UNIVERSITY OF AGDER

Analysis of Power System Options for Rural Electrification in Rwanda

by

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This Master's Thesis is carried out as part of the education at the University of Agder and is therefore approved as a part of this education. However, this does not imply that the University answers for the methods that are used or conclusions drawn.

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Abstract

The development of modernized energy system for developing countries especially in rural areas is constantly a considerable problem to energy utilities. The progressive use of diesel generators in rural areas as main source of electrification is continuously becoming unsuitable because of the following reasons; the diesel generator requires the fuel at every single second of operation and the maintenance of every time is needed and it is very important to worry about the instability of power generated by those generators and the accessibility of fossil fuels is still a challenge for some communities. Whereas the introduction of new technologies by using Renewable Energy systems RESs has given a hope, confidence and security in electrification of rural communities. With a combination of RETs, a traditional diesel generation and batteries, a mini power system of the combination is adequate to manage harmony in operation, therefore granting a stable means of developing electrical power system to the developing countries especially those ones in rural areas.

The target of this development is the analysis of a mini hybrid power system options to come up with the best techno-economic and optimum configuration of RETs for supplying electricity to one village in Rwanda. In this development, a hybrid system with a low cost of energy is presented for electrification of one of isolated village of Burera district, in Northern Province of Rwanda. First of all, the renewable resources are determined, an assessment of the predicted village energy demand is estimated, and using the software called HOMER, a best hybrid system types is described, elements measured, and the optimization of the system configuration is done to come up with the reliable and efficient operation in order to answer to the village demand with an economical cost.

The system type is discovered as follows; a micro hydropower plant, diesel generator and a compound of batteries and this is found as the best option. In detail, for the case studied the best hybrid system has the following configuration: a micro hydro power plant (MHPP) of 20 kW, the diesel generator of 10 kW and the battery bank of 55.5 kWh. The MHPP generates 99.6 % of the total output, which is approximately 198,000 kWh/yr. The diesel generator is used to supply only 0.4 % of the total generation, resulting in 207 hours of operation annually. The obtained system configuration has a rough cost of energy of 0.2 $/kWh and may be further reduced to 0.13 $/kWh, if state subsidies become available for covering 40 – 50 % of the capital investment. It clear that this hybrid system is more economically viable whether it is operated as off-grid or grid connected.

Keywords: Rural electrification, Renewable Energy, Hybrid System, Power System, Homer, PV and Hydro.

Preface

This thesis is presented to the Faculty of Engineering and Science, University of Agder, in partial fulfilment of the requirements for gradation to Master of Science in Renewable Energy. The thesis' main objective was to explore the techno-economic power system solution which is a renewable energy-based technology for electrification of one selected village in Rwanda. The work described here has been conducted under the supervision of Professor Hans Georg Beyer and Programme coordinator Dr. Stein Bergsmark.

My sincere gratitude goes to my supervisor, Professor Hans Georg Beyer for his great encouragement, ideas, comments and continuous support throughout the process of project accomplishment. My special thanks also go to Stein Bergsmark for providing valuable guidance when writing this thesis. His comments and suggestions have helped me to improve my writing. Last but not least, my special thanks to Professor Maurice Ghislain Isabwe for his support and advice throughout my stay at Agder University, to my colleagues who helped me in numerous ways to make this thesis a success.

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List of Abbreviations

CC	Cycle Charging
DC	Direct Current
DG	Diesel Generator
DG	Distributed Generation
DVD	Digital Video Disc
EDL	Economical Distance Limit
EICV3	Third Integrated Household Living Conditions Survey
HOMER	Hybrid Optimization Model for Electric Renewables
IPP	Independent Power Producer
LCOE	Levelized Cost of Energy
LF	Load Following
LUCE	Levelised Unit Cost of Electricity
MHPP	Micro Hydro Power Plant
MPPT	Maximum Power Point Tracker
NPC	Net Present Cost
NPV	Net Present Value
PV	Photovoltaic
PWM	Pulse Width Modulation
REG	Rwanda Energy Group
REMA	Rwanda Environment Management Authority
RES	Renewable Energy Sources
RET	Renewable Energy Technology
SHP	Small Hydropower
USA	United States of America

1 Introduction

Electricity is the backbone and imperative condition for a country to be developed in terms of economy and the good quality in terms of lifestyle for the citizens [1]. The estimation shows that in many developing countries several billion of people do not have mandatory and vital public services because of not having electricity [1]. In most cases, the extension of electricity is either impossible because of geographic allocation, or because of high financial involved in the extension or not enough for the demand. Due to that, the adoption of an off-grid stand-alone RES constitute a useful option for electricity inadequacies in rural area of the developing countries in which the evolution in national grid extension continue to be slower than the population growth [2].

1.1 Background and Motivation

The situation of not having enough electricity especially in the rural villages, this is one important fact that negatively affect the lifestyle of most of Rwandan. The government of Rwanda face the crisis of granting electrical power to its citizens. Currently, the grid connected is estimated around 23%, where the percentage of rural communities is only 5%. This is although 85 % of Rwandan live in rural villages, and mainly employ in subsistence farming for nourishment and a means of securing the necessities of life. In view of Rwanda with a considerable number of populations in rural area, this introduces the energy sectors and regulators to a number of confrontation in energy extension and development.

First of all, there is presently inadequate electrical power to satisfy the power demand in Rwanda. The power production is centralize in the cities or in the developed centers. Furthermore, the cost for the grid extension combined with the complication of the land in the high hills and mountains of Rwanda, all of the latter reasons affect the grid expansion with high rate.

High cost of electricity also results to unaffordability of electrical power for rural consumers. This is connected with their disinclination to contribute for the extension requirement. Thus, the obligation for government involvement.

Due to these factors the task of extending the grid to the people in order to have access to electricity is not easy in Rwanda. Instead the village residents are pushed to move to places with existing grid connection. All these factors have persuaded me to find out the more reliable and sustainable option for the power production in the rural electrification in Rwanda.

1.2 Problem Statement

The republic of Rwanda has an ambitious target of providing electricity to everyone. In the so called vision 2020, this will help in transforming the country into middle income economy, where the goods export will be more than goods import. This is one of the strategic plan for the reduction of poverty so that the country could end up with the development in its economy [3]. To achieve these

targets, the involvement of every one is very important. Different way of participation can be used, research is one way of point out some weak aspect and forecast for the fulfillment of the targets. Currently no more research have been done for the proper option of renewable systems for rural energy purposes in Rwanda. Currently, in rural areas most of the schools, health centers, administration posts and other home house communities use solar systems for each home and fuel generators.
Instead of providing isolated solar systems for each home or fuel generator, the utilization of RET for electrification to the whole community in rural villages is more economical and reliable because the battery capacity of these solar home systems (around 30-100 Wp) is very small. Therefore during the seasons of low solar radiation, particularly in rainy seasons these systems are not able to meet the load, so these systems are not 100 % available. This micro grid can be energized by using renewable energy based on the hybrid system technology, into which multiple combinations of RETs can be integrated. Furthermore, a kind of dispatching for conventional technology can be utilized to improve the quality and availability of the service. No matter how, to make the system economically viable, the appropriate technologies should be attentively privileged and the complex must be conveniently determined so as to reduce the overall cost [1][4].

In various developing countries, many based hybrid systems projects have been implemented for rural electrification. Anyway, still a lot of researches are being conducted for the viability and reliability of using hybrid system for rural electrification projects in various rural communities around the world; That is why, the same technologies should be established in Rwanda, since the combinations of RETs in this country is not taken into account, even if there has been a large improvement in the renewable industry in the past years. Therefore, this project analyses different combinations of RETs in order to obtain the more techno-economics hybrid system based micro grid for supplying electricity to a rural community in Burera District in Rwanda.

The Burera district is one of non-electrified districts in Rwanda and it is far from the urban areas. The EICV3 (Third Integrated Household Living Conditions Survey) results show that the total population of Burera district in 2010–2011 was 354,000. This means 18% of the total comminity of Northern Province and 3.3% of the total society of Rwanda [5]. In the Burera district, only 3.2% of households use electricity as their main source of lighting, this make the district to be the third ranked after Musanze (14.5%), Gicumbi (8.9) in Northern Province [5]. The blackouts of every day is also problem for the ones connected to the national grid.

1.3 Goal and Objectives

The aim of this development is to come up with a hybrid power system solution from the best combination of RET (Renewable Energy Technology) that will use the resources which are available in Rwandan rural area to fulfill the electricity demand in a reliable, affordable and sustainable manner with a cost-effective solution.
The achievement of the upper goal, the ability and the accomplishment of the below objectives is required:

- Estimating the everyday load demand of the selected area.
- Studying the potential of RE resources in the preferred locality.

- Describing the relevant renewable energy resources for the proposed hybrid system
- The selection of component and the analysis of its cost.
- Model electricity produced based on RETs.
- Modeling and simulation of the system with the application of HOMER software.
- Optimization and sensitivity testing of the system type in HOMER.
- Selecting the best option based on the COE (Cost of Energy) generation.
- Performance evaluation of the optimal hybrid system.
- Compare the optimal hybrid system to the grid extension in terms of costs.

1.4 Literature Review

The optimal design of a hybrid system in terms of cost and the reliability has become of great importance with the increase in usage of hybrid renewable energy systems. A lot of studies and researches are being conducted all the day in order to close the knowledge gap that advocates the requirement for the projects in this regard and to grant support for the method. Numerous researches accomplished in this field in few decades, especially in remote area electrification but few of them has been selected in this project because they have some special ideas related to this research[6].

Off-Grid Electrification

Arash Asrari, Abolfazl Ghasemi, and Mohammad Hossein Javidi [7] in their research aims, firstly, was to explore how to expand the contribution of RES by combining the diesel power sources and renewable energy sources so that the system can supply electricity to the rural centers in economical way. On their second stage, they have tried to connect RESs to the national utility grid in order to realize a more cost effective and techno-optimum system. The software called HOMER has been used to see the practicability of possible combination of hybrid configuration using diesel-RES and distributed power system with RES. The results demonstrate that the RES integration is a key for cost effective for the system which is certainly cleaner and more climate-friendly [1]. This paper has been selected because, it deal with some technics used for distributed power system and the combination of renewable energy technology of socio-economic optimization.

Tshering Dorji, Tania Urmee and Philip Jennings [8] in their study the aims was to identify the least-cost and optimum technologies be used in the rural environment [1]. Their study focuses on the energy needed by rural communities, resources available to the selected rural area, and policies and programs that should be fulfilled for the electrification of rural areas. The software HOMER has been used in hybrid optimization model for the design of distributed generation (DG) systems. This paper has been selected due to its comparison between the costs obtained from the RETs systems and the grid extension cost.

Studies on HOMER

HOMER is an acronym which mean Hybrid Optimization Model for Electric Renewables. It is software developed by the American National Laboratory for Renewable Energy. It can be used for handling a number of 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 [9].

D.Saheb-Koussa, M.Haddadi and M.Belhamel [2] in their study, they deal with the design of hybrid system. Techno-economic optimization of two renewable sources; photovoltaic and wind, with the diesel and battery storage has been obtained. Their target was to find the suitable stand-alone hybrid system that will provide the energy autonomy of remote area with minimum COE. This paper has been selected, because of having the same target as the one that I have in my project.

E.M. Nfah and J.M. Ngundam [10] who studied a hybrid which including the Pico-hydro and incorporating a biogas generator. This research has been selected because it use a hydropower as one renewable energy source.

S.M. Shaahid and I. El-Amin [11] the aim of their study was to examine solar system in order to evaluate the best techno-economic of hybrid RES composed with PV–diesel–battery to answer to the load required by the selected remote village with the demand of 15,900 MWh.

Several other literatures have used the Homer software for techno-economic optimum sizing of hybrid systems. Homer algorithms help in the evaluation of techno-economic feasibility of RET options and to see the technology with cost effective. It has also integrated with a product database with different products from a variety of manufactures. Hence this software is widely used for hybrid system optimization.

Knowledge Gap

The above review shows the popularity of HOMER as a tool to analyze decentralized electricity supply systems. However, most of the researches do not account electricity demand in rural areas carefully. As the optimal system configuration is obtained to meet the demand, demand analysis do an important role. Most of the researches also focus on a limited level of supply and do not often acknowledge the productive utilization of electricity. Furthermore, whereas technology selections are based on local conditions, it is likely to investigate alternative combinations more imaginatively. Finally, studies also limit their scope to techno-economic reasoning and ignore the business issues or practical considerations related to their implementation [1]. Without such considerations, most of the development remain theoretical in nature [1]. This chapter tries to bridge the above knowledge gaps and presents an application of HOMER to extend the scope of the work and knowledge base [9].

1.5 Research Method

The research will start with data collection of renewable energy resources, establishment of village load profile, overview of component characteristics and costs, research on hybrid system configurations, modeling and simulation of the hybrid system, selection of optimum system based on simulation results and the performance assessment of the selected system.

First of all, it is necessary to determine the daily load profile of the village. There is no variations of the load profile due to season changes because due to the equatorial location there are no distinct summer or winter seasons in Rwanda.

Here, the calculation of the load profile of the village is done via self-performed survey that I could perform due to my familiarity with this region. In addition, I will use the results from survey forms for households grid connected which have been conducted on other rural villages connected to national grid one year ago. I will use parameters such as, the number of households and public utilities, family income, predisposition and readiness to purchase electrical appliances and potential small businesses that can emerge with the availability of electricity. These in all is quiet enough for load demand for the village [1]. However, a reasonable assumption can be used in case where to get the data from site survey is not possible in order to estimate the load curve. I will use the micro grid optimization software called HOMER. The simulations are needed to make a considerable number of hybrid system arrangement that grant several combinations of renewable energy resources. The lifetime net present cost of the hybrid systems that can supply the village load with the required level of availability should be calculated to determine the lowest energy cost hybrid configuration. The sensitivity analysis of the anxieties regarding the system inputs like solar radiation should be assessed to inspect the best system that can supply the load at the lowest energy cost for diverse conditions.

1.6 Key Assumptions and Limitations

The scope of this development is limited to determining the best techno-economic combination of RE resources in a hybrid configuration for electrification of one community selected in Rwanda and the evaluation for performance of the system is included but this will not deal with the complete configuration of the micro grid powered by this hybrid system. The analysis of this hybrid system will be done by considering the following assumptions.

- Meteorology and solar energy data from NASA Surface Meteorology and Solar Energy website represented by RET Screen International are considered to accurate for computing solar PV systems for off-grid electrification systems[12].
- The same annual variations of solar radiation occur all over the project lifetime.
- The consumers live conforming to a daily routine coming from the same load cycles every day, since there is no summer or winter for the selected location because the temperatures seems to constant in the year.
- Rate of inflation will be considered the same for all types of costs (fuel cost, maintenance cost, labor cost .etc.) occurring all over the 20 years [4].
- The hybrid configuration is not location specific and will be the optimal configuration for other locations where the renewable energy potential is the same as the selected region. This is a good example for other location in Rwanda, depending with the load profile and availability of the renewable energy resources. The same approach can be used for other communities in Rwanda by following the same procedures as it is used throughout this project.
- This study will not discuss the issues related to the micro grid stability and control.

The designed system will have the following limitations.

- Only solar and hydro energy will be chosen for the analysis due to the nonexistence of other renewable resource data in the selected location. For example, this concerns the flow rate data of wind streams and the amount of biofuels available throughout the year.
- This study will use HOMER software for modelling and simulation.

1.7 Analysis Framework

The concept of 'analysis of power system options for rural electrification' is increasingly important for the developing countries. The figure 1.1 shows the framework for analysing the hybrid system or combination of RETs for electrification of rural villages in Rwanda.
The framework shows how, in different contexts, the best techno-economic combination of RE resources are achieved through the modelling and simulation using HOMER software to combine the input data; the load profile, renewable energy resources and the equipment's cost for best configuration.
The key components of this project is shown in the framework as the analysis of the initial site assessment, details assessment, data bank analysis, system design, techno-economic analysis and end up with the best techno-economic combination of RE resources in a hybrid power system for electrification to the selected community in Rwanda.

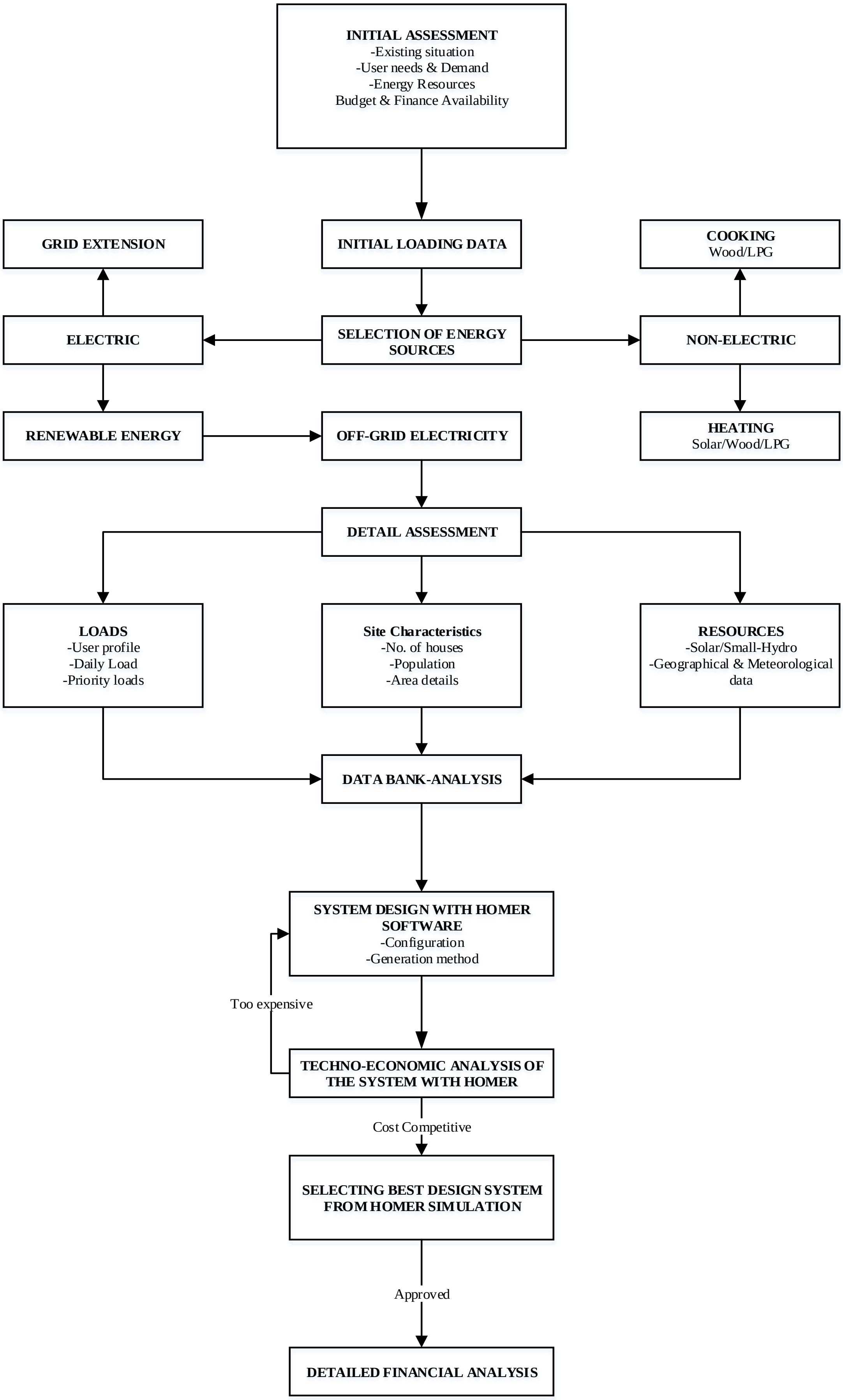


Figure 1.1 : Framework of analysis

1.8 Thesis Outline

Chapter 2 reviews the load profile and available resources in the village location, hydro resource, solar resource and the climate data of the village. Chapter 3 will be concerned with the explanation of the major components used in renewable energy technology system. It illustrates the important characteristics of the system components such as electrical characteristics, costs, operation and maintenance difficulties. Chapter 4 discusses the modeling of the hybrid system in HOMER software. Chapter 5 discusses the results obtained from the simulations of the hybrid system in HOMER software. The results of the optimization and sensitivity analysis, the selection of the optimal hybrid configuration and the performance of the selected system for varying conditions of load, solar and hydro resource will be discussed in this chapter. Chapter 6 then presents the discussion, while concluding remarks and future work are presented in Chapter 7.

