the thesis and a brief introduction to the energy management in the mini-grid system. The main objective of this thesis was to design and an optimized mini-grid solar PV/Diesel Generator/storage battery hybrid power system with energy management to investigate alternative power supply option for rural area/village (**Albasa)** detached from the main grid system. Then this input parameter used to generate simulation result using HOMER Software. Through the simulation work, three different scenarios are considered to increase the probability of finding the best energy system components. From the generated simulation results the combination of components which costs less (minimum total NPC and less COE) is considered as selected energy system for each scenario analysis. Then, finally from different scenario analysis, still the least cost scenario is considered as the best energy system by comparing scenarios with the same design parameter.

### 4.1.1 Optimization Results

During optimization all possible hybrid system configurations are listed in ascending order

according to their total NPC. The best possible combination of solar PV/ Batteries and Convertor is in the first row of the simulation results were able to fully meet **the village** load demands at the lowest cost, and the next best possible combination, is in the second row of the simulation results, and includes the solar PV/Diesel Generator/Batteries and Converter. The simulation software provides the results in terms of optimal systems and the sensitivity analysis. The optimal system configuration for the first case study were mean output power of 25kW solar PV, 14kW Diesel Generator, 80 S4KS25P batteries and 85 kW Converter with a dispatch strategy of load following.

As indicated above in Figure 3.3 of the daily primary load profile of the village, the maximum load demand will cover between 20hr to 21hr which is around **37.5kW**. But this

power is changed to **67kW** due the random variability of 3% for days to day and 5%-time step to time step as to be more realistic load demand growth. As discussed in the preceding chapter three that the Solar PV operates most efficiently when working near its full load as backup of storage battery and diesel generator.

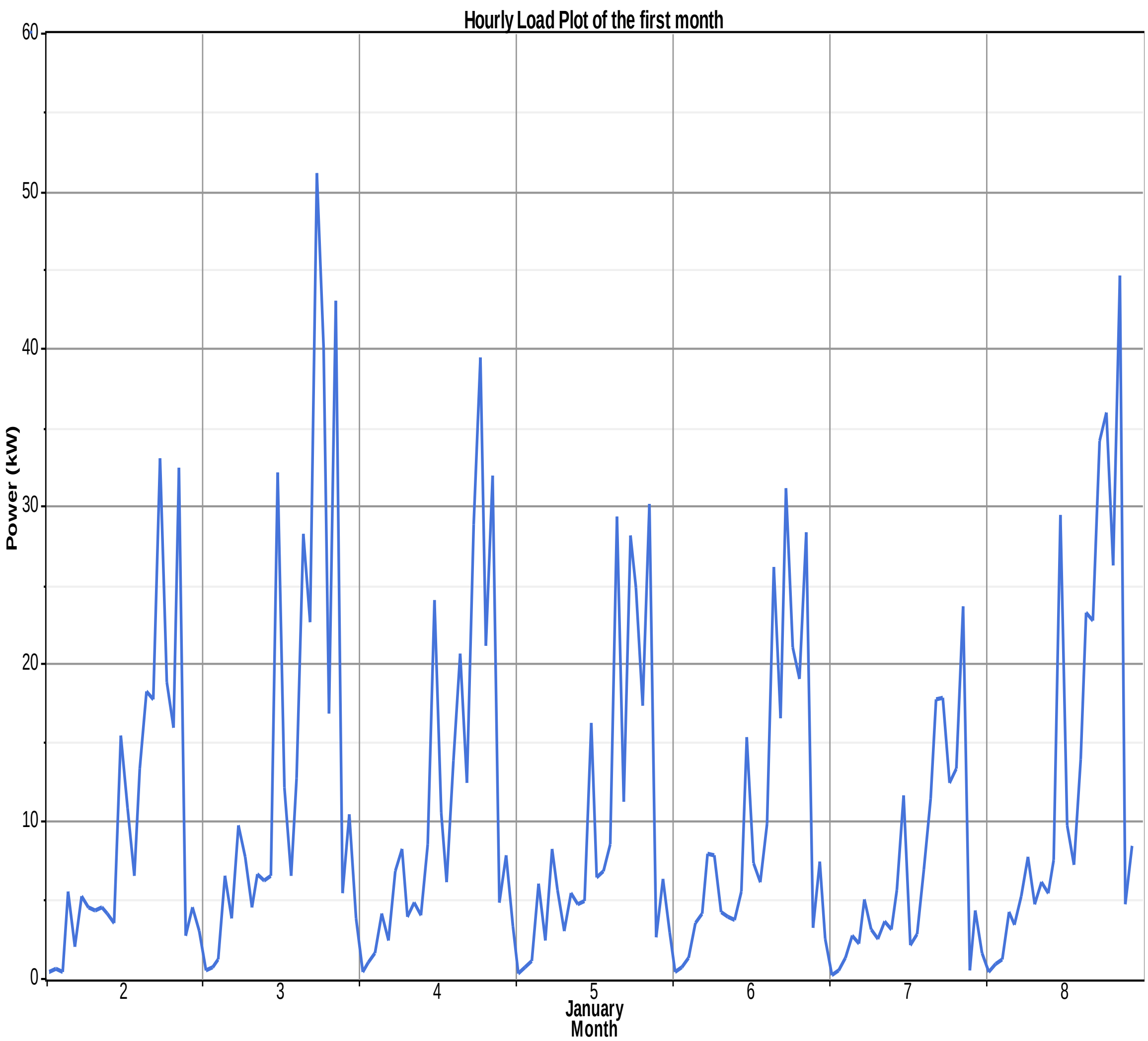



Figure 4. 1: Hourly Load Plot of the First Month

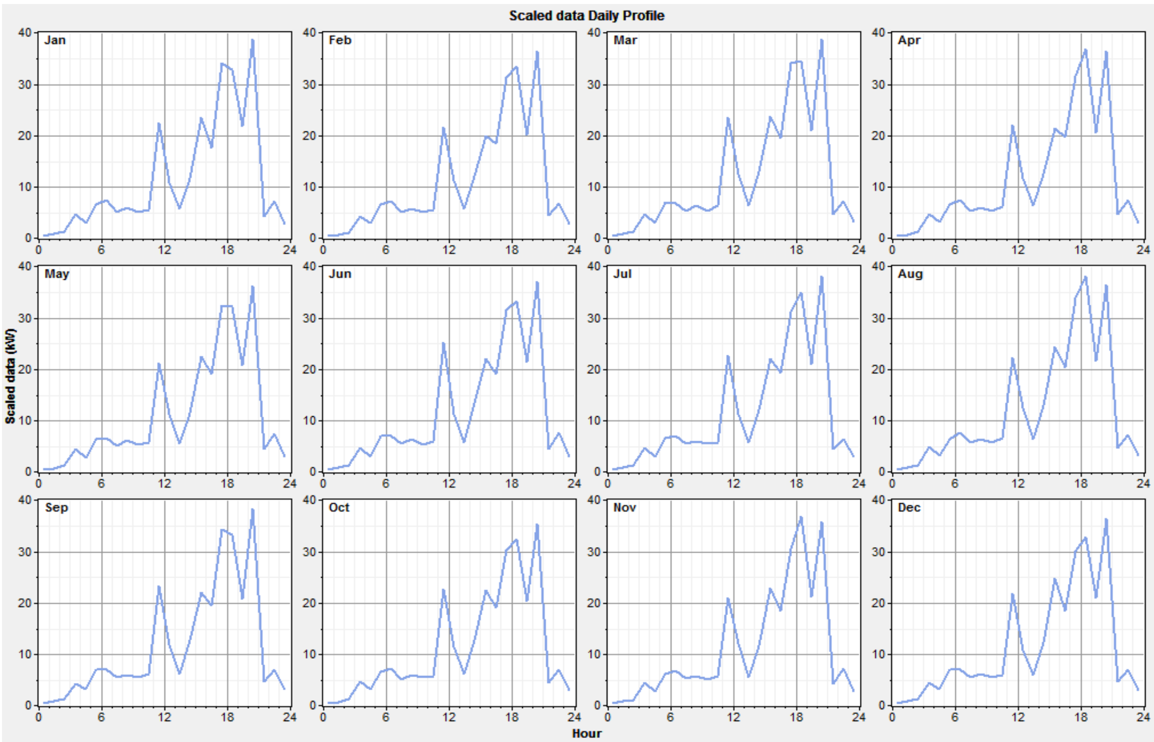



Figure 4. 2: Daily Profile of Load (kw) vs Hour (hrs) of Each Month

This system is considered 5.013kwh/m2/day of average solar radiation for the solar PV and

backup of Diesel Generator and storage battery bank. The total NPC, capital cost, operating cost and levelized COE for the given hybrid system are $114,840, $103,221, $909/year and $0.080/kWh, respectively.

