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Design of Photovoltaic System for Rural Electrification in Rwanda

by

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Abstract

In this century of accelerated development in various domains, some African countries are still facing a challenge of lack of power due to its scarce in some places, where by the main source of power (generation of electricity) is hydro since thermal and fuel are still on a small scale. This problem results in less productivity and economic decline of some countries like Rwanda which is among African countries that are at a very high speed in development, the grid lines from distant places are stack and they are few compared to the need of electricity in all corners of the country, especially in rural areas whereby each household needs power usage instead of using local and traditional means of ironing and lighting at home. This issue can be solved using other alternative sources of Renewable Energy for rural electrification such as Photovoltaic systems. Therefore, this master's thesis project is mainly focusing on the design of off-grid Photovoltaic systems that include an economic evaluation between the use of an individual solar home system of 200W and a village PV system of 10kW so that the satisfactory of people and the targets of the country can be easily achieved. Under this Master's thesis work, the first part is focused on the analysis of electricity consumption based on single house owning individual solar home systems taking a case study of one village in Rwanda called Kanazi located in Eastern Province, Bugesera District, Nyamata Sector. This analysis is done through the evaluation of the average primary load profile in consecutive number of hours per day depending on the PV production capacity.

The purpose of this analysis is to obtain the optimum sizing of the PV panel as well as the battery capacity that can be used for providing electricity to households. The second step is to design a village PV system with a big battery and inverter that can generate electricity for the selected village depending on the estimated the average daily load profile for a typical single house in Kanazi village. Finally, both proposed and designed systems will be compared to obtain a system that is more reliable and economical for electricity production. In this project the design and simulation tasks will be performed through the help of Homer software and Excel Software. The information about the average monthly solar radiation on the selected site and the characteristics of PV system components will be provided by different internet websites, PVGIS (Photovoltaic Geographical Information System) for Africa, different books, scientific research papers, journals and the field survey that have been conducted.

Keywords: *Rural electrification, Renewable Energy, Off-grid PV Systems, Grid lines, solar home systems, mini-grid systems and Homer software.*

Dedication

To my beloved Son **Prince Daniel IGANZE**

Acknowledgements

First and foremost, I would like to give thanks to the Almighty God who has walked with me throughout this journey and before. Without the constant guidance and protection of the Lord, this work would barely be a dream.

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List of Abbreviations

EDPRS	Economic Development and Poverty Reduction Strategy
EICV3	Third Integrated Household Living Conditions Survey
HOMER	Hybrid Optimization Model for Electric Renewables
ESMAP	Energy Sector Management Assistance Program
PVGIS	Photovoltaic Geographical Information System
IRENA	International Renewable Energy Agency
NREL	National Renewable Energy Laboratory
NGOs	Non-Governmental Organizations
MPPT	Maximum Power Point Tracker
IED	Innovation Energy Development
DDP	District Development Plan
SHS	Solar Home System
AC	Alternating Current
NPV	Net Present Value
NPC	Net Present Cost
DC	Direct Current
PV	Photovoltaic

1 Introduction

The application of renewable energies contributes to global warming prevention and as a matter of fact photovoltaic systems have been increasingly developed in recent years due to the global benefit of natural resources conservation. It is also evident that fossil fuel-based energy sources will be depleted over time since they are finite and consequently they have been proven to contribute to global climate change. To protect our environment and increase electricity access in remote areas, green and clean energy alternatives like solar energy, absorbed by photovoltaic systems can be of great importance.

1.1 Background and Motivation

In Rwanda, there is a serious problem of electricity access especially in rural areas, this is very crucial in affecting sustainable development of the country. The current situation shows that the grid connected is estimated to be around 23%, whereby rural villages that are connected to the national grid accounts for only 5% and in addition, statistics shows that 85% of Rwandan population live in rural areas while only 15% accounts for urban citizens. [1] [2]

The most common activity observed in these areas is farming for food provision and other life basic needs security. For the case of Rwanda with many population in rural areas, there is a challenge of energy extension and development in other economic sectors.

The topology of the electric grid in Rwanda is another important aspect. There is presently insufficient electrical power to compensate for electricity demand in Rwanda, most of the power produced from different power plants is distributed to urban areas and business centers. The power supply is done using single lines because the transmission network is very radial in nature. Grid extension is affected by economic constraints such as high cost of electricity that is not affordable for rural consumers as well as geographical conditions, and therefore, it's hard for poor people living in far distances from grid lines to get power.

In fact, there is a lack of alternate paths for electricity in transmission network and notably the power service related to rural areas and this has a negative impact of pushing village residents to move in cities. This vulnerability of rural areas is the major purpose of this thesis work for providing the more reliable and typical solution for rural electrification in Rwanda.

1.2 Problem Statement

Electrical power access plays the vital role in accelerating economic development by improving health and life standards. Significant investments have been made in energy sector to improve electricity access in households and more efforts need to be made by Rwandan government in collaboration with private sectors to meet the sets target of electrifying 70% of households by 2017/18 and 100% by 2020. [1]

For the above targets to be accomplished, a combination of various solutions that focus on the geographical location, income and consumption level is needed instead of using the traditional connection to the grid that may not be suitable for all rural households. Off grid PV systems can be proposed as a sustainable solution to be implemented with a wide range of technologies from a basic solar home system that can produce electricity for the single house with a radio, mobile phone and four lamps to stand-alone systems that can generate high levels of electrical power that can be used by both the households and other business centers.

This approach can serve as an economical and reliable solution for increasing the rate of electricity access by the entire rural community as well as for the country in general [1]. In recognition of the above proposed solutions, the research had also proven that the long term annual average global irradiation in different districts is above 1700 kWh/m2. This shows how many locations of Rwanda are favorable candidates for application of PV solar systems [2].

In this regards, the solar home system and stand-alone system in Eastern Province, Bugesera District, specifically in Nyamata Sector, can bring expected positive benefits for households and public services since many villages in this site people do not have access to national electric grid line. This low accessibility is caused by high cost of transmission line per km which is around $15000 for low voltage and $30400 for medium voltage [1] [2]. Therefore, since the selected place is dry with high intensity of sun radiations, this makes the site more attractive for the use of PV systems for electricity generation and storage.

1.3 Goals and Objectives

The main goal of this project work is to show how a photovoltaic system can be used to solve the problem of electricity access in Kanazi, the village located in Nyamata sector of Bugesera District. Since electricity from the grid is not easily available in this village due to the high cost of transmission lines per km, photovoltaic technology such as solar home system and stand-alone solar systems are proposed in terms of cost and efficiency to generate electricity for households and public service applications. Due to climatic conditions, Nyamata sector receives abundant amounts of sunshine all year around. Since solar energy is available only during the day time, it is important to use it with energy storage device like battery to supply the load during night hours to build a self-sufficient system. These approaches will compensate for electricity demand hence contributing to sustainable and economic development of the country.

The following objectives should be accomplished to achieve the desired goal:

- Analysis of monthly solar irradiation within Nyamata sector in bugesera district of the eastern province of Rwanda.
- Estimation of average daily load profile at the selected site.
- Proposing a basic solar home system layout and stand-alone system configuration.
- Component selection and cost analysis.
- Systems modelling and simulation by using HOMER software.
- Performance evaluation of optimal photovoltaic system.
- Cost comparison between the chosen system and the existing Solar home systems.

1.4 Research Methods

This project work is mainly summarized in several steps and procedures combined with the data collection process based on renewable energy resources. These include the knowledge of village load profile, a clear understanding of photovoltaic system configurations, study of component behavior as well as cost, modelling and simulation of the solar home system as well as the stand-alone solar system, selection of optimum system referring to the simulation results and performance analysis between the proposed individual solar home system and the stand-alone system for the village.

Basically, the preliminary step was the determination of daily load profile for the selected village. Due to the equatorial location of Rwanda, there are no specified season for winter or summer. Therefore, the case of load profile variations caused by change of season is not considered. In fact, the knowledge of the average daily load profile for a typical single house in Kanazi village was obtained through the self-performed field survey during summer holidays, since my family is in the selected site it was easy for me to get important data from many villages.

Furthermore, the data obtained from grid connected rural villages will enable me to do the design for the selected site that do not have access to electricity from the grid. In addition, various parameters such as, family classes based on the number of equipment, the number of households and public services will be considered. Nevertheless, a reasonable assumption can be useful for estimation of the load curve in case of unavailability of specific data for the selected site.

Finally, Homer software will be used for design, modeling and simulation of the entire system to get and analyze the possible profitable solutions.

1.5 Key Assumptions and Limitations

The scope of this project work is limited to the determination of optimal photovoltaic system to generate electricity for rural areas. In addition, a performance evaluation of the system has been done by taking into consideration the following assumptions.

- The important information on the irradiance at the selected site were derived by PVGIS for Africa and the data from this site are helpful for providing the solar resources input to be used for modelling and simulation of solar PV systems
- The Annual solar resources input and the primary load profiles are assumed to remain constant throughout the project lifetime.
- This project life time was estimated based on the guarantee of PV panels which is mentioned to be around 25 years.
- The daily load cycles for consumers were also assumed to be the same because the temperature variations at the selected site are approximately fixed because summer and winter seasons are not distinct.

The final designed system has the following limitations.

- The issues of PV system stability and control will not be included in this research project.
- Design of Rwanda electric grid will not be part of this project work.
- Only Homer software will be used for modelling and simulation of the entire system.

1.6 Outline

This project details the design and simulation of a photovoltaic system in Rwanda for increasing electricity access in rural areas especially focusing in one selected village named Kanazi, located in eastern province, bugesera district, Nyamata sector. Therefore, the work is organized as follows.

Chapter 2 provides a brief literature review about Rwanda, focusing on solar resources, rural electrification strategic plan in general and the application of photovoltaic systems for electricity generation by going into details of different PV system types and their functionalities as well as homer software description.

Chapter 3 shows different data collected in the selected site with a clear presentation of the average daily load profile for a typical single house in Kanazi village selected for case study and available natural resources within the boundaries of the chosen district.

Having the knowledge of both the proposed system sizes to be modelled and site location of the selected village, Chapter 4 will be concerned with the overview of the major components used by a basic solar home system and isolated mini-grid village system technologies. It illustrates the important characteristics of the system components such as electrical characteristics, operation and cost implications.

Chapter 5 describes different designs of a basic solar home system as well as a stand-alone village system. Various components that compose both mentioned systems will be modelled. In this chapter, the behavior and cost estimation of different components that compose a typical PV system are explored and Homer software is used for modelling the entire system.

Chapter 6 illustrates the results obtained from the simulation of both types of PV systems and Chapter 7 discusses about different results obtained for achieving the least cost feasible options.

Chapter 8 summarizes the conclusions from this research project, and gives suggestions for better future work. Finally, a list of bibliography used, appendices of excel sheets and field survey as well as PVGIS data are shown at the end of the project report.

2 Literature Review

Renewable energy which include solar energy insures a clean energy supply and it has been considered to play an important role of global warming prevention by fighting against climate change [3]. Solar Energy is mainly generated depending on the intensity of the sun rays reaching the solar panel and their wavelengths. [4] Electrification by different solar technologies had been deployed in Rwanda since 1980's mainly through support from donors and Non-Governmental Organizations (NGOs) and a study conducted by ESMAP (Energy Sector Management Assistance Program)/World Bank project in 1991 provided an assessment of the market at that time. [5]

The use of solar energy for electricity generation is a non-consumptive use of a natural resource and consumes no fuel for continuing operation since renewable energy is a clean source of energy with the potential to contribute greatly to a more ecologically, socially, and economically sustainable future. Nevertheless, the major challenge in solar power plant is to maximize the wavelength of sun rays and minimize the effect of temperature on solar cells. [4] Solar energy can be made more economical by reducing investment and operating costs and by increasing solar plant performance and the most significant cost reductions are likely to come from innovations in solar field design, which could bring down the Levelized cost of energy (LCOE) by 15% to 28%, depending on the technology. [6]

Furthermore, renewables in combination with batteries allow stand-alone operations and batteries are now a standard component of solar PV lighting systems and solar home systems. The impact of off-grid renewable energy systems will not only be measured in terms of their usage or reduced costs for electricity consumption in rural areas, but also in the context of their effect on the lives of some 1.16 billion people who today are totally without access to electricity. [7]

Regardless of ambitious electrification programs established by the Rwandan government, more than 1 million households will likely still require off-grid electricity by 2020 and Survey results show that average off-grid household energy expenditures in Rwanda are around RWF 500 or US$0.80 per week. [5]

2.1 Integrated Renewable Energies in Rwanda

Rwanda has a range of indigenous resources that complement each other in the energy mix, and the government has a plan of utilizing these to reach its target of increasing total capacity by 80% in the year 2017.This will help to diversify away from fossil fuels due to the related high cost of generation [8]. The following section outlines various physical potential of existing renewable energy resources.

2.1.1 Hydro Power generation

Different Studies prove that Rwanda has significant potential for hydropower generation since Rwanda's topography is most suitable for medium to high head pico and micro hydro run-of-river schemes [9]. The country possesses many rivers and streams which are not yet exploited but there are 333 potential sites discovered across many locations and additional viable sites have already been, and are likely to continue to be identified.

While current installed capacity stands at 59 MW, the government estimates untapped overall technical hydropower potential of over 300 MW which varies according to different studies made at different times [9] [8]. The Rwanda Hydropower Atlas conducted by the Rwanda Ministry of Infrastructure in 2009, found that many potentially feasible sites would be rated between 50 kW and 1 MW in potential capacity. [8] In Rwanda, there are 333 possible sites identified for micro hydropower generation and these sites are located along the major rivers flowing south from Mount Karisimbi in the north of the country, and along the Ruzizi River towards Lake Kivu in the west. Larger projects are already under development in cooperation with Rwanda's neighbors.

The study estimated a potential of 96 MW for the category of micro-hydro projects.12 An assessment of the energy sector undertaken by the African Development Bank in 2013 estimated Rwanda's domestic hydropower potential at 313 MW, broken down into 130 MW of domestic and 183 MW of regional hydro resources. Feasibility studies have been completed or are under way for many of the sites, representing at least 32 MW of technically viable new capacity. [9] In addition, over 192 potential Pico hydro sites (with potential capacity of less than 50 kW) have been identified and Feasibility studies and assessments are being carried out on an ongoing basis, with the result that the amount of technically viable new capacity seems to increase constantly. [8]

Evidently, it would be valuable to have a more detailed resource mapping for the hydropower sector, especially taking a spatial river basin approach before giving priority to specific sites for development. This approach was adopted by an on-going comprehensive assessment of hydro resources on the Akanyaru River basin, located on the border between Rwanda and Burundi. These resources can be developed in cascade form, with 11 domestic sites and 3 shared sites recommended for further feasibility analysis. Based on preliminary assumptions, these projects could potentially increase Rwanda's total installed capacity by over 25 MW [9].

2.1.2 Geothermal energy resources

Rwanda may have geothermal potential which is manifested in the form of hot springs. Potential geothermal resources have been categorized into four main prospect areas, all within the belt along Lake Kivu: Karisimbi, Kinigi, Gisenyi and Bugarama. The potential of geothermal energy is still uncertain. Exploration studies have estimated the potential for commercial power generation to be in the range of 170 to 340 MW [8]. Given the complexity involved in determining the commercial viability of geothermal power, however, much more detailed exploration studies and sub-surface drilling are required [9]. Two preliminary drilling projects have not provided proof of this potential, but as geothermal exploration is a relatively long-term process, more studies are needed to assess and confirm potential.

2.1.3 Wind power

Being located close to the equator, Rwanda's inherent resource potential for wind energy is low. Wind power potential was evaluated in a rapid wind energy resource assessment carried out in five locations in Rwanda over the course of 2011. [8] As results, the preliminary indications from the analysis of recorded field measurements of wind speeds and climate data were that most of Rwanda is not highly suitable for wind energy. The Eastern province was identified as the location with the most promising potential, and a simple analysis comparing wind and solar energy feasibility suggested that wind energy could be competitive in this region. [9] However, more feasibility studies and assessments are needed for this to be precisely determined. Another academic study using modelling analyses based on recorded wind measurements and power density at selected Rwandan meteorological stations noted that electricity production around Gisenyi station could be possible with a good mean value of both wind speed and power density, whereas in areas such as Kigali, Butare and Kamembe, wind energy potential is only sufficient for windmills or water pumping for agricultural and intuitional needs [8]. More detailed resource assessments and feasibility studies are required to determine commercially viable wind energy potential in Rwanda.

2.1.4 Methane Gas

Much of the country's methane gas resources stem from the globally unique geology of Lake Kivu and the naturally regenerating methane gas that is found there. Some 1000 studies have been carried out, the consensus of which is that Lake Kivu is estimated to contain around 55 billion cubic metres of methane gas, with a further 150 to 250 million cubic metres of methane being generated annually [9] .In recent years, Government has put great efforts on proving the technical and commercial viability of safely extracting methane from Lake Kivu to produce power. Indeed, the more methane gas that is extracted, the safer are riparian communities, as there will be less methane gas that could potentially explode in case of a sub-surface volcanic eruption. According to feasibility studies undertaken [by EWSA], it is possible to sustainably extract sufficient gas to generate around 700MW of power [9]. This would put the national potential at 350MW, as the resources are shared equally by Rwanda and DRC through an international agreement.

A small pilot plant, owned and operated by Kibuye Power (KP I), and having an installed capacity of 3.6MW, has been operational for some time [9]. The expected commissioning of the 25MW KivuWatt power plant in late 2014 will go a long way, however, toward corroborating the commercial feasibility of Lake Kivu methane gas as resource for large-scale power generation. In addition to Lake Kivu, Rwanda also possesses inherent methane resources that can be extracted from underground mining seams. Methane gas has a variety of commercial and industrial uses, beyond the production of electricity, although it is currently anticipated that the primary end-use of the resource will be for electricity. Feasibility studies for direct use of methane gas in heating applications, fertilizer, and petrochemical production have already been conducted and more are to be expected with a lower risk of extraction of the resource [9].

2.1.5 Peat to power

Currently peat is used as an input in cottage industries, cement production, and as a cooking fuel in a small number of decentralized institutions. Rwanda has estimated reserves of 155 million tons of dry peat14 spread over about 50,000 hectares in Akanyaru, Nyabarongo, Rwabusoro and other areas [9]. Approximately one-third of this resource is currently commercially extractable for industrial heat or electric power production. These estimates are largely based upon a 'high level' master plan undertaken in 1993, with only a small number of samples having been taken and most work being carried out as desk research. In late 2013 and early 2014, REG undertook more detailed resource assessments to complement and refine the existing peat master plan.

Parallel to this, several projects have independently developed feasibility studies based on resource potentials identified in specific locations. However, it is important that at the national level Rwanda has an accurate assessment of its resources to determine how to use them most efficiently and sustainably, as peat energy is not generally considered to be renewable. In addition, some peat resources are located in environmentally sensitive habitats [9].

2.1.6 Biogas power

Biogas can be generated from a variety of biomass resources, including agricultural, human, and municipal waste. The national resource potential for these alternative sources of methane or biogas has never been systematically estimated through surveys or extensive resource assessments. Pre-feasibility studies have been conducted for a landfill gas-to-electricity project in Kigali, however, which suggested that commercial plant could be feasible in the near-term future given higher population growth and volumes of waste collected and more systematic separation of waste streams [9].

2.1.7 Solar energy

Rwanda's solar radiation and solar resources were assessed by the U.S. National Air and Space Agency (NASA) as well as the University of Rwanda. Rwanda's Eastern Province has the greatest potential for generating energy from solar resources. Another academic assessment, undertaken in partnership with the MININFRA Department of Meteorology in 2007, used a meteorological data set to estimate monthly averaged global solar radiation [9]. Rwanda's daily solar irradiation ranges from 4 kWh/m² north of the city of Ruhengeri to 5.4 kWh/m² south of the capital, Kigali, in the Southern and Eastern provinces. However, conditions vary from season to season, with average daily irradiation levels in the cloudy reaching about 4.5 kWh/m² and the total annual potential is estimated to be around 66.8 TWh [9].

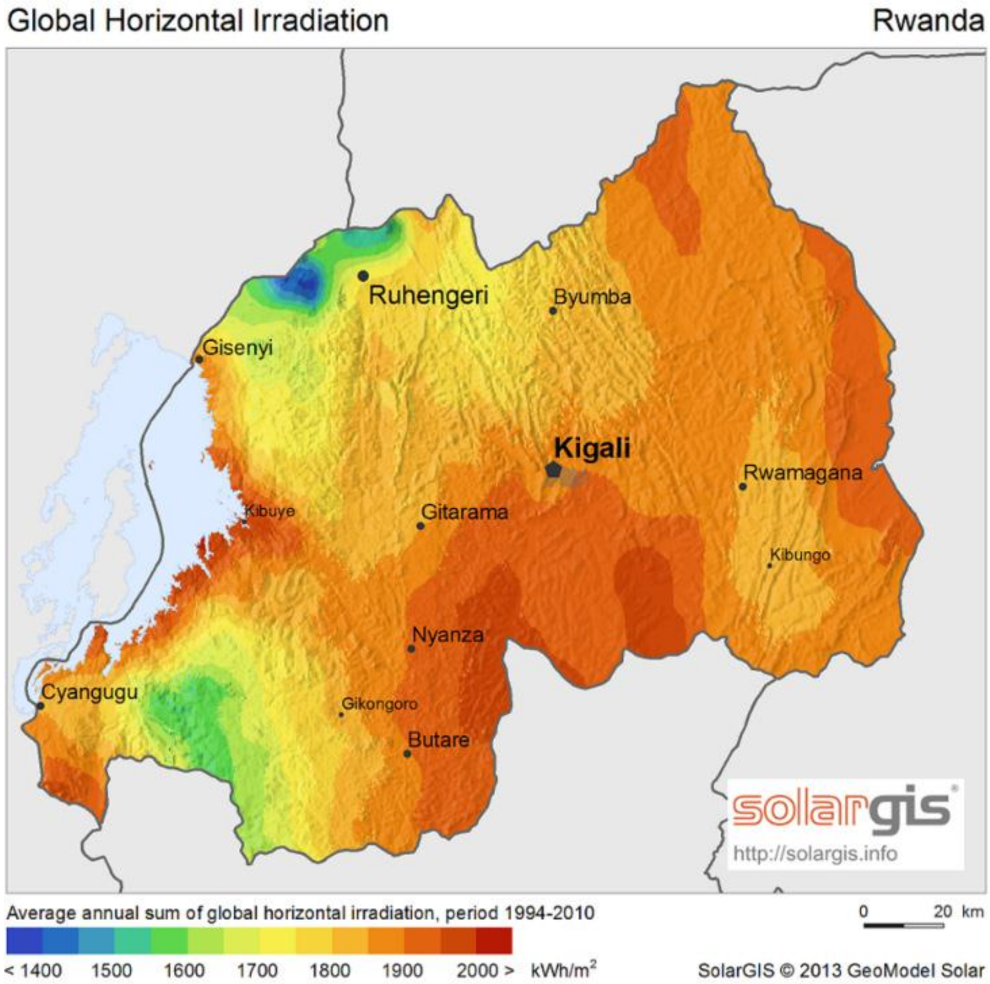


Fig. 2.1: Global horizontal irradiation map for different districts of Rwanda [17].

Rwanda is well benefited with solar energy, even during the months of the rainy seasons there is daily and sufficient sunshine especially in the Eastern province which is known for high irradiance values as it is indicated on the above Figure 2.1, the average daily global solar irradiation on the tilted surface has been estimated to be 5.2 kWh per m2 per day from Photovoltaic Geography Information System (PVGIS) [9]. The long-term monthly average daily global irradiation range from 4.8 kWh/ (m2 day) (location Burera, month of May) of to 5.8 kWh/ (m2 day) (location Nyanza, month of July) which indicates a good potential for solar energy development [9].

2.2 Basic operation mechanism of the photovoltaic cell

The use of PV Systems is the most effective and easy way to harness the solar energy within the building environment [10]. PV facility uses semiconductors (PV cells) which absorb solar energy to produce electricity through the photovoltaic effect. This physical process is a result of the fact that some materials (i.e. silicon) produce electric current when exposed to light. Sunlight is composed of photons or packets of energy and when these photons strike a PV cell they may be reflected or absorbed or they may pass light through. When a photon is absorbed, its energy is transferred to an electron in an atom of the semiconductor. Thereafter, the electron can escape from its normal position associated with that atom to become part of the current in an electrical circuit.

Special electrical properties of the solar cell provide the voltage needed to drive the current through an external load. The electrical efficiency of the solar cell is obtained by firstly determining the power generated by the cell at its maximum power point and the PV efficiency (η) is determined as the fraction between the maximum power which a solar cell can convert from absorbed light to electricity (P_{max}) and the incident power (P_{in}) as shown in the equations below [10] [11].

$$P_{max} = I_{mp} \times V_{mp} \tag{2.1}$$

$$\eta = \frac{P_{max}}{P_{in}} \tag{2.2}$$

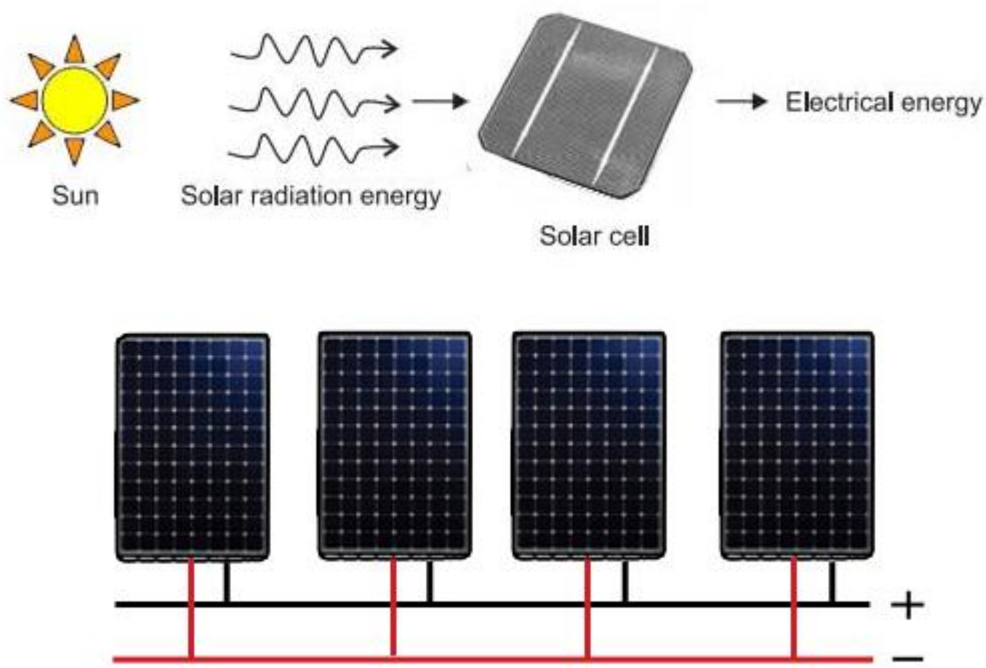


Fig. 2.2: Basic operation mechanism of the solar photovoltaic cell [12].