2 Data Collection

Hybrid system design and optimization requires an evaluation of the load profile of the village and the renewable resources in the region. In this chapter we are going to discuss the estimation of village load profile and the assessment of renewable resources, solar and hydro at the site. The chapter discusses calculation of solar radiation on a tilted PV panel using horizontal radiation data and the monthly average water flow will be carefully estimated based on the average precipitation, average temperatures and topography of the region.

2.1 Introduction

One of the villages from the Burera District in North Province, Rwanda is selected for analysis of option of renewable hybrid energy system for supplying electricity. The map of the Burera district is given in Figure 2.1. Burera district consists with area of 644.5 km² and density of 522.2 inh./km². The EICV3 survey results show that the total population of Burera district in 2010–2011 was 354,000. This represents 18 % of the total population of Northern Province and 3.3 % of the total population of Rwanda [5].

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. In Burera district, only 3.2 % of households use electricity as their main source of lighting, ranking the district third ranked after Musanze (14.5 %), Gicumbi (8.9 %) in Northern Province. The urban area average is 46.1 % of households using electricity as their main source of lighting, while it is only 4.8 % in rural areas and 10.8 % at national level. Hence Burera district is below the national, urban and rural area averages [5].

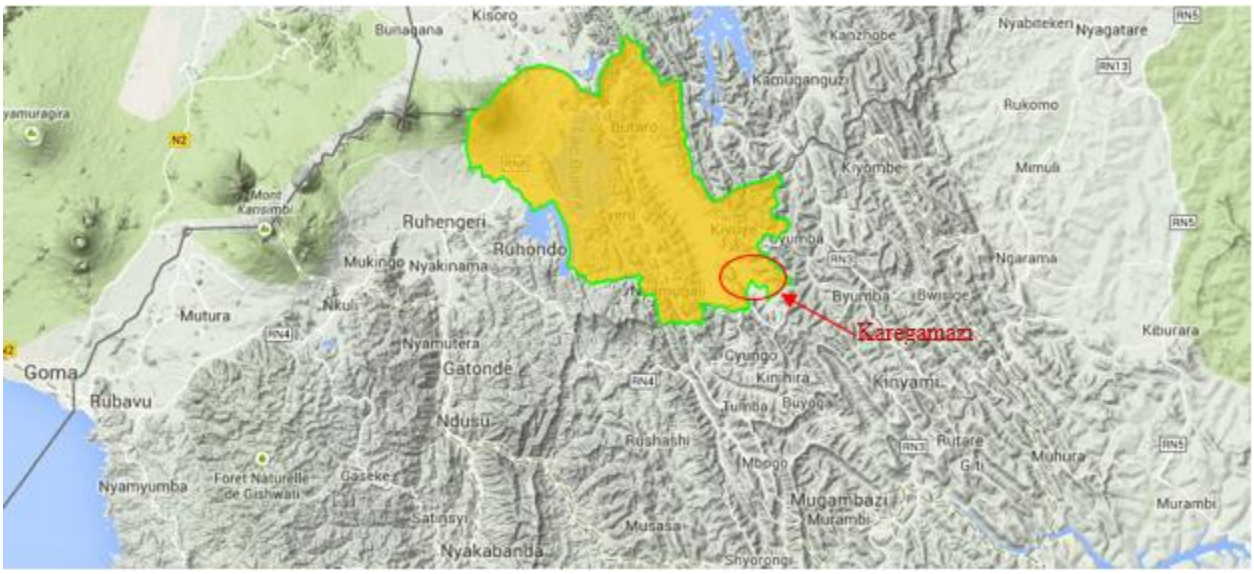


Figure 2.1: Map of Burera District [13].

In this research, a village located at 1°30' S latitude and 29°58' E longitude has been selected for placement of the hybrid system. The geography of the selected village is presented in Figure 2.2 and 2.3. As presented in Figure 2.3, the electrical loads are scattered all over the village.

Figure 2.2 : Map of Geography allocation of Karegamazi site [14].

Figure 2.3 : Closer or zoomed view of Karegamazi village [14].

In order to assess the applicability of a hybrid RES for supplying electricity, firstly it is required to discover the potential of RE resources in the selected area and the demand for the electricity of the selected community [15].

2.2 Village Load Profile

In a remote rural village the need for electricity is not high as match up to urban areas. Electricity requirement is for domestic use (for appliances such as radio, color television, compact fluorescent lamps, DVD player, refrigerator, computer, and an iron, community activities (such as in community halls, schools and health post) and for rural commercial and small scale industrial activities (such as cold storage, small processing plants for cassava flour and sorghum flour and cottage industries).

A survey in the village will be required to conduct for collecting all these data. But real surveyed data is not available for the selected community, the load profile of the village has been derived based on the knowledge that I have on the selected area and assumptions by using the results obtained from the interviews with the households which have been conducted on the new community area where the power extension have been reached. Survey form for Households can be found in appendix A.

The selected village consists of 10 rich families, 40 medium income families, 100 low income families and 50 very poor families, the latter being excluded in this regards. The village has 5 shops and bars, two administration posts, one medical center, one primary and one secondary schools, one community church and 3 small manufacturing units. The detailed daily consumption for selected village and the daily power hourly distribution can be seen in the appendix B and C respectively.

To be more specific concerning “rich”, “medium”, “low income” families; according to Andrew Kettlewell, the Adviser of Technical Team for Rwanda’s Vision 2020 Umurenge Programme also known as VUP;

Rich families are those which have land and livestock, and usually have jobs where they can earning some money. Good housing, generally own a motorbike or vehicle, and people who can do business with bank so that they can easily get credit from the bank [16].

Medium income families are those with larger landholdings on productive soil and sufficient to eat. Own livestock, sometime they have a small paid jobs, and can have access to health care [16].

Low income families are those which have very small land and small house. Live on their own labor and even if they don’t have some savings, they can find something to eat, even though the food is not very healthful and some of them their children may go to primary education [16].

Very poor families are those which have to beg for surviving, no land, no livestock and no safe house and no adequate dress and food. They don’t have access to medical care due to the lack of money and the government have to pay for them. Their Children do not attend school. But some of them may be physically capable to work in the land owned by others and earn some money for nourishment [16].

Table 2.1 : Assumptions on daily consumption for the selected community.

No	Consumers type	Number	Daily consumption in kWh
1	Rich families	10	46
2	Medium income families	40	32
3	Low income families	100	39
4	Shops and bars	5	35
5	Administration posts	2	3
6	Medical center	1	34
7	Primary school	1	5
8	Secondary school	1	11
9	Community church	1	5
10	Small manufacturing units	3	49

Based on these, a typical daily load curve with hourly resolution has been derived for this village and it is given in Figure 2.4. With respect to the derived load profile, the maximum demand of the village is around 28 kW but with the random variability of 10 % (standard deviation: daily and hourly noise to make the load data more realistic) for both day to day and time step to time step, this maximum demand can become 38 kW with the energy consumption of around 249 kWh.

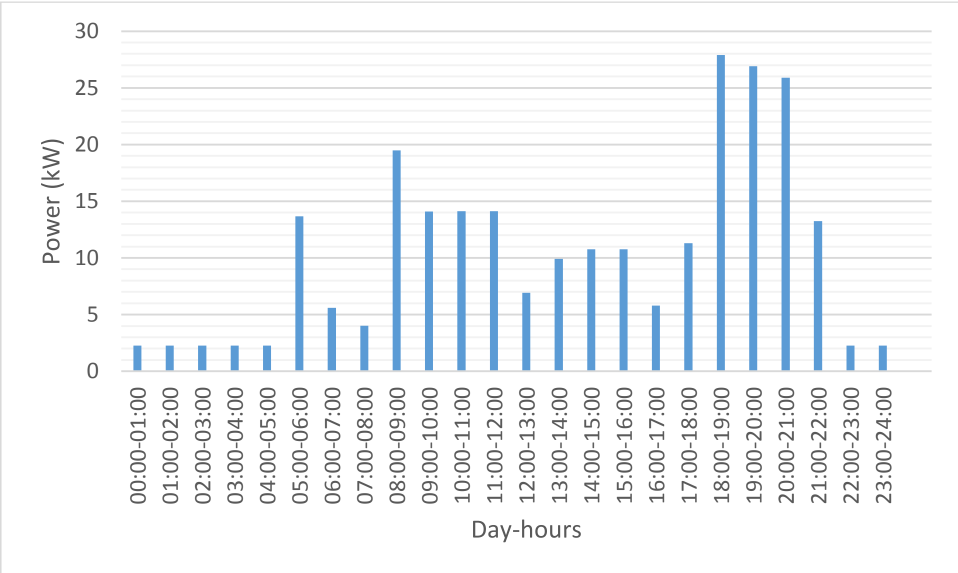


Figure 2.4 : Village load profile

2.3 Solar Resource Assessment

For assessing the option of using solar (photovoltaic) power, we have to consider the solar resources in our simulation. The resource assessment is presented below. As there is a long distance from the selected village to the next weather station where ground measurements of solar radiation are performed, the solar resource information used for selected village at a location at 1^{o}30’ S latitude and 29°58' E longitude was taken from the NASA Surface Meteorology [12] as made available by RET Screen International [12]. Data on the monthly averages of the daily radiation sum on a horizontal surface are plotted in Figure 2.5. In addition, tabulated monthly averaged daily insolation incident are given in Table 2.2 together with the clearness index [17]. The clearness [4] is a measure of the fraction of the solar radiation that is transmitted through the atmosphere to the earth's surface. The annual average solar radiation was found to be 5.13 kWh/m^2/day and the average clearness index was found to be 0.513.

When comparing the selected village in Rwanda and a village in central Germany, the village Niederdorla, located at 51°09' N latitude and 10°26' E longitude, as show on Table 2.3 from the NASA website [12], it shows that the annual average solar radiation of Niederdorla village is 2.72 kWh/m^2/day and its average clearness index is 0.39.
By comparing both results shown in both Tables 2.2 & 2.3, it is clear that, the selected village in Rwanda has both quiet good solar radiation and clearness index than Niederdorla village in Germany. Due to that solar radiation data, it is clear that the average solar radiation in Burera village is relatively good. This would give an approximately good probability and occasion to use the photovoltaic technology as one element of the hybrid RES.

The monthly mean temperatures of the village located at 1°30' S latitude and 29°58' E longitude is given in Table 2.4. They range from 21.6 °C to 24.5 °C throughout the year. Thus this area is not affected by seasonal variations. Also the day length in Rwanda does not vary throughout the year due to its geographical location. Due to the small variations of irradiance and temperature, there it is expected that there are no significant changes in the load curve within the year. Therefore, a constant daily load profile has been assumed for the entire year.

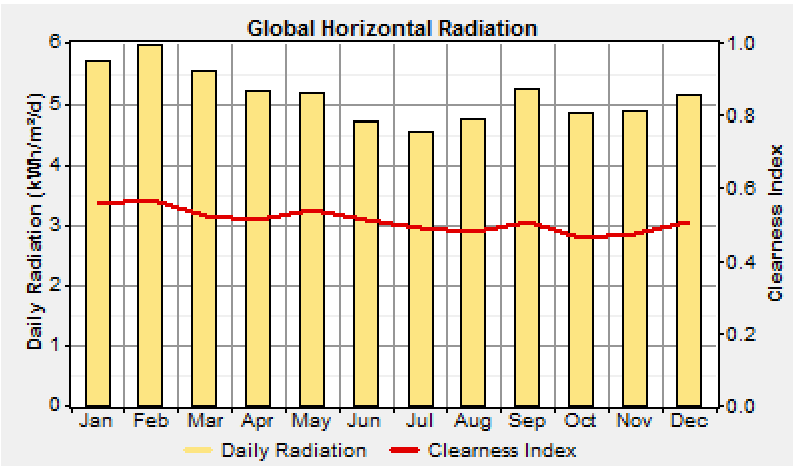


Figure 2.5 : Monthly radiation sums for the selected village, from Homer.

Table 2.2 : Monthly average daily irradiance incident on a horizontal surface for the target location [12].

Month	Clearness Index	Daily Radiation (kWh/m^2/d)
January	0.557	5.69
February	0.569	5.97
March	0.525	5.52
April	0.515	5.22
May	0.542	5.16
June	0.516	4.72
July	0.49	4.55
August	0.483	4.74
September	0.507	5.23
October	0.464	4.84
November	0.477	4.88
December	0.51	5.139
Average	**0.513**	**5.133**

Table 2.3 : Monthly average daily irradiance on a horizontal surface for Germany [12].

Month	Clearness Index	Daily Radiation (kWh/m^2/d)
Jan	0.36	0.84
Feb	0.39	1.54
Mar	0.39	2.42
Apr	0.41	3.64
May	0.42	4.58
Jun	0.41	4.78
Jul	0.42	4.66
Aug	0.44	4.15
Sep	0.39	2.78
Oct	0.35	1.64
Nov	0.32	0.89
Dec	0.34	0.65
Average	**0.39**	**2.72**

Table 2.4 : Monthly mean values for other climatic parameters in Burera District [12].

Month	Air temperature °C	Relative humidity %	Atmospheric pressure kPa	Earth temperature °C
January	23.8	53.4	89.8	24.1
February	24.5	52.9	89.8	24.9
March	23.4	68.3	89.7	23.8
April	22.5	77.0	89.8	22.7
May	22.4	74.0	89.9	22.4
June	22.6	65.9	90.0	22.4
July	23.1	56.7	90.0	23.0
August	22.4	66.3	90.0	22.5
September	21.9	74.8	90.0	22.0
October	21.6	79.0	89.9	21.9
November	21.7	77.2	89.9	21.7
December	22.5	65.2	89.8	22.4
Annual	22.7	67.5	89.9	22.8

2.4 Hydro Resource Assessment

D. Magoma, P.M. Ndomba, F. W. Mtalo, and J. Nobert [18] in their research for Rugezi catchment situated in the Northern province of Rwanda in Burera district, have shown that the rugezi catchment has about 196 km^2 (Figure 2.6). It is located between latitudes 1°21’30” and 1°36’11” South and longitudes 29°49’59” and 29°59’50” East. The Rugezi catchment divided into sub catchments: The Rugezi main (164 km^2) and the Kamiranzovu watershed (32 km^2). The main Rugezi is situated in the east of Lakes Burera and Ruhondo below the Virunga volcanoes. They have done two test and compere them; simulated test and observed stream flows test at the drainage area, Rusumo gauging station [18], the results in Figure 2.8 where the data for calibration period 1976-1981 (four years) shows that; the observed day to day flow for this period of 4 years is 1.38 m^3/s and the simulated is 1.31 m^3/s [18].

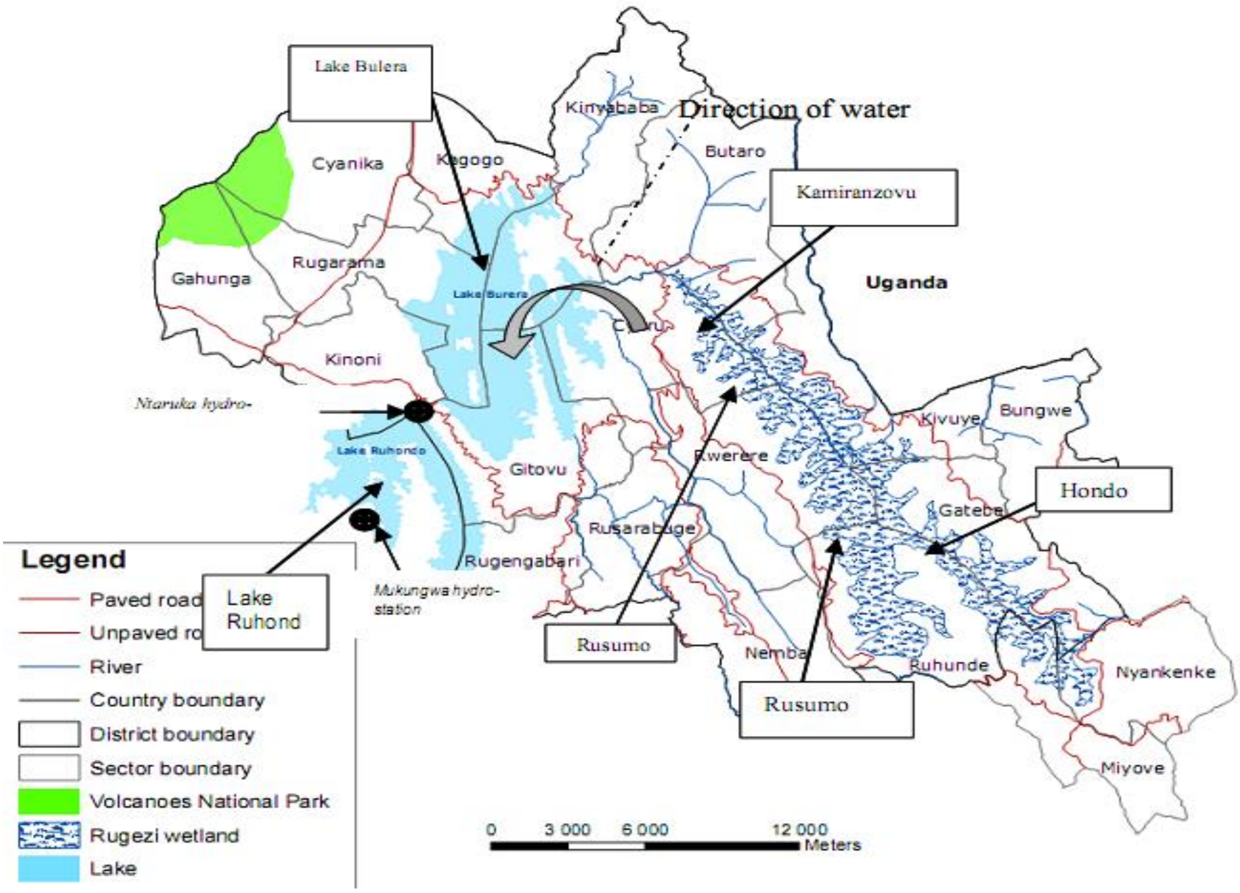


Figure 2.6 : Placement of Rugezi catchment in Burera District [18].