The software displays the result for the inputs in either an overall form in which the top ranked system configurations are listed according to their NPC or in categorized form in which only the most cost effective configuration is considered from each system type.

Double click on a system below for simulation results. ⦿ Categorized ○ Overa

| PV (kW) | Label (kW) | S4KS25P | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. |
|---|---|---|---|---|---|---|---|---|
| 320 | | 5400 | 350 | $ 103,218 | 909 | $ 114,838 | 0.080 | 1.00 |
| 320 | 15 | 5400 | 350 | $ 103,221 | 909 | $ 114,840 | 0.080 | 1.00 |

Figure 4. 3: Categorized Simulation Results of Least Cost-Effective Scenarios.

The overall optimization results below in Figure 4.4 shows that the total NPC increases from the first row to the last row. Because of the increment of total NPC, the first row is only the most cost-effective configuration for hybrid renewable energy generation. In addition to this the initial capital cost also increases from top to bottom when looking in the given Figure 4.4 below.

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. |
|---|---|---|---|---|---|---|---|---|
| 320 | | 5400 | 350 | $ 103,218 | 909 | $ 114,838 | 0.080 | 1.00 |
| 320 | 15 | 5400 | 350 | $ 103,221 | 909 | $ 114,840 | 0.080 | 1.00 |
| 320 | | 5400 | 700 | $ 103,222 | 909 | $ 114,842 | 0.080 | 1.00 |
| 320 | 15 | 5400 | 700 | $ 103,225 | 909 | $ 114,844 | 0.080 | 1.00 |
| 320 | | 5400 | 1000 | $ 103,225 | 909 | $ 114,845 | 0.080 | 1.00 |
| 320 | 45 | 5400 | 350 | $ 103,227 | 909 | $ 114,845 | 0.080 | 1.00 |
| 320 | 15 | 5400 | 1000 | $ 103,228 | 909 | $ 114,847 | 0.080 | 1.00 |
| 320 | 45 | 5400 | 700 | $ 103,231 | 909 | $ 114,849 | 0.080 | 1.00 |
| 320 | 45 | 5400 | 1000 | $ 103,234 | 909 | $ 114,852 | 0.080 | 1.00 |
| 320 | 90 | 5400 | 350 | $ 103,236 | 909 | $ 114,852 | 0.080 | 1.00 |
| 320 | 90 | 5400 | 700 | $ 103,240 | 909 | $ 114,855 | 0.080 | 1.00 |
| 320 | 90 | 5400 | 1000 | $ 103,243 | 909 | $ 114,858 | 0.080 | 1.00 |
| 320 | 180 | 5400 | 350 | $ 103,254 | 908 | $ 114,866 | 0.080 | 1.00 |
| 320 | 180 | 5400 | 700 | $ 103,258 | 908 | $ 114,869 | 0.080 | 1.00 |
| 320 | 180 | 5400 | 1000 | $ 103,261 | 908 | $ 114,872 | 0.080 | 1.00 |
| 320 | | 6000 | 350 | $ 103,242 | 910 | $ 114,875 | 0.080 | 1.00 |
| 320 | 15 | 6000 | 350 | $ 103,245 | 910 | $ 114,877 | 0.080 | 1.00 |
| 320 | | 6000 | 700 | $ 103,246 | 910 | $ 114,878 | 0.080 | 1.00 |
| 320 | 270 | 5400 | 350 | $ 103,272 | 908 | $ 114,880 | 0.080 | 1.00 |
| 320 | 15 | 6000 | 700 | $ 103,249 | 910 | $ 114,881 | 0.080 | 1.00 |
| 320 | | 6000 | 1000 | $ 103,249 | 910 | $ 114,881 | 0.080 | 1.00 |
| 320 | 45 | 6000 | 350 | $ 103,251 | 910 | $ 114,882 | 0.080 | 1.00 |
| 320 | 270 | 5400 | 700 | $ 103,276 | 908 | $ 114,883 | 0.080 | 1.00 |
| 320 | 15 | 6000 | 1000 | $ 103,252 | 910 | $ 114,884 | 0.080 | 1.00 |
| 320 | 45 | 6000 | 700 | $ 103,255 | 910 | $ 114,885 | 0.080 | 1.00 |
| 320 | | 6180 | 350 | $ 103,250 | 910 | $ 114,886 | 0.080 | 1.00 |

Figure 4. 4: Overall Optimization Results

### 4.1.2 Optimization Analysis of the Selected Scenario

The categorized optimization results summarized in Figure 4.3 above depicts the results from HOMER modeling for **Albasa village**. The modeling simulates one year of operation and thousands of different system configurations. The system with the overall least cost of energy is the one highest on the list. The first four columns of the HOMER results in Figure 4.4 show graphic icons representing which components are present in the optimized system. The remaining columns show the optimized capacity of each component, the initial capital cost, the total NPC, the COE (in $ per kWh) and renewable energy fraction. Based on the HOMER modeling, the optimal system for **Albasa village** in categorized optimization results a first row, shows a hybrid solar PV/diesel generator/storage battery, with mean output power of 25kW solar PV, 14kW Diesel Generator, 80 S4KS25P batteries (each of 1900Ah capacity) and 85kW bi-directional converter (85kW rectifier, 85kW inverter) are required power supplied for the selected village. This "optimal" system uses 98.5% renewable energy and the COE is $0.080/kWh. The system set-up in the first row of Figure 4.3 is the cost-efficient system composed of mean power output of 25kW PV panel, 14kW Diesel Generator, 80 S4KS25P batteries, and 85kW converter. All of the power schemes remain producing electricity throughout the year.

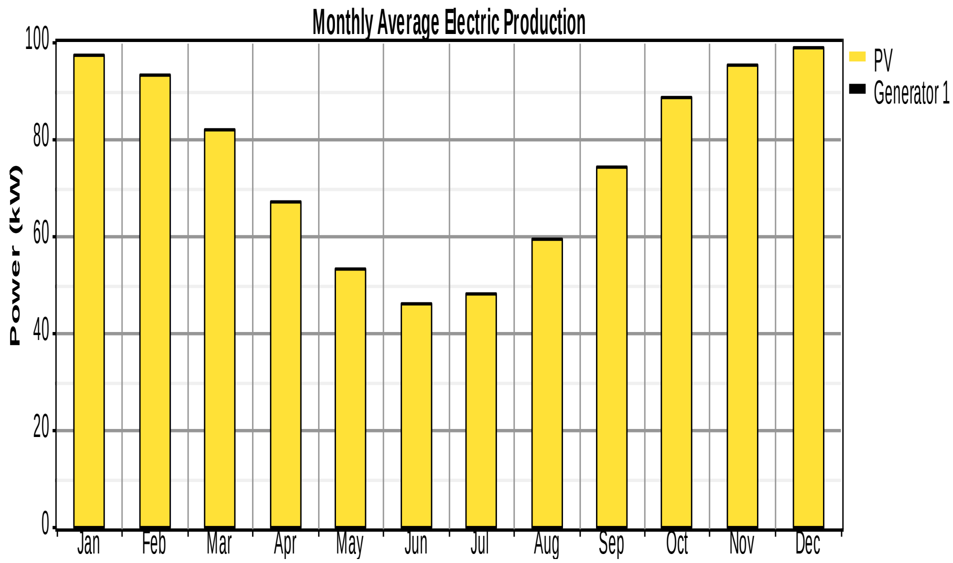



Figure 4. 5: Share of Electricity Generation

The electricity generation by individual power units of the hybrid system and consumptions by AC primary and deferrable load are given in Figure 4.5 PV array power production accounts for 98.5% (659,278kWh/year) whereas Diesel Generator generation covered 1.5% (1,053kWh/year) of total electricity produced by the hybrid scheme.