2.3 Solar Home Systems

Solar Home Systems(SHS) are systems bigger than 15W that are sometimes sold as plug-and-play systems, but more commonly as separate components, which need to be installed by a technician [5]. Given the large size of these systems, proper estimation of the power demand, sizing of the system components and a professional installation and maintenance is important. That is, more consumer education is necessary to ensure proper use of the product. Also, after-sales support may be necessary if one of the components (e.g. the battery) breaks down [5].

Fig. 2.3: A typical Solar home system installation on the roof of a house in Nyamata. [13]

The basic solar home system is represented by the single line diagram shown in Figure 2.4below and this system is used for supplying electricity to residential consumers that use only DC loads such as light bulbs, radio and mobile phones and in this case, they are supplied by a DC bus of 12V since we have considered one battery for the single house analysis in Kanazi village.

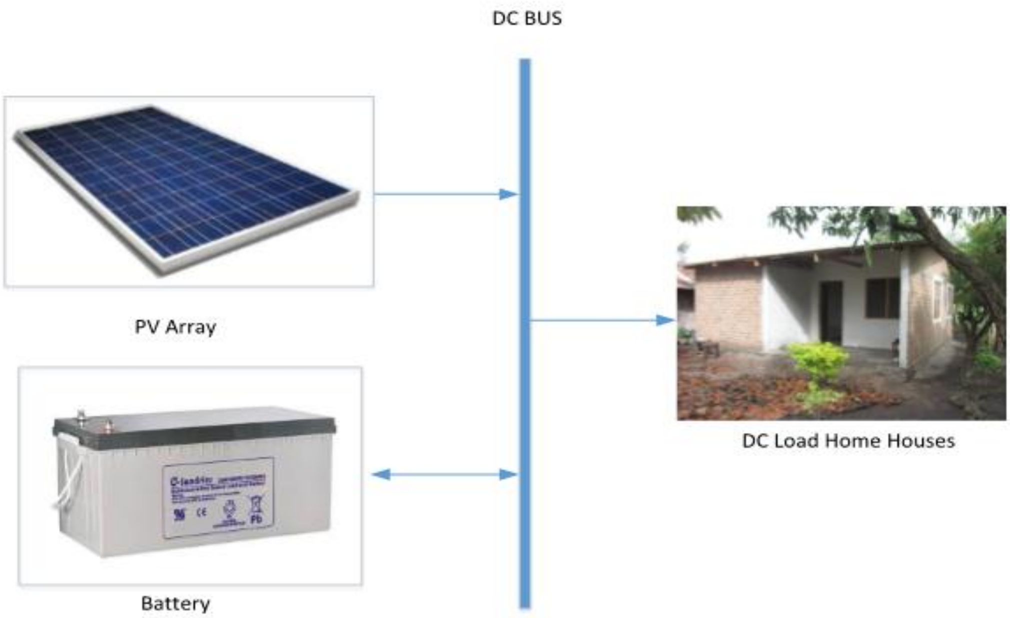


Fig. 2.4: Single line diagram of the basic Solar Home System in Kanazi village.

The Rwandan solar PV market is an early-stage market of small players that is poorly integrated into the global and regional solar energy industry. But the Rwandan Government is working with partners such as the European Union, the World Bank and the Belgium Government to install solar PV in public health centers, schools and government administration facilities in the rural areas. [14]

2.3.1 The Barefoot power pack of 5W micro-kit

This micro Solar Home System includes 4lights of 45 lumens each, powered by a 5W solar panel and stored in a 5Ah lead acid battery. This System will power 4 lights for 12 hours and can also charge a mobile phone or operate a radio.

Fig. 2.5: The Barefoot power pack of 5W micro-kit used for SHS applications. [5]

2.3.2 BBOXX17 of 50W Solar home system

This system presents a portable battery box of 17Ah that can store up to 200Wh of energy from a 50W solar panel. In addition to lighting and cell phone charging, these systems can power small electrical appliances such as a TV, larger ones also fridges, razors etc., in which case an inverter may be required where the appliance uses an AC current. [5]

Fig. 2.6: BBOXX17 of 50W Solar home system used for rural electrification purposes. [5]

In Rwanda, households are the main consumers of electricity with 51 percent where the larger portion of electricity is primarily used for lighting purposes whereas the industrial sector with

42 percent is the second largest consumer of electric energy, which mainly come from motor-drivers and lighting. [15]

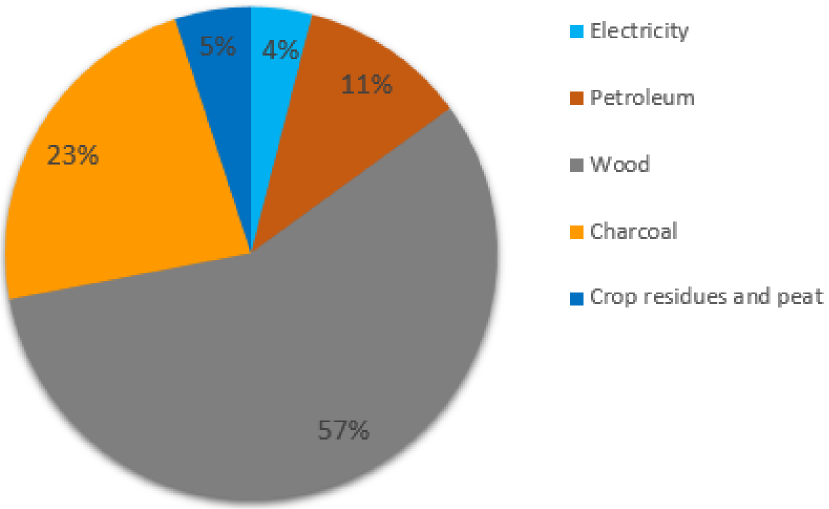


Fig. 2.7: Main Energy Sources in Rwanda [15].

As shown in the above figure 2.7 which indicates different percentages of total primary energy consumption in Rwanda, Biomass contributes 85% of primary energy consumed of which wood contributes a percentage of 57%, Charcoal 23%, Crop residues and peat of 5%. Non-Biomass sources contribution is 14% of which Petroleum products equal to 11% and electricity contribution is approximately 4% [15]. Using clean and renewable primary sources for power generation and reducing diesel-based generation over time along with grid loss minimization would enable the government to lower the long-term cost of service, to align Generation capacity and demand and to gradually allow maintained efficient tariff [15].

2.4 Mini-grid Systems

Mini-grids are small distribution systems isolated from the national power system which includes a source of power generation. This generation is usually provided by hydro or solar, often in conjunction with either battery storage or diesel generation to handle the intermittency of power output presented by renewables. It is likely that they could play a role in energy provision in Rwanda but, given the large investment costs (an EU study for Rwanda estimates around $1500 per connection – more than grid access), there are several pre-conditions that need to be met to make them viable. [1]

Increase access to electricity from 17% to at least 60% by 2020 and give access to all schools and hospitals by 2017 Reduce share of bioenergy in energy demand to 50% by 2020. Expand the transmission network by 2100 km by 2017. [16]

Distance from the grid: Where a connection is available to the national electricity network a mini-grid is unlikely to be financially viable, since the costs of power generation in a mini-grid are usually much higher. In deciding where to locate a mini-grid it must be determined whether this is the least-cost option for providing Tier 3 power to households and businesses. This will, in a large part, be determined by the proximity of the grid. [1]

Demand: Given the large fixed costs of a mini-grid in both the network and the generation technology, there needs to be a demand that is both high, and spread across the day for it to be viable. Most households consume power during the evening but for a mini-grid based on solar or hydro to be viable it is likely that there would need to be a large demand during the day too [1].

The government of Rwanda has pledged to set up 100 solar PV mini-grids in rural areas as part of an effort to mitigate the effects of climate change. Since Rwanda is a country that is very heavily affected by climate change, the country is taking extensive measures to become a developed, climate resilient and low carbon economy by 2050. [16] The massive integration of renewable energy in power systems implies new challenges to the system operator due to their intermittent nature attributed to climatic conditions. The system operator has limited control over the amount of electricity produced by these means. Thus, a strong contribution of these energies can cause imbalances and makes the electric system management more difficult [17].

The inherent intermittence of the renewable energy unit results in fluctuations at the level of the produced power. Integrating the latter will have a significant impact on the grid. These effects are manifested by voltage variations and overloads in the network. As far as power quality, both harmonics and flicker need to be minimized since harmonics result from non-linear electric loads [17]. Harmonic currents can cause voltage drops that result in the distortion of the supply voltage. They can also cause resonance in the supply and load components, leading to excess heat, malfunctions, premature failures and reductions in the lifetime of the transmission and distribution systems as well as in the electrical components. In the PV system, harmonics are caused by the conversion from DC to AC. A low-pass filter is normally used at the inverter output to reduce the harmonics. [17]

For the sake of cost reduction and de-risk investment for prospective mini-grid developers, Government will first identify eligible sites and undertake a financial and technical feasibility study. Where the provision of access through a mini-grid represents the least cost option, Government will undertake measures to stimulate demand, through either policy or investment. These sites will then be tendered out to private developers. [1] Rwanda's abundant natural resources and growing demand for electricity make the development of renewable energy in the country an investment with large upside potential [16].

Rwanda is a country endowed with plentiful natural resources. Despite its large reserves of methane gas, large river systems and high levels of solar irradiation, Rwanda's electric generation capacity amounts to barely 186 MW, spread out among its 10.5 million residents [16]. In February 2015, the first utility-scale solar energy project in East Africa was commissioned at the Agahozo-Shalom Youth Village in Rwanda as shown by the figure 2.8

below taken from Gigawatt global, providing 8.5 MW of grid-connected power to 15,000 homes. This increased total grid capacity by 6% [8].

Fig. 2.8: utility-scale of 8.5MW PV power plant constructed in Agahozo-Shalom Youth Village in Rwanda [9].

The above PV Power plant is 20 hectares (49 acres) of land and uses 28,360 photovoltaic panels and produces 6% of total electrical supply of the country. The project was built with U.S., Israeli, Dutch, Norwegian, Finnish and UK funding and expertise [9].

Off-grid renewable energy systems are not only urgently needed to connect a vast number of people with a source of electricity, but are also most appropriate due to geographical constraints and costs for grid extension. At the same time, off-grid systems could become an important vehicle to support the development of renewables-based grids. In developed countries including Rwanda, mini-grids are increasingly considered an option to improve energy security, power quality and reliability, as well as to avoid power blackouts due to natural disasters [7].

Despite the growing attention and market opportunities, there are to date only limited data available and only inadequate definitions of what exactly constitutes an off-grid renewable energy system. Furthermore, data sources are scarce and inconsistent across countries and regions. To address this challenge, IRENA has identified many of key areas where methodological improvements are needed. These methodological improvements include: 1) an overview of systems; 2) a categorization of off-grid renewable energy systems based on their application and system design; 3) consistent indicators to differentiate, evaluate, compare and aggregate data on off-grid renewable energy systems, including hybrid systems; and 4) measures to compile existing data sources, identify their limitations and create consistency. [7]

Table 2.1: Total number of solar power plants and total capacity [9].

No	Plant Name	Installed Capacity (MW)
1	Jali	0.25
2	Ndera	0.16
3	Gigawatt / Rwamagana	8.5
	Total	8.91

Although, only 24.5% of Rwanda's population has access to electricity, the country's location just a few degrees south of the Equator makes it a prime candidate for the development of solar PV plants but this is not yet implemented in potential areas since most of energy is generated by Hydro and thermal power plants as illustrated by the figure 2.9 below [16].

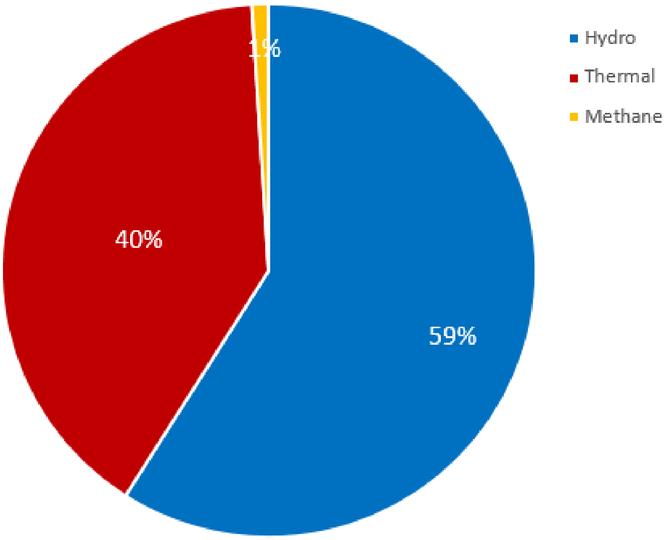


Fig. 2.9: Rwanda's total production in terms of energy generated by various sources [16].

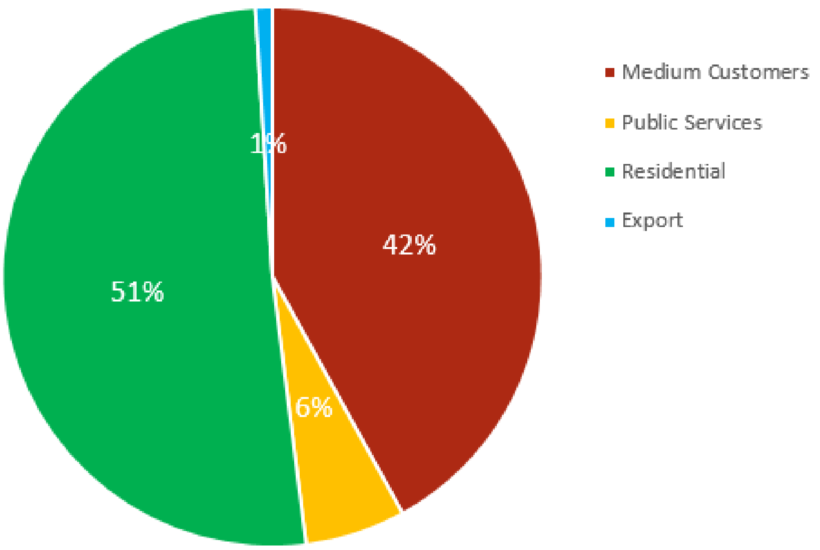


Fig. 2.10: Rwanda's total energy consumption through public and private services [16].

Rwanda’s total electrical generation capacity amounts to 186 MW, 59% of which comes from the country’s 7 largest hydroelectric power plants [16]. Thermal power generation, mostly from diesel and heavy oil fuel, account for the remaining 40% of electrical generation capacity, with methane gas representing barely 1% of total capacity [16]. Rwanda’s national electrification rate sits at 24.5%, which 23% coming from on-grid systems and only 1.5% coming from off-grid-systems [16]. This leaves over several million of the country’s residents without access to electricity and ranks Rwanda among the countries with the least annual electricity consumption per capita [16].

Table 2.2: Electricity tariff for residential and non-residential consumption in Rwanda [17].

End-users Electricity tariff in Rwanda (RWF // USD per kWh)	
Low Voltage (Industrial)	182 // 0.23
Medium Voltage (All residential and Non-residential)	126 // 0.16

2.5 Overview on HOMER Software

HOMER means Hybrid Optimization of Multiple Energy Resources. It is the main tool used in this research project and it was developed by the National Renewable Energy Laboratory (NREL) which is a division the United States Department of Energy. This software is useful in handling various technologies including PV, boilers, wind, hydro, fuel cells, and loads which may be AC/DC, thermal and hydrogen. HOMER is an hourly simulator which is used as an optimization tool for deciding the system configuration. It is used in both developing as well as developed countries to analyze the off-grid electrification issues. [18]

The approach of HOMER is quite robust and done in three stages to provide a comprehensive analysis of the entire system as well as a clarification on the technical and financial implications of design choices. The three stages are simulation, optimization, and sensitivity analysis [19].

There is a study conducted by S.M. Shaahid and I. El-Amin [20] to examine solar system for evaluating the best techno-economic option of hybrid System composed of PV-diesel-battery to respond to the load requirement regarding the chosen remote village with demand of 15,900 MWh. This research paper has been selected because it includes a solar PV as one renewable energy source which is related to my project.

HOMER accepts input for the daily load values in hourly increments. This load profile is extrapolated to the whole year. While it was noted that seasonal changes are not extreme near the equator to grossly affect the load curve, slight random variability was added to account for day to day variability, and to make the load more realistic. It has an attractive ability to do the evaluation of many equipments and resource options over a varying range of constraints with much effectiveness and high efficiency. [21] These are the main reasons why this software has been used in a various number of literatures for system design and optimization since it becomes easy to get a least-cost feasible option as well as optimum sizing of the entire system.

3 Data Collection and selected site

PV system design and optimization requires data collection as a preliminary stage for the project work to be carried out successfully. This include the selection of the site at which the project will be implemented for future work, load profile analysis for the selected village, Analysis of solar irradiance in the chosen area and evaluation of renewable resources available taking into consideration the topography of the region together with geographical characteristics of that specific location.

3.1 Introduction

Rwanda is divided into five provinces which act as intermediary between the national government and their constituent districts. The map shows the new provinces of Rwanda which include: The Southern Province, the Northern Province, the Western Province, the Eastern Province, and Kigali Province which is a province-level city and the capital of Rwanda.

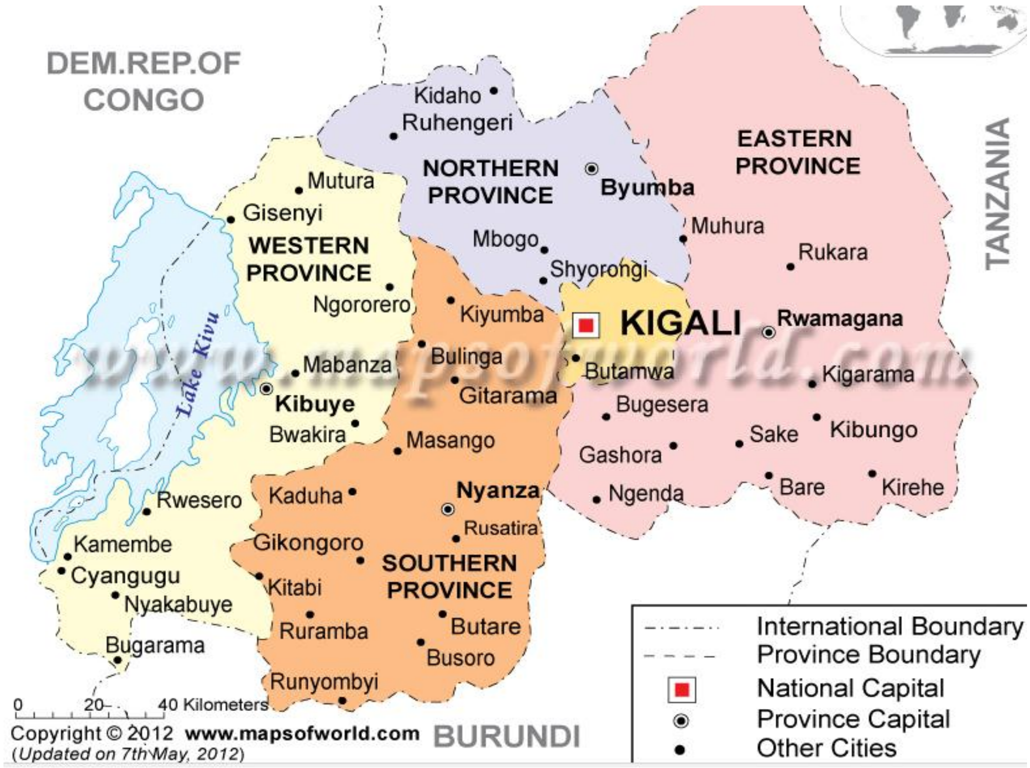


Fig. 3.1: Rwanda administrative map with a clear illustration of all provinces and their districts. [22]

Rwanda is a country located to the south of the equator and its climate is more moderate. The tropical climate is influenced by the mountainous landscape and the temperature is stable throughout the year at approximately 28 °C. [23] The rainy season in Rwanda is from September through to May, the wettest months are April and November. During the sunny season, the average daily radiation in the month of July is around 5.09 kWh/m2/d and the driest season is observed from June to August.

3.2 Rwanda Energy Sector Overview

The Government of Rwanda, under its latest Economic Development and Poverty Reduction Strategy, envisions transitioning from a developing country to a middle-income country by 2020. But Rwanda's ability to achieve this ambitious goal is constrained by challenges in the power sector. Thus, Rwanda's government is working to target 100 percent access to electricity by 2020. Although Rwanda is endowed with several natural resources, including hydro, solar, and methane gas, and has plans to generate 563 megawatts (MW) of electric power from these sources, it currently only has about 186 MW of installed generation capacity to serve a population of more than 10.5 million people [24].

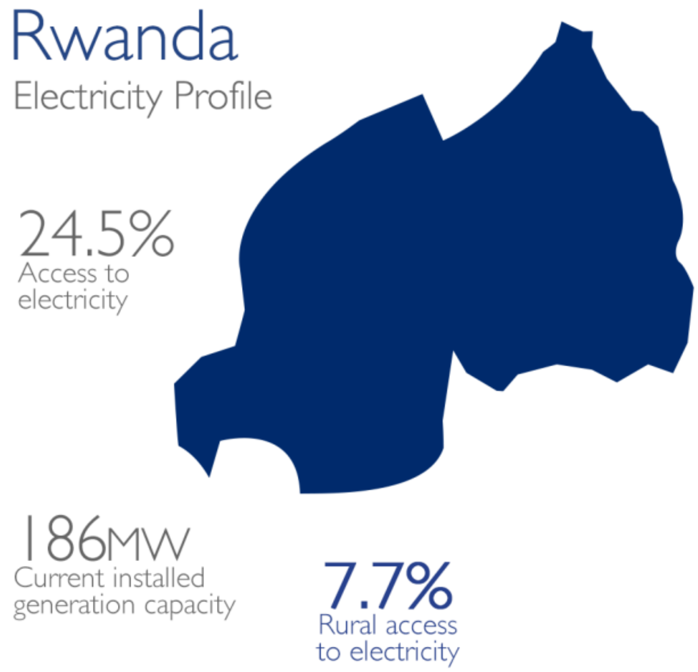


Fig. 3.2: Rwanda electricity profile showing the current installed capacity and rural access to electricity [24].

Based on current data, Rwanda's national electrification rate has reached 24.5% which implies 1.5% off-grid and 23% on-grid but more seven million people still lack access to electricity. Despite high resource potential and opportunities for cross-border export, Rwanda's power sector faces significant challenges, including a constrained transmission system. The annual consumption of electricity per capita is among the lowest in Africa, with approximately half of consumers using an average of less than 20 kWh per month. [24]

3.3 Data for Bugesera District

Bugesera is a densely populated district in the eastern province of Rwanda with a population density of 282 people per km2. It covers a total surface area of 1337 Km² and it is composed of 15 Sectors, 72 Cells and 581 Villages with a total Population of 363,339 people, where 177,404 are males and 185,935 are females with an annual Population Average Growth Rate of 3,1%. [25] This area has no distinct temperature seasons; the temperature is relatively constant during the year. Temperatures drop sharply at night and July is on average the month with high quantity of solar radiations as the driest season of the year is mostly observed in this month. [26] The time around July is driest. Rainfall and other precipitation peaks around the month of April as shown by the Figure 3.3 below.