Figure 2.7 : Reservoir of karegamazi at which the hydropower plant is possible [14]

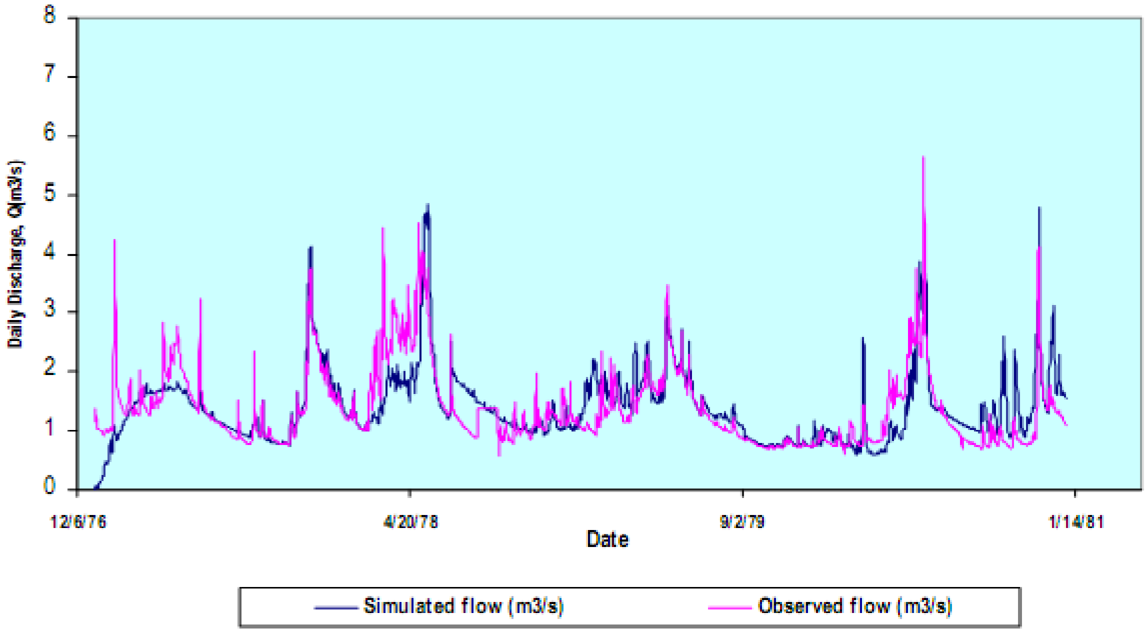


Figure 2.8 : Discovered and simulated daily stream flow [18].

Since the above data is not sufficient for the assessment because the Homer software will require the monthly water stream flow in liter per second , I have tried to search for other information so that I can compare the results from [18] Figure 2.8 and the current hydro resources for Rugezi. The current information of water stream flow at Rusumo gauging station is shown on the Figure 2.9, source from the Rwanda Energy Group (REG) by E-mail correspondence.

These data have been obtained by the recording from Rugezi Micro Hydro Power Plant which was working in the day of 2012, unfortunately this plant has stopped due to the wrong design and construction.

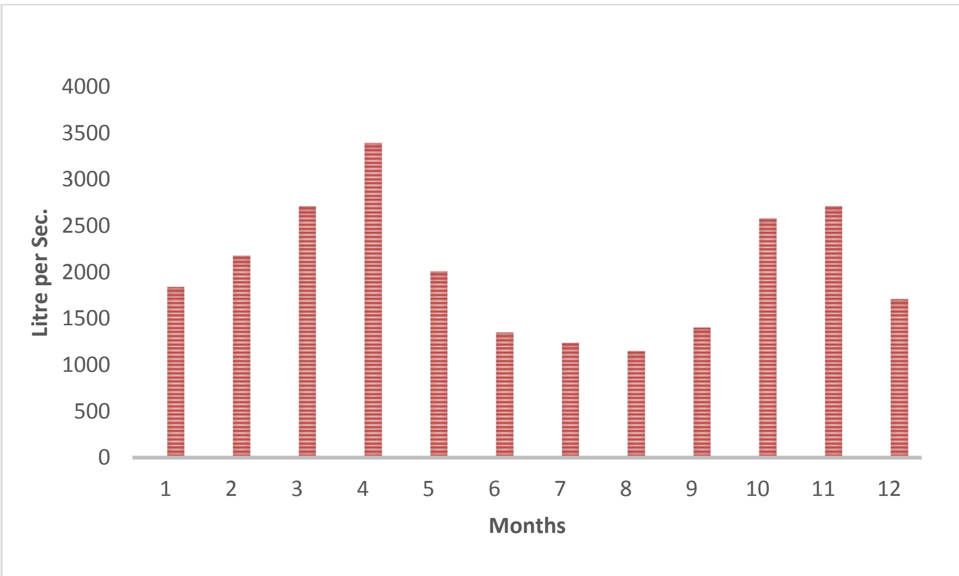


Figure 2.9 : Average monthly stream flow at Rusumo gauging station.

With the data above show that the annual flow is maximum in April with a stream flow of 3390 litres per second and the minimum is in the month of august with a stream flow of 1150 litres per second. The annual average water release from Rugezi catchment is 2019 litres per second, and the residual flow which is around 350 litres per second is not included. The residual flow is part of water which is undistributed in the plant for ecological causes to support fish populations [4].

In this project, it is assumed that only a small portion of this water can be used. As given in figure 2.7 of the reservoir where the micro hydropower plant is possible, is situated in the east of the Rugezi main catchment. Since water from the Rugezi catchment is the source of two other lakes; Burera and Ruhondo and those lakes are the source of other big two hydro power plants which are Mukungwa and Ntaruka respectively. As explained in the following, this situation sets limits to new hydro power stations.

There are some rules and regulations from the ministry of environment, lands and mines required to use all kind of activity related with the Rugezi catchment. This is due to vulnerability which has taken cover in the year of 2000, when the country has passed through the crisis of electricity supply and due to this Rwanda has been negatively affected in many aspects[19]. The trouble stimulated by an extreme reduction of power generated from Ntaruka power station and that one from Mukungwa power station, and at that time, these two power stations cover 90 % for the whole country power demand. The decreases of electricity generation from Ntaruka and Mukungwa has been affected by the drop of water in Lake Burera the reservoir of the two stations [19]. This water drop has been affected by several factors, like; bad management for surrounding of the Rugezi watershed caused by human activity and technical problem connected with bad maintenance of stations.

Due to the above reasons, even if there is a water flow of 2019 litre per second from the rugezi catchment, in this project 280 litres per second will be used with the head of 9.7 metres to produce the output power approximated to 20kW.

As the typical forecasted load profile of the selected community and the identification of the possible renewable energy resources was presented, it is good idea to see and discuss the system layout caused by the fact that the maximum load is more than 20 kW and Off-grid renewable energy-based power systems cannot provide a continuous supply of electricity without a storage medium, consequently batteries are added to the hybrid system. In order to ensure the continuity of the supply, a diesel generator are also incorporated. Further, various component configurations for the system have to be characterised.

3 Hybrid System Components Characteristics and Costs

In this chapter we will discuss the characteristics, operation, maintenance and the relevant costs of the hybrid system components. We will start by discussing the basic technological configurations of hybrid systems. Then the chapter explains the characteristics of the components; PV panel, Micro hydropower system, diesel generator, storing bank and the inverters. These are the relevant components used in the hybrid system studied in this project.

3.1 Introduction

In this HOMER analysis, solar PV, and run-off river micro hydro power are the principal resources and the diesel is used for the emergence cases. Batteries and converter will be used for storing and converting from one form to other form system of electricity, respectively. The performance and cost of each of the system's components is a major factor for the cost results and the design.
Depending with the kind of voltage system and bus that interconnect the sources, there are many different types of hybrid system,

- DC coupled system,
- DC/AC coupled system
- AC coupled hybrid system

In this study, I prefer to use the AC coupled hybrid system where all electricity generating sources are connected to the AC bus because of the following reasons:

DC coupled Hybrid system all sources are networked to the DC bus. This means that the PV generating source is equipped with charging controller and AC generating sources with rectifiers, this means that the power generated by the diesel generator and the alternator are first rectified and then converted back to AC which reduces the efficiency of energy conversion due to several power processing stages. Due to this reason, the DC coupled hybrid system have not been selected for this study.

In DC/AC coupled hybrid system, electricity generating sources can be connected to either DC or AC bus depending with the generating voltage form. This hybrid system uses a bidirectional inverter to link the DC bus and the AC bus. Also the efficiency of the generator can be maximized due to the capability to operate the inverter in parallel with the AC sources. Unfortunately this system have not been selected due to its two buses and to ignore the danger which may be generated due to failure of the bidirectional inverter.

In AC coupled hybrid system the DC generating sources are linked to the AC bus through inverters and AC sources can be immediately bridged to the AC bus or maybe through a medium to facilitate stable link. Regarding the battery bank, the energy supply is controlled by a bidirectional inverter. AC coupled systems is more flexible, easily expandable and it offer a flexibility for grid extension when necessary [4]. Due to the above functionality, this type of system has been selected for this project.

Since the AC coupled hybrid system has been selected, as it is shown on the Figure 3.1 the main components for the system are the follows; PV panels, Micro hydro power plant, batteries, diesel generator and inverters. In this project, two inverters have been used for a solar inverter and a bidirectional battery inverter. That is why this chapter will discuss each of this component's functionalities, specifications and costs.

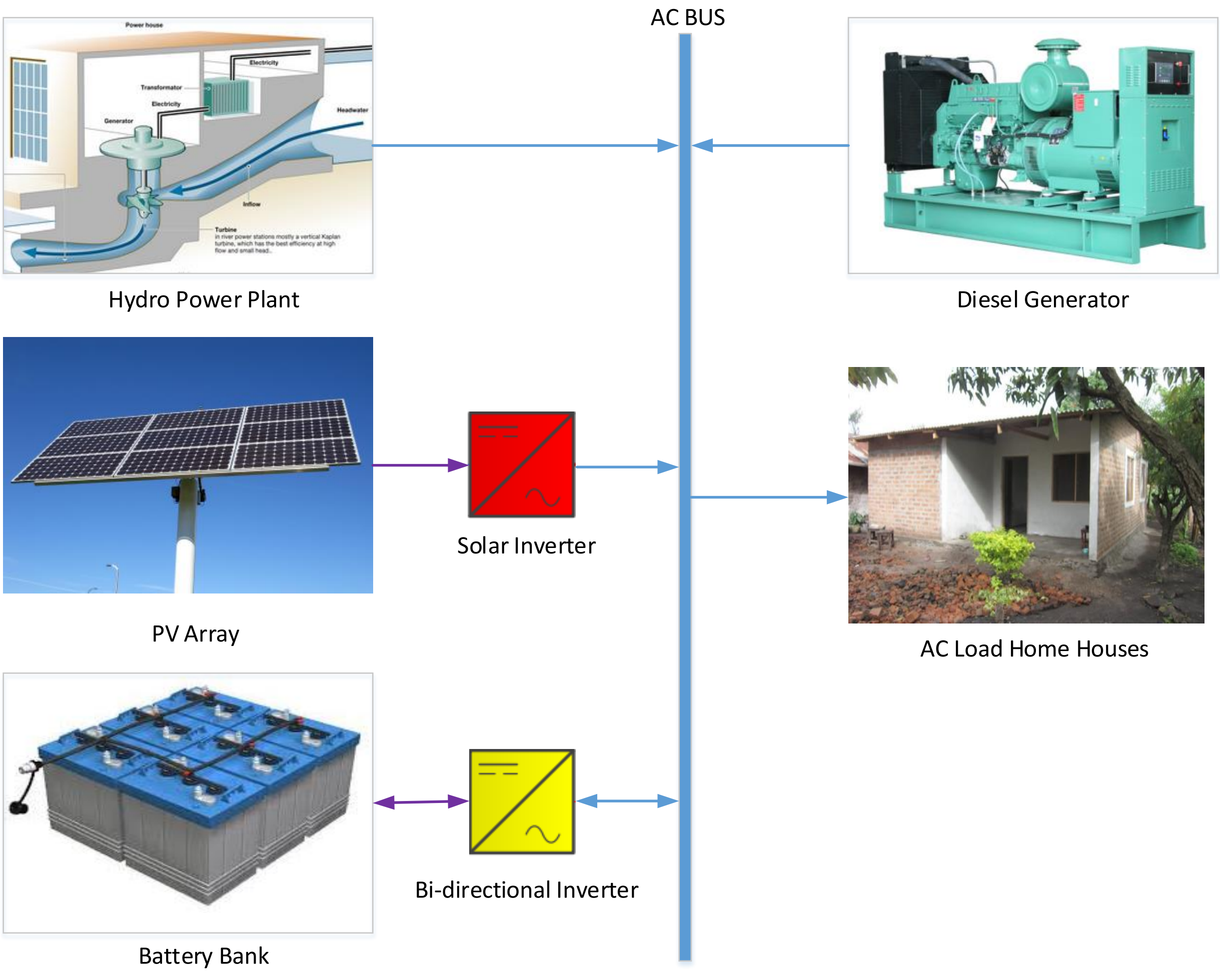


Figure 3.1 : AC coupled hybrid system.

3.2 PV Panels

Solar system is the greatest and favorable of the renewable sources because of its apparent indefinite potential [1]. The sun emits its energy and the latter is transmitted as electromagnetic radiation, the letter can be used by photovoltaic module to produce a direct current. After the sun radiation being passed through the atmosphere, 1kW of solar power can be experienced on an area of one square meter [20]. The output power from a typical solar cell is around 1 watt. That is why to generate the required amount of power a certain number of cells are connected in compound in order to have a complete module.

3.2.1 Electrical characteristics of PV cells

A perfect solar cell is presented by the combination of a current source connected in shunt with a diode[21]. Its equivalent I-V characteristic is calculated by the equation (3.1) [21][22].

$$I = I_{ph} - I_o(e^{\frac{qV}{k_B T}} - 1) \tag{3.1}$$

Where

k_B : Constant of Boltzmann,
T : Absolute temperature,
q (>0) being electron charge,
V the voltage of the cell and
I_o is the diode saturation current.

A solar cell act as a diode during the darkness. Figure 3.2(Top) shows the I-V characteristic of Equation (3.1). In theoretical, the I_{sc} is equal to the photo generated current I_{ph}, and open voltage V_{oc} is given by

$$V_{OC} = \frac{k_B T}{q} ln(1 + \frac{I_{ph}}{I_0}) \tag{3.2}$$

The power produced by the solar cell is shown in Figure 3.2(Bottom) [21]. The cell generates the maximum power P_{max} and it is appropriate to calculate the fill factor FF by

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} = \frac{P_{max}}{I_{sc} V_{oc}} \tag{3.3}$$

The Figure 3.2 below shows the I-V characteristic of an perfect solar cell (Figure 3.2 top) and the power produced (Figure 3.2 bottom) and the power at the maximum power point is the shaded rectangle in Figure 3.2 top [6].

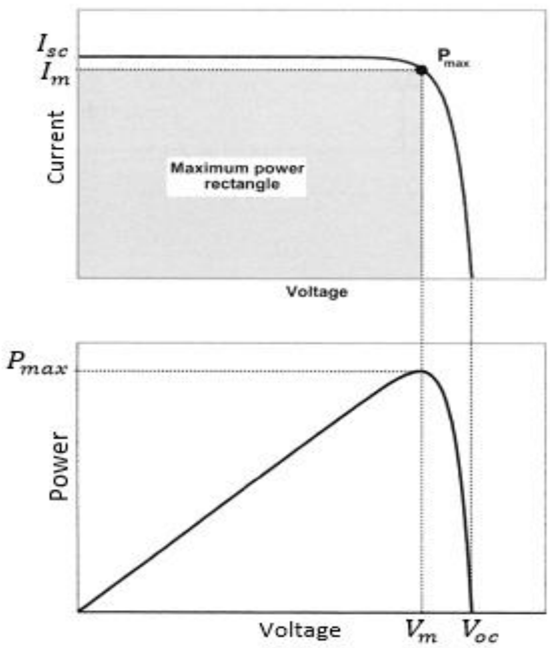


Figure 3.2 : The I-V and Power aspect of a perfect solar cell [22].

The I-V nature of a solar cell in practice normally has some difference with the ideal characteristic [21][22]. A two-diode model is often used to be able to obtain an observed curve, with the second diode has an ideality factor of two in the denominator of the argument of the exponential term [21]. Its circuit may also have series (Rs) and parallel (Rp) resistances, conduction to the following equation [21].

$$I = I_{ph} - I_{01}\left\{e^{\frac{V+IR_S}{k_B T}} - 1\right\} - I_{02}\left\{e^{\frac{V+IR_S}{2k_B T}} - 1\right\} - \frac{V+IR_s}{R_p} \tag{3.4}$$

where the light-generated current Iph may, in some cases, depend on the voltage [21]. These features are presented in the equivalent circuit in Figure 3.3 by the dotted lines [21]. The effect of both resistance and the second diode on the I-V characteristic of the solar cell is presented in Figures 3.4 and 3.5, respectively [21]; further information see the Figure 3.6.

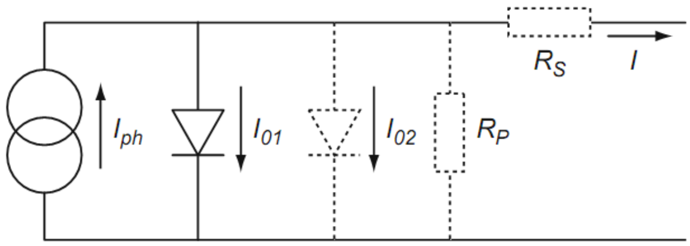


Figure 3.3 : The equivalent circuit of non-ideal solar with components in dotted line [22].

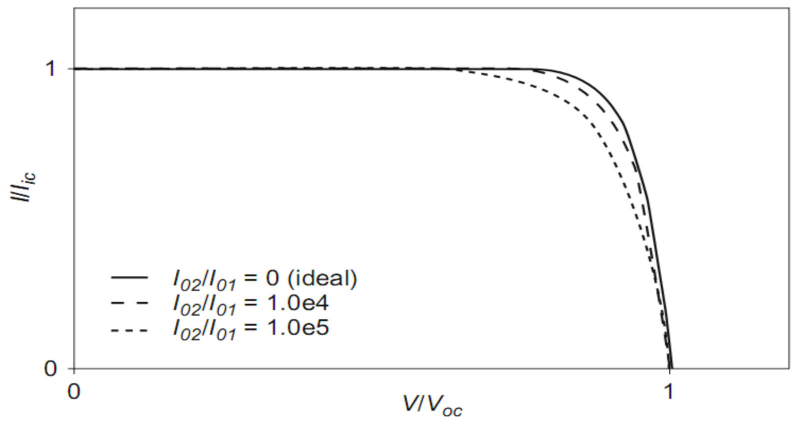


Figure 3.4 : The I-V characteristic of PV in the two diode model [22].

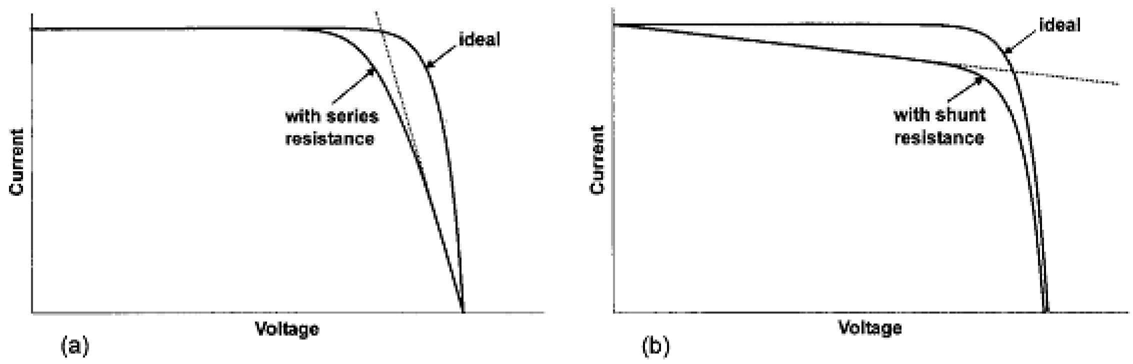


Figure 3.5 : The effect of resistance on the I-V characteristic of PV [22].