The total power generation of this power system setup was 660,331kWh/year (100%), whereas the total electric power consumption of the AC load was about 101,835kWh/year i.e 91% of the electricity consumed by AC load and the consumption of deferrable load 10,602kWh/year i.e 9% were consumed by deferrable load. In addition to this an excess electricity of 79.5%, a capacity shortage of (0.0%) and unmet electric load of (0.0%) were experienced during the year**.**

Actually, this power system architecture indicates that excess electricity would enable to supply the demand growth of the community in the future. In addition to this, excess electricity could provide to neighboring villages or introduce small businesses to increase the load factor of the power system; consequently, the cost of electricity will also decrease.

**Similarly,** the system set-up in the second row of Figure 4.4 is the cost-efficient system composed mean output power of 25kW PV panel, 14kW Diesel Generator, 80 S4KS25P batteries, and 85kW convertor. All of the power schemes remain producing electricity throughout the year.

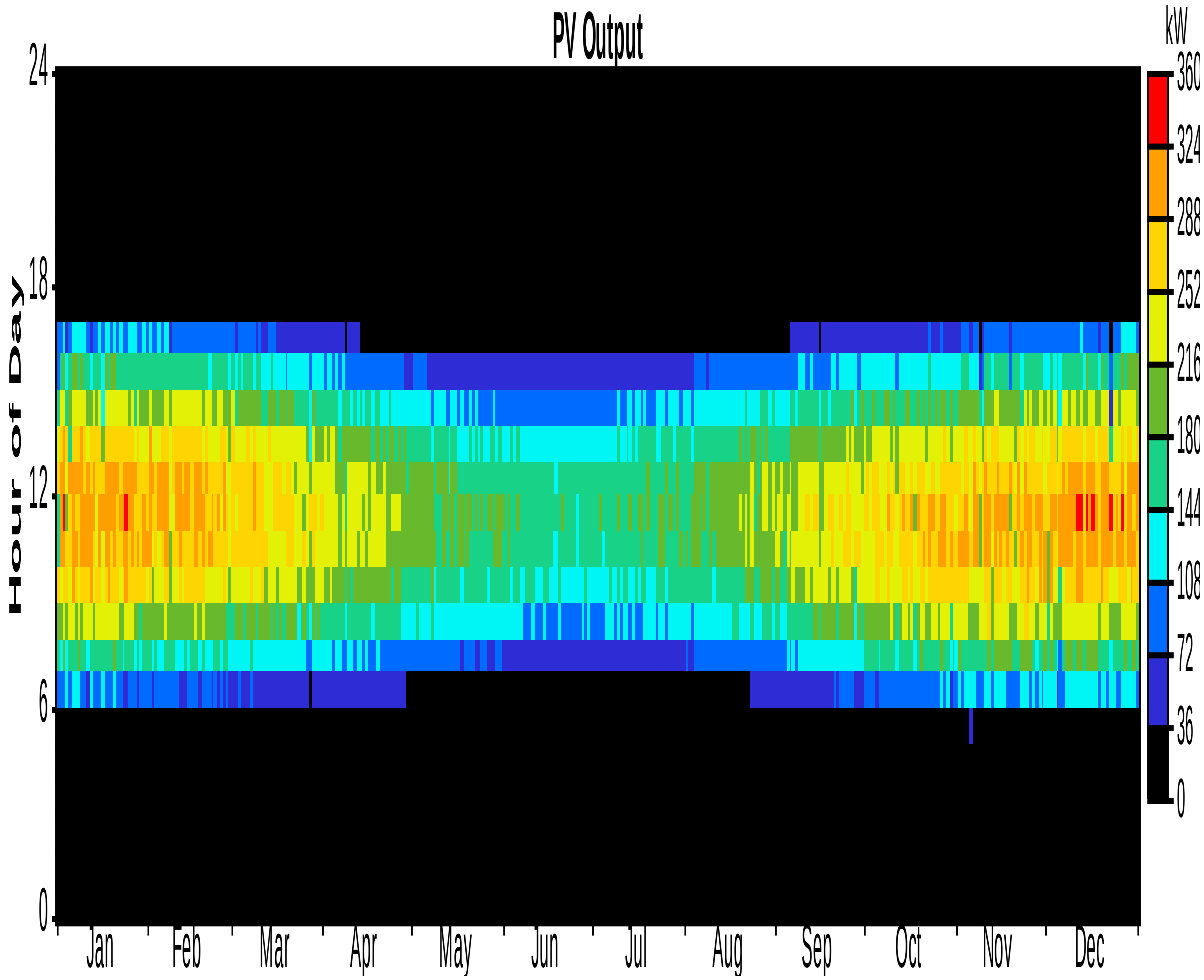
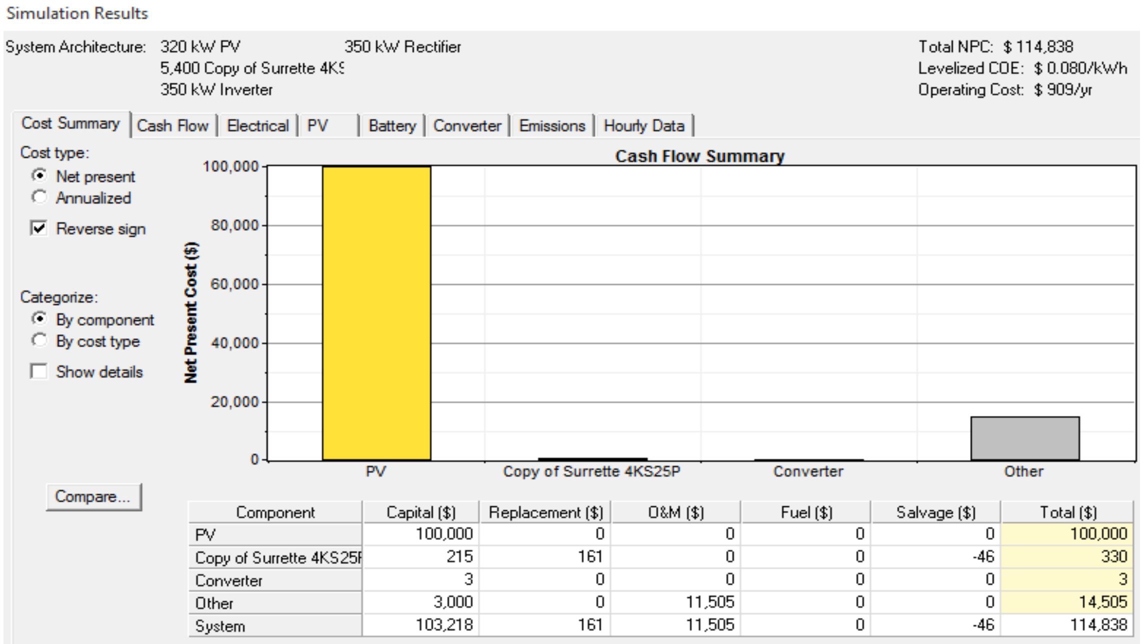



Figure 4. 6: Solar PV Power Productions

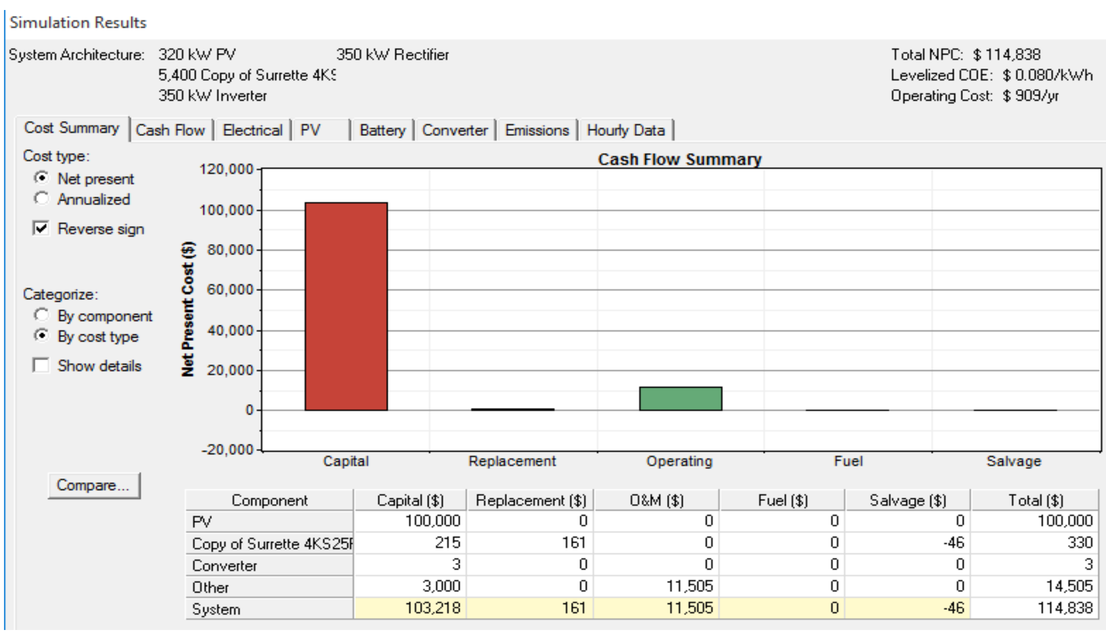
**<u>Cost Summary in terms of NPC by Component Type</u>**.- The following Figure 4.7 shows that the cost summary in terms of NPC by component type which were the system set-up in the first row of above Figure 4.3. It shows graphical representation of each component and also other required materials NPC ($). In addition to these, it shows table representation of the capital cost ($), replacement cost ($), O & M cost ($), salvage cost ($) and total cost ($) of each component as given below.




| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 100,000 | 0 | 0 | 0 | 0 | 100,000 |
| Copy of Surrette 4KS25F | 215 | 161 | 0 | 0 | -46 | 330 |
| Converter | 3 | 0 | 0 | 0 | 0 | 3 |
| Other | 3,000 | 0 | 11,505 | 0 | 0 | 14,505 |
| System | 103,218 | 161 | 11,505 | 0 | -46 | 114,838 |

Figure 4. 7: Cost summary in Terms of NPC by Component Type

**Cost Summary of the System by Cost Type. -** The Figure 4.8 below displays cost breakdown summary of the components with 100% renewable fraction hybrid power scheme. It is clearly seen from the graph the total capital cost, NPC and COE of the optimal configuration of the hybrid system is calculated by the HOMER software to be $114,838, $103,221 and $0.080/kwh respectively.




| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 100,000 | 0 | 0 | 0 | 0 | 100,000 |
| Copy of Surrette 4KS25F | 215 | 161 | 0 | 0 | -46 | 330 |
| Converter | 3 | 0 | 0 | 0 | 0 | 3 |
| Other | 3,000 | 0 | 11,505 | 0 | 0 | 14,505 |
| System | 103,218 | 161 | 11,505 | 0 | -46 | 114,838 |

Figure 4. 8: Cost Summary of the System by Cost Type

### 4.1.3 Sensitivity Results Consideration

Sensitivity is a measure of how the optimal mix of components changes for any parametric variations in the lifelong of the system. The HOMER software simulates all the systems in their respective search space for each of the sensitivity values. An hourly time series simulation is performed for one complete year.

In Figure 4.9 the line graph below shows PV array capacity variations (KW) and AC primary load (KW) is displayed within given month of April. Considering only two of the sensitivity cases (solar PV power (KW) and AC primary load (KW)) by keeping the other variables as fixed minimum renewable fraction were one.

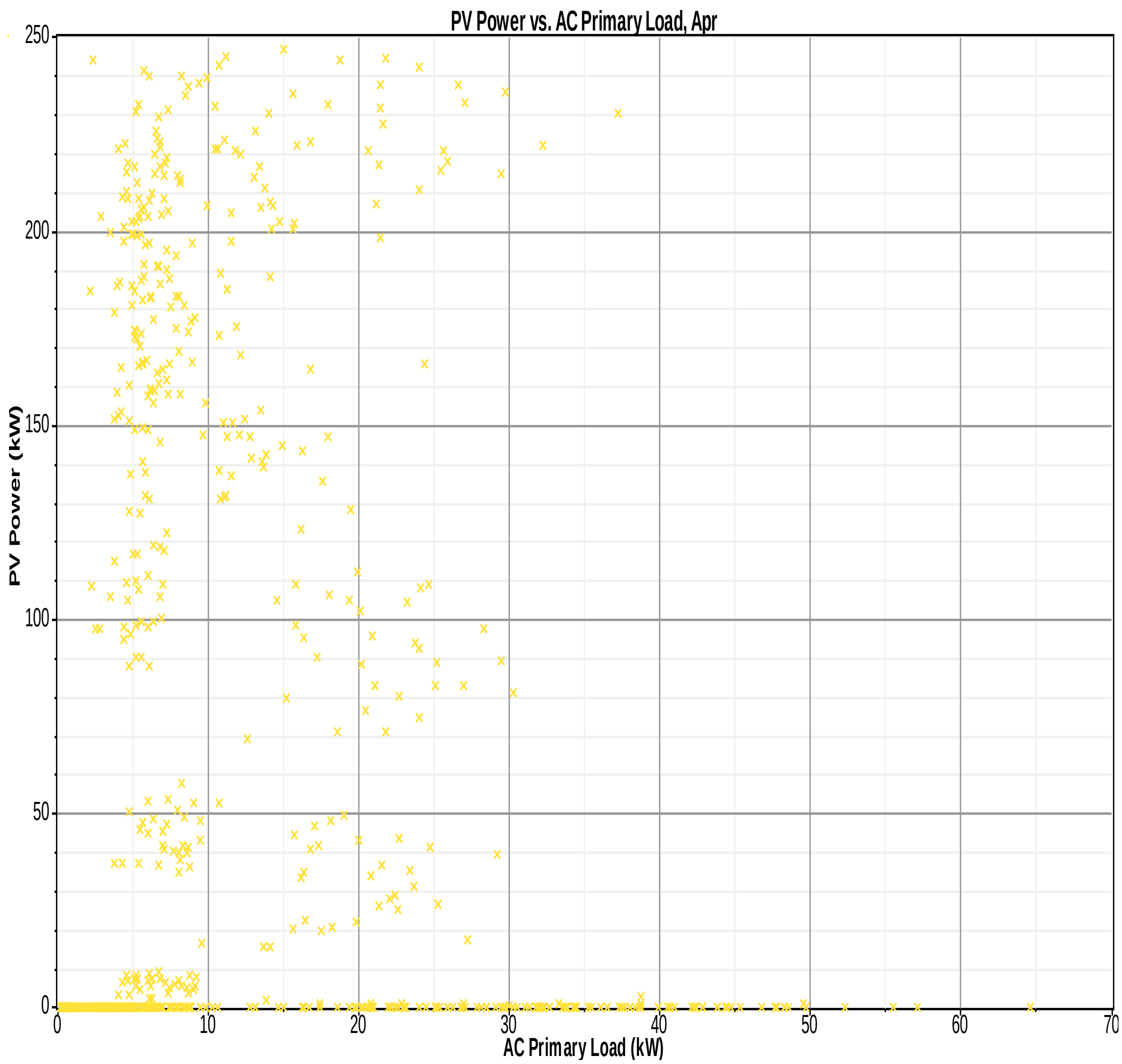



Figure 4. 9: PV Array Capacities vs. AC Primary Load

## 4.2 Programmable Logic Control System Results

Based on the above Table 3.12 Source control (switching) which type source at what time (solar, diesel generator and battery) supplies to get continuous and reliable operation at economic level given depicts energy management system using PLC as a reference of generation and demand was discussed as follows the result given below. A system has more than two sources it is necessary to have an energy management system which is expected to optimize the power sharing among resources, the cost production and emission.

The PLC SIMATIC manager control makes decision on the output based on the operating state of the input variables. The results of PLC SIMATIC were as network 1 for household loads, commercial loads, community loads and deferrable loads given in parallel as follows.