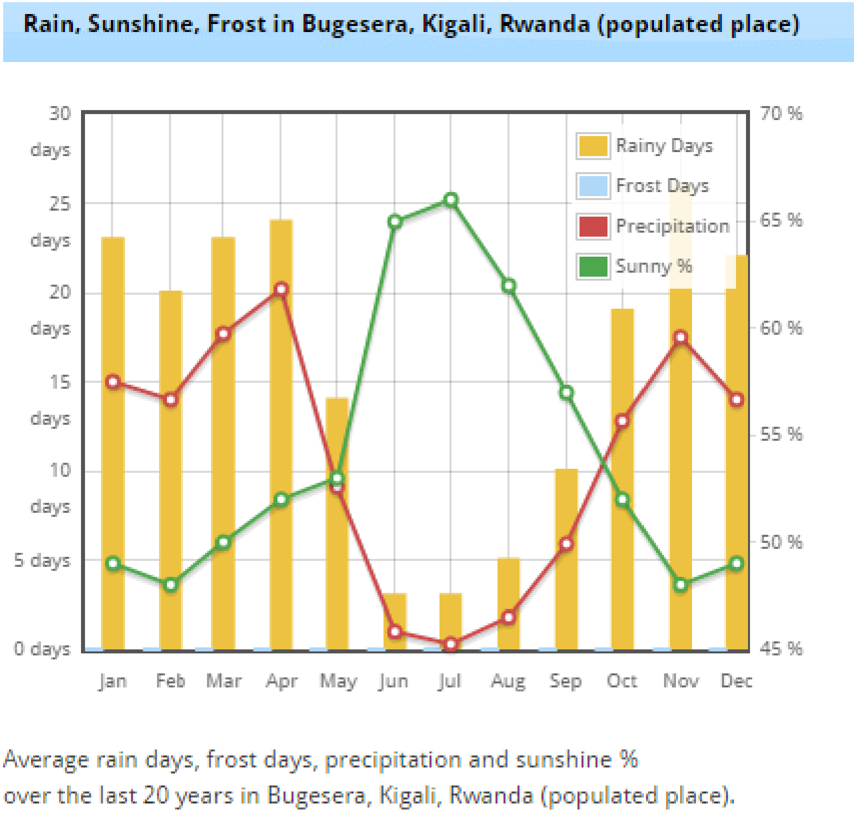


Fig. 3.3: Monthly average values of various climate data for Bugesera District. [26]

Bugesera District is situated in the South-Eastern plains of Rwanda notably in the south west of the Eastern Province. It borders are Republic of Burundi (Kirundo Province) in the south, Ngoma district in the East, Kigali city and Rwamagana district in the North. The district is sandwiched between Rivers Nyabarongo and Akanyaru which converge at the southern part to form Akagera River. Bugesera district's area is characterized by numerous lakes, the biggest of which are Rweru and Cyohoha. [25]

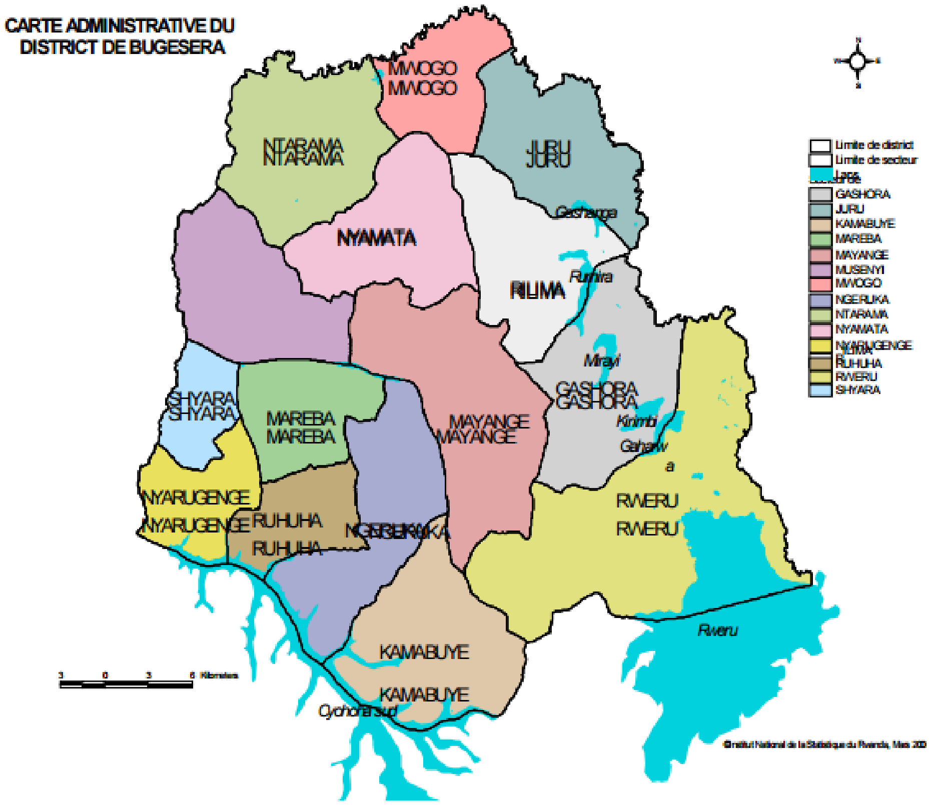


Fig. 3.4: Administrative Map of Bugesera District with all different sectors and rivers. [25]

The topography of Bugesera is characterized with a mixture of plateaus with an altitude varying between 1,100m and 1,780m and undulating hills dominated by varying heights. Most prominent of these hills are; Kabuye (1,772m the highest), Juru (1,667m), Maranyundo (1,614m), and Mwendo (1,575m). The relief is also constituted by a succession of low-plateaus with hills and dry valleys. The district is equally rich in marshlands alongside rivers; they cover an estimated area of 6,100 ha and are exploited at an average of 46.3%. [27]

Fig. 3.5: Map of Geography allocation of Nyamata Sector in Bugesera district. [28]

Fig. 3.6: View of Kanazi village of Nyamata Sector showing the topography. [29]

The largest proportion of Bugesera population is rural based with just a small percentage living in urban areas as reported by EICV3 statistics proved that, 7% of people in Bugesera live in town while 93% are rural based. [30] Bugesera district is among the districts with a high percentage of the population identified as poor since it was ranked to be the 13th country-wide by percentage of extreme-poor and poor population categories. [30]

The poverty line was defined based on the level of household consumption per adult below which a household is deemed to be poor. [30]

Fig. 3.7: A Typical house for the poor family in Kanazi cell of Bugesera district. [31]

Even though the energy sector registered great achievement in the last few years, there is still a long way to go in Bugesera because a negligible number of people have access to electricity and Electric power is far from arriving in all the significant centres of the District and due to the current low incomes of the populations, it will be difficult to count on it to satisfy the requirements in energy. The primary sources of energy used for lighting by households were categorized as follows: electricity, oil lamp, firewood, candle, lantern, battery, and other unspecified sources. [30] Due to the problem of accelerated poverty in this area, Bugesera DDP (District Development Plan) was elaborated within the general frame work of the second generation of Economic Development and Poverty Reduction Strategy (EDPRS2) whose overall aim is to increase the quality of life of all Rwandans through rapid and sustainable economic growth. [27]

3.4 Single house load profile

The selected house for a poor family is composed of few electrical and electronic equipments. These include 4lamps for lighting purposes, 2 cell-phones as communication facilities and 1 radio serving as a source of daily information. The daily power consumption in watt and daily load profile for this specific single house are presented in the Table 3.1 and in Figure 3.8 below respectively. The table 3.1 gives the load assumed for a single house as used in this study (compare to appendix D for more details related to single house load profile).

Table 3.1: Daily load evaluation for a poor single house in Kanazi village.

No.	**Equipments**	**No. in use**	**Power (W)**	**Total Power**	**Hours/day**	**Watt-hrs/day**
1	Lamps	4	11	44	5	220
2	Cell-Phones	2	5	10	1	10
3	Radio	1	10	10	12	120
4	TV	0	120	0	3	0
5	DVD Player	0	30	0	3	0
6	Computer	0	100	0	2	0
7	Refrigerator	0	500	0	4	0
8	Iron	0	1000	0	1	0
9	Water pumps	0	500	0	1	0
Total						350
No. of houses						100
Total for Poor families						35000

Based on these values, a typical daily load curve for a single house in Kanazi cell, Nyamata Sector of Bugesera District with hourly resolution has been described and it is shown in Figure 3.8 below.

The maximum power consumption demand with respect to the obtained load profile, for the chosen single house is approximately equal to 0.2 kW but with the random variability of 10 % (standard deviation: daily and hourly noise to make the load data more realistic) for each day and time step to time step, this maximum demand can become 0.07kW with the energy consumption of around 0.2 kWh.

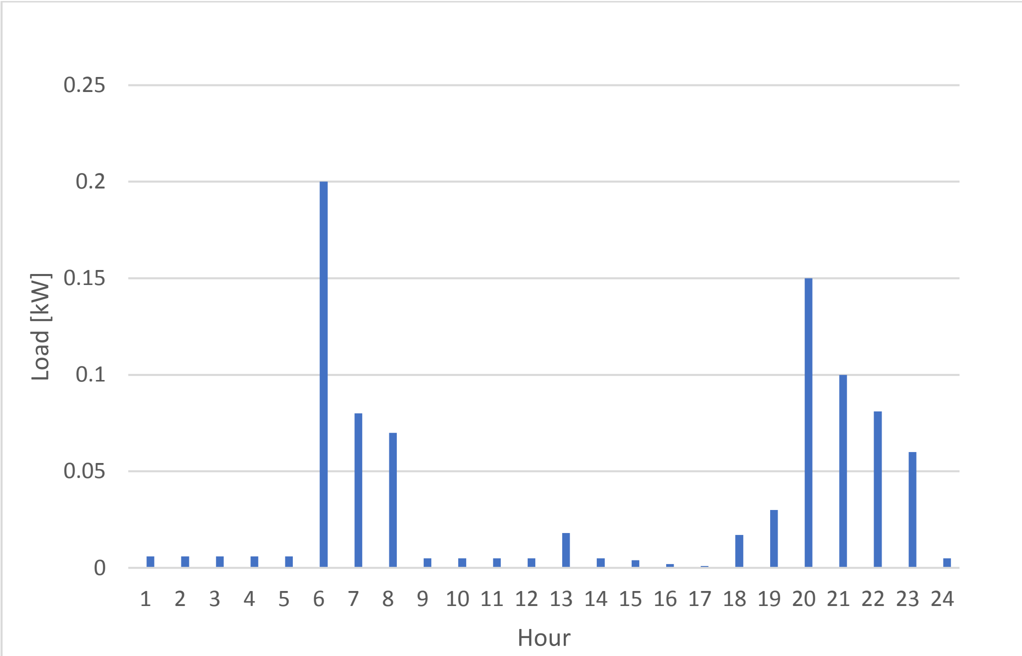


Fig. 3.8: Average daily load profile for a typical single house in Kanazi village selected for case study.

3.5 Solar resources analysis for Nyamata Sector

For sizing a photovoltaic system or any other system that uses solar energy to convert it into electricity or thermal energy, it is very important to have data relating to solar radiation. [3] The solar resource information used for selected village at a location at 2o8' S latitude and 30o5' E longitude was derived by PVGIS for Africa. [32] Data on the monthly averages of the daily radiation sum on a horizontal surface are plotted in Figure 3.7. In addition, tabulated monthly averaged daily insolation incident are given in Table 3.1, including the calculated clearness index values for each month. The clearness [5] is defined as a measure of the fraction of the solar radiation that is transmitted through the atmosphere to the earth's surface.

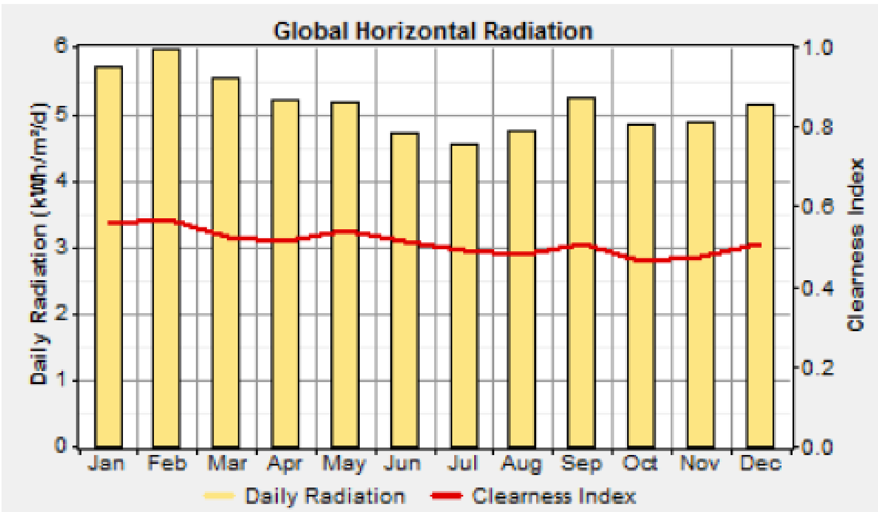


Fig. 3.9: Monthly global radiation for the selected village in Nyamata, from Homer Software.

For an optimal use of photovoltaic energy, a good knowledge of all the data describing the solar potential of the area is essential [3]. The Large amount of solar radiation for the selected site can be observed in the month of July since the value is 5.87 kWh/m2/day. The annual average solar radiation was found to be 5.415 kWh/m2/day and the corresponding average clearness index calculated by Homer is 0.541 as shown by the Table 3.2 below.

Table 3.2: Monthly global radiation for the selected village in Nyamata sector, from Homer tool.

Month	**Clearness Index**	**Daily Radiation (kWh/m2/d)**
January	0.532	5.47
February	0.531	5.59
March	0.531	5.59
April	0.502	5.07
May	0.527	4.98
June	0.597	5.41
July	0.638	5.87
August	0.586	5.72
September	0.551	5.68
October	0.529	5.53
November	0.485	4.99
December	0.5	5.08
Average	**0.541**	**5.415**

3.6 Additional resources for the selected site

Additional climatic parameters such as air temperature, earth temperature, wind speed, atmospheric pressure and relative humidity for the selected site in different months of the year and their annual average values are presented in the Table 3.3 below.

Table 3.3: Average monthly values for other climatic parameters in Nyamata Sector. [33]

Month	**Air temperature** °C	**Relative humidity** %	**Wind speed** m/s	**Atmospheric pressure,** kPa	**Earth temperature,** °C
January	25	43.30%	3.8	89.7	26.4
February	25.5	44.50%	3.9	89.7	27.2
March	24.2	62.60%	3.9	89.6	25.4
April	22.8	75.00%	3.7	89.7	23.6
May	22.3	75.50%	3.6	89.8	22.6
June	22.2	68.70%	3.5	89.9	22.4
July	22.4	62.20%	3.5	90	22.7
August	22	69.70%	3.5	90	22.4
September	21.7	75.20%	3.6	89.9	22.1
October	21.7	78.10%	3.7	89.8	22.1
November	22	72.70%	3.6	89.8	22.3
December	23.5	54.80%	3.6	89.8	24.2
Annual	22.9	65.20%	3.7	89.8	23.6

4 PV System Components behaviors and Costs

The performance and cost of each component of the PV System are the most important parameters to consider before the design process. The main components that will be described in this chapter are the solar panels and the storage battery. There are various types of PV System configuration based on the kind of voltage system and bus that interconnect the source to the loads. The two most common types are known as DC coupled system and DC/AC coupled system. In this energy research project, DC coupled PV system has been chosen because the PV generating source is connected to a DC bus that is used to supply DC loads present within the selected house in Kanazi village. These loads include, four lamps for lighting purposes, one radio as a source of information and two cell phones for communication facilities.

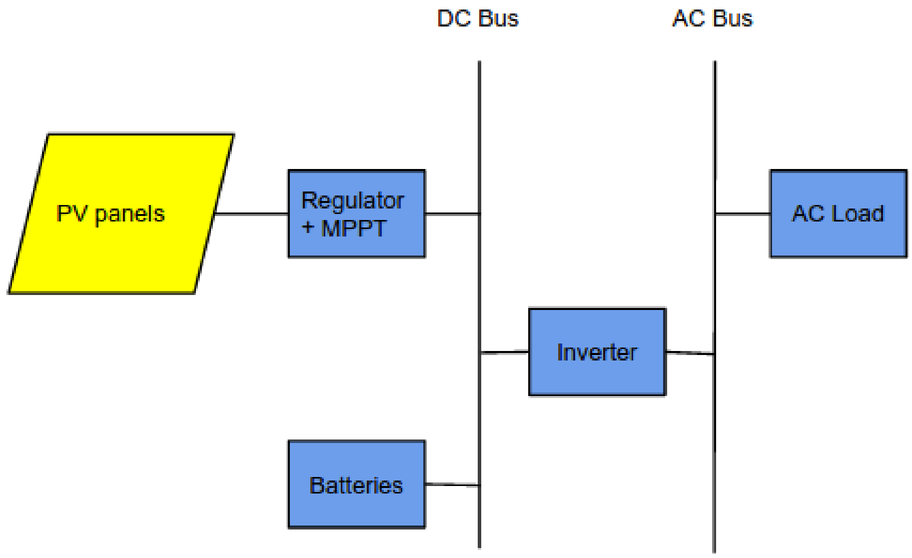


Fig. 4.1: General diagram of the PV system showing the main components. [3]

A complete electricity-management system using PV as its source for power will contain, in addition to the photovoltaic array, one or more of the following:

- Storage devices
- Power-conditioning equipment, including devices to
  - Limit current and voltage in order to maximize power output
  - Convert direct-current to alternating current
  - Match the converted DC electricity to the utility's AC electrical network
  - Safeguard the utility network and its personnel from possible damage caused by the PV system. [34]

There are two basic forms of electricity: alternating current (AC) and direct current (DC) [34]. The difference between them is that the alternating current (AC) is made up of electrons alternately flowing in one direction and then in the opposite direction under the influence of a cycling force (voltage) that acts a part of a time in one and then the opposite direction, while for DC electricity, the electrons flow in a single direction and it is generated by devices such as batteries and photovoltaic systems [34].

In a battery, electrons gather at an electrode as the result of a chemical reaction within the battery. In the PV cell, the electrons are generated by light and the ability of the PV cell to move charge carriers to opposite sides of the cell. The electrons move because there is a driving force, a voltage which is characteristic of the electric source, for example an electrochemical cell (battery) or a PV cell [34].

Direct current is a perfectly useful form of electricity for many applications. At an isolated location, there is no need to do anything more than use PV-generated electricity and perhaps store it for times when there is no daylight to activate the cells. This is possible so long as the devices being powered can use direct current. But some types of motors and appliances cannot be designed for direct current [34]. PV arrays are useful energy producers only when the sun is shining on them and thus are unproductive a good deal of the time. This extends the availability of electricity through periods when there is no illumination. If a utility grid is convenient to the PV system, then it can be used as a low-cost way to store electricity. Excess electricity from the PV system can be suitably made compatible with grid electricity [34]. When more PV electricity is being generated than is being used, the excess can be metered and fed to the grid. When the PV system is not providing enough power, the extra amount needed can be purchased from the utility grid [34].

4.1 Solar Panels

A PV module consists of several interconnected solar cells (typically 36 connected in series) encapsulated into a single, long-lasting, stable unit. The key purpose of encapsulating a set of electrically connected solar cells is to protect them and their interconnecting wires from the typically harsh environment in which they are used. For example, solar cells, since they are relatively thin, are prone to mechanical damage unless protected. In addition, the metal grid on the top surface of the solar cell and the wires interconnecting the individual solar cells may be corroded by water or water vapor [35]. The two key functions of encapsulation are to prevent mechanical damage to the solar cells and to prevent water or water vapor from corroding the electrical contacts.

A fundamental characteristic of a photovoltaic system is that power is produced only while sunlight is available [36].The current and power output of photovoltaic solar panels are approximately proportional to the sun’s intensity. At a given intensity, a solar panel's output current and operating voltage are determined by the characteristics of the load [37]. To generate large amount of power output, solar cells are connected in a compound structure within the PV module and the output power from a typical solar cell is approximately equal to 1 watt.

4.1.1 Electrical characteristics of a solar panel

A Solar Panel produces its maximum current when there is no resistance in the circuit, i.e. when there is a short circuit between its Positive and Negative terminals. This maximum current is known as the Short Circuit Current and is abbreviated as Isc. When the Panel is shorted, the voltage in the circuit is zero. Conversely, the maximum voltage occurs when there is a break in the circuit. This is called the Open Circuit Voltage (Voc). Under this condition, the resistance is infinitely high and there is no current, since the circuit is incomplete. These two extremes in load resistance, and the whole range of conditions in between them, are depicted on the I-V Curve. Current, expressed in Amps, is on the vertical Y-axis. Voltage, in Volts, is on the horizontal X-axis [35].

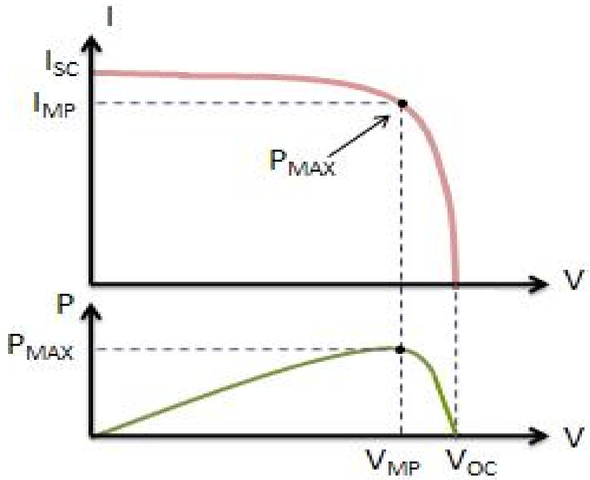


Fig. 4.2:The I-V and Power Curves for the Solar Panel [38].

A Current (I) versus Voltage (V) Curve of a solar panel shows the possible combinations of its current and voltage outputs. A typical I-V curve for the solar panel is shown at Figure 2 presented above. The power (P) available from a photovoltaic device at any point along the curve is just the product of the voltage and the current.

Mathematically,

$$P = V \times I \qquad (4.1)$$

- **The short circuit current:** Isc corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals 0. I (at V=0) = Isc. It occurs at the beginning of the forward-bias sweep and is the maximum current value in the power quadrant. For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation. Isc = Imax = Iℓ for forward-bias power quadrant.

- **The open circuit voltage (V_{OC}):** occurs when there is no current passing through the cell. V (at I=0) = Voc. It is also the maximum voltage difference across the cell for a forward-bias sweep in the power quadrant. Voc= Vmax for forward-bias power quadrant

At the short circuit current, the power output is zero, since the voltage is zero. At the open circuit voltage point, the power output is also zero, but this time it is because the current is zero. There is a point on the knee of the I-V Curve where the maximum power output is located and this point is called the Maximum Power Point (MPP). The voltage and current at this Maximum Power Point are designated as Vmp and Imp. The rated power of the solar panel in Watts (Pmax) is derived from the above values of voltage Vmp and current Imp at this Maximum Power Point (MPP): Rated power in Watts, Pmax = Vmp x Imp [35].

Example of I-V Curve and Ratings of a 12 V Solar Panel.

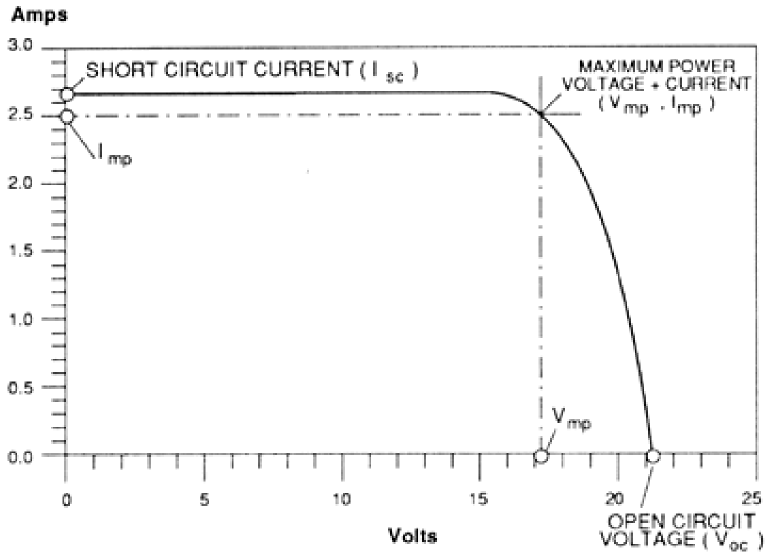


Fig. 4.3: I-V Curve and ratings of Solar Panel designed to be connected to a 12V battery [39].

The Maximum Power Point: in the example curve given above is where Vmp is 17 Volts, and the current Imp is 2.5 amps. Therefore, the rated or the maximum power Wmax in watts is 17 Volts times 2.5 Amps, or 42.5 Watts. The I-V curve is also used to compare the performance of PV Modules. The curve is, therefore generated based on the performance under Standard Test Conditions (STC) of sunlight and device temperature of 25 °C. It assumes there is no shading on the device. Standard sunlight conditions on a clear day are assumed to be 1,000 Watts of solar energy per square meter (1000 W/m2 or 1 kW/m2). This is sometimes called one sun, or a peak sun. Less than one sun will reduce the current output of the PV device by a proportional amount. For example, if only one-half sun (500 W/m2) is available, the amount of output current is roughly cut in half [39].

- **The total current I**: in an ideal cell, is equal to the current Iℓ generated by the photoelectric effect minus the diode current ID, as shown in the equation below:

$$I = I_l - I_D = I_l - I_o(e^{\frac{qV}{kT}} - 1) \tag{4.2}$$

Where,

I_o is the saturation current of the diode,

q is the elementary charge 1.6×10^{-19} Coulombs,
k is a constant of value 1.38×10^{-23} J/K,
T is the cell temperature in Kelvin, and V is the measured cell voltage that is either produced (power quadrant) or applied (voltage bias).

Effect of Series Resistance (R_S) and Shunt Resistance R_{SH}

The series resistance is caused by the movement of electrons through the emitter and base of the solar cell, the contact resistance between the metal contact and the silicon and the resistance of metal grids at the front and the rear of the solar cell. The shunt resistance is due to manufacturing defects and lightly by poor solar cell design. It corresponds to an alternate current path for the photocurrent [40]. The total current in terms of both series and shunt resistance is given by the following equation:

$$I = I_l - I_o\left(exp^{\frac{q(V+I.Rs)}{n.k.T}} - 1\right) - \frac{V+I.Rs}{R_{SH}} \tag{4.3}$$

Where,

n is the diode ideality factor (typically between 1 and 2), and
$\mathbf{R_S}$ and $\mathbf{R_{SH}}$ represents the series and shunt resistances.

Expanding the equation gives the simplified circuit model shown below. During operation, the efficiency of solar cells is reduced by the dissipation of power across internal resistances. These parasitic resistances can be modeled as a parallel shunt resistance (R_{SH}) and series resistance (R_S), as depicted in Figure 4.4 below.

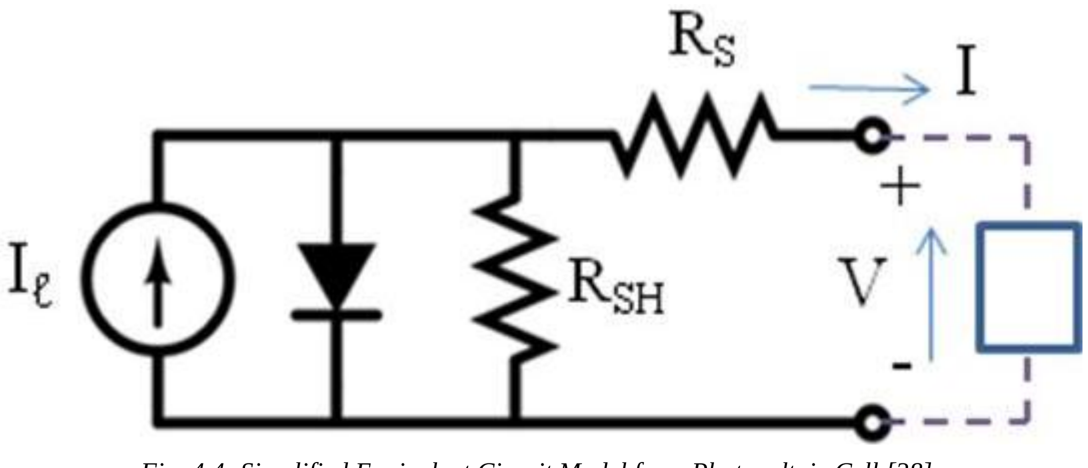


Fig. 4.4: Simplified Equivalent Circuit Model for a Photovoltaic Cell [38].