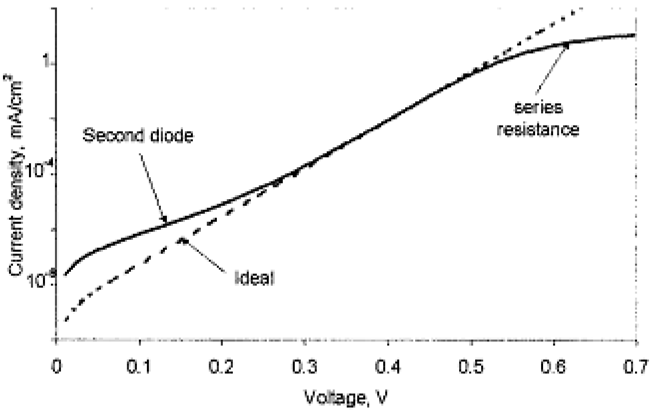


Figure 3.6 : The dark I-V characteristic of PV in the two diode and series resistance [22].

The power produced by a crystalline PV module is affected by two key parameters;

- Solar irradiance
- Cell temperature

The effect of the solar irradiance and the module temperature on the I – V characteristic of the German Solar GSM6-250P, the information from the datasheet as presented in Figure 3.7 shows that the output current of the cell drops when the solar irradiance level decreases. The same case take cover for the output power which decreases also but the open circuit voltage is not much affected. In case of temperature this happen in opposite where open circuit voltage decreases with the increases of temperature in the module but this does not affect significantly on the short circuit current. The German Solar GSM6-250P have been used for the explanation but this happen for all the kind of solar cells.

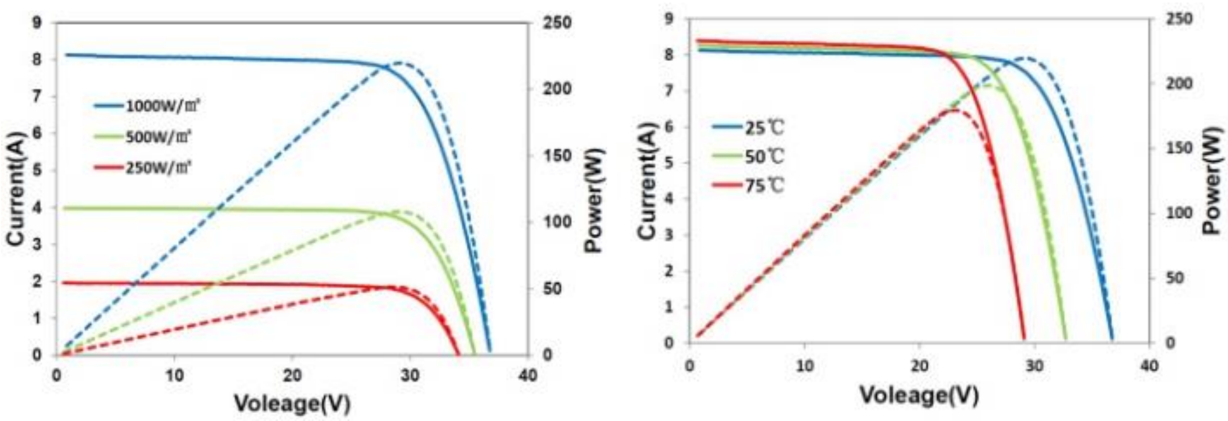


Figure 3.7 : Effect of solar irradiance and cell temperature on the I–V curve [23].

3.2.2 Operating Temperature of PV cells

Solar irradiance on the solar cell is the cause of its electrical power output put also causes a heating up of the module. For the good working condition, the cells should work on the minimum possible temperature. An energy balance on a unit area of module can be used to find out the temperature at which the cell should operate [6]. This is obtained by the equation 3.5 [6][24].

$$\tau\alpha G_T = \eta_c G_T + U_L(T_c - T_a) \tag{3.5}$$

Where

τ: The solar transmittance of the cover in percentage

α: The solar absorptance in percentage

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

η_c: The electrical efficiency of array in percentage

U_L: Heat transfer coefficient (kW/m^2 ^{0}C)[4][6]

T_c: The temperature of the cell (^{0}C)[4][6]

T_a The ambient temperature (^{0}C)[4][6]

To characterize the heating up of the module due to irradiance. The cell temperature for steady state conditions under constant irradiance and temperature can be measured. According to US-standards, the cell temperature should be measured at 800 W/m$_2$ and an ambient temperature of 20ºC called the nominal operation conditions NOCT.

Measurement of cell & ambient temperature, and solar radiation can be used for calculating the ratio $\tau\alpha/U_L$[24]

$$\tau\alpha/U_L = \frac{T_{c,NOCT} - T_a}{G_{T,NOCT}} \tag{3.6}$$

Where

$T_{c,NOCT}$: The Nominal Operating Cell Temperature (^{0}C)[4][6]

T_a: The ambient temperature for NOTC is defined (20 ^{0}C)[4][6]

$G_{T,NOCT}$: The radiation of solar with NOCT is defined (0.8 kW/m^2)[4][6], this is for standard of USA characterization for solar module. Homer also use this as input variable.

By considering the ratio $\tau\alpha/U_L$to be constant, the temperature at any other condition can be calculated with

$$T_c = T_a + G_T(\frac{\tau\alpha}{U_L})(1 - \frac{\eta_c}{\tau\alpha}) \tag{3.7}$$

The $\tau\alpha$ is not known in most of the case but this can be approximated to be 0.9 because the ratio $\eta_c/\tau\alpha$ is so small than a unity.

When solar operate on its MPP the PV efficiency is the efficiency at MPP [4].

$$\eta_c = \eta_{mpp} \tag{3.8}$$

Since the efficiency at MPP changes with the changes of the cell temperature then the variation can be calculated as follows

$$\eta_{mpp} = \eta_{mpp,STC}\{1 + \alpha_P(T_c - T_{c,STC})\} \tag{3.9}$$

Where

$\eta_{mpp,STC}$: The MPP efficiency under the test at standardized conditions (%)

α_P: The temperature coefficient (%/^{0}C)[4][6]

$T_{c,STC}$: The cell temperature under the test at standardized conditions (25^{0}C)

Using equations, 3.6, 3.8 and 3.9 and put into equation 3.7, the temperature of the cell at any irradiance can be obtained with the equation (3.10)[6].

$$T_c = T_a + G_T(\frac{T_{c,NOCT} - T_a}{G_{T,NOCT}})(1 - \frac{\eta_{mpp,STC}\{1+\alpha_P(T_c - T_{c,STC})\}}{\tau\alpha}) \tag{3.10}$$

$$T_c = \frac{T_a + (T_{c,NOCT} - T_a)(\frac{G_T}{G_{T,NOCT}})\{1 - \frac{\eta_{mpp,STC}(1-\alpha_P T_{c,STC})}{\tau\alpha}\}}{1 + (T_{c,NOCT} - T_{a,NOCT})(\frac{G_T}{G_{T,NOCT}})(\frac{\alpha_P \eta_{mpp,STC}}{\tau\alpha})} \tag{3.11}$$

In practice, as the $\frac{\tau\alpha}{U_L}$ in this formula are not known from standard module test 3.11 is replaced by

$$T_c = T_a + c * G \text{ [25]} \tag{3.12}$$

With c being a constant reflecting the type of module mounting (freestanding, roof integrated,…), see e.g in [25].

3.2.3 PV module Power output

The power output of a PV as it has been discussed that it is a function of the temperature and the irradiance of the solar and can be found by equation 3.13 where cell temperature is calculated as it has been proved in the equation 3.7.

$$P_{PV} = Y_{PV}\, f_{PV}(\frac{G_T}{G_{T,STC}})(1 + \alpha_P(T_c - T_{c,STC})) \tag{3.13}$$

Where

Y_{PV} : is the module rated capacity (kW)

f_{PV}: is [6]the module derating factor (%), HOMER exercises this factor to the output power PV array to take into account some factors which lower the output in real conditions [4][6]. Such factors may be dusty of the panels, network losses, aging, snow cover, shading, and so on.

$G_{T,STC}$: is the incident radiation under the test at standardized conditions (1 kW/m^2) [4]

T_c: is the cell temperature (^{0}C) [4]

3.2.4 PV cost

Photovoltaic Solar panels cost has been reduced drastically in the past years and it is assumed to continue its down slope for the future; the cost of solar panels is a variable that actually depends on the time, place and scale of the solar panel installation.
According to the reported pricing for PV system installations, the current overall cost figures in recently updated prices are as follows [26]:
• Residential and small commercial (≤10 kW) was $ 4.69 /W (median)
• Large commercial (>100 kW) was $ 3.89/W (median)
• Utility-scale (≥5 MW, ground-mounted) was $ 3.00/W (capacity weighted average).
PV modules certified for conformity with the IEC61215 (Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval) standard for the mono-crystal and with similar IEC standard for the poly-crystal, the costs are given for a 10 kW fixed slope PV system.

- The price of Monocrystalline Solar Panel SUNTECH STP250S is 245.63 € [27] equal to US $ 360. The 10kW will cost $ 360*40 = $ 14400, considering transport of 20% and taxes of 18%, the total cost for 10 kW comes to $ 20000
- The cost of solar inverter is $0.435/Wp [28] this means that the cost of 10kW will be $ 4350, by considering transport of 20% and taxes of 18%, the total for 10 kW will be $6000.

Balance of System Cost

- The estimated cost for the solar ground mounting system is $ 100 per module, since the module of 250 Wp have been selected, then the cost for the 10 kW which is 40 modules of 250Wp system is $ 4000.
- The Local transportation cost of the equipment from Kigali to Burera is estimated as $ 500.
- The estimated installation cost and other relevant cost is $4500

The total costs is around $ 35000 which is the estimation costs for 10 kW solar PV system. Solar system do not require a lot of maintenance work as compared with other technologies with moving parts. Thus the operating and maintenance cost of a PV system is relatively small. The annual O&M cost of a 10 kW PV system has been considered as $ 30.

Figure 3.8 : Solar PV ground mounted system [29].

3.3 Micro-Hydro Power Plant

It is a non-polluting and environmental friendly source of energy. Hydropower is established with simple concepts. Water movement rotates a turbine which is mechanically connected to generator, and electricity is produced. Many other components are required, but it all starts with the energy from water. The use of water falling through a height has been utilized as a source of energy a very long time [30].

3.3.1 Components Overview

Figure 3.9 presents the principal elements of a run-of-the-river micro-hydropower system. As the Figure shows, no storage of water but instead the pipe connect the river and the penstock, then the latter connect the stream of water to the turbine. The power poles or tower can be used to transmit the power from the power plant up to end users [31][30].

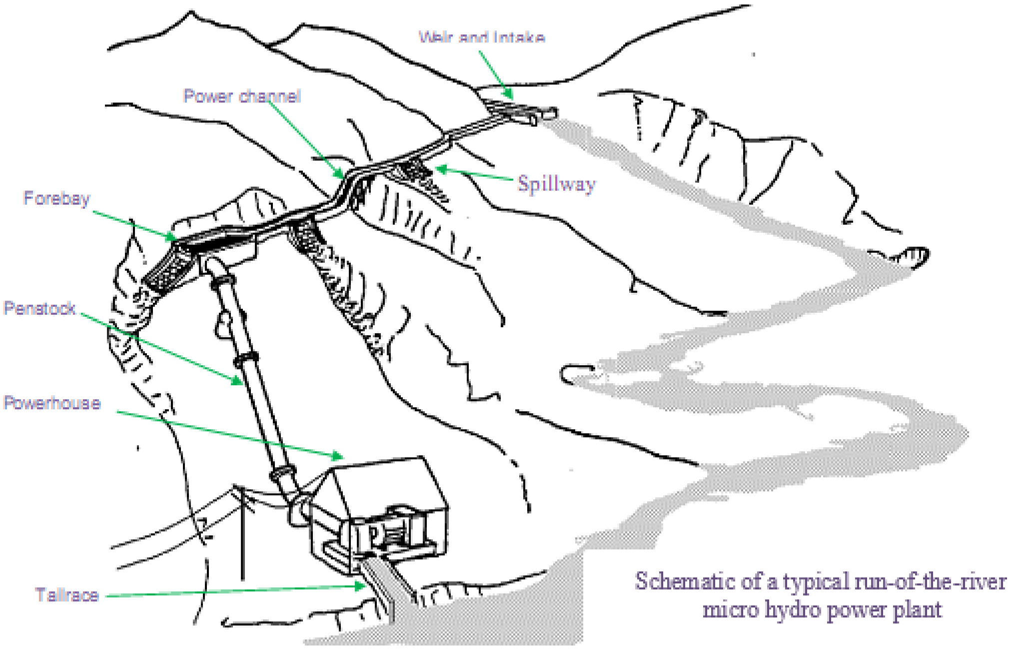


Figure 3.9 : Micro hydropower plant overview [30].

Many aspect can be used to build up a micro hydro power plant depending in accordance with the geographic and hydrological conditions, but general concept is the same.
The following figures are the principal components of a run-of-the-river micro-hydro system [32].

- Diversion Weir and Intake
  The diversion weir is a block barrier constructed over the river and it is used to redirect the water through the 'Intake' opening into a settling basin.

Figure 3.10 : Diversion Weir and Intake [32]

- Settling Basin
  The settling basin help to filter the water before entering the penstock. This can be constructed at the intake or at the forebay.

Figure 3.11 : Settling Basin [32]

- Headrace
  A conduct that govern the water to a forebay or turbine. The headrace pursue the contour of the hillside so as to maintain the elevation of the diverted water.

Figure 3.12 : Headrace [32].

- Head tank
  Small reservoir at entrace of a pipeline; this is taken as final settling basin, provides overflow of penstock inlet and integration of trash rack and overflow/spillway arrangement.

Figure 3.13 : Head Tank [32].

- Penstock
  An enclosed conduit which is used for furnish the pressurized water to a hydro turbine.

Figure 3.14 : The penstock [32].

- Water Turbine and alternator
  A turbine is a machine converting the kinetic energy of water into a rotational energy at the same time, the alternator is another electrical machine for converting mechanical energy into electrical energy.

Figure 3.15 : Connection arrangement between Turbine and Generator [32].

3.3.2 Micro Hydropower Capacity

For information about the power potential of water in a stream, it is very important to know the quantity of water flow available from the stream (for power generation) and the available head. The available water for power generation is the amount of water (in m^3 or litres) which can pass via an intake into the pipeline (penstock) in a given amount of time. This is normally expressed as (m^3/s) or in litres per second (l/s). The head is the vertical difference in level (in meters) through which the water falls down. The theoretical power (P) can be calculated using the following equation [31][32].

$$P = Q \times H \times e \times 9.81 \text{ Kilowatts (kW)} \quad (3.14)$$

Where

- P: Generator Output Power (kW)
- H: The water head in metres (m)
- Q: The water flow (m^3/s)
- e: The total efficiency (%)
- g: 9.81 is a constant

The output power will be the function of several loss which will take cover in the production system as indicated in the figure 3.16.

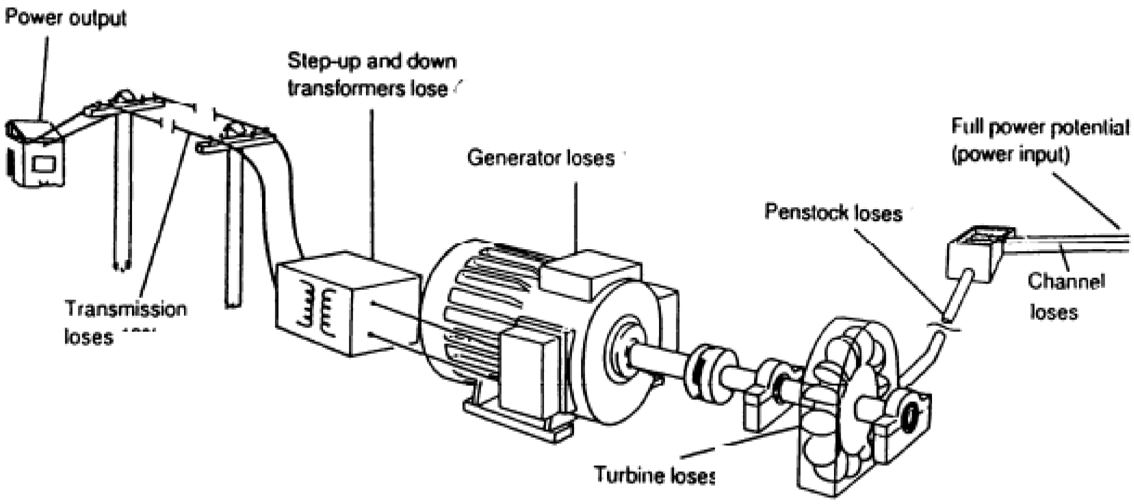


Figure 3.16 : Typical system losses for a system running at full design flow [32].

3.3.3 Micro Hydro Power Plant Cost

While performing a trial calculation of construction cost in the planning stage, this can be done by following some method. However, before the calculation, it is necessary to carry out a field survey for confirmation and decide the item mentioned in the table 3.1 below [32].

Table 3.1 : Items to make a trial calculate of construction cost.

Description	Item
Plan	Maximum Out Put (kW)
	Turbine Discharge (m^3/s)
	Effective Head (m)
Intake Facilities	Height of Dam (m)
	Length of Dam (m)
Headrace	Length of Headrace (m)
Penstock	Diameter of Penstock (m)
Distribution	Number of Households
	Distance to the most far house from P.S

In addition to the direct costs, indirect costs, such as Tax, Contractor fee, Design Cost, and Supervision cost, are contained in the cost of construction. When part of these indirect costs is missing, some explanation is required separately [32].

Items of direct cost

Typical items of a direct cost are the following [32].

1. Preparatory Works
   Preparatory Works consist of item as follows.
   - Location Setting Out,
   - Filling and Measurement,
   - Equipment & Materials Mobilization

2. Civil Works
   Civil Works consist of item as follows
   - Intake facilities,
   - Settling basin,
   - Headrace,
   - Head tank,
   - Spillway,
   - Penstock and Foundation,
   - Powerhouse base,
   - Tailrace,
   - Power house,

3. Electro-Mechanical Works
   Electro-Mechanical Works consist of item as follows.
   - Turbine,
   - Controller,
   - Dummy load,
   - Generator,
   - Accessories,
   - Spare parts and Tools
   - Set up and Installation

4. Distribution Works
   Distribution Works consist of item as follows.
   - Transmission pole,
   - Distribution Wires,
   - Step up/down Transformer,
   - Other extra

Quantities

In order to know the direct cost of construction for MHPP, it is required to know the quantity for every work or material based on the design. For example, in case of Headrace made of stone masonry, quantities of excavation, foundation rubble stone, stone masonry, backfill, and plastering shall be estimated.