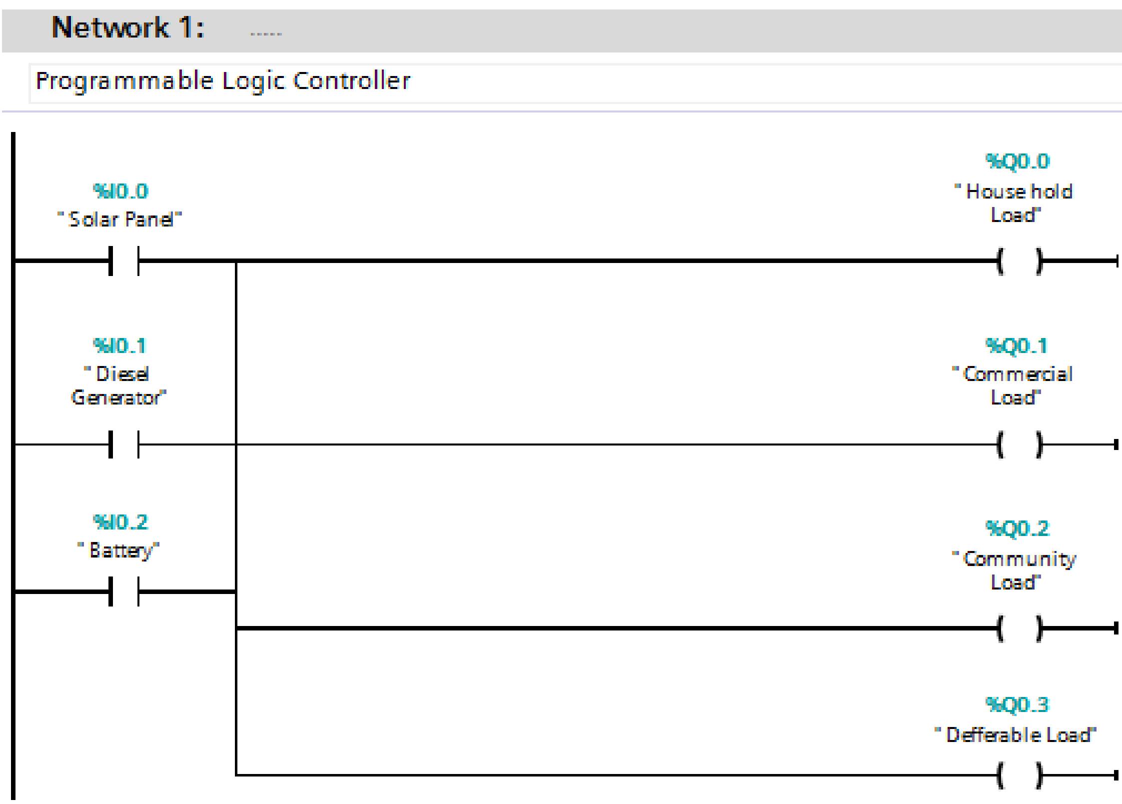



Figure 4. 10: Hybrid System Energy Management Model Using PLC SIMATIC Manager

# CONCLUSIONS AND RECOMMENDATIONS (CHAPTER FIVE)

## 5.1 Conclusions

Hybrid PV/diesel Storage battery mini-grids appear to be one of the most promising technological options for electrifying remote and rural areas. The mini-grid utilizes a mix of renewables and diesel generator along with battery storage to reliably meet modest household, community service, commercial, and in some cases electrical loads. The hybrid PV/Diesel and battery configuration has several advantages: meeting the system load demand in the optimal way; minimizing diesel usage and maintenance; optimal use of renewables etc. The crucial objective of this thesis was to find a best techno-economic of a mini-grid power system to supply a rural area in **Albasa Village** with energy management system. In the design of solar PV/Diesel Generator and battery bank for **Albasa village**, the thesis arrived at 5.013 $kWh/m^2/day$ average daily solar radiation and Diesel Generator/Storage battery backup for a household with a total number of 1110 households and the total average energy demand was about 279kWh/day with maximum load of 67kW. Mini-grid renewable energy-based power systems cannot provide a continuous supply of electricity without a storage medium. Consequently, storage battery banks were added to the hybrid system. After selecting the appropriate components and studied their characteristics, the hybrid system has been modeled in HOMER, PLC software and simulations have been made to determine the best system which can supply the village load with the required level of availability. The usefulness cost of all hybrid structure that can fulfill the continuous load demand has been calculated to determine the system which provides the lowest cost.

A solar PV/Diesel Generator/battery bank and converter hybrid system has been found as the optimum system with mean power output of 25kw, 14kw, 80 S4KS25P batteries and 85kw converter respectively.

As a final Conclusion, respective governments should get involved in providing financial support for procurement and installation of PV system, make it a popular choice and propagate this energy solution.

## 5.2 Recommendation

Furthermore, investigations need to be carried out to modify this thesis work the following recommendations are given by the author of this thesis. This thesis was deal to solve the electricity problem in the Albasa village found in Metekel zone/Benshangul Gumuz region, Ethiopia. Other may work optimize to this system for rural electrification as well by integrated with micro hydro power and also extend the electrification to another area which were detached from the main grid.

A major hindrance to use of renewable hybrid energy systems were high initial capital cost. So, the governmental and non-governmental organizations should subside to motivate and increase the interest of the community to use electricity.

The implementation of hybrid solar PV/Diesel Generator/storage battery bank systems in residential, non-governmental and governmental institutions and also commercial areas across Ethiopia would reduce unexpected power interruption, high power loss and blackouts on the national power grid.

As far as the environmental aspects are concerned, these kind of renewable hybrid systems have to be wide spread in order to cover the energy demands of rural areas and used to apply green energy policy, by reducing the greenhouse gases emission and environmental pollution were an important point taken to account.

## 5.3 Future Works

Since the issue of alternative energy source is worldwide and hot issue; a special attention was given to researches related to these areas since last few decades. In related with global

warming, an environmental friendly energy source is highly needed.

There are opportunities to further carry on this thesis in different directions. The future prospect of this thesis work is as follows:

1. This system can be a model for other remote areas of not only Albasa but also rest of the national area.
2. Other renewable resources such as Solar PV energy, Biomass/Biogas, Wind energy, Hydro energy, Geo-thermal energy, etc. can be added to the system.
3. Besides, it can also be implemented and then compared with the simulation results.

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# APPENDICES

## APPENDIX 1. Ethiopia's Solar PV Capacity

Over the past five years, Ethiopia's solar PV capacity has almost tripled. However, despite the abundant solar resources in the country, as of now, only 14 MW has been installed, representing 0.3% of the country's total energy capacity. Still, it was the only growing category of renewables year-on-year from 2016-2017, when compared to the stagnated growth of wind and hydro energy applications. Solar capacity in Ethiopia is expected to soar in the near future with several large scale projects under development.

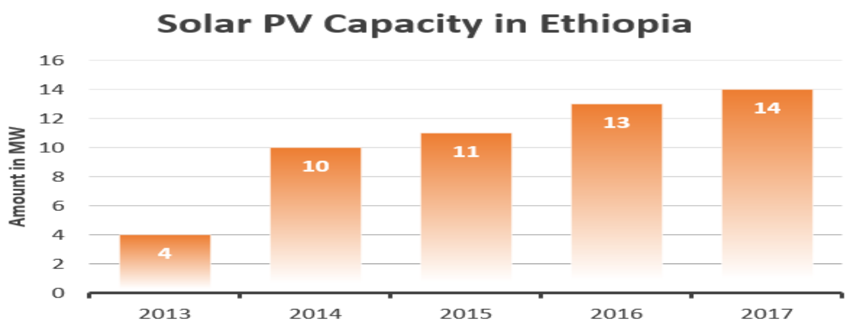



Figure 1A. 1: Ethiopia's PV Capacity 2013-2017 (2-4 July 2019 in Addis Ababa, solar future.com).