For an ideal cell, R_{SH} would be infinite and would not provide an alternate path for current to flow, while Rs would be zero, resulting in no further voltage drop before the load. Decreasing R_{SH} and increasing Rs will decrease the fill factor (FF) and P_{MAX} as shown in Figure 4.6

below. If R_{SH} is decreased too much, V_{OC} will drop, while increasing R_S excessively can cause I_{SC} to drop instead.

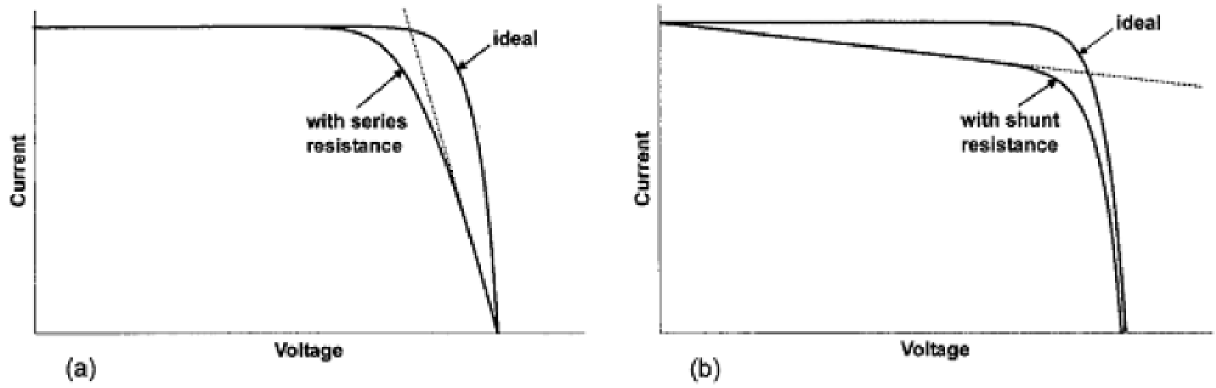


Fig. 4.5: Effect of series (a) and shunt(b) resistance on I-V characteristics of the PV Cell [41].

The Fill Factor (FF) is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (P_T) that would be output at both the open circuit voltage and short circuit current together.

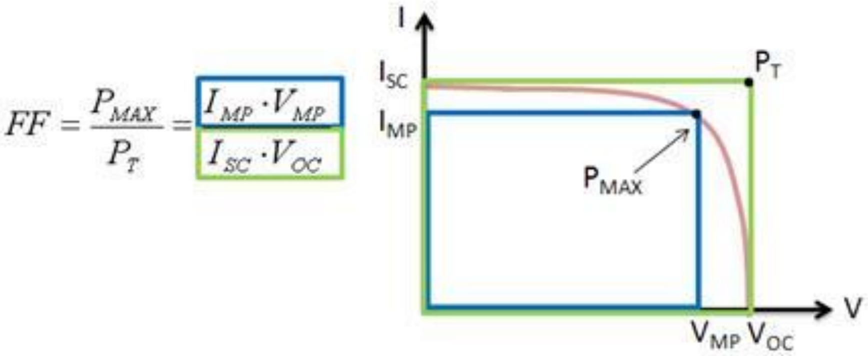


Fig. 4.6: Getting the Fill Factor from the I-V Curve [38].

A larger fill factor is desirable, and corresponds to an I-V sweep that is more square-like. Typical fill factors range from 0.5 to 0.82. Fill factor is also often represented as a percentage.

Efficiency is the ratio of the electrical power output P_{out}, compared to the solar power input, P_{in}, into the PV cell. P_{out} can be taken to be P_{MAX} since the solar cell can be operated up to its maximum power output to get the maximum efficiency. [37].

$$\eta = \frac{P_{out}}{P_{in}} \rightarrow \eta_{MAX} = \frac{P_{MAX}}{P_{in}} \tag{4.4}$$

Pin is taken as the product of the irradiance of the incident light, measured in W/m^2 or in suns (1000 W/m^2), with the surface area of the solar cell [m^2]. The maximum efficiency (η_{MAX}) found from a light test is not only an indication of the performance of the device under test, but, like all the I-V parameters, can also be affected by ambient conditions such as temperature and the intensity and spectrum of the incident light [42].

4.1.2 Effect of Temperature on the performance of a Solar panel

It is important to understand the effect of the temperature on the output performance of the solar module. Temperature affects how electricity flows through an electrical circuit by changing the speed at which the electrons travel. The module temperature has a dramatic effect on voltage parameters. Open circuit voltage and maximum voltage are decrease with increasing module temperature. This is due to an increase in resistance of the circuit that results from an increase in temperature. Likewise, resistance decreases with decreasing temperatures [43].

There are many different methods used for increasing the efficiency of the solar module, such as water cooling methods that are employed to reduce the temperature of the panel and other methods like dust cleaning, mppt tracking, effective selection of cell materials as well as panel orientation are also used. [44]

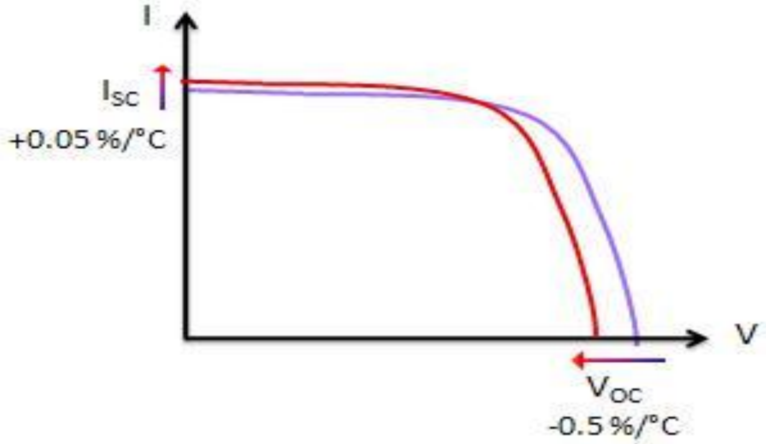


Fig. 4.7: Temperature Effect on I-V Curve [38].

The Performance of solar cells is dependent on environmental conditions and their output parameters such as output voltage, current, power, and fill factor vary by temperature. Experimental results showed that the most significant changed by temperature is voltage which decreases with increasing temperature while output current slightly increase by temperature. Reduction in the open-circuit voltage for silicon solar cells is about 2mV/°C. As well as the effect of temperature on the maximum power output is menus 0.005 mw/°C [40].

Table 4.1: Output Parameters of Solar Cell Under Different Temperatures [40]

Sample	Temperature [^{0}c]	V_{OC} [mv]	I_{SC} [mA/cm^2]	V_{mp} [mv]	I_{mp} [mA/cm^2]	FF	η [%]
Mono-crystalline silicon solar cell	15	570	33.99	450	30.99	0.727	14.63
	25	563	34	443	31	0.72	13.95
	30	559	34	439	31	0.716	13.61
	40	554	34.01	434	31.01	0.714	12.93
	50	549	34.02	429	31.02	0.712	12.25

4.1.3 Effect of irradiance on the performance of a Solar panel

The sun radiation plays an important role on the performance of photovoltaic (PV) solar modules due to its variation from time to time, the output of PV module increases as the sun radiation increases. The amount of sunlight received by any surface on earth will depend on several factors including; geographical location, season, local landscape, time of the day and local weather. The light's angle of incidence on a given surface will depend on the orientation since the Earth's surface is in round-form and the intensity will depend on the distance that the light should travel to reach the respective surface [45].

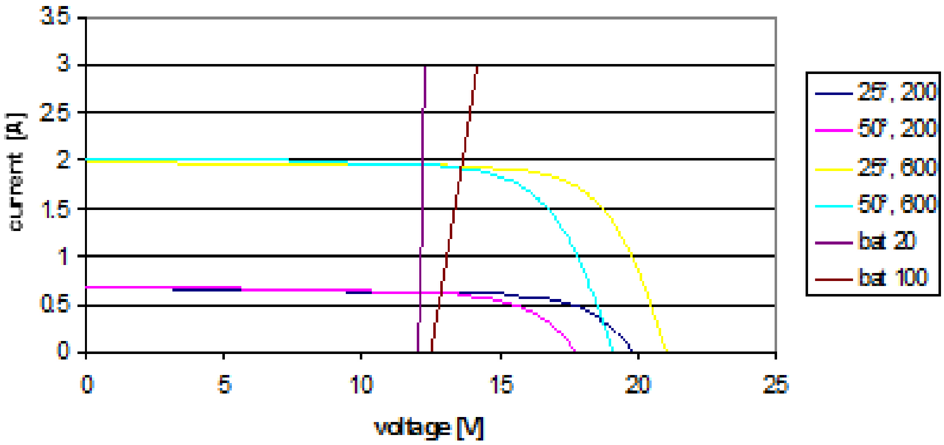


Fig. 4.8: The effect of Irradiance on I-V curve of a solar panel [46].

The above Figure 4.8 shows I-V curves for irradiance values of 20, 100, 200 and 600 W/m2. The I-V curve at 600 W/m2 is for a module that faces the sun directly. When the sun is exactly overhead in tropical countries, the module should be horizontal for maximum current. When the sun is low in the sky at 30° above the horizon, the module should be tilted towards the sun at an angle of 60° from horizontal for maximum current. However, modules are usually fixed in one position. Thus, they face the sun directly only for a few times a day [46]. Therefore, the current produced by the module which position is fixed varies through the day, even when the weather is clear with no clouds. When the sun is covered by thick clouds, the irradiance could be reduced to 100 W/m2 or less. The reduction in the intensity of irradiation involves a reduction in the photocurrent because the photocurrent is practically proportional to luminous flow and since the open circuit voltage is also related to the short circuit current, it will undergo a small reduction [47]. From the above Figure 4.8, the first vertical line represents the empty battery and the second line represents the fully charged battery for different values of irradiance and temperature. Therefore, it is optimal to use the 12V battery since it always matches with changing climatic conditions. For crystalline silicon modules, the main material properties are temperature coefficient and the solar radiation coefficient, which are normally given by the PV Manufacture having values of 0.0045K and 0.12 respectively [40]. Considering a solar panel with variations in ambient temperature and irradiance, the cell temperature (in ^{o}C) can be estimated quite accurately by using the linear approximation which results to the following useful formula below,

$$T_C = T_a + \frac{T_{NOCT} - 20}{0.8kW/m^2} \times I(t) \tag{4.5}$$

Where,

T_C is the cell temperature; Ta is the ambient temperature and TNOCT is the nominal operating cell temperature [48] [4].

4.2 Battery storage

The Energy storage represents a critical part of any energy system, and chemical storage in the form of a battery is the most frequently employed method for long term storage. In any photovoltaic system that includes batteries, the batteries become a central component of the overall system which significantly affect the cost, maintenance requirements, reliability, and design of the photovoltaic system. Electrochemical battery storage is the most utilized method for storing electrical power [34]. Because of large impact of batteries in a stand-alone photovoltaic system, understanding the properties of batteries is critical in understanding the operation of photovoltaic systems. For systems in which the photovoltaics is the sole generation source, storage is typically needed since an exact match between available sunlight and the load is limited to a few types of systems.

By being part of the circuit into which electrical power from the PV supply flows, the battery keeps the electrical load more nearly constant, and the PV array can be easily designed to operate more nearly at its optimum power output [34]. Of course, the battery must be protected from being overcharged by a highly productive array, and a darkened array must be protected from current flowing to it from a charged battery [34]. This is readily done by placing protective electronic components such as diodes, which limit the flow of electricity to a single direction and devices comparable to automobile voltage regulators that prevent battery overcharge while maintaining a uniform system voltage [34]. Note that a battery storage system without a regulator must be larger than one so equipped because it must be large enough to ensure against overcharge [34]. The important battery parameters that affect the photovoltaic system operation and performance are the battery maintenance requirements, lifetime of the battery, available power and efficiency [36].

Fig. 4.9: Vision 6FM55D, 12V, 55Ah Battery storage [49].

The general features for the above type of battery are:

- Absorbent Glass Mat (AGM) technology for efficient gas recombination of up to 99% and freedom from electrolyte maintenance or water adding.
- Not restricted for air transport.
- Can be mounted in any orientation.
- Computer designed lead, calcium tin alloy grid for high power density.
- Long service life, float or cyclic applications.
- Maintenance-free operation.
- Low self-discharge.

Fig. 4.10: Surrette battery 6CS25P, 6V. [50]

Some distinctive advantages of Surrette battery: [50]

- Premium Battery Brand
- Excellent Stock Availability
- Fast Order Processing & Delivery
- Technical Back Up & System Support
- Competitive Commercial Terms
- Controlled Distribution Channels

For the above battery to last longer, it is important that it is properly charged. Over and under-charging a Rolls battery will result in shortened service life. The best protection from improper charging is the use of a quality charger and routinely checking that the charger current and voltage settings are maintained. [51]

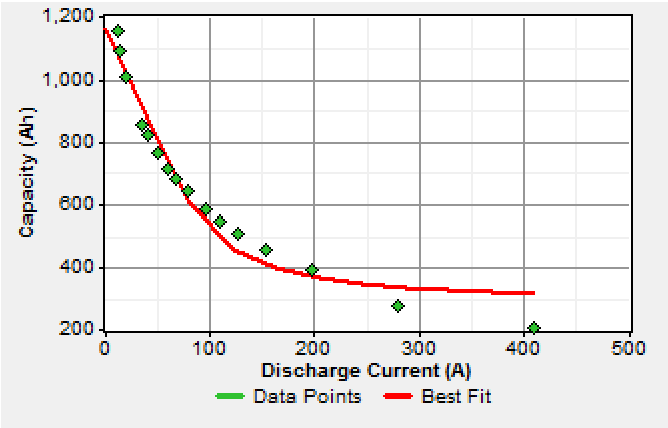


Fig. 4.11: Capacity curve of the Surrette battery 6CS25P, 6V, from Homer.

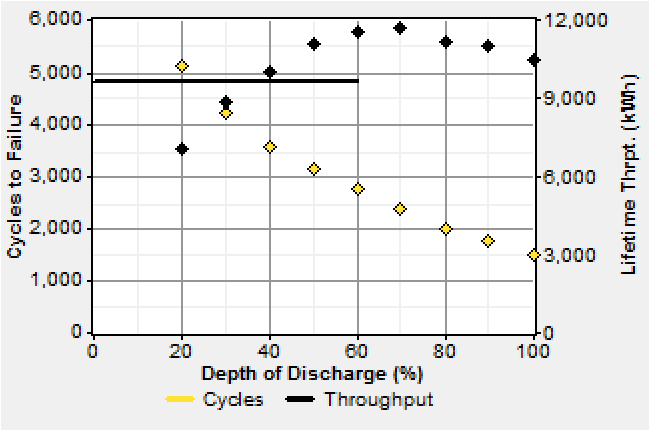


Fig. 4.12: Life cycle curve for Surrette battery 6CS25P, 6V, from Homer.

The capacity curve for the Surrette battery 6CS25P is shown in Figure 4.2. The nominal capacity of this battery type is indicated as one point on this capacity curve and specified by the manufacturer as 1156 Ah. The life cycle curve for the Surrette battery 6CS25P is shown in the above figure 4.3. The Figure indicates clearly that the number of cycles to failure drops rapidly when the depth of discharge arises and this can be used as a proof to show that the battery lifetime also depends on the number of cycles to failure.

4.3 Solar Inverter and MPPT System

A solar inverter is needed by the PV system in case of AC loads to convert the generated DC voltage into AC voltage as required by different AC loads. Also for insuring the best performance of the PV modules, an MPPT system is important and since the technology has improved this system is usually incorporated with solar inverters in most stand-alone PV systems. The efficiency of an inverter varies per load demand and their efficiency curve is usually provided by the manufacture. An inverter provides a factor of compatibility, but its use can reduce the array's available electricity if it is not suitably designed to match the electrical load [34]. Essentially an inverter is a set of automatic switches that provide polarity reversals from the solar array as shown by the figure below. If there is no utility-grid interconnection, then the direct-current supply need only be converted to an alternating current output that will suitably power the AC equipment on hand [34].

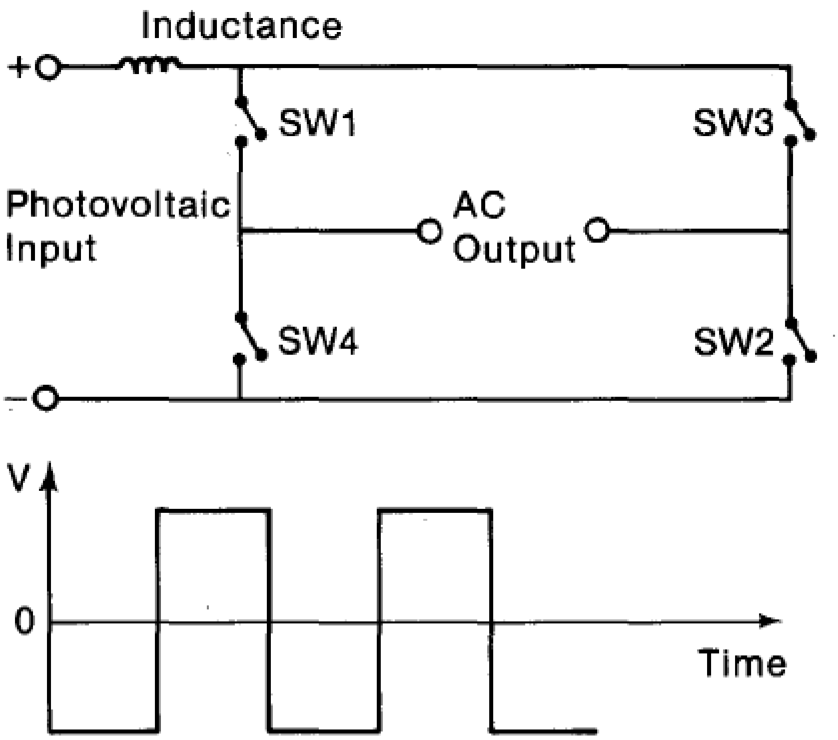


Fig. 4.13: Inverter's circuit diagram with different electronic switching circuits [34].

In the system illustrated above, when switches 1 and 2 are closed the AC output is positive at the left terminal. When switches 3 and 4 are closed the positive AC terminal is on the right. Opening and closing, alternately, the switches in pairs (1/2 and3/4) produces square waveform as shown in the bottom portion of the illustration [34].

4.4 Other Devices

Most other power-related equipment placed in a PV system is likely to be present because the PV system is hooked to a utility grid. In such cases, it is important that meters record the quantities of electricity being sold to an being bought from the utility. Other pieces of PV system equipment that utilities probably will require are automatic lock-out switches or isolation transformers which are used for ensuring the separation of the PV and utility-grid systems in the event of a grid failure [34].

4.5 Cost Estimation for Solar Panels, Battery storage and Inverter

The cost of solar panels is a variable that usually depends on the time, place and size of the solar panel required for the entire Solar home system installation. The difference between reported and modeled pricing is due to various factors pertaining to the inherent variability in the type of systems that are installed each year, their location, state and federal policies, and the ability of buyers and sellers to agree to a sales price which may be effected by the supply and demand market factors.

Referring to the reported modeled system prices for different types of solar panels depending on system size, the recently updated prices are as follows [52].

- Residential Small commercial (≤5 kW) is $ 3.12 /W
- Large commercial (>100 kW) was $ 2.17/W (median)
- Utility-scale (≥8 MW, ground-mounted) was $ 1.78/W (capacity weighted average).

Table 4.2: Range of Cost Estimation for monocrystalline Solar Panels depending on the system size [44].

System Size (in watts per hour)	Monthly Output Capability (based on 5 hours of collectible sunlight per day)	Approximate NUmber of Solar Panels	Approximate Cost,*BEFORE subtracting up to 30% for the Federal Tax Credit* or state rebates or other financial incentives.
190 - 560	28 - 75 kWh	2 - 4	$1,000-$1,875
1,000 - 1,600	135 - 215 kWh	4 - 6	$6,500-$8,000
2,250 - 3,200	305 - 425 kWh	9 - 12	$8,000-$9,888
3,750 - 5,250	510 - 715 kWh	15 - 21	$9,500-$15,300
6,000 - 9,540	800 - 1,300 kWh	24 - 36	$16,000 - $20,890
11,250 - 14,300	1,530 - 1,900 kWh	45 - 54	$26,000 - $32,000

Based on the information given by the above Table 4.2, the approximated cost for the PV system size between 190W and 560W, used in homer is $1000 [53]. I have chosen different sizes for Monocrystalline solar panel [54]. The analysis in Homer software is based on the current system sizes that are used in Rwanda between 30W and 200W. For the storage system, I also used various types of battery with different nominal voltages and currents to compare the simulation results and propose the optimal system. The first battery selected in Homer for solar home system is named Vision 6FM5DD was selected in Homer with a cost of $478 and it has the following specifications: 12V as nominal voltage, 55Ah as nominal current handling capacity [55]. The second battery chosen in Homer library for 10kW stand-alone village system is described as Surrette 6CS25P of 6V, 1156Ah nominal capacity and with a cost of $1200 per one single unit which implies that for 8 batteries in series the total cost is $9600 [56].

5 PV Systems Modelling

The focus in this chapter is the design of a basic solar home system and mini-grid system by the help of the optimization software named HOMER. The design process begins by enumerating the important inputs data that demonstrate the technical specifications, resources data and the costs which are relevant for designing the entire system in HOMER tool.

5.1 Design of 0.2kW Solar Home System

The inputs data used for designing the solar home system in Homer for the selected area are summarized below.

- PV panel size is 0.2 kW, with a capital cost of $1000, replacement cost of $500 and the maintenance together with operating cost per year were assumed to be $10.
- Average load demand is 0.008 kW, peak load demand is 0.071 kW, and average of the daily demand is 0.2 kWh/d and the load factor of 0.117.
- Solar irradiance is 5.41 kWh/m^2/d, the clearness index is 0.541 and the average temperatures is 22°C.
- The battery is Vision 6FM55D of 12V, 55Ah (0.66 kWh) and with a round trip efficiency of 80 %.

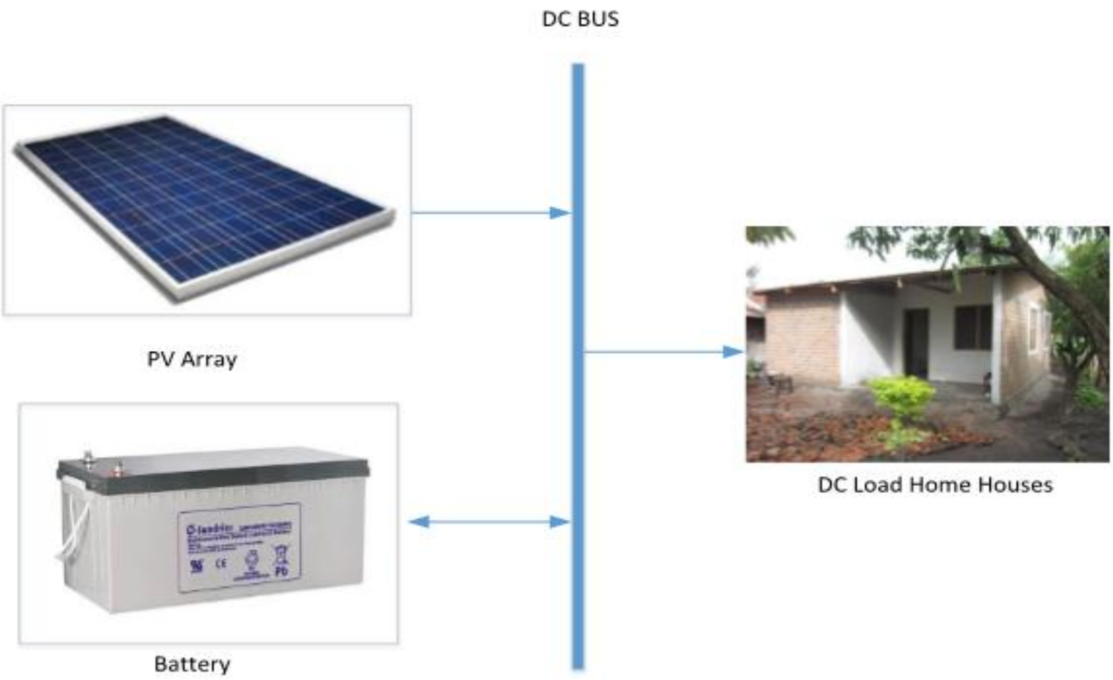


Fig. 5.1: Single line diagram of the basic Solar Home System in Kanazi village.

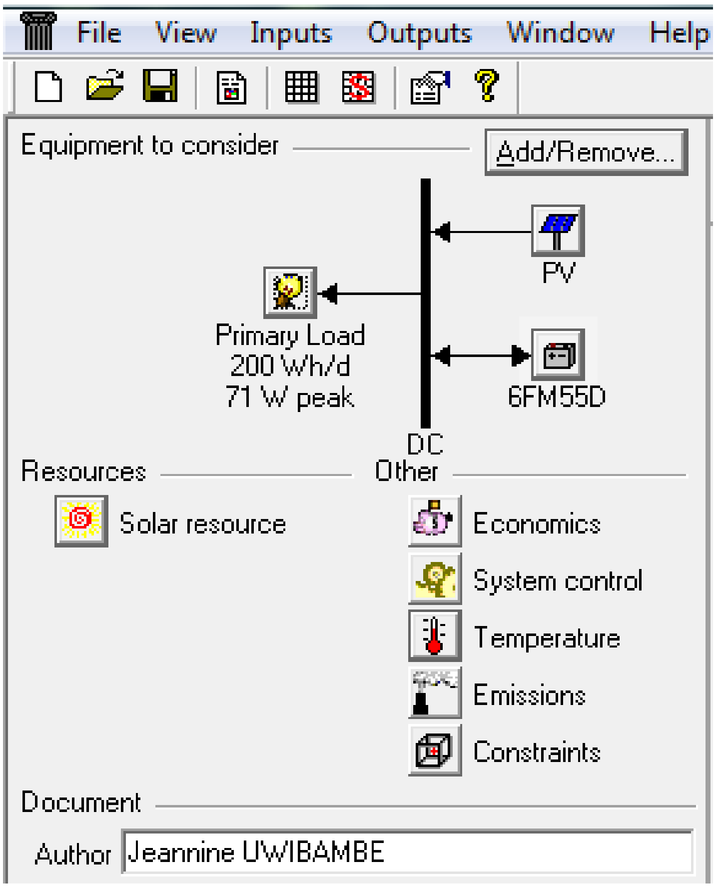


Fig. 5.2: Inputs for modelling a solar home system of a single house in HOMER.