Unit Cost

Since the cost of micro hydro power plant differs according to various items in which it is very hard to know the cost of every one because most of the items require a lot of understanding, in this project I prefer to estimate the cost of micro hydro power plant using other researches which have been demonstrated for the cost per watt of the output power produced.
In Renewable Energy – Based Mini – Grid for Rural Electrification: Case Study of an Indian Village[9], Rohit Sen and Subhes C. Bhattacharyya in their research, they have demonstrated that the capital cost for a 30-kW SHP can be assume as $42,000 while the replacement cost and O&M cost are considered to be $35,000 and $4,000, respectively. I will use the same approach in my project because, this is true when using the information from [33] saying that, internationally an initial capital cost estimated for micro hydro power plants, with new technologies, is estimated in between US$ 1500 to $ 2500/kW where this cost is composed with around 75% of the development cost and it is decided by the location conditions, and the remaining 25% is the cost of purchasing engineering components(the turbine, generator, electronic load control, manual shunt-off valve, and other components) [15].
In “Economic Analysis and Application of Small Micro- Hydro Power Plants” by Mrs. Sarala P. Adhau[34] state that, the investment cost for a micro hydro power plant can be estimated as $ 1500 per kW.
In this development, the cost is taken as an average at $ 1500/kW because of the remote area, and thus complicated position of the village and neighbouring areas [15].
A design flow rate of 280 l/s at 9.7 metres head, a turbine coupled to an alternator will be able to produce an electrical output power of 20kW, at an overall efficiency of 75%.
The capital, renewal, and O&M worth of the micro-hydropower system were estimated at $ 40000, $ 30000 and $ 800 /year respectively.

3.4 Diesel Generator

Diesel generators are very important in renewable energy hybrid systems to improve the quality and the availability of the electricity supply. Since diesel generators is used for extra load in an occasion of necessity, or in a case of black-out and battery bank is not sufficient for supplying the load [17].

The initial investment for a diesel generator is relatively small when compared with the initial investment of the micro hydro power plant, PV or wind power plant system. The big problem with this is that, the operating and maintenance cost of a diesel generator is very high because it requires a continuous supply of fuel (diesel), and frequent maintenance and inspection of the engine throughout its operating life.

Normally diesel generators operate most efficiently when working near its full load. That is why it is good to work the generator beyond a certain load factor for controlling the proper efficiency of the energy conversion and then lowering the fuel cost by reducing the utilization of fuels. The fuel consumption curve of a diesel generator is normally given in the product data sheet and the efficiency curve can be derived using that product specification.

The Figure 3.17 below represents a typical genset fuel curve. Diesel generators are most efficient when used near its highest output. As well as the load decreases, the efficiency will decrease significantly. When increasing the load from 20% to 80% doubles the efficiency of the generator, reducing fuel consumption per kWh by two. The diesel fuel consumption is given in a Table 3.2 depending with the power of the generator and the percentage of its full load.

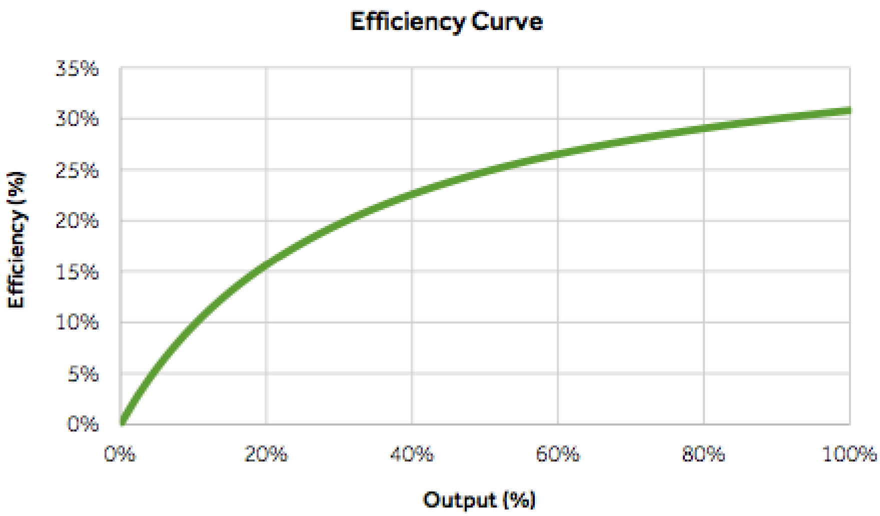


Figure 3.17 : Typical generator efficiency curve [35].

Table 3.2 : Approximate Diesel Fuel Consumption Chart [36].

Generator Size (kW)	1/4 Load (litre/hr)	1/2 Load (litre/hr)	3/4 Load (litre/hr)	Full Load (litre/hr)
20	2	3	5	6
30	5	7	9	11
40	6	9	12	15
60	7	11	14	18
75	9	13	17	23
100	10	16	22	28
125	12	19	27	34
135	12	20	29	37
150	14	22	32	41
175	16	26	37	48
200	18	29	42	55

3.4.1 Operation and Maintenance of Diesel Generators

The lifetime of a diesel generator is operation hours and it depends on various aspects. When the generator will be used in standby power applications, it is assumed to start at full-rated load in less than 10 seconds. However the maintenance of generator like other mechanical device is a paramount for ensuring that a diesel powered standby generator will start and run when desired [37].
To manage the efficient operation and expand the operating life of diesel generators it is required to provide and obey to the maintenance schedule based on the specific power application and the severity of the environment [37]. The Table 3.3 below gives the required regular and typical diesel maintenance schedule and their estimated costs:

Table 3.3 : Regular and typical diesel maintenance schedule and their estimated costs.

Maintenance Items	Service time					Estimated Cost US $
	Daily	Weekly	Monthly	1/2 Year	Year	
Inspection	✓					35 to $ 70
Check coolant heater	✓					
Check coolant level	✓					
Check oil level	✓					
Check fuel level	✓					
Check charge-air piping	✓					
Check/clean air cleaner		✓				70 to $ 140
Check battery charger		✓				
Drain fuel filter		✓				
Drain water from fuel tank		✓				
Check coolant concentration			✓			140 to $ 280
Check drive belt tension			✓			
Drain exhaust condensate			✓			
Check starting batteries			✓			
Change oil and filter				✓		280 to $ 560
Clean crankcase breather				✓		
Change air cleaner element				✓		
Change coolant filter				✓		
Change fuel filters				✓		
Clean cooling system				✓		
Replacement of crankshaft					✓	1030 to $ 2060
Change bearings					✓	
Change valves					✓	
Change valve springs					✓	
Change injectors					✓	
Change fuel pumps					✓	
Change piston					✓	
Change piston rings					✓	

3.4.2 Cost of Diesel Generator

In Rwanda, the cost of available diesel generators is primarily dependent on the size of the generator and the brand of the generator. For example, the smaller capacity generators have higher costs per kW and the larger capacity generators have a lower cost per kW. Therefor the cost of diesel generators does not vary linearly with the capacity of its output power.
The cost of diesel generator have been taken as shown in table 3.4 below [38] but the replacement cost has been approximated depending with working aspect.
At present, in Rwanda the diesel price is 850 Frw ($ 1.2) and the transportation taken into consideration since the diesel will be transported from the urban areas (Diesel Stations) to the rural community [1]. Thus for this analysis the fuel cost has been considered to be $ 1.3.

Table 3.4 : Cost of Diesel generator on the market.

	Size (kW)	Capital Cost($)	Replacement ($)	O&M Cost ($/hr)
1	10	7000	5000	0.5
2	15	8400	6000	0.6
3	20	9800	7000	0.7
4	25	10500	8000	0.8
5	30	11200	9000	0.9

3.5 Storage Battery

An off-grid hybrid system requires a storage to store the excess energy from the renewable sources for later utilization when required. A backup in the system and the maintaining a constant voltage during peak loads or a shortfall in generation capacity, batteries can help for the letter reasons [1]. Batteries are the most common storage method used in renewable energy system applications. A battery is an electrochemical device capable to store energy in form of electricity when placing different metals in an acid solution.
The Rwanda market we have two types of batteries; Primary batteries and Secondary batteries. The batteries which can only be used only one time are called primary batteries while the batteries that can be recharged are called secondary batteries. Renewable applications use secondary batteries. The open circuit voltage of a battery is obtained by the type of electrodes and the electrolyte which have been used. The voltage of a battery is not constant during charging and discharging of the battery. Typically at the equilibrium conditions is known as the nominal battery voltage [4].
The battery chosen for this Study is 6CS25P-Surrette of 6V with a nominal capacity of 1,156 Ah (6.94 kWh). The letter can be found on market with the capital cost of $ 1200, then the approximated replacement cost and O&M costs for one unit of this battery has been considered to be, $ 1200 and $ 30/year, respectively.

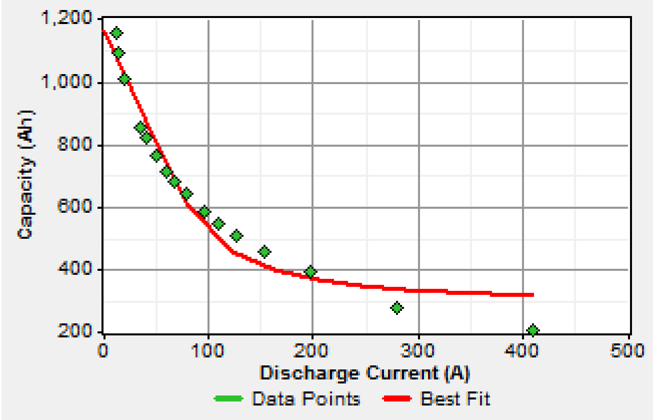


Figure 3.18 : Capacity curve of the Surrette 6CS25P, 6V battery, from Homer.

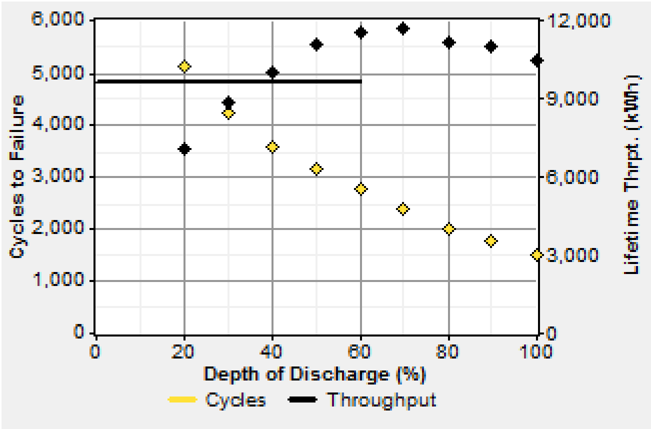


Figure 3.19 : Lifetime curve of the Surrette 6CS25P, 6V battery, from Homer.

The capacity of a battery is defined as the energy that can be withdrawn from starting to fully-charged state and it is measured in Ampere hours. But the capacity of a battery depends on the proportion at which energy is withdrawn from it [1]. The higher the discharge current, the lower the capacity. For example, the capacity curve of the Surrette 6CS25P battery is given in Figure 3.18. The nominal capacity of this battery is given as 1156 Ah by the manufacturer and it is just one point on this capacity curve.

The life of a battery primarily affected by the range of discharge and the temperature at which it is operating. Depth of discharge is the level at which batteries are discharged in a cycle before they are charged again. Usually the manufacturer specifies the nominal number of complete charge and discharge cycles as a function of the depth of discharge in the product data sheet. For example, Figure 3.19 gives the lifetime curve of the Surrette 6CS25P battery. The Figure indicates the number of cycles to failure drops quickly with increasing depth of discharge [4]. It also shows the lifetime of the battery which also depends on the number of cycles to failure [4].

3.6 Inverter

An inverter is a vital element in any solar system where the AC is required. It converts the DC form of solar system or wind system into AC form for AC appliances [1]. A hybrid system needs an inverter to convert DC voltage from the batteries to AC voltage required by the load. Some aspect is needed to be taken into consideration when selecting an inverter for a certain application. Usually the inverters used in renewable applications can be divided into two; inverter for solar and for wind electric system [39].

Inverters for solar electric system are also divided into four types depending with its application. **Stand-alone inverter or off-grid inverter**, **Grid connected inverter, hybrid power inverter and Grid interactive inverter**.

Also there are inverters which are specifically designed for PV applications and they are integrated with Maximum Power Point Trackers (MPPT) and some inverters are bidirectional so that they can operate in both inverting and rectifying modes. That is why a proper inverter must be carefully selected for the power system according to the requirement and also paying attention to the hybrid system configuration as well. With this project, we will use the following inverters:

Off-grid inverters, this is good for the remote stand-alone power system which has some batteries for the backup. The pure sine inverters are the best for home and rural village systems.

Hybrid power inverters are good for the combination solar and diesel generator or any other RE sources.

The DC side voltage of a battery inverter have to be matched with the battery bank voltage. Generally stand-alone battery inverters operate at 12, 24, 48, 96, 120 or 240 V, DC depending on the power level. For high power applications system it is required to use an inverter with a higher DC voltage due to the current ratings of the wires and the rated capacities of other DC components such as fuses, breakers decrease. The efficiency of the inverters have been improved a lot in this days and 90 % and above is the typical efficiency. However, the latter varies with the load and normally the manufacturer specifies the efficiency curve of the inverter.

The cost of the bidirectional inverter is $ 8239 for 10kW. By estimating the transportation and tax all together on 38%, the capital cost comes to $ 11370. In this project the approximation of replacement and O&M cost has been taken as $ 11370 and $ 2 /year respectively.

Table 3.5 : Inverter specifications [28][40][41].

	Solar Inverter	Battery Inverter
Brand	SMA Sunny TriPower	SMA
Rated Capacity	10 kW	10 kW
Maximum Efficiency	98 %	95 %
DC voltage	330 V-800 V	41 V – 63 V
AC voltage	230/400 V, 50 Hz	230/400 V, 50 Hz
Price	$ 4345	$ 8239

4 Hybrid System Modelling

The chapter presents the modelling of hybrid system using the optimization software called HOMER. The chapter start by describing the important inputs that demonstrate the technical specifications, resources data and the costs which are relevant for modelling the system in HOMER and the chapter will end by giving a brief discussion on how the software calculates the levelized cost of energy using the economics inputs.

A brief summary of the site specific information that I entered into Homer

- Average load demand is 10 kW, peak load demand is 38 kW, and average of the daily demand is 249 kWh/d and the load factor of 0.275.
- Water flow is 280 L/s and the head is 9.7 m.
- Solar irradiance is 5.13 kWh/m^2/d, the clearness index is 0.513 and the average temperatures is 22.7**°C**
- As explained in the section 2.4, that situation sets limits to this new hydro power stations. The maximum water flow of 280 litres per second is a limitation to 20 kW as max power from the micro hydropower plant.
- The battery is Surrette 6CS25P of 6V, 1,156 Ah (6.94 kWh)
- Diesel generator with a lifetime of 15,000 operating hours is used.
- Efficiency of 98 % for converter.

4.1 Introduction

The major components of the hybrid system with their technical details and relevant costs have been discussed earlier in Chapter 3. As stated in problem statement the aim of this development is to find out the best hybrid configuration which can supply the electricity at the lowest price with an accepted level of availability. For this, it is required to consider several combinations of RES and diesel generator with different component capacities. This is achieved by the software called HOMER [1].

HOMER is a computer model that facilitate the assignment of assessing the design options for both off-grid and grid connected hybrid systems for isolated, stand-alone and distributed generation system. It facilitates a range of renewable energy and conventional technologies including solar PV, wind turbine, hydro power, generator, battery bank and hydrogen. HOMER's optimization analysis algorithms help to assess the cost effective and technical practicability of a certain number of technology options [4]. The sensitivity in HOMER allows to find the effect of uncertainty in the input variables to the energy cost and the optimal configuration.
HOMER hybrid model requires several inputs which basically describe the technology options, component costs, component specifications and resource availability. HOMER uses the energy balance in optimization calculations. Electric and thermal load demand are compared to the produced energy in that hour and then compute the flow of energy going to or coming from each element of the system [4]. This comparison is done for every 8760 hours of the year for every

system type that the user wants to consider [4]. It then determines whether the hybrid configuration can supply the demand under the conditions that the user has specified. If it can, then HOMER calculates the NPV of installation and operating cost of the project throughout its lifetime and the COE based on the Levelized (LCOE) [4]. The resulting hybrid configuration that has the least LCOE or the least total NPV of the project is considered as the optimum hybrid system [4].

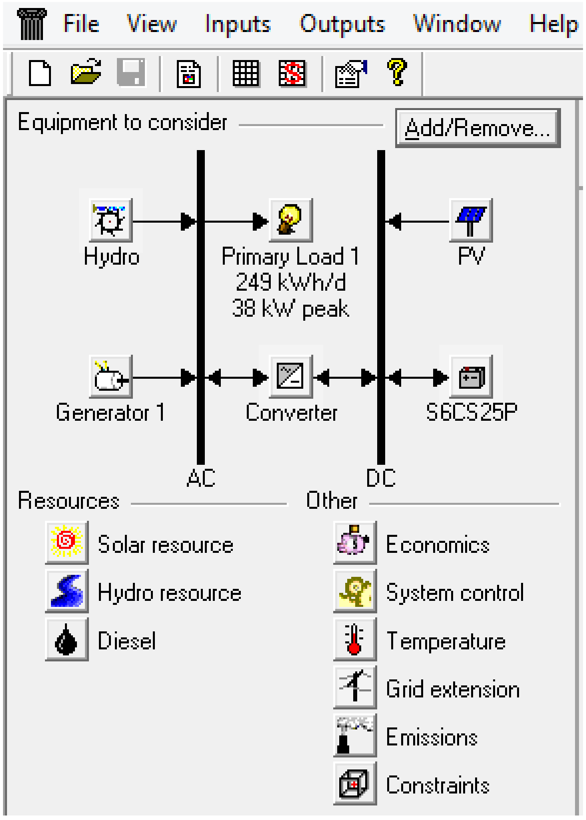


Figure 4.1 : Inputs required by HOMER hybrid model.

4.2 Modelling of Equipment

The hybrid system will be modelled in HOMER as shown in Figure 4.1 above by using AC coupled hybrid configuration.
Once the required components of the hybrid system are selected as in Figure 4.1, there are several inputs which must be entered in each of the component input windows in HOMER. These inputs basically describe the costs, technical specifications and resource data that have been already discussed in Chapter 2 and 3. A summary of these data are discussed here below.

4.2.1 Load input

Primary load is the one to be met immediately in such way that no unmet load [4]. An addition of two separate primary loads to the system from the Add/Remove window. Each hour, HOMER calculate the power produced by the elements of the system to serve the total primary load [4].

The baseline data is a number of 8,760 values that represent the average of electric demand and it is expressed in kW, and this values is taken for each hour [4].

Two technics to produce baseline data [4]: Either by HOMER to synthesize data, or by importing hourly data from a file [4].
The technic of synthesize, just put at least one load profile, which is a set of 24 hourly values of electric load [4]. 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. HOMER adds randomness according to the values you enter for daily noise and hourly noise.