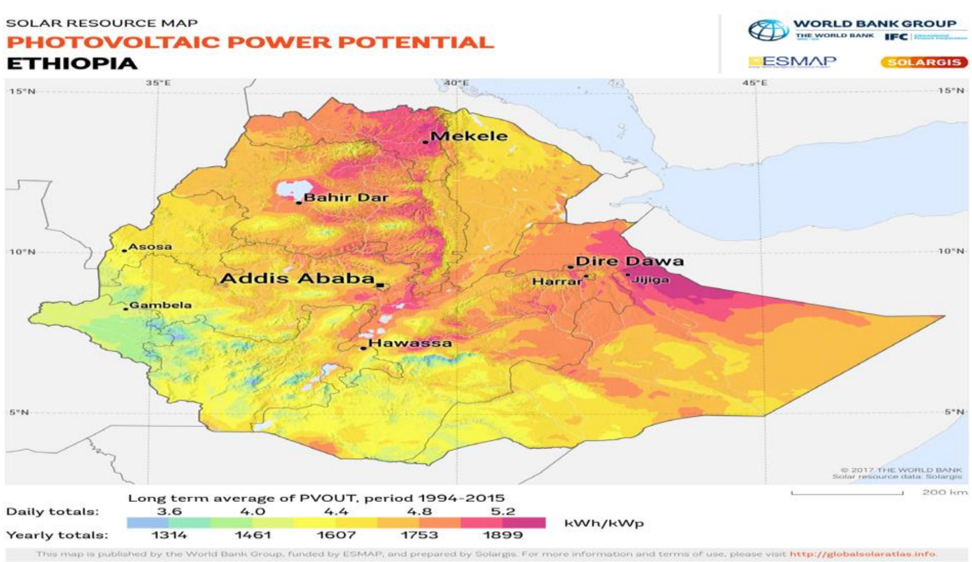
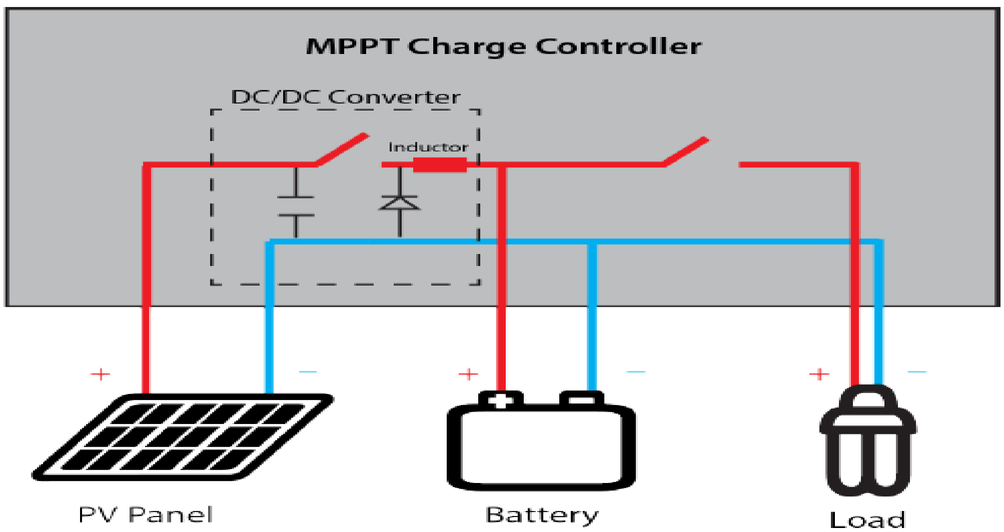



Figure 1A. 2: Solar PV Power Potential Ethiopia (2-4 July 2019 in Ababa, solar future.com)

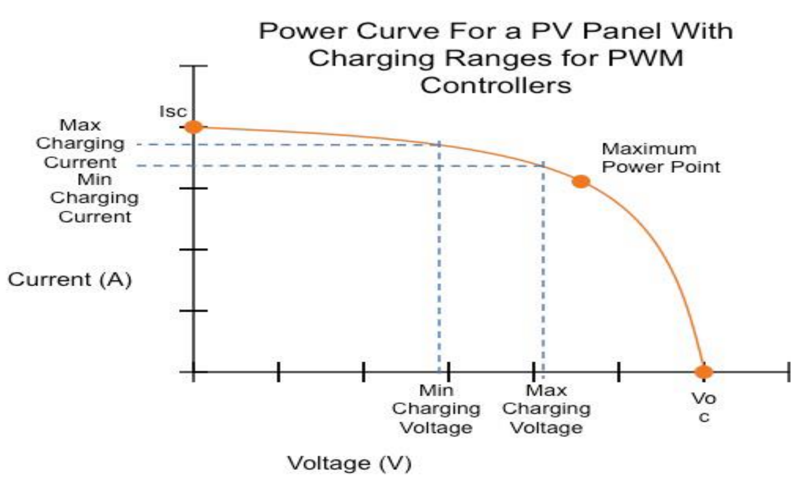
# APPENDIX 2. MPPT Charge Controllers

## 1. MPPT Charge Controllers

Maximum Power Point Tracking features an indirect connection between the PV array and the battery bank. The indirect connection includes a DC/DC voltage converter that can take excess PV voltage and convert it into extra current at a lower voltage without losing power.




MPPT controllers do this via an adaptive algorithm that follows the maximum power point of the PV array and then adjusts the incoming voltage to maintain the most efficient amount of power for the system.



# APPENDIX 3. PLC Input and Output HardWare Device

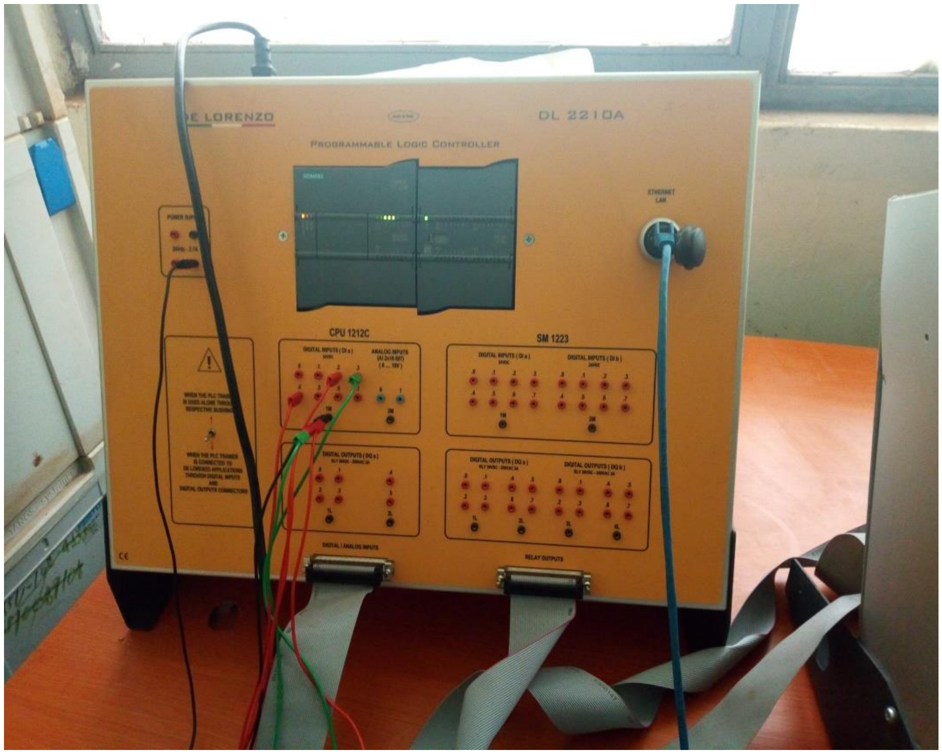



Figure 3A.1: Input Device of the PLC (Assosa Univercity Laboratory)

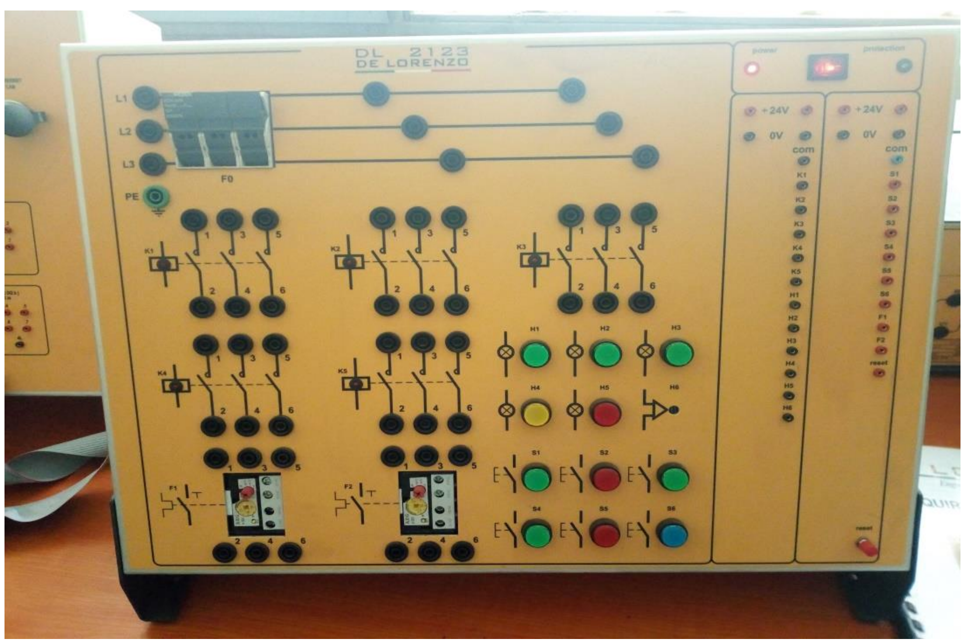



Figure 3A.2: Input Device of the PLC (Assosa Univercity Laboratory)