5.1.1 Primary Load Input

The primary load for the single house is the load required to be met immediately in such a way that there will be no unmet load [56]. This load was measured in different hours of the day for the selected houses in Kanazi cell to obtain the average daily load profile and the seasonal profile for a typical single house. Therefore, Homer tool calculates the annual average load, the peak load and the load factor based on the value entered for each hour of the day with DC load type.

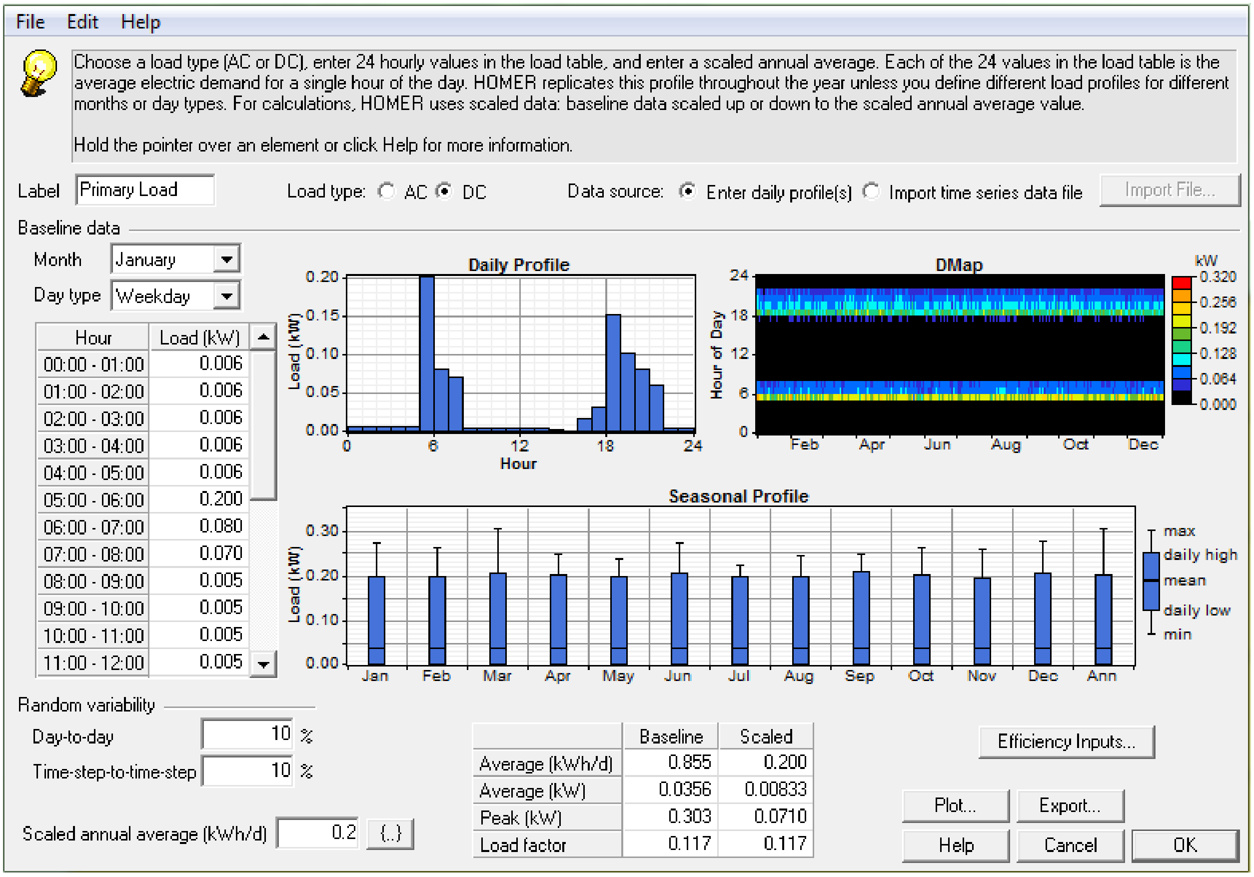


Fig. 5.3: Input window for primary load of a typical single house in Homer.

The baseline data is defined as many of 8,760 values recorded for each hour that are used to represent the average value of electricity demand and it is expressed in units of Kw [56].Basically, there are two main technics for production of baseline data such as: either by using Homer to synthesize data, or by importing hourly data from a selected file [56]. The difference between these technics is that the one of synthesizing data by Homer just enters at least one load profile, which is described as a set of different 24 hourly values of electric load [56]. It is possible to enter different load profiles for different months, and for weekdays and weekends too. But if only one load profile has been entered, it will be used throughout the year.

5.1.2 PV inputs

In this project work a monocrystalline solar panel type SUNTECH STP250S is selected and related specifications are mentioned in the data sheet and on the name plate by the manufacturer [54]. In using Homer software, the selected PV system type is supposed to work under maximum power point to achieve the desired output power form this system. The important parameters required by homer for the PV input are summarized in the Figure 5.4 below.

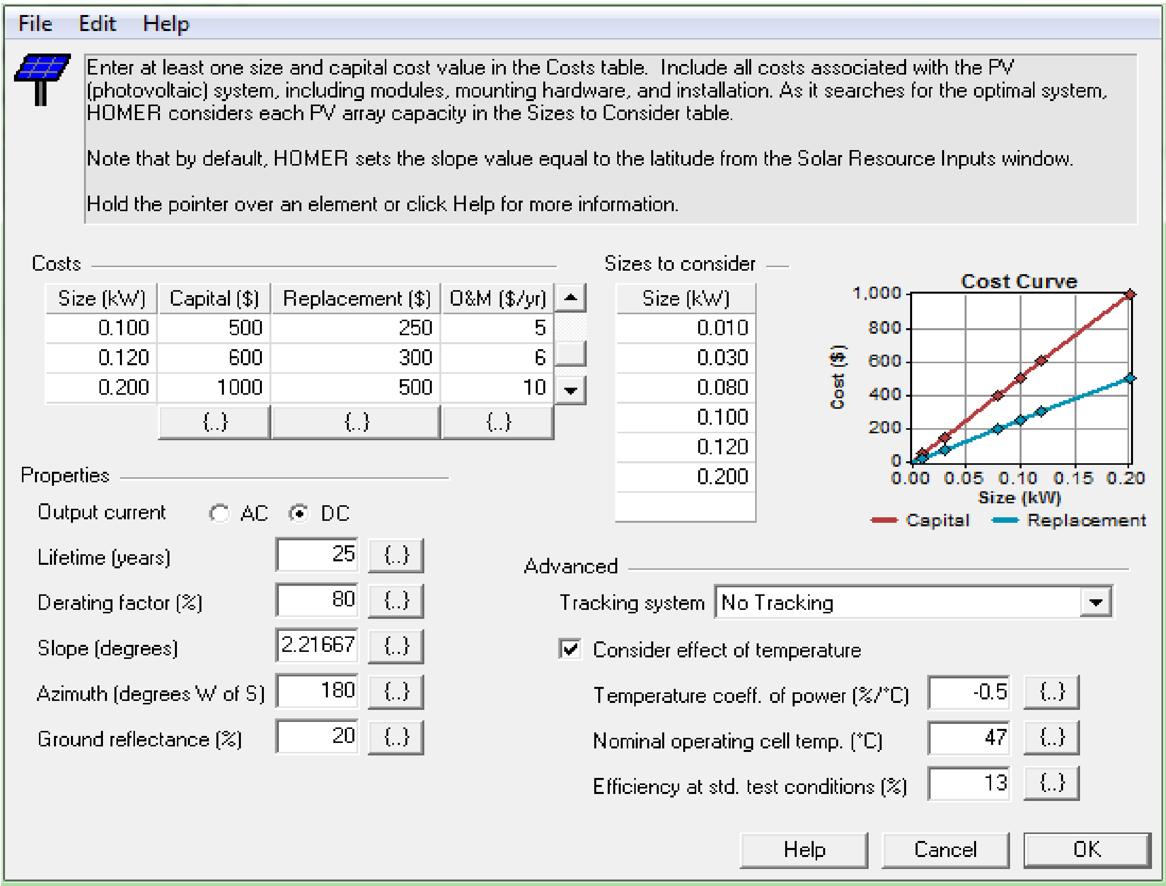


Fig. 5.4: Homer Input window for PV system used for electricity generation for a house in Kanazi cell.

The above PV input window is used to show the cost characteristic curve for PV panels, select the range of sizes that can be evaluated by Homer to obtain the optimal system for single house analysis and indicated the position of the solar panel. The cost of PV panel depends mainly on the system size as shown by the cost table in the above Figure 5.3. Since PV costs are generally assumed to be linear with size, there is a necessity of using only a single row [56].During the development of this work, the capital investment cost of the selected PV panel size of 0.2 kW has been specified and considered to be $1000 and the replacement cost is assumed to be $500. The operation and maintenance (O&M) cost is taken as $10.

5.1.3 Battery inputs

The input window displayed in Figure 5.5 below, contains all the types battery that are present within the homer component library. When the Homer user needs which type of battery to be considered, Homer provides many various types of batteries and their different properties by just clicking on details button. It is then easier to choose an appropriate battery type from the list based on predetermined specification that can efficiently match with the used PV system production. After selecting the optimal battery type, the user must enter the chosen values for capital cost, replacement cost, operation and maintenance cost and the size to consider for the storage system depends on the number of batteries per string regarding the desired nominal voltage and current or the optimal configuration.

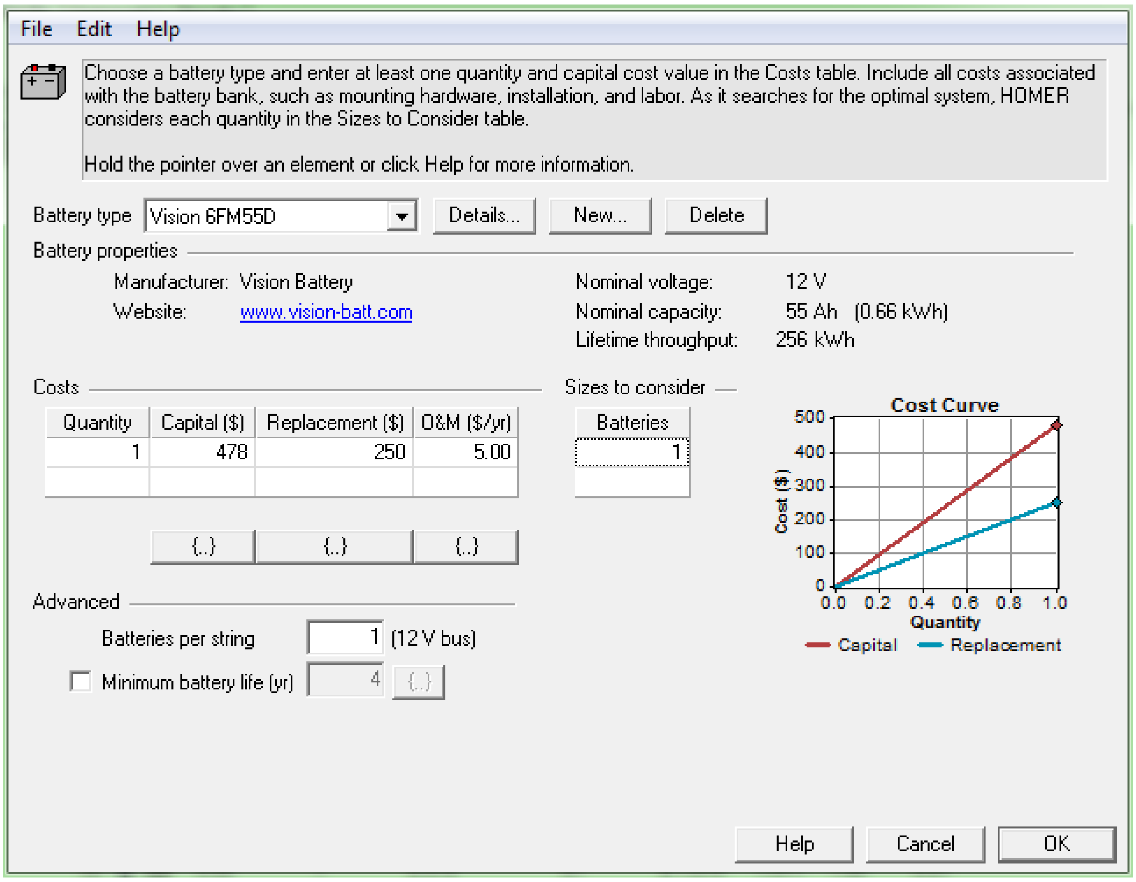


Fig. 5.5: Input window for the battery selected for solar home system design in Homer.

In this project work, the type of battery selected is Vision 6FM55D having a nominal voltage of 12V and 55Ah as nominal current capacity. For solar home system configuration, one battery is enough as shown in the above Figure 5.4 but for a bigger system if the number of batteries is k, then the costs for the total has be multiplied respectively. Finally, different costs for one battery unit have been considered as follows $478 for initial capital investment, $250 for replacement and $ 5 for annual O&M [55].

5.1.4 Modelling of Solar resource inputs

A resource in Homer terminology is defined as any external parameter that can be used by a component for production of electricity or heat [56]. In this research project, the solar radiation input has been taken as the main resource needed for optimum performance of the selected photovoltaic system configuration. The entered data for average daily radiation for each month for the village was provided by PVGIS (Photovoltaic Geographical Information System) for Africa. The latitude and longitude are used to specify the exact location of selected village site on the Earth's surface depending on the specified time zone. These two parameters are very important for obtaining the average daily radiation for each month that will enable homer to calculate the monthly clearness index of the chosen area. In this research work, the selected village in Nyamata used as case study for PV system is located at 2^o 13' latitude South and 3^o 6' longitude East as displayed by the Figure 5.6 below.

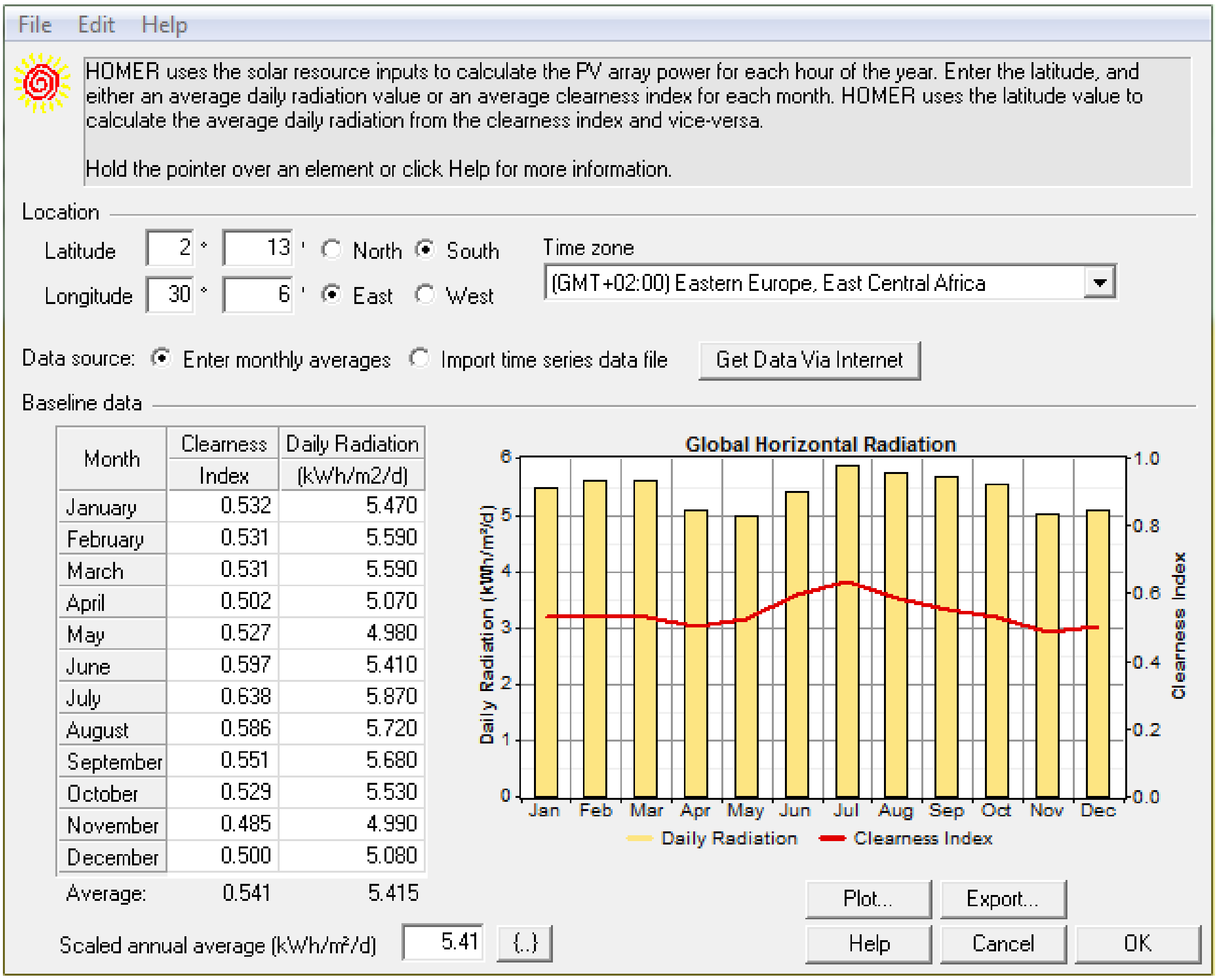


Fig. 5.6: Resource window with data for Kanazi village taken from PVGIS entered [19].

The Yearly scaled data for solar radiation intensity in Kanazi village based on hourly load for each day of every month is shown in Figure 5.7 below. Therefore, Homer uses the obtained PVGIS radiation data for Africa to compute the hourly solar radiation data based on the monthly average radiation and clearness index for the selected area as shown in appendix B for more details.

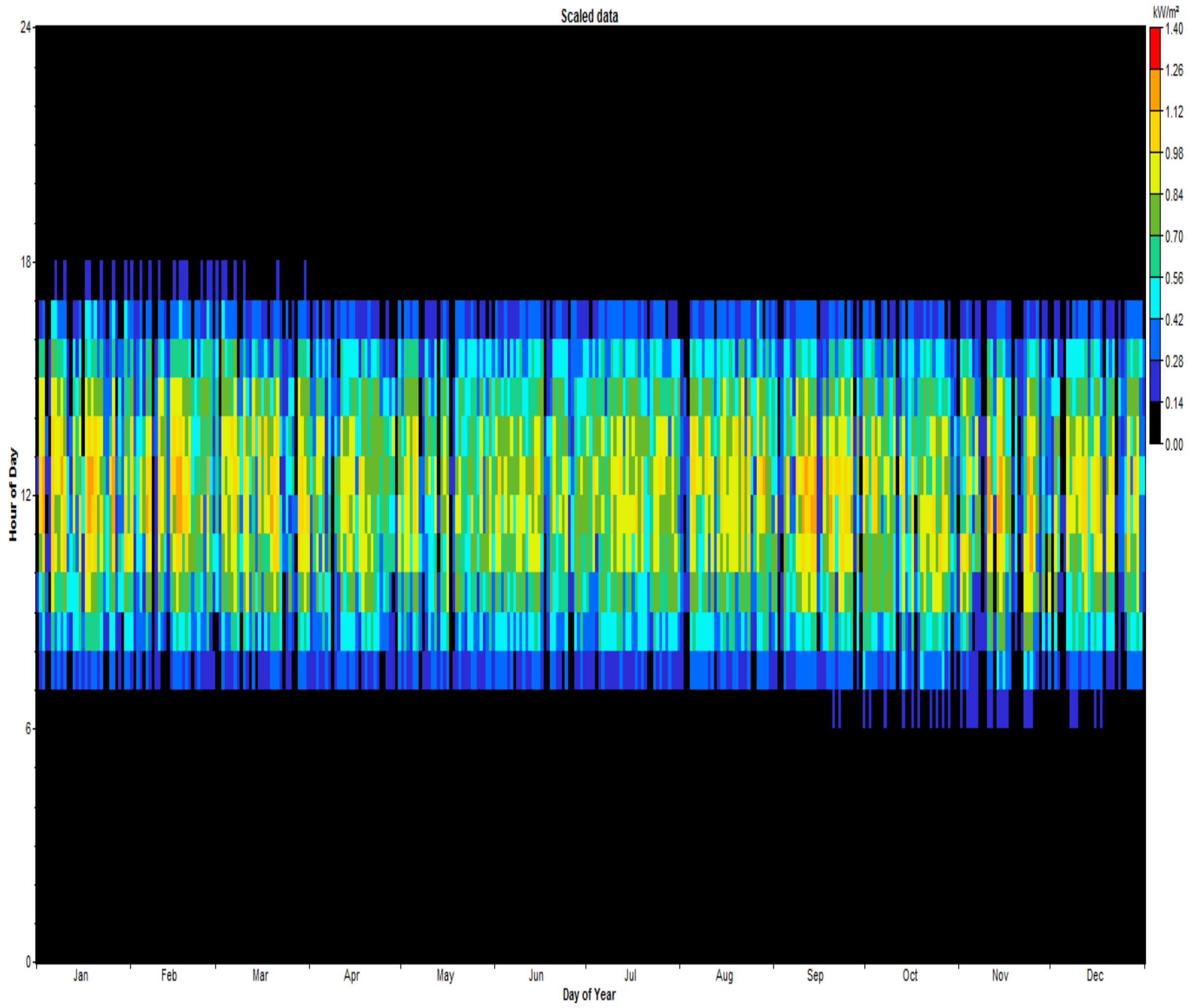


Fig. 5.7: Yearly scaled data for solar radiation intensity in Kanazi village based on hourly load.

Based on the results from the above Figure5.7, It is seen that for the selected village the sun rises around 7 in the morning with irradiance varying between 0.14 to 0.42 kW/m^2 and sets at 6 in the evening. The peak hours of sunshine are observed from 9 am to 3 pm with irradiance variation in the range of 0.56 to 1.26 42 kW/m^2 and the average number of peak hours is assumed to be equal to 5 hours per day.

5.2 Design of 10kW off-grid PV System for the village

The following are the inputs data used for designing the stand-alone village PV system and the design was done using Homer software so that both results will be later compared, discussed and analyzed in the next chapter.

- PV panel size is 10 kW, with a capital cost of $35000, replacement cost of $25000 and the maintenance together with operating cost per year were assumed to be $30.
- The peak load demand is 3.8 kW, and average of the daily demand is 48 kWh/d with a load factor of 0.528.
- Solar irradiance is 5.41 kWh/m^2/d, the clearness index is 0.541 and the average temperatures is 22°C.
- The selected battery for this project work is 6CS25P-Surrette of 6V presenting a nominal capacity of 1,156 Ah (6.94 kWh) and a round-trip efficiency of 80% with the capital cost of $ 1200, then the approximated replacement cost and O&M costs for one unit of this battery have been, assumed as $ 1200 and $ 30/year, respectively.

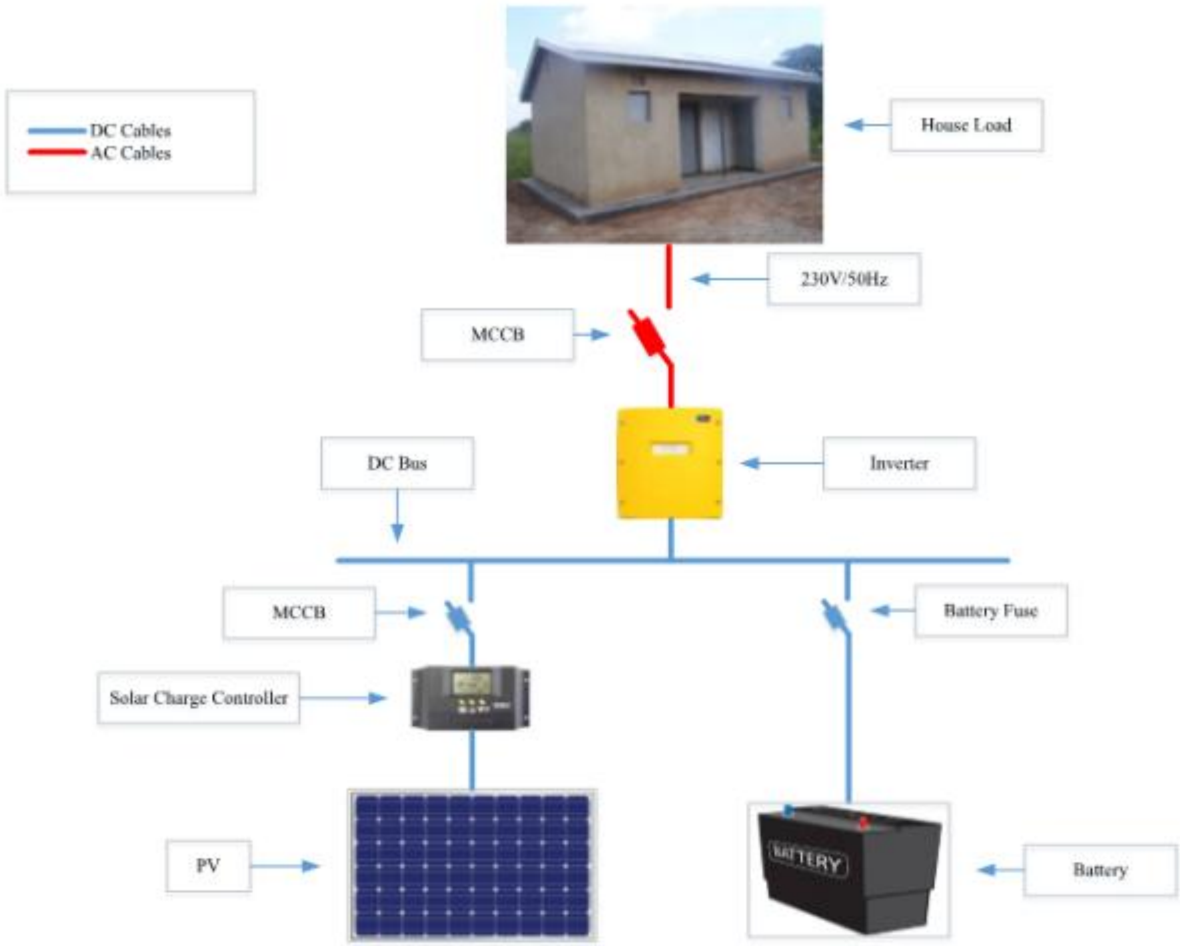


Fig. 5.8: Single line diagram for a village PV system of 10kW capacity in kanazi cell.