The daily and hourly noise inputs help to add randomness to the load data to make it more realistic [4]. Figure 4.2 shows how this noises will affect the average load profile [4]:

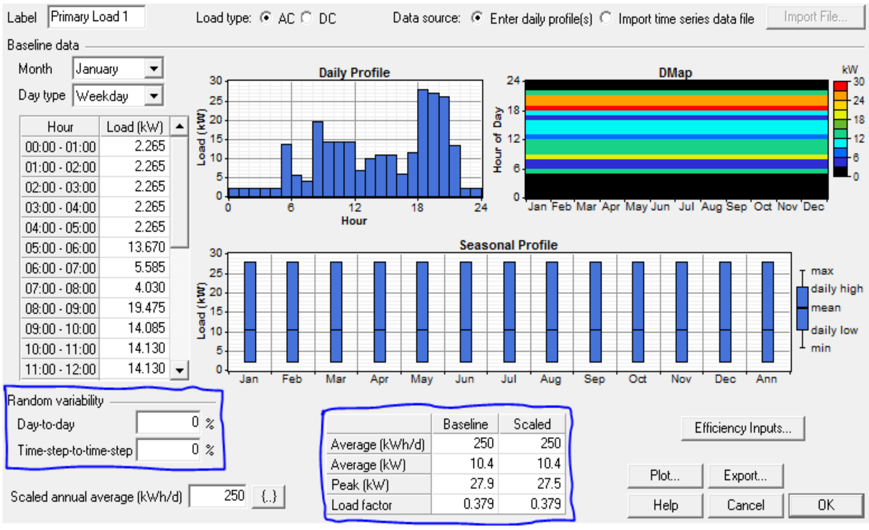


Figure 4.2 : Random variability (daily and hourly noise) set to zero.

Firstly, take a look of load without any added noise [4]. As shown on the plot in Figure 4.3 below of the first week of the year [4].

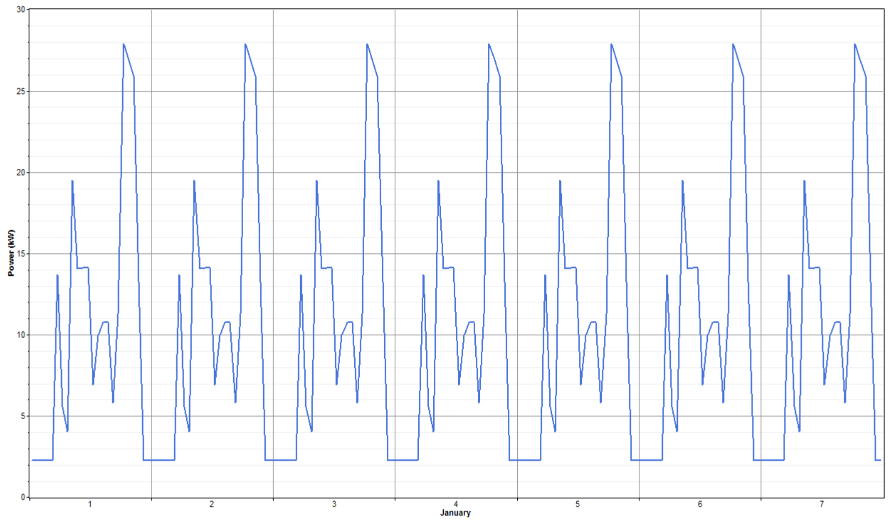


Figure 4.3 : Load plot without any added noise for the first week.

So without any noise, the load profile repeats precisely day after day [4]. In reality, the magnitude and the form of the load will change from day to day [4]. This standard deviation come up with more realistic load demand. With 10% daily noise and 10% hourly noise, a result of plot is shown in the below Figure 4.4 for the first week in year one [4].

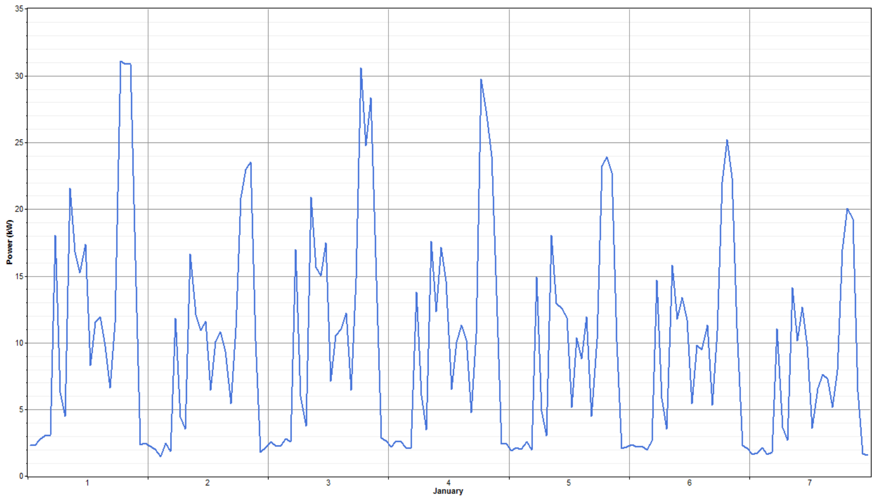


Figure 4.4 : Load plot with an added random variability for the first week.

Daily noise will affect the size but the shape doesn't change where the hourly deviation affect the shape but without affecting its size [4].
The mechanism for adding daily and hourly noise is simple. First HOMER bring together the 8760 hourly values of load data from the specified daily profiles [4]. Then it multiplies each hourly value by a factor

$$\alpha=1+\delta_d+\delta_h \qquad (4.1)$$

Where; δ_d = daily perturbation factor and δ_h = hourly perturbation factor

The following Figure 4.5 is the results of different parameters which have been used and obtained for this project from the homer load input window.
As decided in Chapter 2, a constant load profile has been assumed throughout the year, but hourly and daily randomness has been added to this load profile in HOMER to generate realistic load profile [17]. I have added 10 % randomness for both these cases. Adding 10 % randomness to the load profile results increase in annual peak demand to 38.9 kW and the load factor of 0.275. HOMER calculates the parameters, annual average of the daily demand, peak load and load factor based on the load profile and the random variability inputs given by estimation.

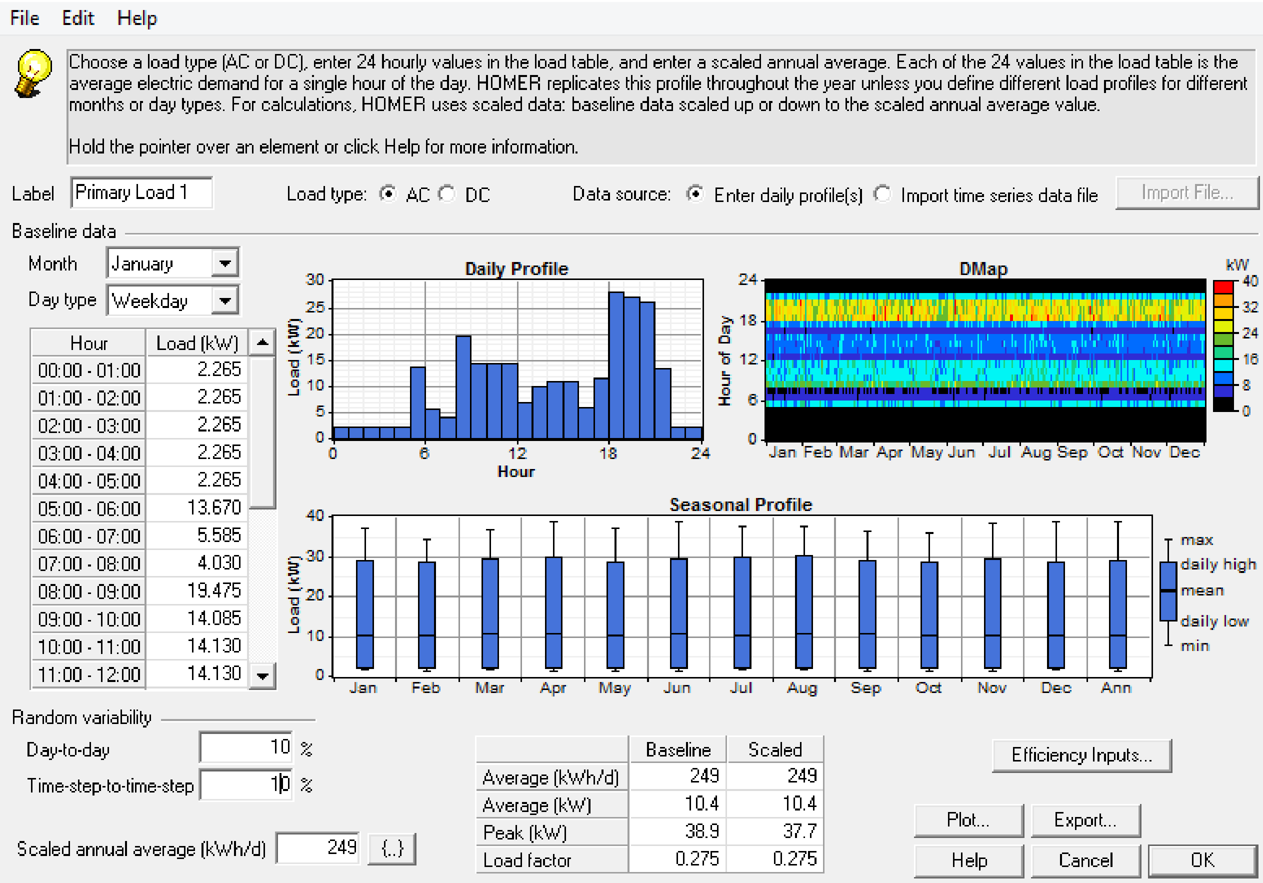


Figure 4.5 : Homer primary load input window.

4.2.2 PV input

This opening is used to characterize the cost curve of PV panels, select the sizes that HOMER will deal with for the optimal system, and specify the placement of the array [4].

In the cost table as shown in the Figure 4.6, the PV cost depend with how big is the system. Normally this necessitate only a single row because PV costs are commonly assumed to be linear with size [4]. In this project, the capital price of PV panels for a 10kW photovoltaics system has been specified and taken at $35,000 and the cost for replacement is assumed to be $25,000. The O&M cost is specified as $30.

The PV derating factor (f_{PV}) [6]**:** This is a factor which is used by HOMER to consider some factor that can affect the output power of PV in real-life operating conditions when relating with the standard conditions [6].

It is used to take into consideration for those factors like dirtying of the panels, losses due to wires, shadow, snow cover, oldness, and so on [6]. In this project, this factor have been estimated to 80% so that Homer can calculate the output power by taking into account other factors which may reduce the PV’s output power.

HEffect of Temperature on the PV Array: The PV Inputs opening gives the choice of explicitly modelling the consequence of temperature exercises on the array [4][6]. The ambient temperature will be required so that HOMER can use it in calculation of the cell temperature and this will be executed in each time step [4][6]. If you desire to not explicitly consider the effect of it, then the temperature-related difference between real and rated power output by reducing the PV derating factor have still to be considered [4][6]. In this project, the choice of explicitly modelling the temperature effect on array is selected and the ambient temperature data [4][6] in Table 2.3 from NASA Surface Meteorology and Solar Energy website is used.

The slope (β) is the placement angle of the panels to the horizontal [4]. A slope of 0° means horizontal, and 90° to vertical [4]. Taking the system as fixed-slope systems, an approximation of slope equal to latitude of the location will practically maximize the PV energy production [4]. The azimuth indicated the direction followed by the panels slope [4].

Therefore two axis solar tracker can be used to follow both of these sun's movements. Generally the costs of these two axis trackers are relatively high. Hence, they are not widely used in commercial applications. In most the applications, the panels are mounted with a fixed slope.
Fixed slope solar collectors normally face towards the equator and the tilt angle is set to an angle which is equal to the geographical latitude of the collector location on the earth. This angle is a good to maximize the annual performance of the collector. In this project the slope would be 1.30 degree of latitude, but this slope is very small by considering the rain water which may depose to the solar modules, due to this an estimation of 15^{o} have been set so that rain water may fall down very easily.

The azimuth (γ) is the orientation which is supposed to be followed by placement of panels in terms of slope [4]. 0° for south, 90° for east, 90° for west and 180° for north [4]. If the azimuth angle of the system is set to be fixed then the modules will be orientated as 0° azimuth for the systems situated in the northern hemisphere and 180° azimuth for the systems situated in the southern hemisphere)[4].
The ground reflectance (ρg) is the percentage of radiation that is reflected on the ground [4]. A grass-covered is 20 %. Snow areas may go as high as 70 % [4]. For this project, the ground reflectance is set to 20 %.
The temperature coefficient of power (α_P) this express how the output power of an array depends on its surface temperature [4][6]. Since output power is reduced with the increasing of cell temperature, that is why this number is negative [4][6]. Manufacturers give this number in their product brochures. In this project a monocrystalline solar panel SUNTECH STP250S has been selected and in its data sheet, the manufacturer has specified the temperature coefficient of power of -0.44 %/^{o}C[27].
The nominal operating cell temperature ($T_{c,NOCT}$), this gives the level of how the solar radiation and the ambient temperature affect the temperature of the PV array on its surface [4][6]. HOMER uses this to compute the PV cell temperature [4][6].
PV manufacturers typically give this number in the data sheet [4][6]. The same case in this project a crystalline solar panel SUNTECH STP250S has been selected and in its data sheet, the manufacturer has specified the NOCT of 45^{o}C[27].

PV Efficiency at Standard Test Conditions ($\eta_{mp,STC}$) [4][6]: HOMER uses this to compute the PV cell temperature [4][6].
The following equation can be used to find out this number:

$$\eta_{mp,STC} = Y_{PV}/(A_{PV}*G_{T,STC}) \text{ [6]} \qquad (4.2)$$

Where

$\eta_{mp,STC}$ is the module efficiency tested under the standard conditions (%) [4]

Y_{PV} is the rated output power of the module tested under the standard conditions (kW) [4].

A_{PV} is surface area in m^2 [4]

$G_{T,STC}$ is the radiation tested under the standard conditions (1 kW/m^2) [4].

HOMER suppose the PV to work under maximum power point.

In this project a monocrystalline solar panel SUNTECH STP250S is selected and in its data sheet, the $\boldsymbol{\eta_{mp,STC}}$ equal to 15.4% was stated by the manufacturer. The Figure 4.6 below summarize the parameters required by homer for the PV input.

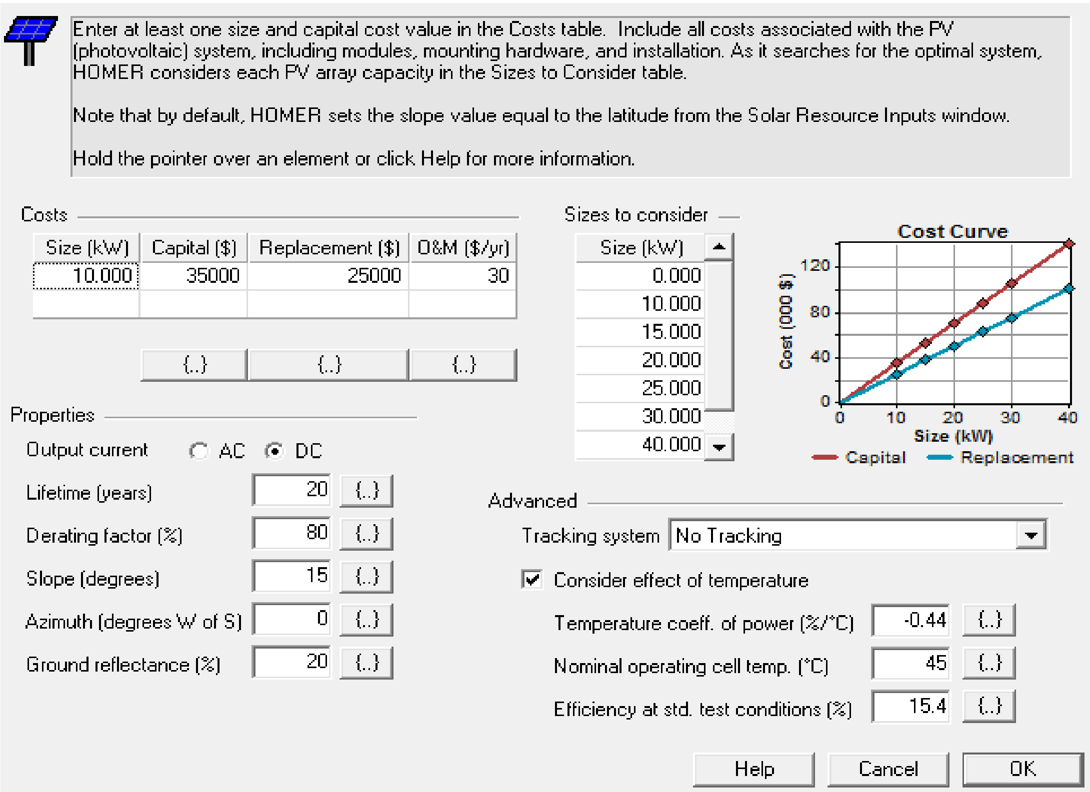


Figure 4.6 : PV input window, from homer.

4.2.3 Hydropower input

HOMER consider only a single size of hydropower system [4]. Reason being, no tables of costs or sizes to consider in the opening for hydro Inputs [4]. Instead, it designate the cost and properties of size of hydro to be considered [4].

Available Head (h), this is the difference in height between the intake and the turbine [4]. In this project, the available head has been estimated to 9.7 m.

HOMER uses this number to compute the output power of the hydropower turbine [4].

Effective Head (h_{net}); this is the actual head but minus the losses which have been take covet into the penstock and it is expressed in term of head loss [4]. HOMER use equation 4.3 to compute this net head [4]:

$$h_{net} = h*(1-f_h) \tag{4.3}$$

Where

h = available head [m] and

f_h = pipe head loss (%)

HOMER uses the effective head to calculate the power output of the hydro turbine in each time step.

Pipe Head Loss (f_h); Water and any other viscous fluid moving through a conduct encounter a loss in pressure because of resistance in friction [4]. This number is specified in HOMER as a percentage of the actual head [4].
The design flow rate ($\dot{Q}_{design}$) is the rate of flow designed for hydro turbine [4]. It is the one which operates the turbine at its maximum efficiency, although HOMER takes the latter efficiency as a constant [4]. In this study, the flow rate has been taken as 280 liters per second.

The minimum flow rate, using the equation 4.4 can be calculated [4]. HOMER suppose that the hydro turbine can run only if the flow is greater or equal to this minimum flow[4]

$$\dot{Q}_{min} = w_{min} * \dot{Q}_{design} \tag{4.4}$$

Where

w_{min} = The minimum flow ratio of the hydro turbine (%) [4]

$\dot{Q}_{min}$ = the minimum flow rate (m^3/s) [4]

The maximum flow rate is the extreme flow that can be supported by the turbine [4]. To calculate this flow, Homer use the equation 4.5 below[4]:

$$\dot{Q}_{max} = w_{max} \times \dot{Q}_{design} \tag{4.5}$$

Where

w_{max}: The maximum flow ratio of the hydro turbine (%)

$\dot{Q}_{max}$: The maximum flow rate (m^3/s)

The detailed parameters which have been discussed above can be summarized in the Figure 4.7 as it is required by homer software to compute the output power of the desired micro hydro power plant [4].

Economy
These inputs gives the details on system costs including the civil works and details on the turbine resources [4] as shown in the Figure 4.7.
Capital cost; the initial cost for 20 kW hydropower system is taken as $40.000.

Replacement cost is $30.000, O&M cost is taken as an approximation to $800.
Lifetime of the plant is 25 years.