Figure 3A.3: Integrated Input and Output Device (Assosa Univercity Laboratory)

# APPENDIX 4. Other Thesis Results Obtained From the HOMER Simulations

The results of the designed output of a **PV/Diesel Generator/Storage battery** hybrid power system is presented

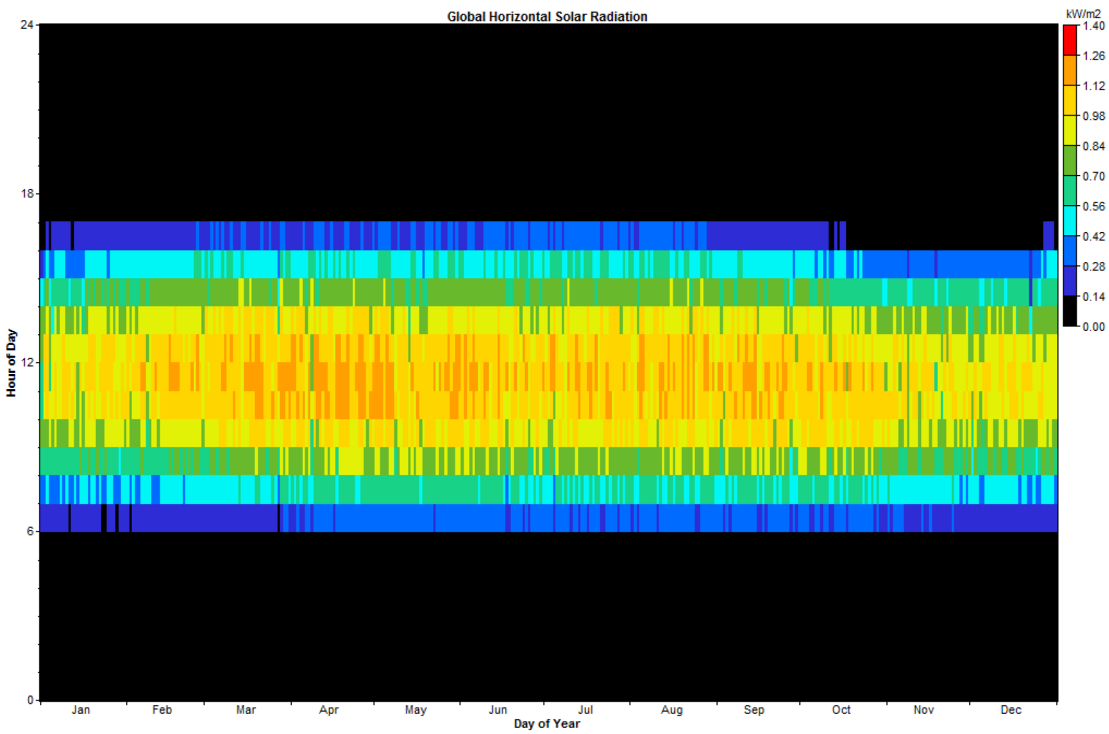



Figure 4A.1: Global Horizontal Solar Radiation

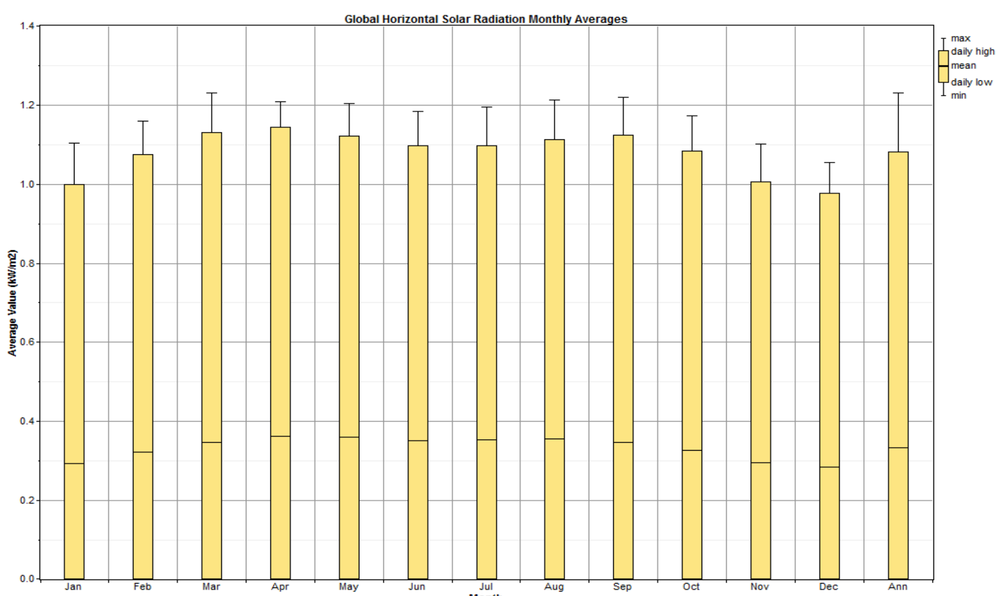