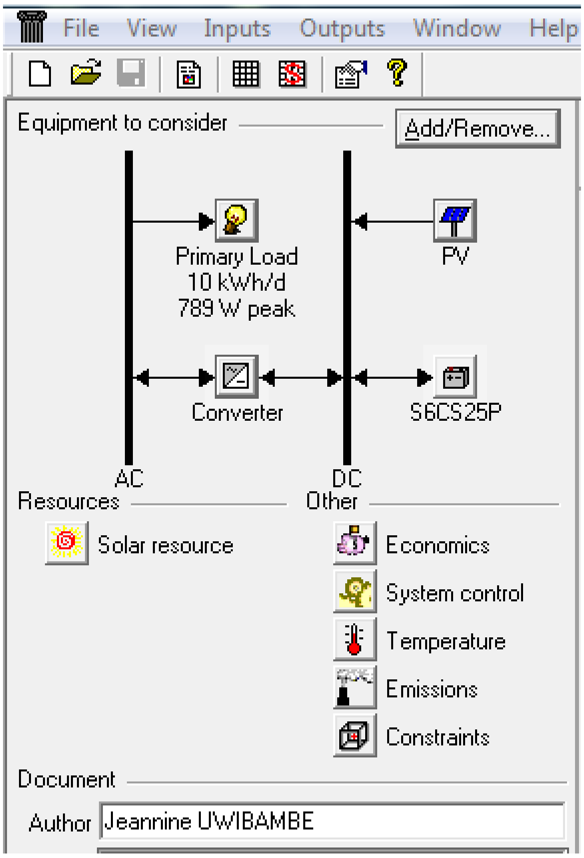


Fig. 5.9: Inputs for modelling a 10kW PV system for kanazi village using Homer Software.

The main factors that have been considered in this design include the solar resource that indicates the clearness index as well as the average daily radiation for each month based on latitude and longitude, the PV panel, the average primary load, the battery type, the converter type, the AC and DC buses. Therefore, Homer uses the solar resource inputs to calculate the PV array power for each hour of the year and it also uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa. From The above figure 5.9, the load demand for this village can increase up to 48kWh/day but in this case study, we will consider residential and commercial loads that can be supplied by a 10kW PV system.

5.2.1 Battery input

For obtaining the number of batteries to be used for optimal configuration, the user of Homer software can use the name plate shown in the figure below and first choose which type of battery to be used depending on the needed storage capacity as well as its cost [56].

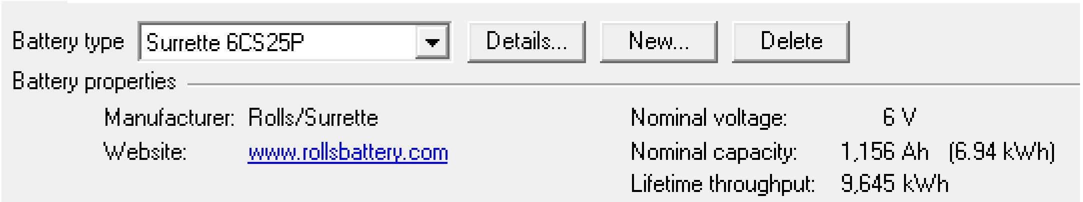


Fig. 5.10: Battery storage window with properties in homer component library.

The above library contains different types of battery found in homer component library and this provides the possibility for the Homer user to select from the existing list which type of battery to be used for system design and modelling. By clicking on details button on the right-hand side of the box, Homer displays many more various kind of battery storages and their different properties. For this case study, the chosen battery type is Surrette 6CS25P of 6V and 48V voltage system that requires 8 strings composed of 8 batteries in series.

As indicated by the below formula, the battery charging efficiency is assumed by the software to be the square root of the round-trip efficiency [56]:

$$\eta_{batt,c} = \sqrt{\eta_{batt,rt}} \tag{5.1}$$

$$\eta_{batt,d} = \sqrt{\eta_{batt,rt}} \tag{5.2}$$

Where

$\eta_{batt,c}$: charge efficiency,
$\eta_{batt,d}$: discharge efficiency
$\eta_{batt,rt}$: round-trip efficiency [56]

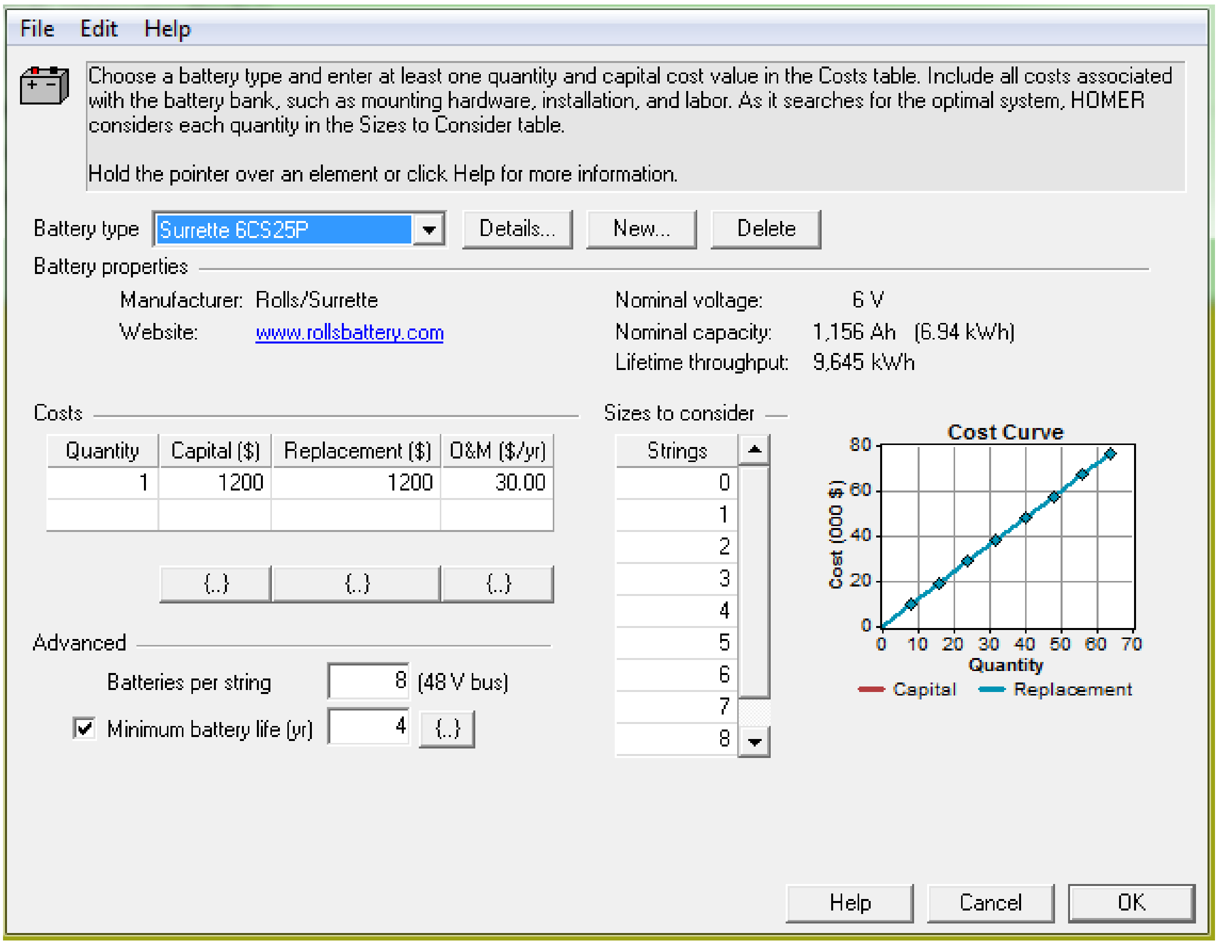


Fig. 5.11:Battery input window, from homer showing properties and cost curve.

The above figure 5.11 represents the window into which can be found all the necessary details regarding the battery selected for this case study. Those details show properties and cost estimation including the capital cost of $1200, replacement cost of $1200 as well as annual operation and maintenance costs of $30 [56]. The total cost will depend on the number of batteries multiplied by the cost per one single battery unit [56].

5.2.2 Converter input

A converter is needed for any system that is composed of both the AC and DC configuration [56]. It can be an inverter in case of DC to AC conversion or a rectifier for AC to DC or can serve both purposes. In this case, we have considered it as an inverter since it is used to convert the DC power generated by PV system into AC power supplied to loads.

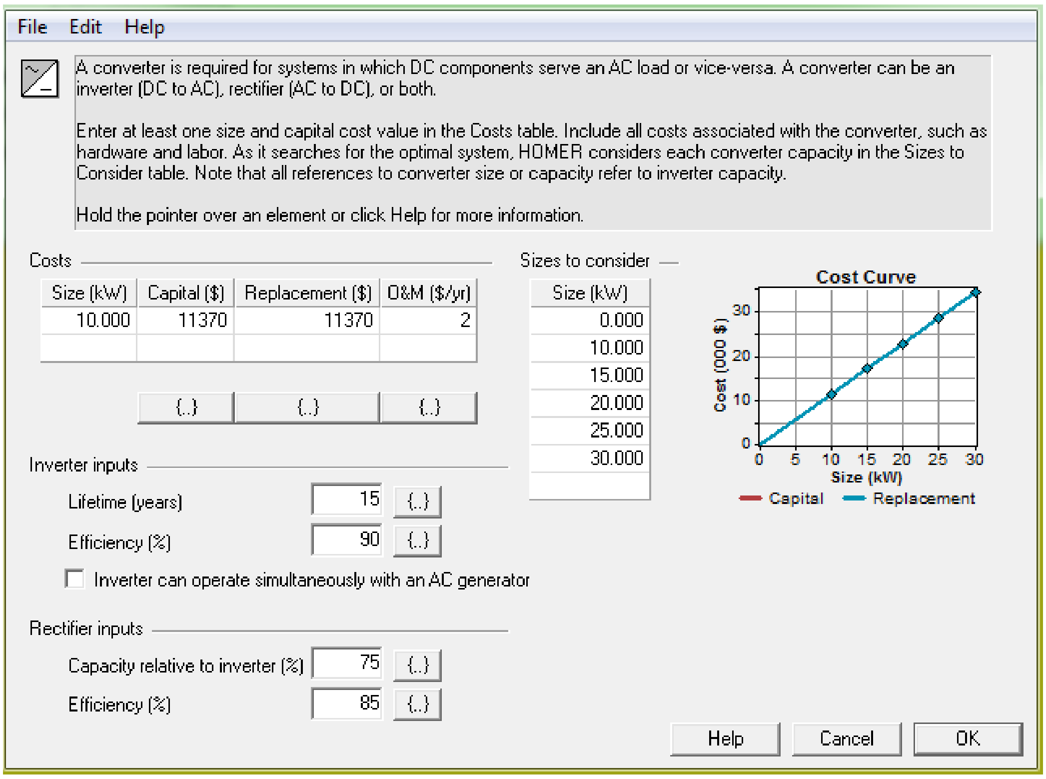


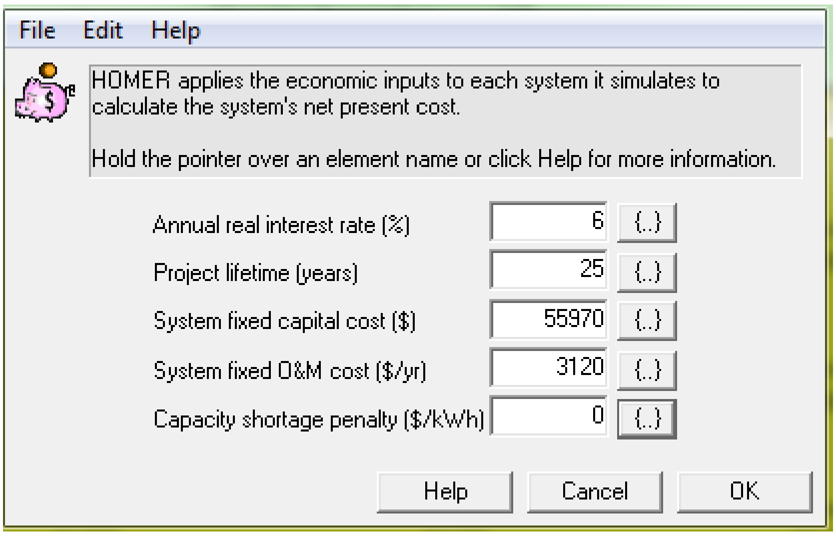
Fig. 5.12: Converter input window, from homer showing the cost curve and different sizes for the converter.

The above figure 5.12 shows the details concerning the sizes to be considered for optimal system, different types of costs as well as the cost curve for the converter referring to the capital and replacement costs. The cost of inverter is related to its size and in this case the capital as well as replacement costs for 10 kW converter is considered at $ 11,370. The efficiency of 90% used by the inverter for conversion from DC into AC form is provided by the manufacturer of the inverter and it is entered as input data for further Homer calculations, and the rectifier efficiency for converting AC into DC form is entered as 85% [56]. The project life time is defined as the number of operational years for the entire system [56]. In this case study, the life time for the selected inverter was estimated to be 15 years from Homer as displayed in the above figure 5.12.

5.2.3 Economic inputs

Homer software is useful for obtaining the optimal system configuration based on the Levelized COE analysis by calculating the Net Present Value (NPV) including all the costs for the lifetime of the project [56]. Furthermore, Homer classifies different types of configuration depending on how incremental is the total NPC and LCOE values [56].

Table 5.1: Economic inputs used by Homer for calculating the NPC for the system.



The total Net Present Cost (NPC) of the system is the difference between the present values of all the costs that occur over the project lifetime and the present values of all the revenue earned over project lifetime [56]. The formula below is used to calculate the net present value of the costs that will be made with n year later.

$$C_{NPC} = C\left(\frac{1+i'}{1+d}\right)^{n} \tag{5.3}$$

Where

i': is the annual inflation rate (%)

d: is the nominal interest rate (%)

The interest rate is used to convert between one-time costs and annualized costs [56]. It is also known as discount rate. Since renewable energy technologies such as solar PV systems have a higher capital cost but with lower operating and maintenance cost, the Levelized COE analysis must be conducted for the system depending on the life time to facilitate the economic evaluation of stand-alone systems supplied by solar PV systems. In contrast, due to fuel costs, generator maintenance and replacement costs fossil fuel based electricity generation systems have lower capital cost but higher operation and maintenance cost compared to the existing renewable energy technologies. Therefore, LCOE analysis can be used to compare the economic viability of various technological solutions for cost effectiveness.

6 Results

This chapter will be focusing on the analysis of results obtained from Homer simulations and the comparison between solar home systems and off-grid village systems based on the cost and availability. The simulation results are essential in obtaining the optimal PV system which means a system that is available and can supply electrical power at a lower cost referring to the total NPC, Levelized COE as well as the cost of operation.

6.1 Results for Solar Home System

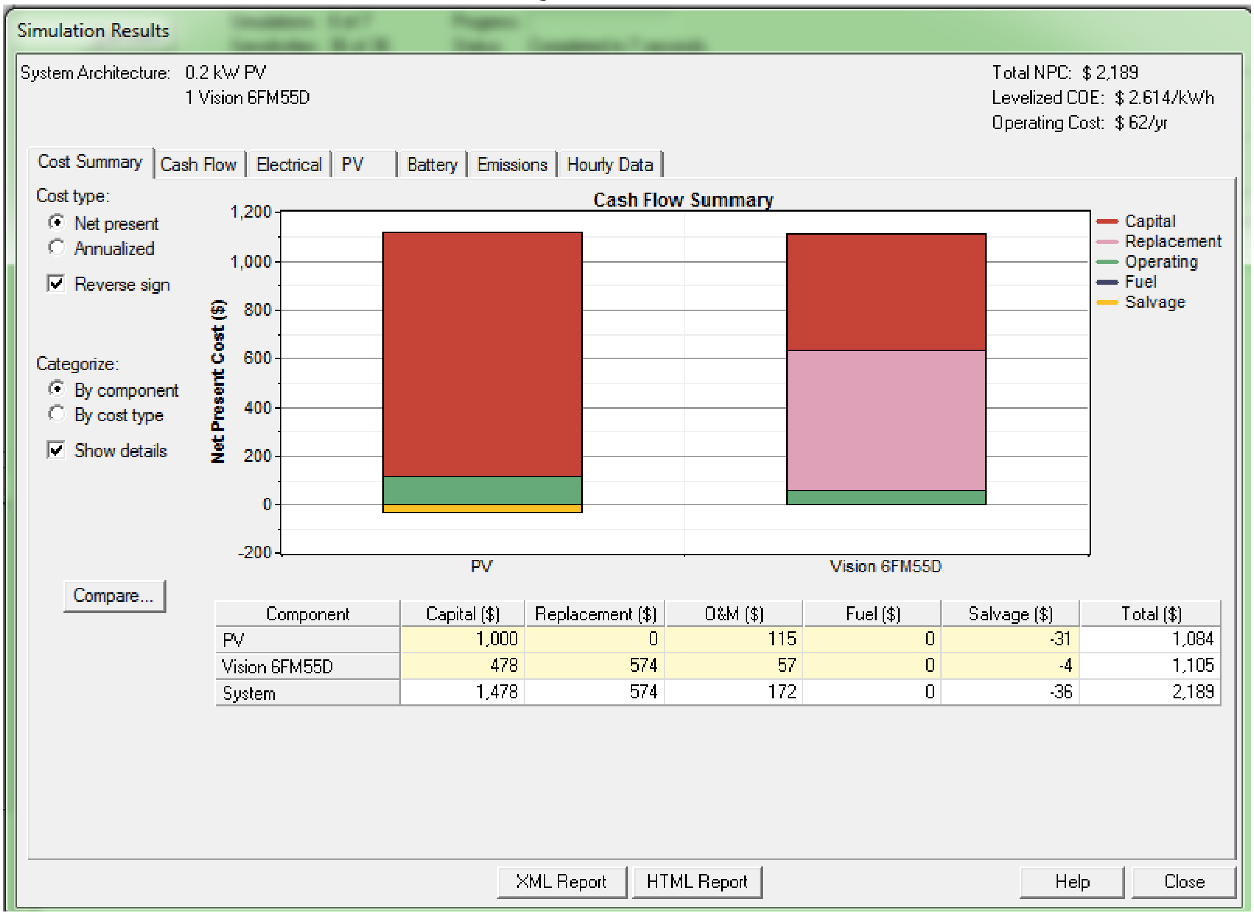


Fig. 6.1: Simulation results based on cash flow summary and Net Present Cost categorized by component.

The results obtained from different PV system sizes have been analyzed based on the Net present cost and the overall performance of the system using the same battery with different PV production capacity and the maximum size for SHS used in Rwanda for DC loads is 200W. This battery was chosen since it has the required nominal capacity for voltage and current to be used for solar home systems in Rwanda.

6.1.1 Overall Optimization Results

The solar home system designed for a typical single house with DC loads in Kanazi village was composed by the PV production capacity of 0.2 kW and a battery storage system of 55Ah as nominal capacity with a nominal voltage of 12V. Since the mentioned nominal capacity corresponds to 0.66 kWh, this implies that the used storage system can supply power to different loads in the house for a period of 3 days in case of low radiation intensity at the selected site.

Table 6.1: Overall Optimization Results without shortage.

Calculate | Simulations: 7 of 7 | Sensitivities: 36 of 36 | Progress: | Status: Completed in 6 seconds.

Sensitivity Results | Optimization Results

Sensitivity variables

Max. Annual Capacity Shortage (%) 0 | Min. Ren. Fraction (%) 0

Double click on a system below for simulation results.

		PV (kW)	6FM55D	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
		0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
		0.20	1	$ 1,478	62	$ 2,189	2.614	1.00	0.00

From homer optimization results in the above Table 6.1, representing a screen shot displaying the summary of outcomes for different size of PV system used for simulation considering no shortage. These include the initial capital, operating cost per year, total net present cost, capacity shortage for each system and the renewable fraction that explains the availability of the system as well as increase in reliability of supply from lower to bigger size. Therefore, since the renewable fraction was found to be the same from 0.03 kW to 0.2 kW this gives the possibility of designing a bigger PV system for the entire village community. The chosen optimal system configuration for my case study is the PV system size of 0.2kW, 1 Vision 6FM55D battery and the power dispatch strategy will depend on the load demand.

Table 6.2: Overall Optimization Results with Shortage.

Calculate   Simulations: 0 of 7   Progress:
Sensitivities: 36 of 36   Status: Completed in 7 seconds.

Sensitivity Results   Optimization Results

Sensitivity variables

Max. Annual Capacity Shortage (%) 50   Min. Ren. Fraction (%) 10

Double click on a system below for simulation results.

PV (kW)	6FM55D	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
0.10	1	$ 978	61	$ 1,683	2.016	1.00	0.00
0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.20	1	$ 1,478	62	$ 2,189	2.614	1.00	0.00

The above table 6.2 displays the optimization results considering a maximum annual capacity shortage of 50% and a minimum renewable fraction of 10%. The lowest energy cost is observed for a solar home system of 80W which is $1.780/kWh and for a SHS of 200W capacity, the energy cost is $2.614/kWh. Therefore, it is more economical to use one SHS of 200W instead of using two systems of 80W.

6.1.2 Sensitivity Results

By considering zero shortage and zero renewable fraction, the optimum system size for solar home system calculated by Homer was found to be 120W capacity with an initial capital of $1.078, operating cost of 61$/year, total NPC of $1.783 and the COE in $/kWh is 2.130.

Table 6.3: Tabular Sensitivity Results without shortage.

Calculate

Simulations: 7 of 7
Sensitivities: 36 of 36

Progress:
Status: Completed in 6 seconds.

Sensitivity Results | Optimization Results

Double click on a system below for optimization results.

Max. Cap. Shortage (%)	Min. RF (%)			PV (kW)	6FM55D	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
0.0	0			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	10			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	20			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	30			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	40			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	50			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
50.0	0			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	10			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	20			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	30			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	40			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	50			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
40.0	0			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	10			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	20			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	30			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	40			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	50			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	0			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	10			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	20			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	30			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	40			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	50			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
20.0	0			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
20.0	10			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01

Table 6.4: Tabular Sensitivity Results with shortage.

Calculate | Simulations: 7 of 7 | Sensitivities: 36 of 36 | Progress: | Status: Completed in 6 seconds.

Sensitivity Results | Optimization Results

Double click on a system below for optimization results.

Max. Cap. Shortage (%)	Min. RF (%)			PV (kW)	6FM55D	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
0.0	0			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	10			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	20			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	30			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	40			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
0.0	50			0.12	1	$ 1,078	61	$ 1,783	2.130	1.00	0.00
50.0	0			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	10			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	20			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	30			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	40			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
50.0	50			0.03	1	$ 678	27	$ 984	2.298	1.00	0.50
40.0	0			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	10			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	20			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	30			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	40			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
40.0	50			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	0			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	10			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	20			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	30			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	40			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
30.0	50			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01
20.0	0			0.08	1	$ 778	60	$ 1,470	1.780	1.00	0.01

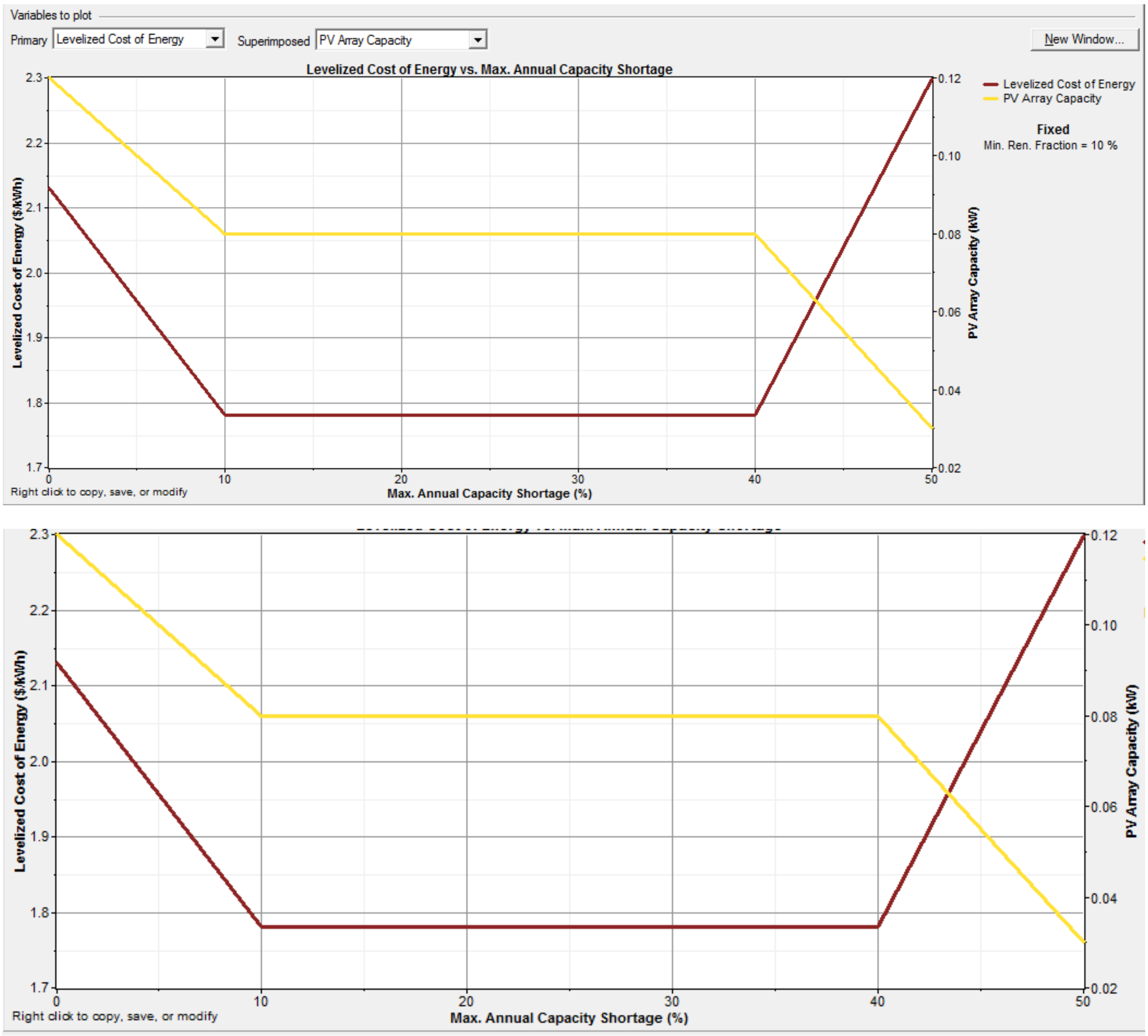


Fig. 6.2: Levelized cost of energy vs PV array capacity with a fixed renewable fraction of 10%.