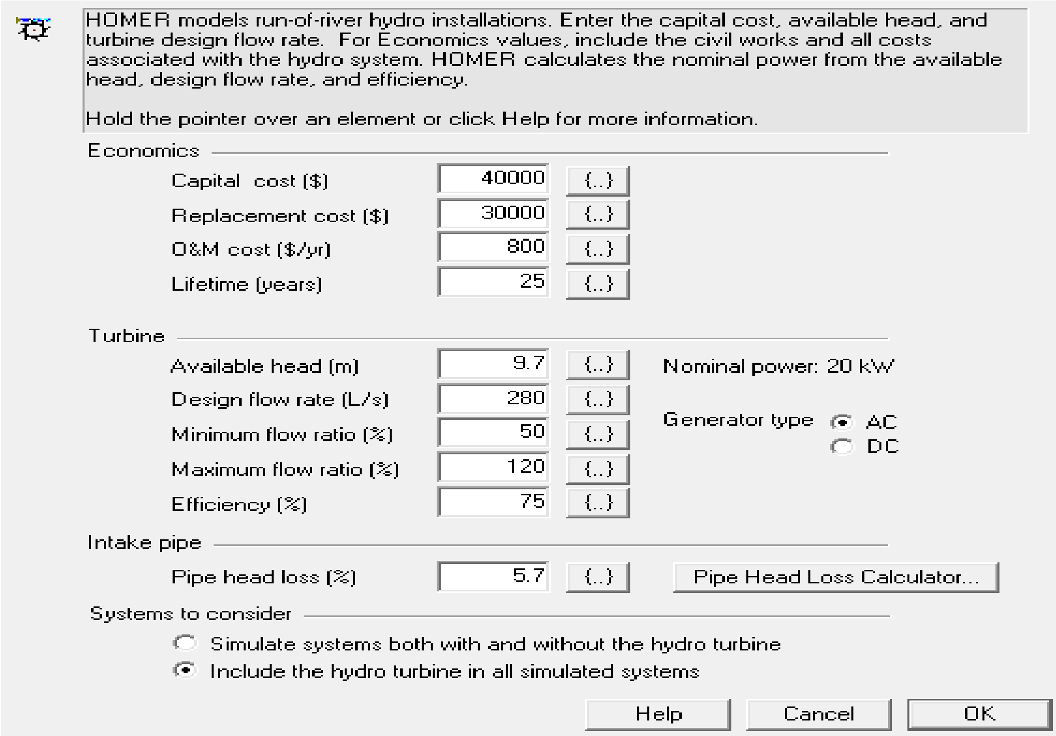


Figure 4.7 : Hydro input window, from homer.

4.2.4 Diesel generator input

This opening in homer allows user to enter the cost, characteristics and performance of a diesel generator [4].

Generator Minimum Load ($f_{gen,min}$):This is the minimum percentage of rated capacity for the generator for good functioning [4]. But this minimum load will not stop the generator from being shut down, it will only avoid it from operating at too low load [4]. The existence of this parameter is required because some manufacturers recommend that their machines not to be operated under a certain load [4].

Lifetime (Operating hours of generator): This is the number of hours that can be used by the generator during its life and the manufacturers of diesel generators usually provide this number of working hours in their product brochures or data sheet. The lifetime of the selected generator has been assumed to be 15,000 hours this project.

Generator Average Total Efficiency [4]: This is a summation of energy out; electrical and thermal and divide the in energy, the latter is the energy of fuel [4]. The equation 4.6 is used to calculate the efficiency [4][6]:

$$\eta\mathrm{gen,tot} = \frac{3.6.(Egen+Hgen)}{mfuel.LHVfel} \qquad (4.6)$$

Where

E_{gen} is the electrical production per year (kWh/yr)
H_{gen} is the thermal production per year (kWh/yr)
m_{fuel} is the used fuel per year (kg/yr)
LHV_{fuel} is the lower heating value of the fuel (MJ/kg)

3.6 is because 1 kWh equal 3.6 MJ [4]

Electrical Efficiency, the homer use the equation 4.7 to compute it.

$$\eta gen = \frac{3.6\, Egen}{mfuel.LHVfel} \tag{4.7}$$

Where the parameters are the same as in equation 4.6.

Economics

In the cost table as shown in the Figure 4.8, the cost changes with the power of the generator [4]. In this project, a machine of 10 kW costs $ 7,000 initially, $ 5,000 for replacement and $ 0.50/h for O&M [4]. A machine of 15 kW generator costs $ 8,400 initially, $ 6,000 for replacement and $ 0.60/h for O&M [4].

The Figure 4.8 below shows the diesel generator input parameters required by the homer software

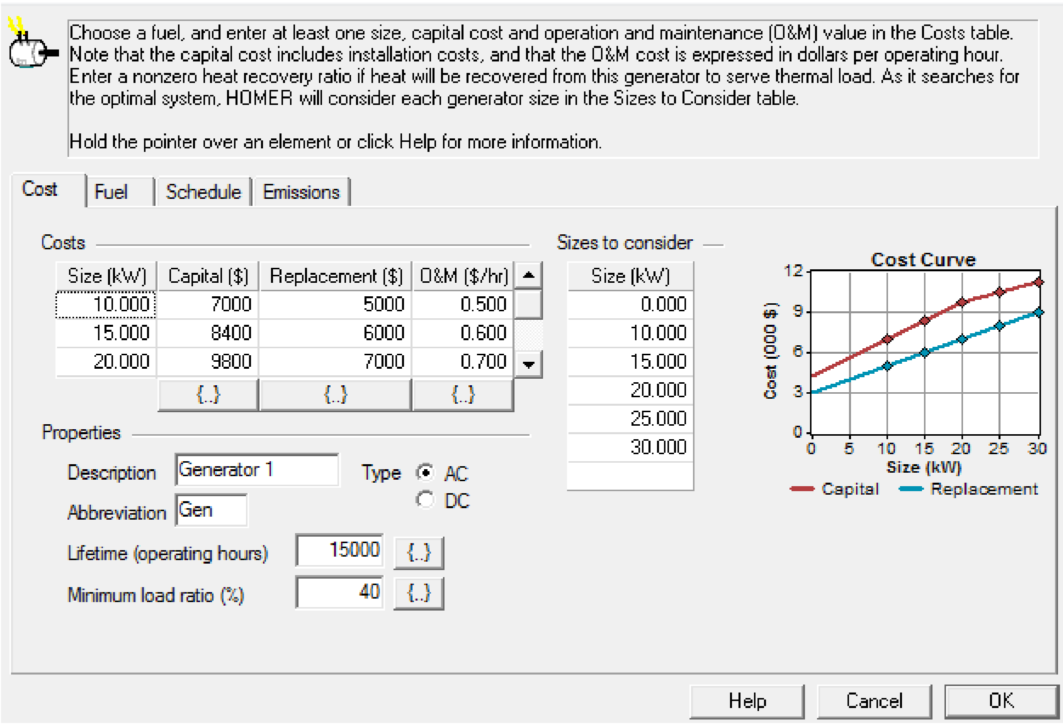


Figure 4.8 : Hydro input window, from homer.

4.2.5 Battery input

This window shown in Figure 4.9 allows the Homer user to select the type of battery, describe its costs, and tell the software how many batteries to be considered for the optimal configuration [4].

Figure 4.9 : Batteries stored in homer component library.

This drop-down box contains all the batteries stored in homer component library. It help to choose an appropriate battery model from this list. When selecting with this drop-down box, HOMER shows more different types of batteries and its characteristics when you click on details button. In this project a Surrette 6CS25P of 6V has been selected and 48V voltage system which require 8 batteries in series this means eight strings.

Battery Charge Efficiency: the software assumes the battery efficiency to be the square root of the round trip efficiency [4]:

$$\eta batt,c = \sqrt{\eta batt,rt} \tag{4.8}$$

$$\eta batt,d = \sqrt{\eta batt,rt} \tag{4.9}$$

Where

$\eta_{batt,c}$: charge efficiency,
$\eta_{batt,d}$: discharge efficiency
$\eta_{batt,rt}$: round trip efficiency[4].

Economics

In the figure below, this is the window that help to introduce the cost of battery [4]. I have entered an amount of one battery for capital, replacement and O& M costs. In this project as shown on below Figure 4.10, the costs of one unit is as follows $ 1,200 initially, $ 1,200 replacement, and $ 30 annually for O&M [4]. If the number of batteries is n, then the costs for the total will be multiplied accordingly [4]

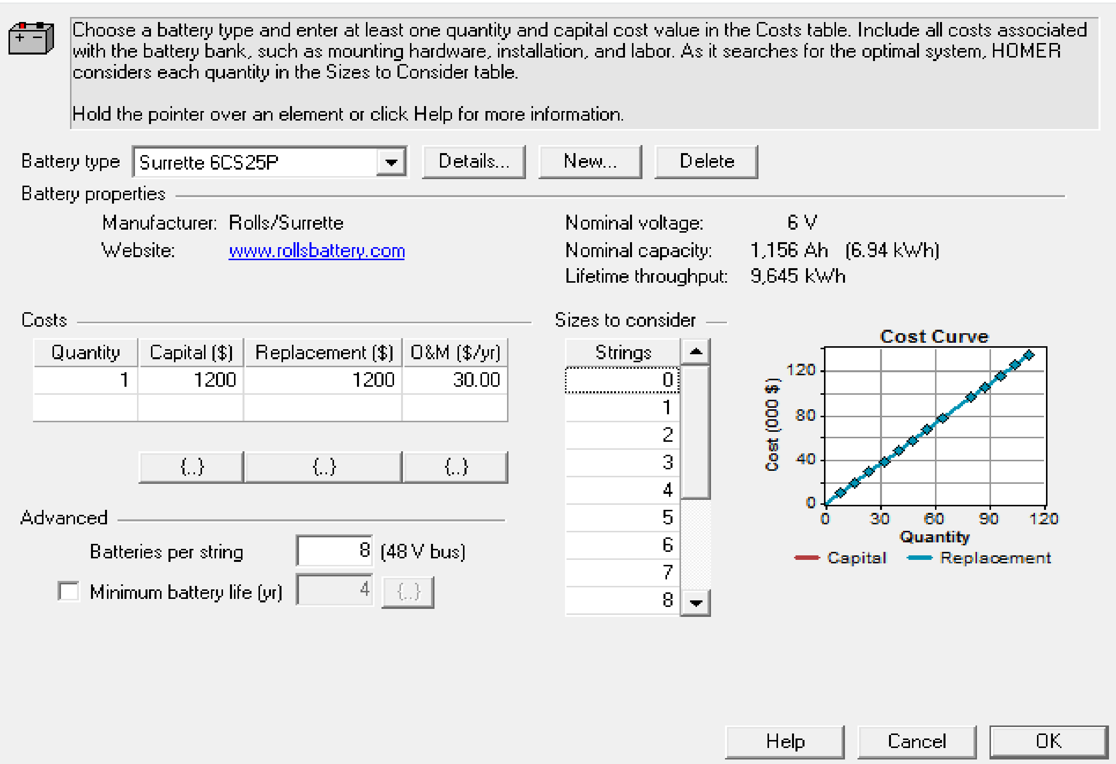


Figure 4.10 : Battery input window, from homer.

4.2.6 Converter input

Any system that is consisted with both AC and DC configuration necessitate a converter [4]. This opening help to introduce the cost curve for the converter and preferred sizes to be for the optimal system [4].

Lifetime: operating years [4]. In this project 15 years has been assumed.
Efficiency: The efficiency for converting DC form to AC form [4]. Homer will use in the calculations the efficiencies which have been entered in the its input data. In this project the efficiency from the manufacturer of the inverter have been taken as 98 %.
The efficiency of rectifier to convert AC form to DC form [4], in % is taken as 95.

Economics
In the cost table as shown in the Figure 4.11, the cost of converter depend with its size. In this project, the capital and replacement price for 10 kW converter is taken at $ 11,370.

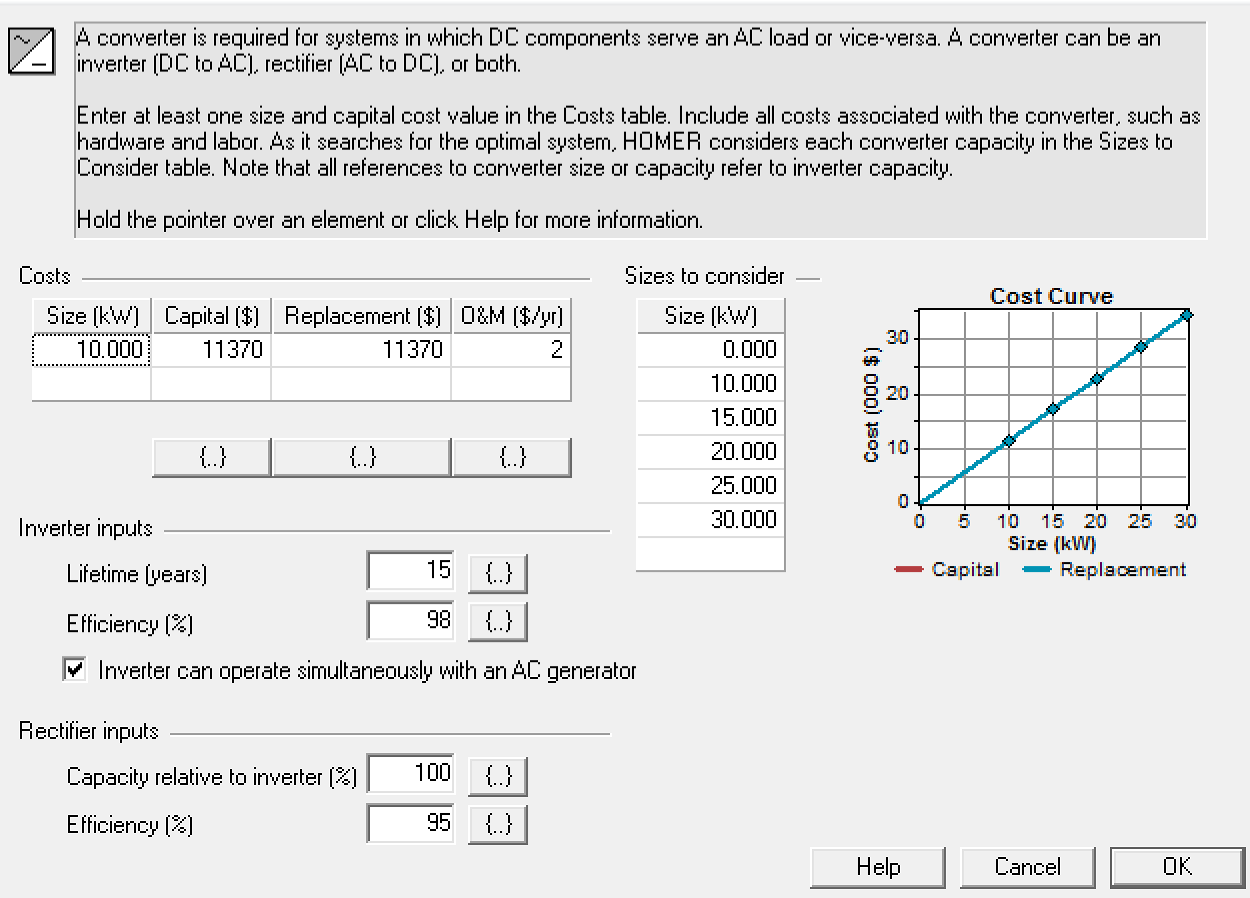


Figure 4.11 : Battery input window, from homer.

4.3 Modelling of Resources

In HOMER, a "resource" is those external parameters used by component in order to have electric or thermal energy [4]. Hydro, solar radiation, wind and diesel fuel are resources [4].

4.3.1 Solar resource inputs

This window is used to specify the latitude, longitude and the solar radiation of the selected area for the photovoltaic system in the year [4][6]. HOMER uses these data to compute the hourly output power in the year. HOMER can also calculate hourly solar radiation data based on the monthly average radiation and clearness index. There is a method which is used to produce synthetic hourly solar radiation data. Figure 4.12 shows the synthetic in Burera which is calculated by HOMER using the NASA radiation data.

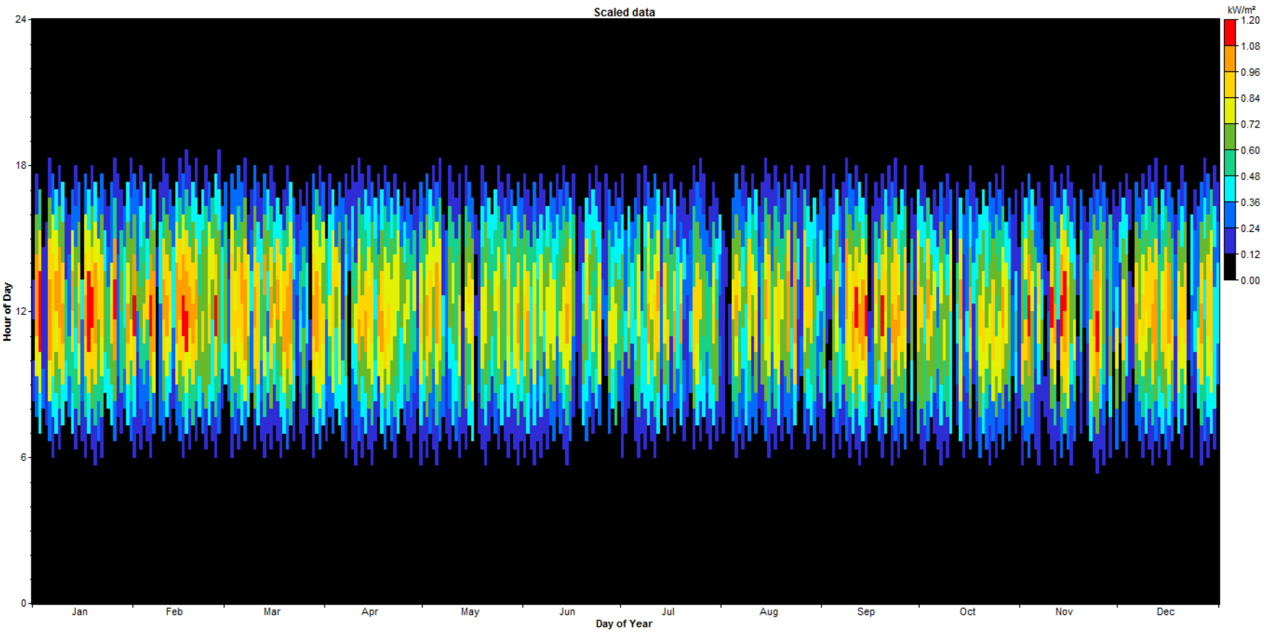


Figure 4.12 : Synthetic solar radiation data over a period of a year.

The latitude specifies the location of selected community on the Earth's surface. It is an important variable in solar calculations. This parameter is required for calculating radiation values from clearness indices, and conversely. To calculate the radiation incident on a tilted surface that one can also be used. In this research, a village located at 1°30’ S latitude and 29°58’ E longitude is selected for studying the hybrid system.
This results has been presented in the Figure 4.13.