Figure 4A.2: Global Horizontal Solar Radiation Monthly Averages

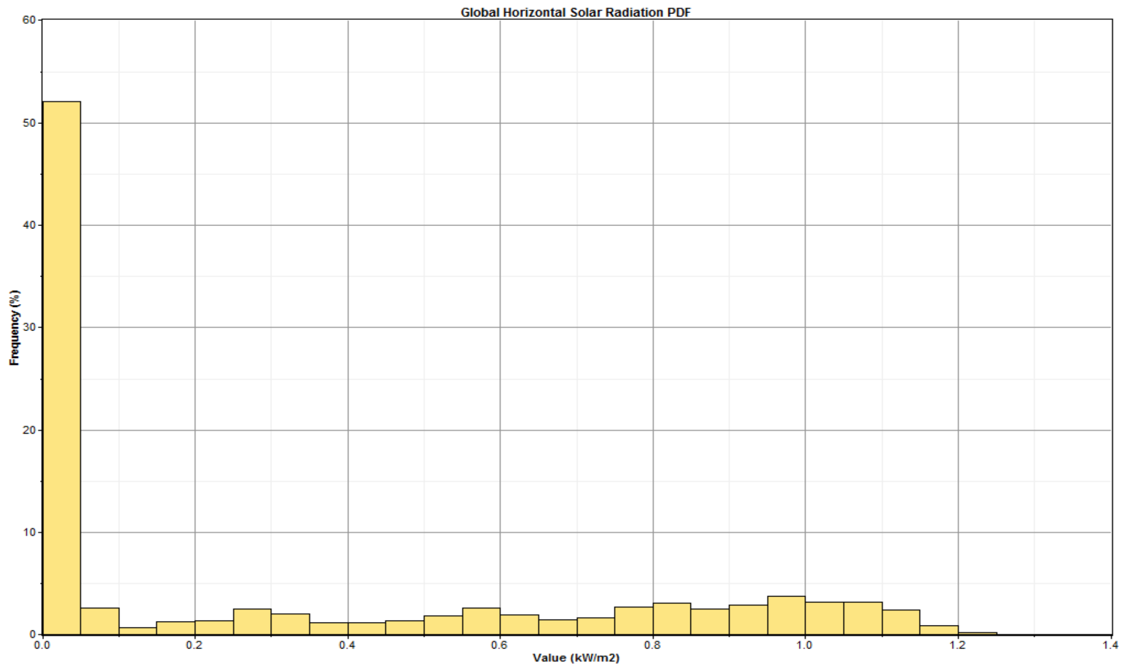



Figure 4A.3: Global Horizontal Solar Radiation PDF

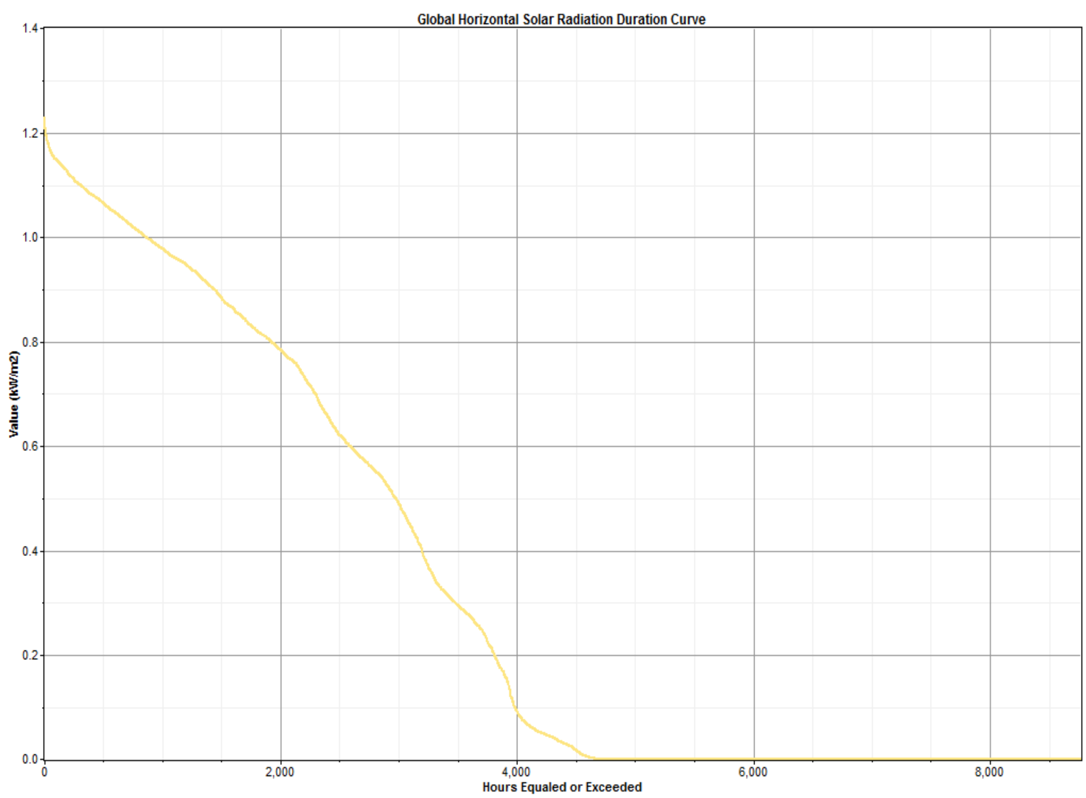



Figure 4A.4: Global Horizontal Solar Radiation Duration Curve

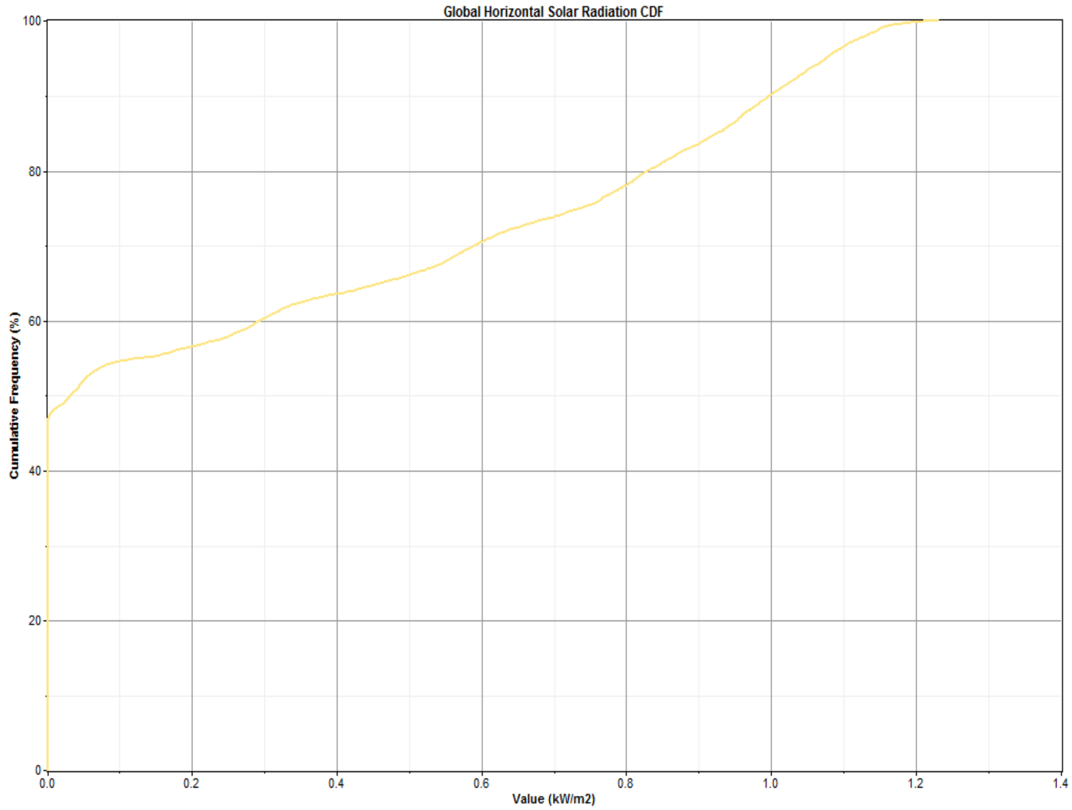



Figure 4A.5: Global Horizontal Solar Radiation CDF

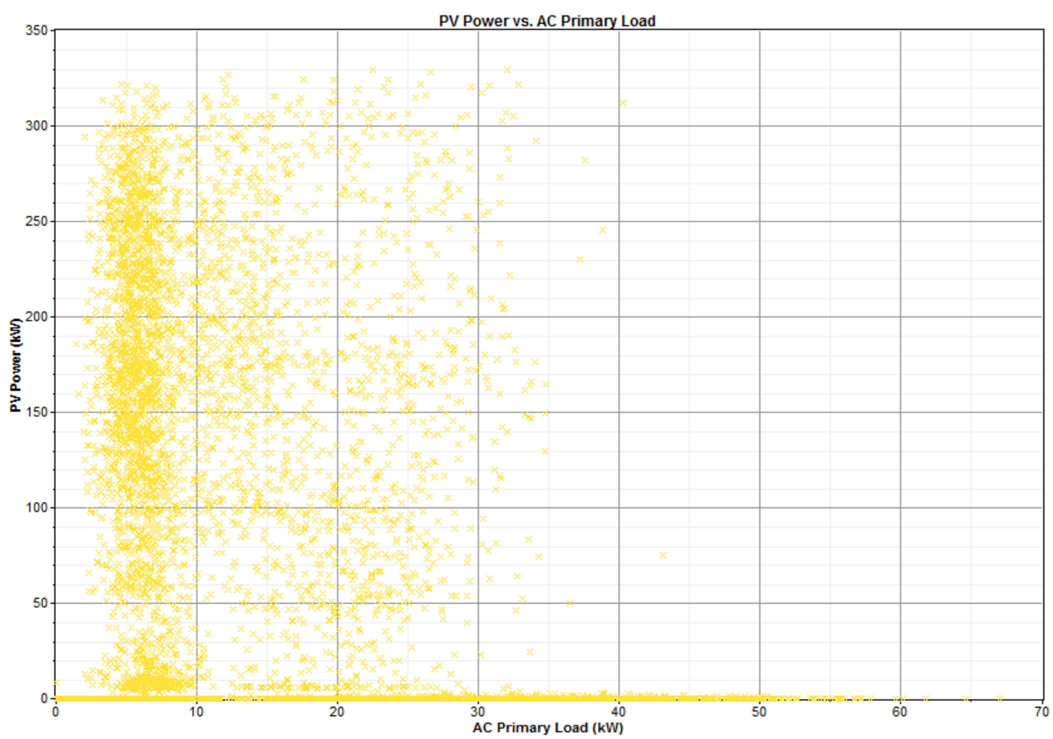



Figure 4A.6: PV Power vs.AC primary Load