In the above figure 6.2, the red line represents the Levelized cost of energy and the yellow line represents the PV array capacity regarding the maximum capacity shortage for the system. Considering a case of the maximum capacity shortage of 50% and minimum renewable fraction of 10%, when the capacity shortage is less than 40% the LCOE and the PV array capacity are directly proportional but above 40% they become inverse. Therefore, the optimum size for solar home system calculated by Homer is 30W presenting an initial capital of $678, operating cost of $27 per year, total NPC of $984 and the COE is $2.298/kWh as shown by the above table 6.4. This implies that the reliability of supply depends upon the maximum capacity shortage and the minimum renewable fraction of the system.

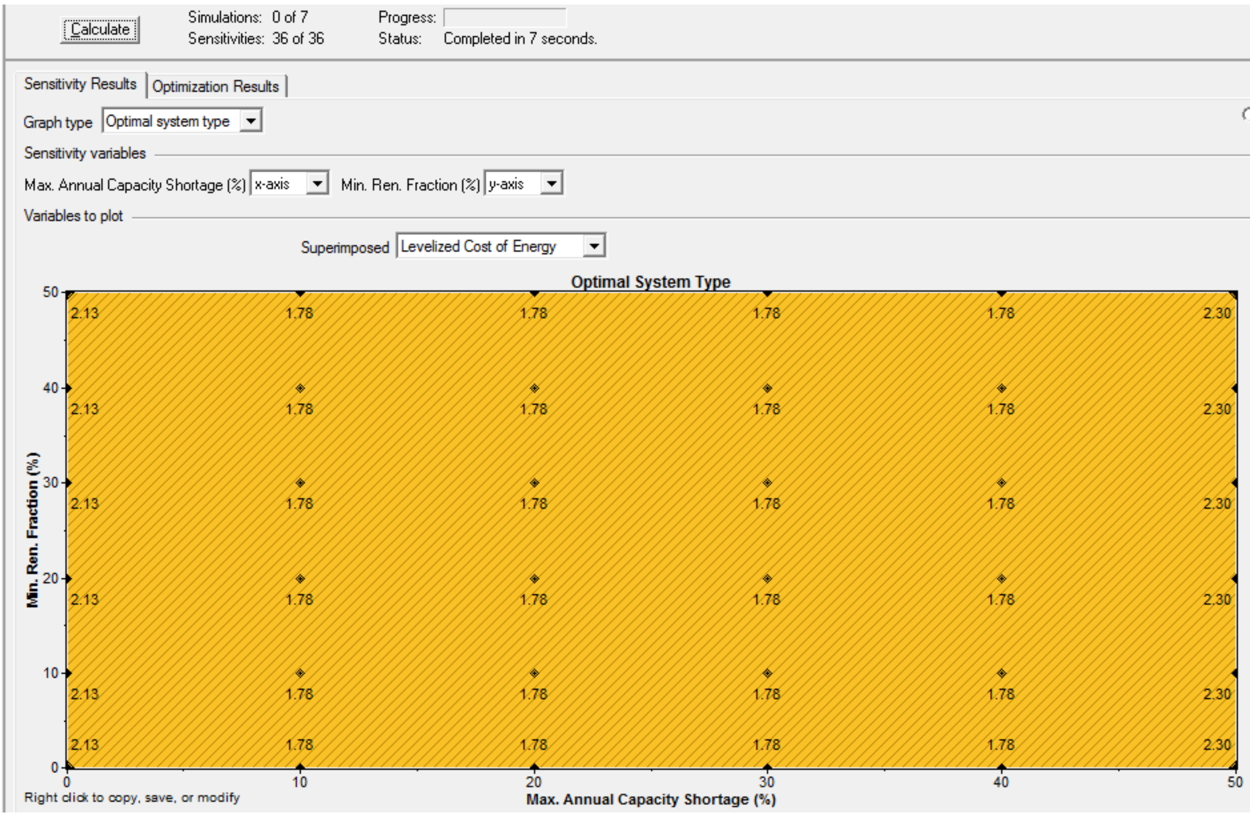


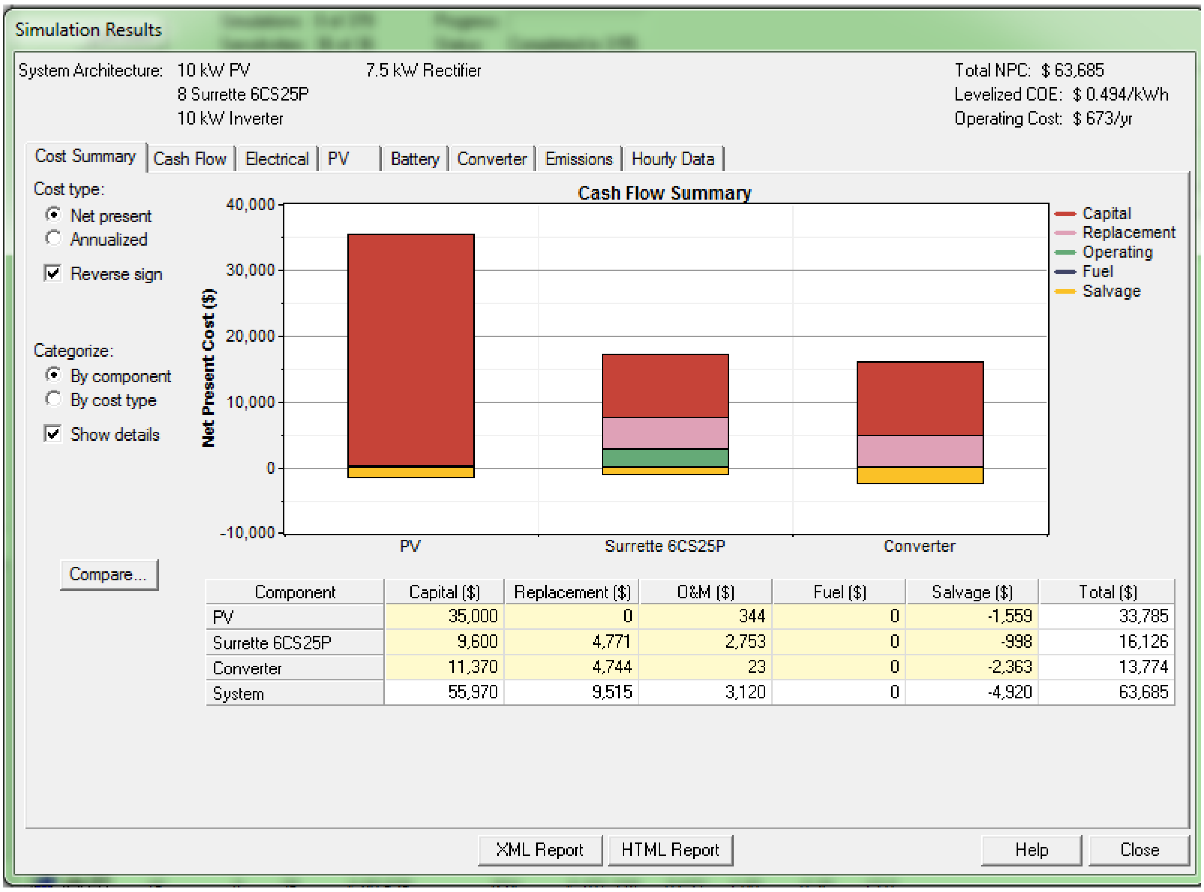
Fig. 6.3: Graphical Sensitivity Results based on Levelized COE.

The above figure 6.3 displays the graphical sensitivity results calculated by Homer based on the Levelized COE which is defined as the cost per kWh of electrical energy consumed throughout the lifetime of the PV system. The LCOE analysis has been performed considering a lifetime of 25 years with all relevant costs namely the initial capital investment and operating as well as maintenance costs. The Levelized COE for electrical power produced by a photovoltaic system can be calculated from the following equation below.

$$LCOE = \frac{Total\ Annualized\ Cost\ (\frac{€}{year})}{Total\ Energy\ Consumed\ (\frac{kWh}{year})} \tag{6.1}$$

6.2 Results for 10kW Village PV System

The analysis was done for different PV sizes using Homer software and a specific system of 10kW capacity was chosen to be optimum since it is more economical and reliable in terms of cost and availability of the supply compared to the use of individual solar home system. In addition, the key input parameters have been modified for sensitivity analysis to be performed.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	35,000	0	344	0	-1,559	33,785
Surrette 6CS25P	9,600	4,771	2,753	0	-998	16,126
Converter	11,370	4,744	23	0	-2,363	13,774
System	55,970	9,515	3,120	0	-4,920	63,685

Fig. 6.4: Simulation results based on cash flow summary and Net Present Cost categorized by component

The above figure 6.4 shows the selected PV system of 10kW capacity with an inverter of 10kW and 8 batteries per string. The total NPC calculated by Homer is equivalent to $63,685 and the Levelized COE as well as the cost of operation are $0.494 per kWh and $673 per year respectively. The system architecture obtained displays the simulation results in details based on cash flow summary and the NPC categorized by each component considering the capital, replacement, salvage, operation and maintenance costs.

Table 6.5: Overall Optimization Results with no Shortage.

Sensitivity Results | Optimization Results

Sensitivity variables

Max. Annual Capacity Shortage (%) 0 Min. Ren. Fraction (%) 0

Double click on a system below for simulation results.

PV (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Batt. Lf. (yr)
20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
20	32	15	$ 125,455	2,378	$ 152,734	0.761	1.00	0.00	12.0
20	32	20	$ 131,140	2,483	$ 159,621	0.795	1.00	0.00	12.0
20	40	10	$ 129,370	2,843	$ 161,973	0.806	1.00	0.00	12.0
25	32	10	$ 137,270	2,221	$ 162,740	0.810	1.00	0.00	12.0
30	24	10	$ 145,170	1,599	$ 163,507	0.814	1.00	0.00	12.0
20	32	25	$ 136,825	2,588	$ 166,508	0.829	1.00	0.00	12.0
20	40	15	$ 135,055	2,947	$ 168,860	0.840	1.00	0.00	12.0
25	32	15	$ 142,955	2,325	$ 169,627	0.844	1.00	0.00	12.0
30	24	15	$ 150,855	1,703	$ 170,394	0.848	1.00	0.00	12.0
20	32	30	$ 142,510	2,693	$ 173,395	0.864	1.00	0.00	12.0
20	40	20	$ 140,740	3,052	$ 175,747	0.875	1.00	0.00	12.0
25	32	20	$ 148,640	2,430	$ 176,514	0.878	1.00	0.00	12.0
30	24	20	$ 156,540	1,808	$ 177,280	0.882	1.00	0.00	12.0
20	48	10	$ 138,970	3,411	$ 178,099	0.886	1.00	0.00	12.0
25	40	10	$ 146,870	2,790	$ 178,866	0.890	1.00	0.00	12.0
30	32	10	$ 154,770	2,168	$ 179,633	0.894	1.00	0.00	12.0
20	40	25	$ 146,425	3,157	$ 182,634	0.909	1.00	0.00	12.0
25	32	25	$ 154,325	2,535	$ 183,401	0.913	1.00	0.00	12.0
30	24	25	$ 162,225	1,913	$ 184,167	0.917	1.00	0.00	12.0
20	48	15	$ 144,655	3,516	$ 184,986	0.921	1.00	0.00	12.0
25	40	15	$ 152,555	2,894	$ 185,753	0.924	1.00	0.00	12.0
30	32	15	$ 160,455	2,272	$ 186,520	0.928	1.00	0.00	12.0

Table 6.6: Categorized Optimization Results with zero shortage

Sensitivity Results | Optimization Results

Sensitivity variables

Max. Annual Capacity Shortage (%) 0 Min. Ren. Fraction (%) 0

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

PV (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Batt. Lf. (yr)
20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0

The above tables 6.5 and 6.6 show homer optimization results, representing a screen shot displaying the summary of outcomes for different sizes of PV system used for simulation considering no shortage. These include the initial capital, operating cost per year, total net present cost, capacity shortage for each system and the renewable fraction that explains the availability of the system as well as increase in reliability of supply from lower to bigger size. Therefore, since the renewable fraction was found to be the same from 20kW to 30kW this gives the possibility to select a 20 kW PV system for the entire village community in case of increase on demand side management.

Table 6.7: Overall Optimization Results with Capacity shortage

Sensitivity Results | Optimization Results

Double click on a system below for optimization results.

Max. Cap. Shortage (%)	Min. RF (%)	PV (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Batt. Lf. (yr)
0.0	0	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	10	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	20	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	30	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	40	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	50	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
50.0	0	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	10	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	20	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	30	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	40	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	50	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	0	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	10	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	20	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	30	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	40	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	50	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
30.0	0	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	10	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	20	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	30	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	40	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	50	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0

Table 6.8: Categorized Optimization Results with capacity shortage

Sensitivity Results | Optimization Results

Sensitivity variables

Max. Annual Capacity Shortage (%) 50 Min. Ren. Fraction (%) 10

Double click on a system below for simulation results.

PV (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Batt. Lf. (yr)
10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
15		10	$ 63,870	51	$ 64,451	0.599	1.00	0.49	

The above optimization results are not enough to be considered for obtaining the optimum sizing of the PV system since Homer does not cover all costs related to the performance of the village system. Also, the inputs data entered in Homer may not be fully accurate because they were taken from PVGIS and this may result in a small difference between those inputs and the real data. Therefore, the above optimization results can be made more reasonable by considering some uncertainties in the input variables and this can be achieved through the sensitivity analysis.

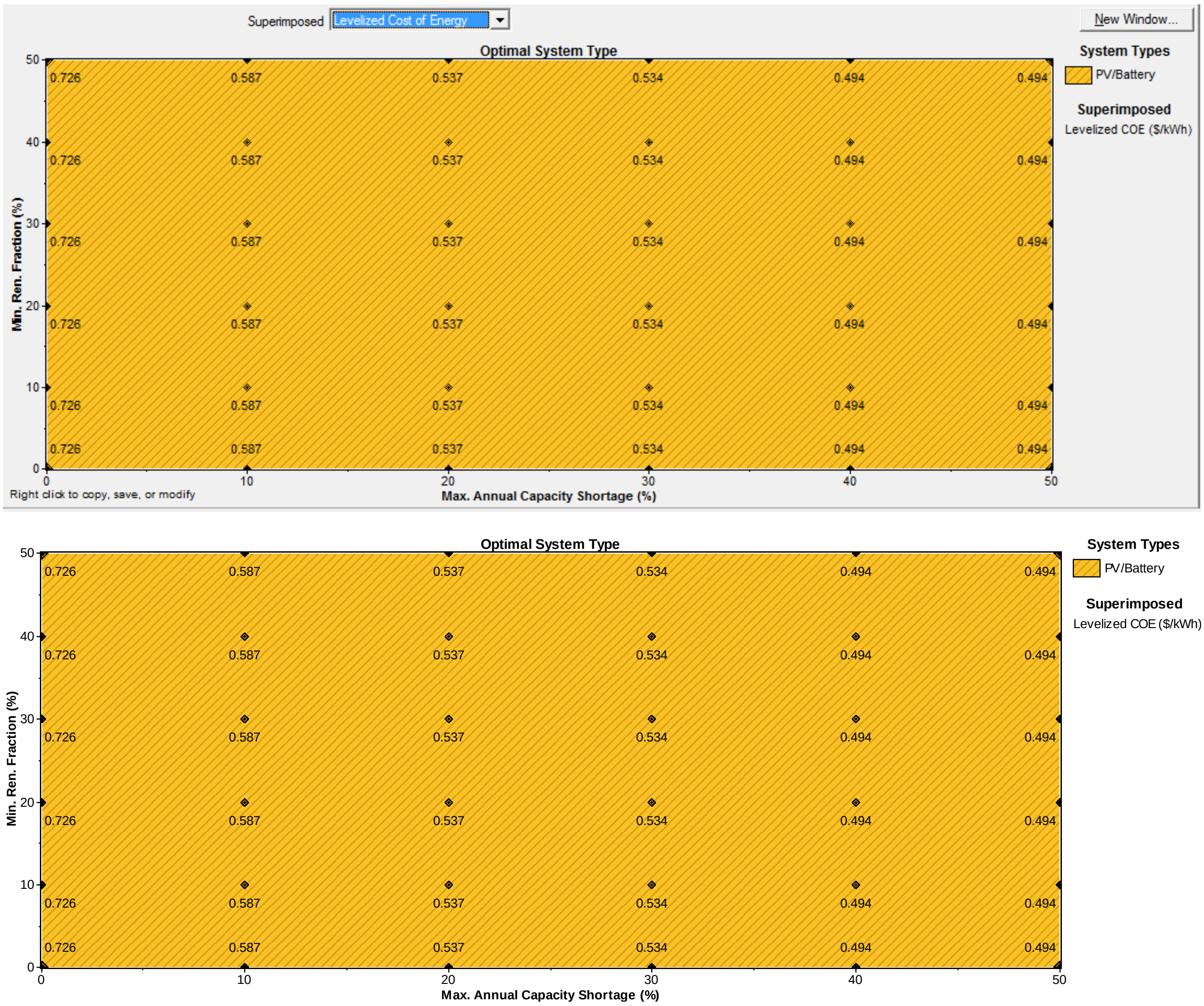


Fig. 6.5: Graphical Sensitivity Results based on LCOE:

The optimal system type present a Levelized COE of 0.587 considering the sensitivity analysis which is different from the LCOE obtained by optimization results which was 0.494 but the difference is very small about 0.093 and this is due to the intermittency of renewable energy resources which varies depending on different climatic conditions making them unpredictable.

Table 6.9: Tabular Sensitivity Results with shortage.

Sensitivity Results | Optimization Results

Double click on a system below for optimization results.

Max. Cap. Shortage (%)	Min. RF (%)	PV (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Batt. Lf. (yr)
0.0	0	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	10	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	20	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	30	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	40	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
0.0	50	20	32	10	$ 119,770	2,274	$ 145,848	0.726	1.00	0.00	12.0
50.0	0	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	10	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	20	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	30	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	40	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
50.0	50	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	0	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	10	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	20	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	30	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	40	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
40.0	50	10	8	10	$ 55,970	673	$ 63,685	0.494	1.00	0.38	12.0
30.0	0	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	10	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	20	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	30	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	40	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
30.0	50	15	8	10	$ 73,470	620	$ 80,577	0.534	1.00	0.26	12.0
20.0	0	15	16	10	$ 83,070	1,189	$ 96,703	0.537	1.00	0.11	12.0

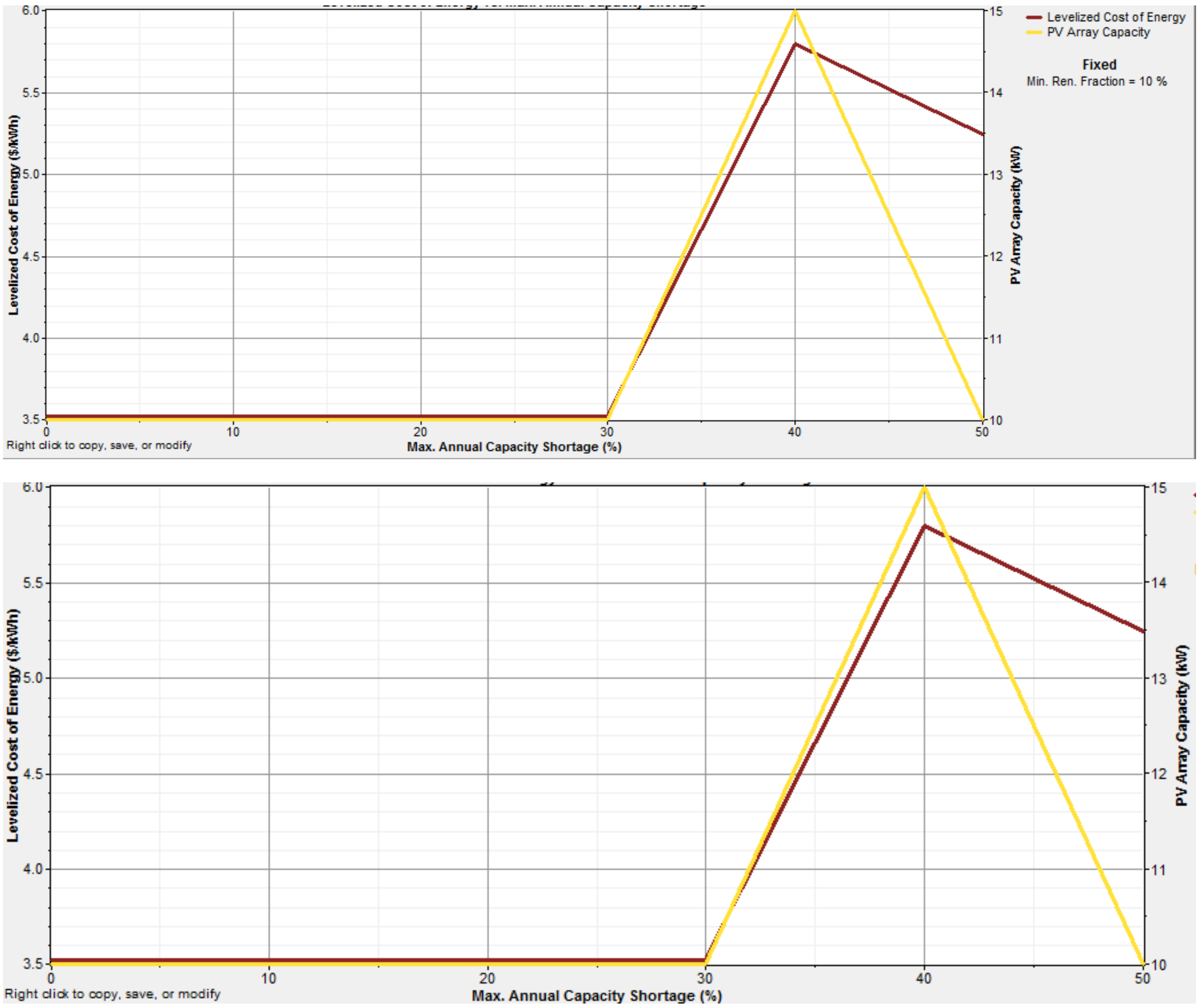


Fig. 6.6: LCOE vs PV array capacity with a fixed renewable fraction of 10% for the village system of 10kW.

The above table 6.9 displays the sensitivity results considering a maximum capacity shortage of 50% and a minimum renewable fraction of 10%. Also, the figure 6.6 above shows the LCOE by a red line and the PV Array capacity by a yellow line which implies that they are proportional to each other and this provides a chance for designing bigger systems. In this case the optimum sizing for PV system is 10kW with 8 Surrette batteries and a 10kW inverter as highlighted in a blue color in the table above, all having an initial capital of $55,970, operating cost of $673 per year, total NPC of $63,685 and the COE of $0.494 per kWh. Sensitivity analysis also shows in table 6.9 that in terms of reliability and economic constraints, it is much more efficient to use two systems of 10kW each instead of using a 20kW system

7 Discussion

The aim of this master's thesis was to analyze the use of PV system to convert solar energy into electric power to supply the electricity need in rural areas. The preliminary design step was based on the comparison of different solar home systems for a typical single house in Kanazi village, Nyamata sector of Bugesera district. This village is located at a far distance from national grid lines and most of the population do not have access to electricity from the grid. The Bugesera district receives a large amount of sunlight with an annual average solar radiation of 5,28 kWh/m^2/day. In addition, Bugesera is one of the driest site among other districts of the eastern province of Rwanda since its average temperature is high, with values above 21°C and the precipitation amount in this area is the lowest in the whole country, with values below 900 millimeters per year. Therefore, the above factors have been taken into consideration while selecting Bugesera district as an interesting site on which this study was performed, using solar PV technology as a renewable energy resource for electricity. A fixed daily load profile shown in Figure 3.3 has been assumed throughout the year because Rwanda is located closer to the equator, therefore Bugesera district is not affected by seasonal variations and the day length does not change in a significant way. The average daily load demand for the single house in Kanazi village is 200Wh/day and the peak load is 71W, thus the system size has been chosen to be above that peak of load.

The used overall system consists of a PV panel with a rated power of 200W and a storage battery consist of Vision 6FM55D with a nominal capacity of 55 Ah, 12V. For this system, the maximum annual capacity shortage calculated by homer is 50% and the minimum renewable faction is 10%. Further analysis was performed based on different PV sizes used in Rwanda for existing solar home system (SHS) in the range of 30 W to 200W, to identify which system is more efficient and compare it with a 10kW PV village system. If we compare in terms of total cost for the village with only SHS to a village system of 10kW It is evident that the village system becomes more economical. For example, considering a village of 300 homes having each a SHS of 200W that costs \$1478 including additional cost of operation and maintenance means that the total is 300×\$1478 which equals \$443400 yet for the village system of 10kW that can supply a minimum of 50 houses the cost is \$55970 which means that it is required to have 6 systems of 10kW each to supply 300 houses and the total cost for those systems is \$55970×6 which equals \$335820. Therefore, there is a difference of \$107580 that can be saved by taking an option of using a much bigger solar PV system for the rural community with a suitable operation and maintenance scheme which can ensure the sustainable operation of the system.

Moreover, the obtained solar home system solution and village system can only be implemented in other rural locations if the environment's conditions such as solar radiation, sun hours and temperature requirement are similar. Furthermore, the PV system performance and efficiency should also remain unchanged but there is a possibility of moving to the design of bigger off-grid system in case of high load demand. A study conducted for a year by Zakaria Bouzid and Nassera Ghellai to ensure an optimal configuration and to prevent energy deficit has proven that for many hours of the year, the batteries are fully charged and the energy produced by the photovoltaic panels is lost. Therefore, an increase in the total energy storage capacity could solve this problem for a better management of energy flow. [3] Instead of waiting for the grid power in case of increase in demand, the best option is the design of higher capacity stand-alone PV system of 10kW with a big battery storage capacity that can supply the entire village community. This is proposed as the best option because the cost of extending the grid to rural villages is extremely high, around 21.000 $ per km of one power distribution line and the current national grid electric power price for the domestic consumers in Rwanda lies in the range of 0.2 – 2.4 $/kWh. Therefore, it is confirmed that the cost of the energy consumption is high compared to the alternative use of photovoltaic system.

8 Conclusion and Future work

The main purpose of this master's thesis project work was to design and compare a solar home system with an off-grid village system of 10kW capacity to obtain an economical option for rural electrification in Kanazi cell, Bugesera District of Rwanda which is composed of 300 houses taken for this case study. The goal was achieved by considering the global horizontal radiation at the selected site and by considering the primary load obtained during the survey conducted for single house analysis in daily hours considering the cost for an individual solar home system and the overall cost for the village system. In addition, an evaluation of the climate data as well as the potential of renewable energy resources available in that area has been done for finding feasible solutions for the entire population.

In fact, the method of gathering climate data and solar resources has been a useful approach to understand where this system can mostly be suitable for usage. As shown by the research, Bugesera district is a region with high intensity of solar radiation and low rain-fed, especially in Nyamata Sector. Therefore, the use of photovoltaic technologies for electricity production and supply has been a sustainable solution for the population in rural villages that are far from national electric grid. Photovoltaic systems are not capable of ensuring a continuous electric power supply unless if they are connected to an additional storage system. Since this became a serious challenge during rainy days it was impossible for the PV panels to provide the needed electrical power. Hence batteries have been associated with solar home system, village system and other solar based technologies.

Furthermore, after selecting the appropriate components for the entire system and describing their behavior, both systems have been modelled in HOMER software, and system simulations have been conducted to determine the best system which can be more economical and reliable for supplying power to rural areas predicting the increase in load demand and consumption. The simulation results have shown that it is more advantageous to use a 10kW off-grid system for village electrification, although the initial capital investment is higher, it is much more economical throughout the lifetime compared to the grid connection since the electricity prices in Rwanda stand around $0.226/kWh as announced in the report published by the African Development Bank regarding the energy sector review and action plan [57]. Solar PV is indeed a good alternative for electricity generation because it is both cheaper and beneficial towards energy independence, in addition to being one of the most abundant renewable energy resource that is available in Rwanda.

Finally, this project work provides a basis and framework for the evaluation of this solution not only in Bugesera, but also in other parts of the country where the sun shine is relatively intensive and based on the results from simulation, an additional step of grid connection during the rainy season can also be embraced. Therefore, the village system of 10kW is selected to be the best since solar home systems are limited to household applications and the availability of supply is low. The option for grid connection will depend on the increase of load demand and climate change and this will enable the solar system to sell power to the grid in case of excess production of PV modules and to buy power from the grid during the rainy season.

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Appendices

Appendix A Mobisol customers in Kanazi cell, Nyamata sector, Bugesera district.

Db id	Name	Location	System size	Approved at
98375	Rwanda Online/ Bihari	Bihari, Kanazi, Nyamata, Bugesera, RW	Solar Home System 200W RW	2016-09-26
48410	Karanganwa Papias	Musagara, Kanazi, Nyamata, Bugesera, RW	Family V8 SHS 100 W	2016-01-07
48176	Nsanzumuhire Celestin	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 200W RW	2016-01-05
44069	Shyaka Bernard	Musagara, Kanazi, Nyamata, Bugesera, RW	Family V8 SHS 100 W	2015-12-02
39267	Hagenimana Theoneste	Rugando, Kanazi, Nyamata, Bugesera, RW	Family V8 SHS 100 W	2015-10-22
32759	Nyamata Teacher Training College(ttc)	Musagara, Kanazi, Nyamata, Bugesera, RW	Solar Home System 200W RW	2015-08-24
23461	Barawigirira Angelique	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 30W RW	2015-05-19
15845	Bagirigomwa Octave	Nyarugati I, Kanazi, Nyamata, Bugesera, RW	Solar Home System 120W - V7 -17"	2014-12-19
11222	Mutesi Annonciathe	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 100W RW	2014-09-25
6025	Ntakirutimana Marie Rose	Nyarugati I, Kanazi, Nyamata, Bugesera, RW	Solar Home System 80W - V7 - 17"	2014-07-03
5345	Senzira Jean Bosco	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 80W - V7 - 17"	2014-06-15
5308	Bihezande Aimable	Nyarugati I, Kanazi, Nyamata, Bugesera, RW	Solar Home System 120W - V7 -17"	2014-06-14

5063	Nsanzimana Bruno	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 30W - V7	2014-06-08
4473	Ngayaberura Gerard	Nyarugati I, Kanazi, Nyamata, Bugesera, RW	Solar Home System 30W - V7	2014-05-23
4299	Ngoga Emmanuel	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 120W - V7 -17"	2014-05-16
4176	Uwamariya Angele	Gitovu, Kanazi, Nyamata, Bugesera, RW	Solar Home System 80W - V7 - 17"	2014-05-11
3984	Habirora Herman	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 30W - V7	2014-05-04
3523	Ukobukeye Philbert	Rugando, Kanazi, Nyamata, Bugesera, RW	Solar Home System 120W - V7 -17"	2014-04-25
3427	Ndayisaba Daniel	Nyarugati I, Kanazi, Nyamata, Bugesera, RW	Solar Home System 120W - V7 -17"	2014-04-21

Appendix B Photovoltaic Geographical Information for Nyamata Sector.

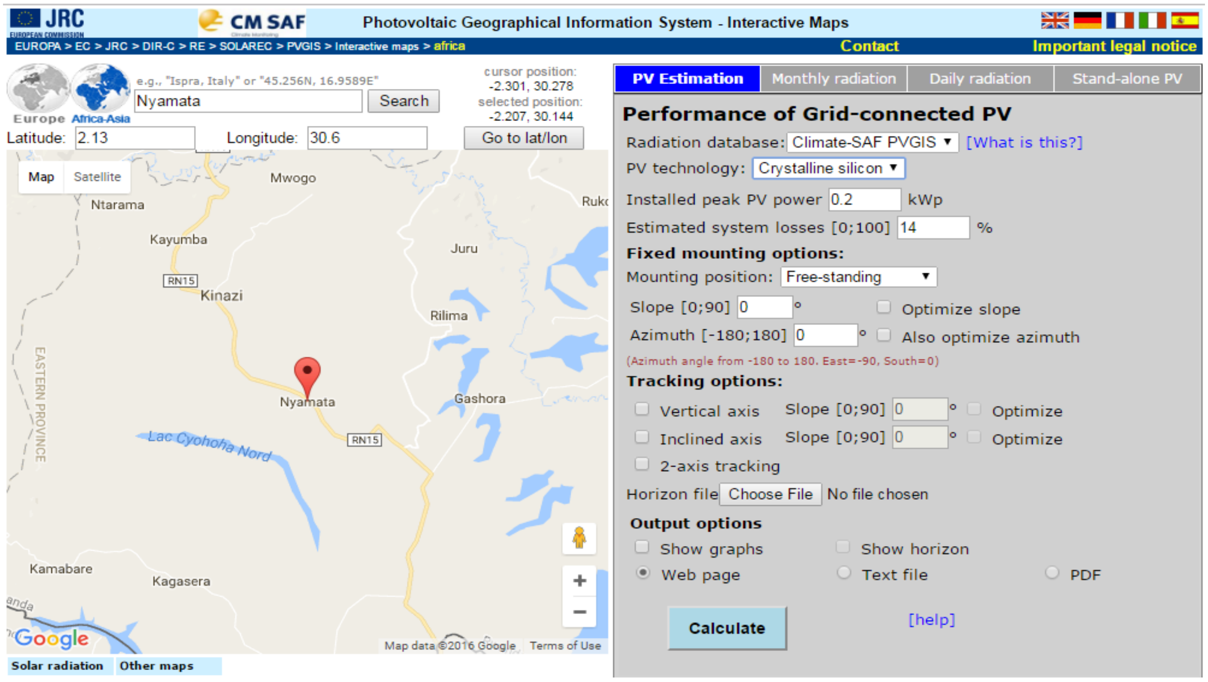
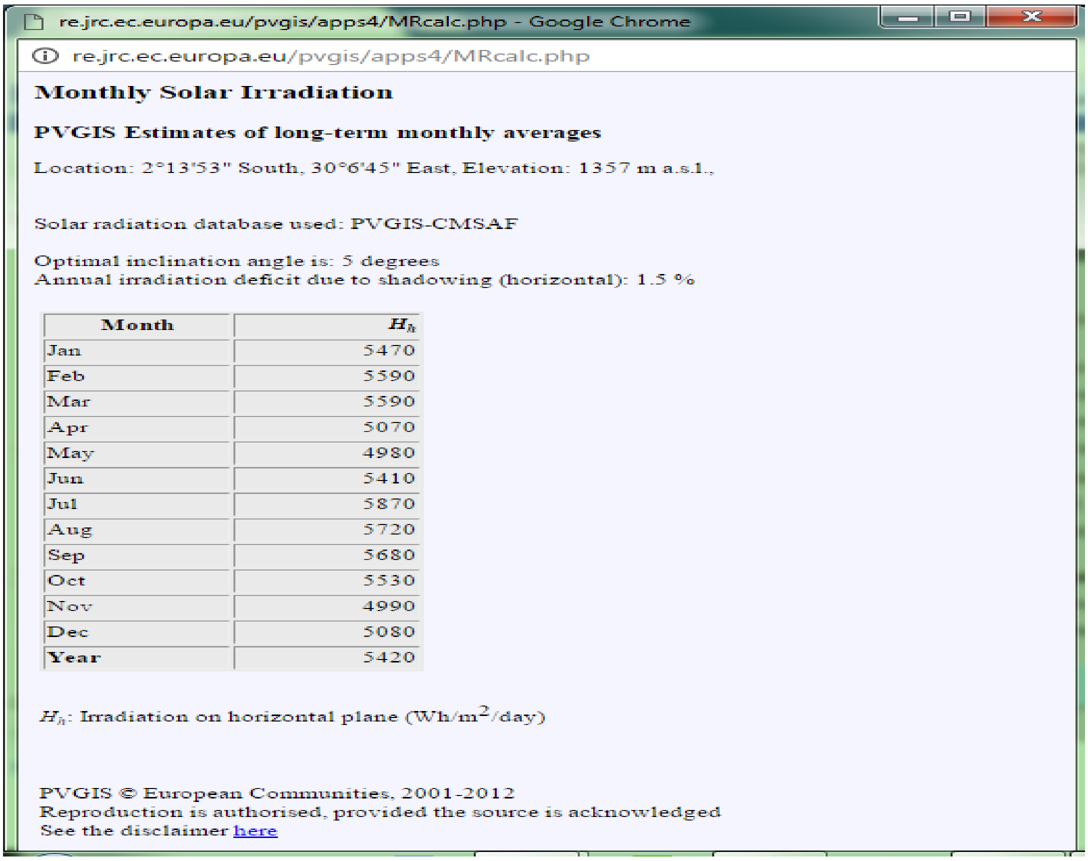


Fig. B1: Interactive map of Photovoltaic Geographical Information System.



re.jrc.ec.europa.eu/pvgis/apps4/MRcalc.php - Google Chrome

re.jrc.ec.europa.eu/pvgis/apps4/MRcalc.php

Monthly Solar Irradiation

PVGIS Estimates of long-term monthly averages

Location: 2°13'53" South, 30°6'45" East, Elevation: 1357 m a.s.l.,

Solar radiation database used: PVGIS-CMSAF

Optimal inclination angle is: 5 degrees
Annual irradiation deficit due to shadowing (horizontal): 1.5 %

Month	H_h
Jan	5470
Feb	5590
Mar	5590
Apr	5070
May	4980
Jun	5410
Jul	5870
Aug	5720
Sep	5680
Oct	5530
Nov	4990
Dec	5080
Year	5420

H_h: Irradiation on horizontal plane (Wh/m^2/day)

Fig. B2: PVGIS Estimates of long-term monthly averages for solar irradiation.

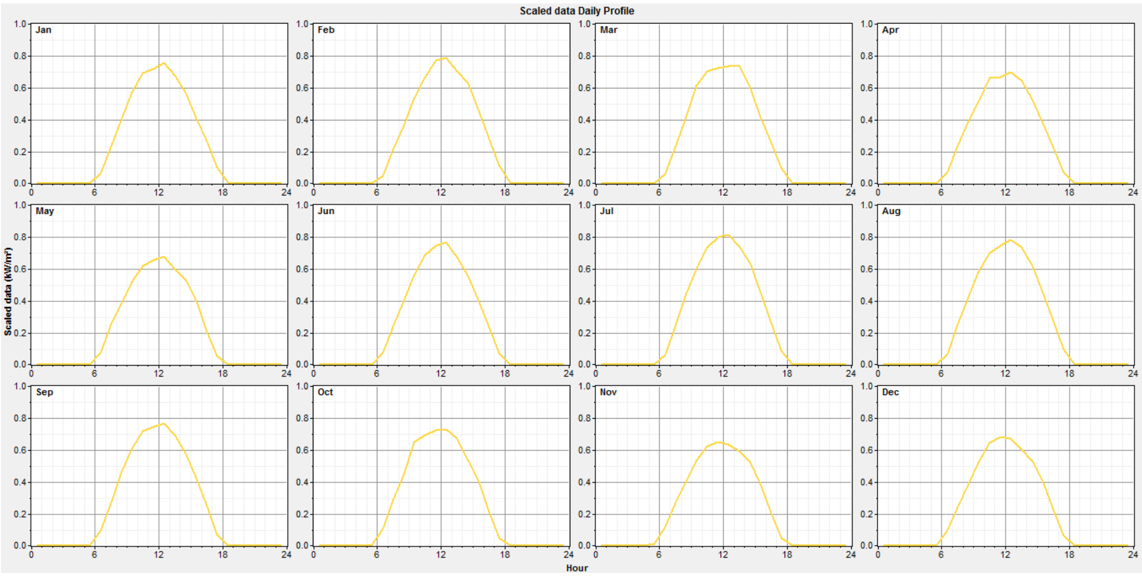


Fig. B1: The scaled data on average monthly radiation in 24hrs of different days.

The above Figure B1 displays the scaled data of average monthly radiation on a daily profile of different days and the peak intensity of solar radiation in the selected village is observed in the month of July which is known as the hottest month but the lowest intensity of sun shine is recorded for the month of November which is the coldest month of the year.

Appendix C Details on daily consumption for Kanazi village.

Domestic loads

Rich family

No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day	Hours/day
1	Lamps	6	11	66	5	330	6600	05:00-06:00	18:00-22:00
2	Cell-Pnones	2	5	10	1	10	1000	05:00-06:00	
3	Radio	1	10	10	12	120	1000	05:00-17:00	
4	TV	1	120	120	3	360	12000	18:00-21:00	
5	DVD Player	1	30	30	3	90	3000	18:00-21:00	
6	Computer	1	100	100	2	200	10000	17:00-19:00	
7	Refrigerator	1	500	500	4	2000	50000	17:00-21:00	
8	Iron	1	1000	1000	1	1000	100000	06:00-07:00	
9	Water pumps	1	500	500	1	500	50000	08:00-09:00	
	Total					4610			
No.of houses						100			
Total for Rich Families						461000			

Middle class family

No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day	Hours/day
1	Lamps	4	11	44	5	220	17600	05:00-06:00	18:00-22:00
2	Cell-Pnones	2	5	10	1	10	4000	05:00-06:00	
3	Radio	1	10	10	12	120	4000	05:00-17:00	
4	TV	1	120	120	3	360	48000	18:00-21:00	
5	DVD Player	1	30	30	3	90	12000	18:00-21:00	
6	Computer	0	100	0	2	0			
7	Refrigerator	0	500	0	4	0			
8	Iron	0	1000	0	1	0			
9	Water pumps	0	500	0	1	0			
	Total					800			
No.of houses						400			
Total for Middle class families						320000			

Poor family

No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day	Hours/day
1	Lamps	4	11	44	5	220	44000	05:00-06:00	18:00-22:00
2	Cell-Pnones	2	5	10	1	10	10000	05:00-06:00	
3	Radio	1	10	10	12	120	10000	05:00-17:00	
4	TV	0	120	0	3	0			
5	DVD Player	0	30	0	3	0			
6	Computer	0	100	0	2	0			
7	Refrigerator	0	500	0	4	0			
8	Iron	0	1000	0	1	0			
9	Water pumps	0	500	0	1	0			
Total						350			
No.of houses						1000			
Total for Poor families						350000			

Industrial/commercial loads

Bars and Shops

No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day
1	Lamps	4	11	44	5	220	1100	18:00-22:00
2	Cell-Pnones	1	5	5	1	5	125	12:00-13:00
3	Radio	1	10	10	12	120	250	10:00-22:00
4	TV	1	120	120	10	1200	3000	12:00-22:00
5	DVD Player	1	30	30	10	300	750	12:00-22:00
6	Computer	1	100	100	2	200	2500	12:00-14:00
7	Refrigerator	1	500	500	10	5000	12500	12:00-22:00
8	Iron	0	1000	0	0.2	0		
9	Water pumps	0	500	0	1	0		
		Total				7045		
No.of Bars and Shops						25		
Total for Bars and Shops						176125		

Administration Post

No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day
1	Lamps	2	11	22	12	264	110	18:00-06:00
2	Cell-Pnones	2	5	10	1	10	50	05:00-06:00
3	Radio	0	10	0	12	0		
4	TV	0	120	0	3	0		
5	DVD Player	0	30	0	3	0		
6	Computer	2	100	200	4	800	1000	08:00-12:00
7	Refrigerator	0	500	0	4	0		
8	Iron	0	1000	0	0.2	0		
9	Water pumps	1	200	200	1	200	1000	08:00-09:00
		Total				1274		
No.of Post						5		
Total for Administration Post						6370		

Medical centres

No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day	Hours/day
1	Lamps	30	11	330	12	3960	660	18:00-06:00	
2	Cell-Pnones	5	5	25	1	25	50	09:00-10:00	
3	Radio	0	10	0	12	0			
4	TV	1	120	120	8	960	240	08:00-16:00	
5	DVD Player	1	30	30	8	240	60	08:00-16:00	
6	Computer	6	200	1200	6	7200	2400	08:00-12:00	14:00-16:00
7	Refrigerator	2	500	1000	24	24000	2000	00:00-24:00	
8	Iron	0	1000	0	0.2	0			
9	Water pumps	2	500	1000	3	3000	2000	05:00-08:00	
		Total				39385			
No.of Centres						2			
Total for Medical centres						78770			

	Primary Schools							
No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day
1	Lamps	20	11	220	12	2640	880	18:00-06:00
2	Cell-Pnones	0	5	0	1	0		
3	Radio	2	10	20	2	40	80	10:00-12:00
4	TV	1	120	120	2	240	480	12:00-14:00
5	DVD Player	1	30	30	2	60	120	12:00-14:00
6	Computer	1	100	100	2	200	400	08:00-10:00
7	Refrigerator	0	500	0	4	0		
8	Iron	0	1000	0	0.2	0		
9	Water pumps	1	500	500	3	1500	2000	05:00-08:00
Total						4680		
No.of Schools						4		
Total for Primary Schools						18720		

	Secondary School							
No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day
1	Lamps	40	11	440	12	5280	880	18:00-06:00
2	Cell-Pnones	5	5	25	2	50	50	05:00-07:00
3	Radio	3	10	30	3	90	60	05:00-08:00
4	TV	1	120	120	3	360	240	18:00-21:00
5	DVD Player	1	30	30	3	90	60	18:00-21:00
6	Computer	12	200	2400	4	9600	4800	08:00-12:00
7	Refrigerator	0	500	0	4	0		
8	Iron	1	1000	1000	1	1000	2000	06:00-07:00
9	Water pumps	1	500	500	4	2000	1000	18:00-23:00
Total						18470		
No.of Schools						2		
Total for Secondary Schools						36940		

	Churches							
No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day
1	Lamps	12	11	132	12	1584	528	18:00-06:00
2	Cell-Pnones	2	5	10	2	20	40	05:00-07:00
3	Radio	1	10	10	3	30	40	09:00-12:00
4	TV	1	120	120	4	480	480	18:00-22:00
5	DVD Player	1	30	30	4	120	120	18:00-22:00
6	Computer	3	200	600	4	2400	2400	08:00-12:00
7	Refrigerator	1	500	500	12	6000	2000	10:00-22:00
8	Iron	1	1000	1000	1	1000	4000	14:00-15:00
9	Water pumps	1	500	500	3	1500	2000	05:00-08:00
Total						13134		
No.of churches						4		
Total for churches						52536		

	Small factories							
No.	Appliances	No. in use	Power (W)	Total Power	Hrs/day	Watt-hrs/day	TT Power	Hours/day
1	Lamps	3	11	33	12	396	495	18:00-06:00
2	3-phases motor	1	3000	3000	4	12000	45000	08:00-12:00
3	1-phase motor	1	1000	1000	3	3000	15000	13:00-16:00
4	TV	0	120	0	3	0		
5	Ceiling Fan	1	100	100	8	800	1500	08:00-16:00
6	Computer	0	100	0	2	0		
7	Refrigerator	0	500	0	4	0		
8	Iron	0	1000	0	1	0		
9	Water pumps	0	500	0	1	0		
Total						16196		
No.of units						15		
Total for Small manufacturing units						242940		

Appendix D Hourly power distribution per day for selected houses.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	00:00-01	01:00-02	02:00-03	03:00-04	04:00-05	05:00-06	06:00-07	07:00-08	08:00-09	09:00-10	10:00-11:	11:00-12:	12:00-13:	13:00-14:	14:00-15:	15:00-16:	16:00-17:	17:00-18:	18:00-19:	19:00-20	20:00-21	21:00-22	22:00-23	23:00-24:00
	0	0	0	0	0	6600	0	0	1000	1000	1000	1000	0	0	0	0	0	0	6600	6600	6600	6600	0	0
	0	0	0	0	0	1000	0	0	1000	50	0	0	480	480	0	0	0	0	12000	12000	12000	0	0	0
	0	0	0	0	0	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	0	3000	3000	3000	0	0	0
	0	0	0	0	0	17600	100000	0	50000	0	80	80	120	120	0	0	0	10000	10000	0	0	0	0	0
	0	0	0	0	0	4000	0	0	240	240	240	240	240	240	240	240	0	50000	50000	50000	50000	0	0	0
	0	0	0	0	0	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	0	17600	17600	17600	17600	0	0
	0	0	0	0	0	44000	2000	0	60	60	60	60	60	60	60	60	60	0	48000	48000	48000	0	0	0
	0	0	0	0	0	10000	0	0	400	400	0	0	125	4000	4000	0	0	0	12000	12000	12000	0	0	0
	0	0	0	0	0	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	0	44000	44000	44000	44000	0	0
	0	0	0	0	0	50	0	0	0	0	250	250	250	250	250	250	250	250	1100	1100	1100	1100	0	0
	0	0	0	0	0	2000	2000	2000	2400	2400	2400	2400	2500	2500	2400	2400	0	0	250	250	250	250	0	0
	0	0	0	0	0	2000	2000	2000	4800	4800	4800	4800	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	0	0
	880	880	880	880	880	880	0	0	0	40	40	40	750	750	750	750	750	750	750	750	750	750	0	0
	880	880	880	880	880	880	0	0	2400	2400	2400	2400	12500	12500	12500	12500	12500	12500	12500	12500	12500	12500	0	0
	110	110	110	110	110	110	0	0	45000	45000	45000	45000	0	15000	15000	15000	0	110	110	110	110	110	110	110
	660	660	660	660	660	660	0	0	0	0	0	0	0	0	0	0	0	660	660	660	660	660	660	660
	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
	0	0	0	0	0	50	50	0	1500	1500	1500	1500	1500	1500	1500	1500	0	0	880	880	880	880	880	880
	0	0	0	0	0	60	60	60	0	0	0	0	0	0	0	0	0	0	880	880	880	880	880	880
	528	528	528	528	528	528	0	0	0	0	0	0	0	0	0	0	0	0	240	240	240	0	0	0
	0	0	0	0	0	40	40	0	0	0	0	0	0	0	0	0	0	0	60	60	60	0	0	0
	0	0	0	0	0	2000	2000	2000	0	0	0	0	0	0	0	0	0	0	1000	1000	1000	1000	1000	0
	495	495	495	495	495	495	0	0	0	0	0	0	0	0	0	0	0	0	528	528	528	528	528	528
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	480	480	480	480	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	120	120	120	120	0	0
	0	0	0	0	0	0	0	0	0	0	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	495	495	495	495	495	495
TOTAL	5553	5553	5553	5553	5553	109953	125150	23060	125800	74890	76770	76770	40525	59400	58700	54700	35560	81270	230253	220253	220253	94953	6553	5553
	5.553	5.553	5.553	5.553	5.553	109.95	125.15	23.06	125.8	74.89	76.77	76.77	40.525	59.4	58.7	54.7	35.56	81.27	230.25	220.25	220.25	94.953	6.553	5.553

Hours	Average load (kWh)
00:00-01:00	0.006
01:00-02:00	0.006
02:00-03:00	0.006
03:00-04:00	0.006
04:00-05:00	0.006
05:00-06:00	0.2
06:00-07:00	0.08
07:00-08:00	0.07
08:00-09:00	0.005
09:00-10:00	0.005
10:00-11:00	0.005
11:00-12:00	0.005
12:00-13:00	0.01812
13:00-14:00	0.005
14:00-15:00	0.004
15:00-16:00	0.002
16:00-17:00	0.001
17:00-18:00	0.017
18:00-19:00	0.03
19:00-20:00	0.15
20:00-21:00	0.1
21:00-22:00	0.081
22:00-23:00	0.06
23:00-24:00	0.005