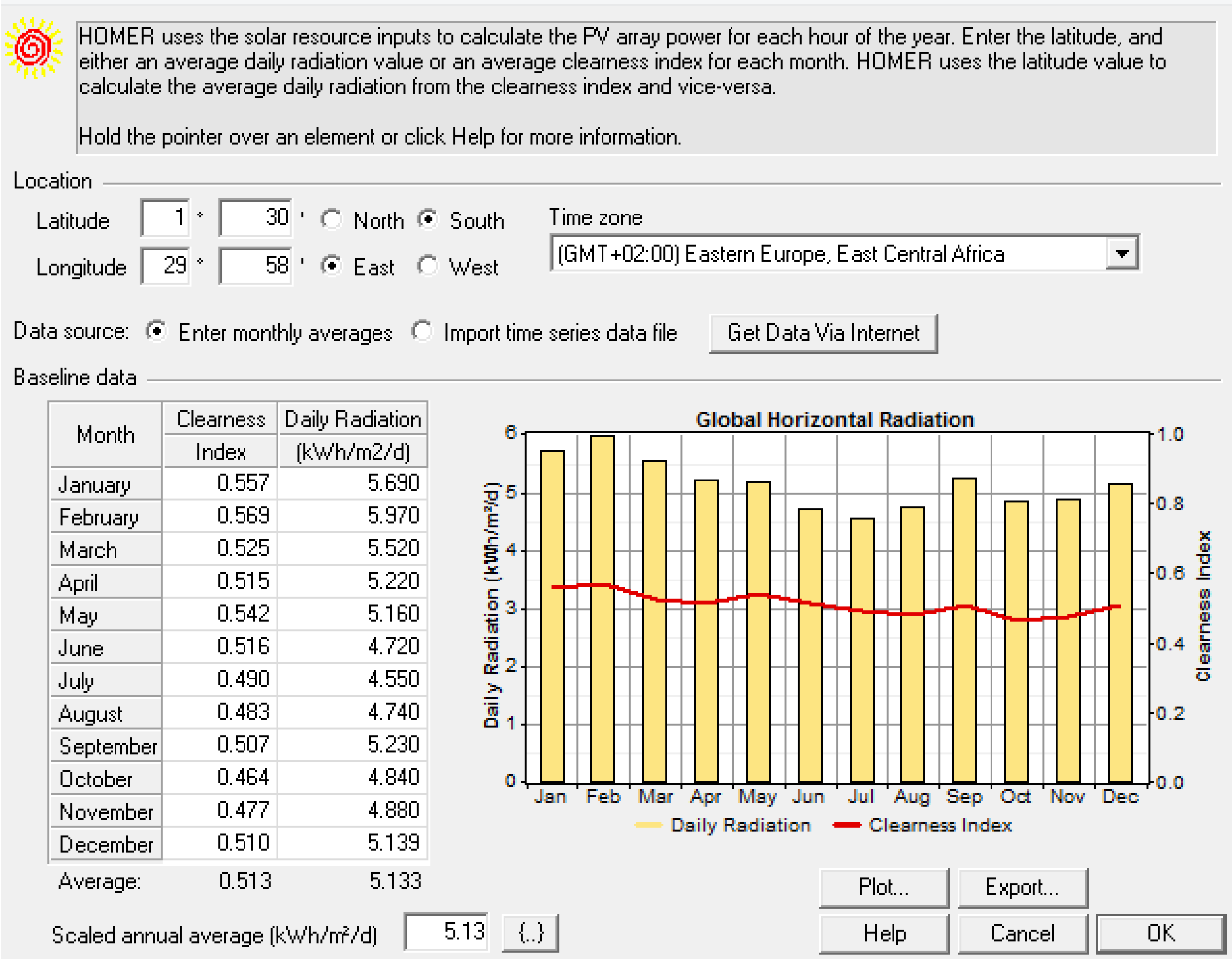


Figure 4.13 : Solar resource inputs window, from Homer.

4.3.2 Hydro Resource inputs

Hydro Resource opening is used to describe and introduce the flow available to the hydro system [4]. The HOMER software will use these parameter to computer the annual output power of the hydropower plant [4].

The set of 8,760 called baseline values characterizing the average flow in L/s, for each hour of the year [4].

The residual flow is the unused water for ecological reasons for fish and other aquatics animals [4]. HOMER uses this number for computing the available flow rate to the hydro turbine [4].

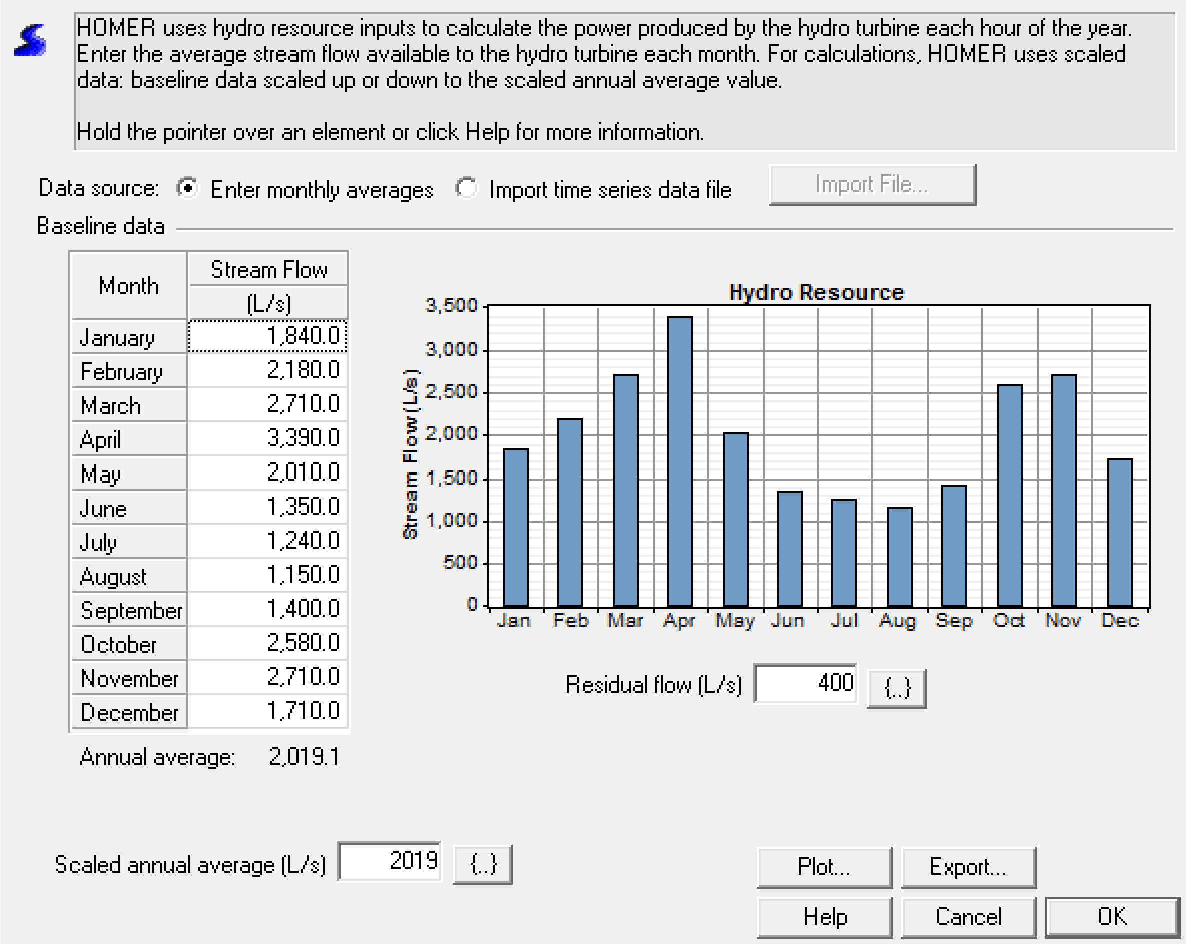


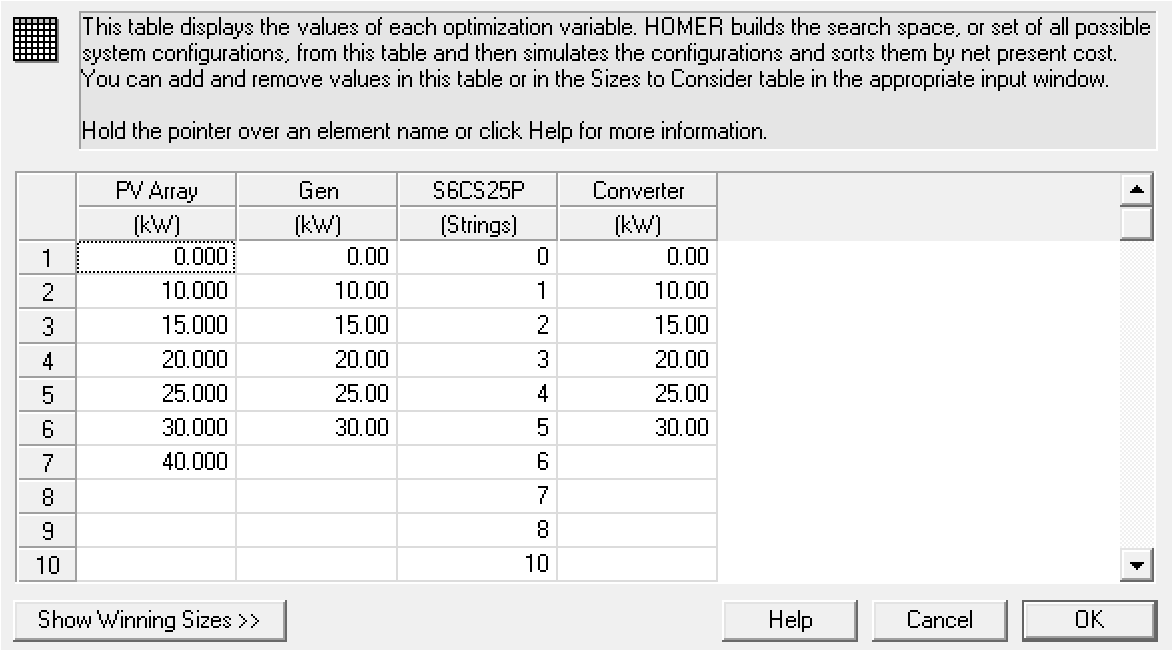
Figure 4.14 : Hydro resource inputs window, from Homer.

4.4 Modelling of Other Important Factor

4.4.1 Search space window

This window gives convenient access to the search space, which is the set of all allowable sizes and quantities of each component. You can also specify this information separately in each of the component input windows (for example, you can enter the allowable sizes of the PV array in the PV inputs window) but the Search Space window allows convenient access to the entire search space. The search space for this project is presented in the Figure 4.15.

In its optimization procedure, HOMER evaluates each configuration type and then grade each according to the total NPC. The specification of the search space almost always involves a trade-off between accuracy and run time.


This table displays the values of each optimization variable. HOMER builds the search space, or set of all possible system configurations, from this table and then simulates the configurations and sorts them by net present cost. You can add and remove values in this table or in the Sizes to Consider table in the appropriate input window.

Hold the pointer over an element name or click Help for more information.

	PV Array (kW)	Gen (kW)	S6CS25P (Strings)	Converter (kW)
1	0.000	0.00	0	0.00
2	10.000	10.00	1	10.00
3	15.000	15.00	2	15.00
4	20.000	20.00	3	20.00
5	25.000	25.00	4	25.00
6	30.000	30.00	5	30.00
7	40.000		6	
8			7	
9			8	
10			10	

Show Winning Sizes >> Help Cancel OK

Figure 4.15 : Values of elements optimization.

4.4.2 Economic inputs

The interest rate also known as discount rate. It is used to convert between one-time costs and annualized costs [4]. It is seen in the Economic window [4]. In order to evaluate the economic viability of micro-grids supplied by hybrid power systems, the levelized cost analysis of systems must be done by considering the lifetime of the system, because hybrid systems with renewable technologies have a higher capital cost, but small O & M cost during the life of the system [1]. In contrast, fossil fuel based electricity generation systems have lower capital cost but higher O & M cost due to fuel costs, generator maintenance and replacement costs. Thus, LCOE analysis can compare the economics of different technological solutions.
HOMER optimization algorithms are based on the LCOE analysis. It finds the optimum system by calculating the Net Present Value (NPV) of the lifetime cost of the project by including all the costs that arise within the life of the project for every system configurations considered in the search space [4]. Then it grades all the possible configuration types according to increasing NPC and LCOE [4]. The following gives a brief summary on the total NPC and the LCOE [4].

The total Net Present Cost

The total Net Present Cost (NPC) of the system is the difference between the present values of all the costs occurs over the project lifetime and the present values of all the revenue earns over project lifetime [1][4]. The present value of the costs that will make n-year later can be calculated by the following formula.

$$C_{NPC} = C\left(\frac{1+i'}{1+d}\right)^{n} \tag{4.10}$$

Where

i' : is the annual inflation rate (%)

d: is the nominal interest rate (%)

In order to find the LCOE, the total NPC of the project must be converted to series of equal annual cash flows which is known as total annualized cost calculated by the equation 4.11 [4].

$$\text{Total annualized cost (\$/year)} = \text{Total NPC*CPF} \tag{4.11}$$

Where, CPF is the capital recovery factor and it is given by the formula,

$$\text{CPF} = \frac{i(1+i)^N}{(1+i)^N-1} \tag{4.12}$$

Where

N: number of years

i is the real interest rate,

The lifetime of the project has been studied here is 20 years. Therefore N is 20. The real interest rate is determined using the nominal interest rate (d) and the annual inflation rate (i') by equation 4.9 [4].

$$i = \frac{d-i\prime}{1+i\prime} \tag{4.13}$$

HOMER suppose the rate of inflation to be the same for all types of costs (fuel cost, maintenance cost, labour cost, etc.) occurring over the life of the project [4]. The variation of the real interest in Rwanda over the years is given in Figure 4.16. According to Figure 4.16 the average real interest rate in Rwanda during the past 32 years (1978 – 2010) has been about 8.4 % [42]. If the effect of the peak occurred in 1986, 1999 & 2002 is removed, the real interest become 6.65 % is selected for the analysis and it is presented in Figure 4.17.

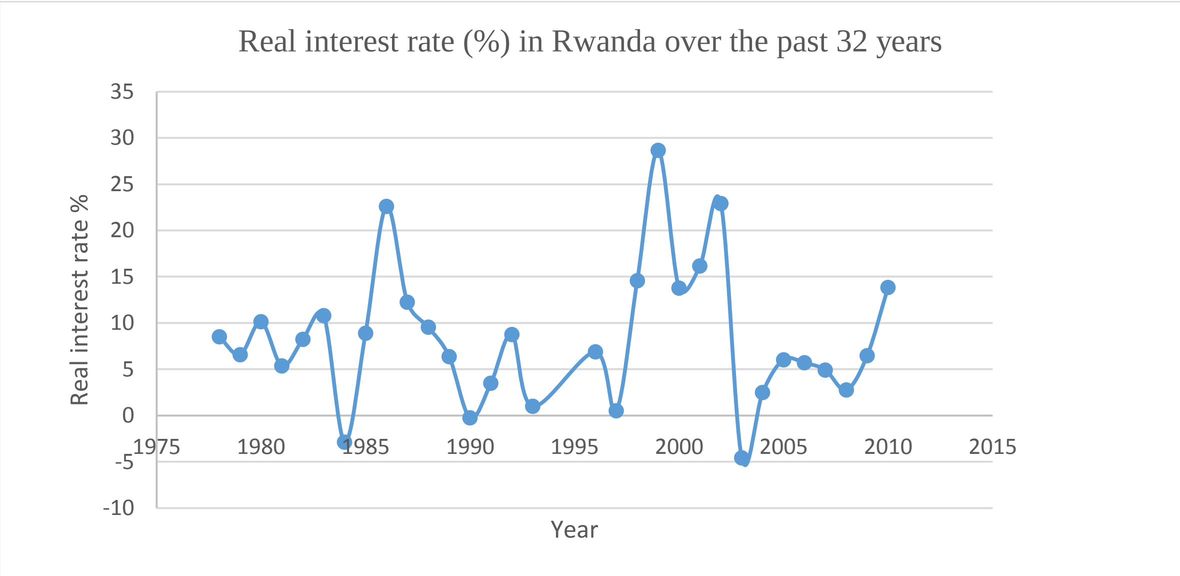


Figure 4.16 : Changes in the real interest rate in Rwanda over the past 32 years [42].

Levelized Cost of Energy (LCOE)

It is the cost per kWh of electrical energy, such that the total NPC of the useful energy generated throughout the whole lifetime of the hybrid project is equal to the total NPC of the project [4]. The calculation of LCOE of the electricity generated by an off grid hybrid system is done as shown in the equation 4.14 [4].

$$LCOE = \frac{Total\ Annualized\ Cost\ (USD/yr)}{Annual\ load\ served\ (kWh/yr)} \tag{4.14}$$

System fixed capital cost

The fixed capital cost of the system is normally allocated for building a house for keeping the battery bank, charge controllers, generator, inverter and other relevant electrical instruments and constructing the distribution lines throughout the village. It also includes the site preparation cost, labour cost, engineering design cost and other various cost. An estimate of the fixed capital cost by considering 3 km long three phase distribution lines has been estimated as $ 45,000.

System fixed operation and maintenance cost

System fixed O & M cost firstly includes labour cost and insurance costs. If a full time engineer or a technician is working in the hybrid system place, then he has to be paid a monthly salary. Assuming a technician is full time employing in the power house annual fixed O & M cost has been taken as $ 7,000.

The project lifetime

It is the number of years the project is forecasted in the [4]. HOMER uses this number to compute the annualized replacement cost and annualized capital cost of each component, as well as the total NPC of the system[4]. In this project, the project lifetime has been taken as 20 years.

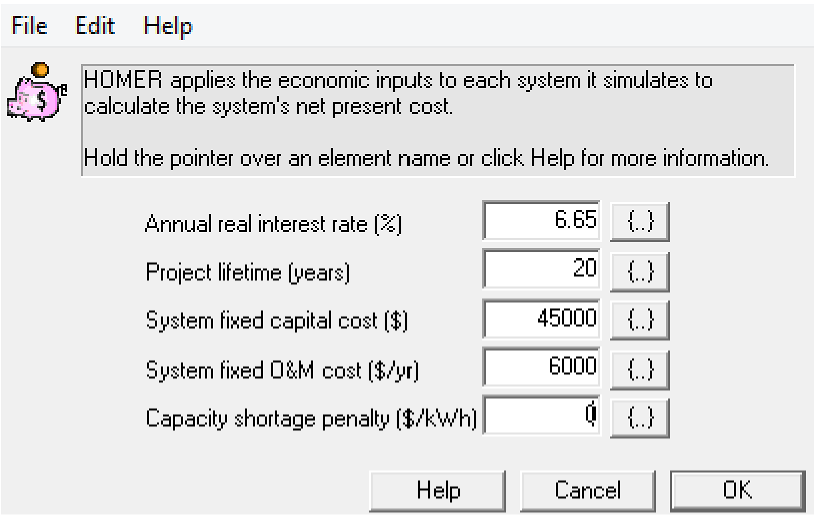


Figure 4.17 : Economic input window.

4.4.3 System control inputs

The diesel generator is the only none renewable and dispatchable energy source used in this hybrid energy system. Since the energy output from renewable sources is highly intermittent and cannot be controlled by the user, then it have to be used when it is available for supplying the load or to charge the battery bank. If renewable energy systems or the battery bank is not able to meet the load then the diesel generator has to be auto-started so that it can supply the load without causing power interruptions. Therefore using a diesel generator is essential in hybrid systems to supply the load in a controlled mode to improve the availability of the system. However controlling the performance of a diesel generator is rather complex due to several aspects. The main aspect is the efficiency conversion of energy. As it is discussed in chapter three, the generator's efficiency is very low at low load factors. Therefore if the generator is chosen to supply the load that cannot be supplied by the renewable sources, then the diesel generator operate in a low load factor which lead to a low efficiency. Normally, operating the generator at its full capacity when required and using the excess energy for charging the battery bank may be more economical than the previous case. This one is optimal approach which depends on many factors; like the power size of the generator [17]. Therefore, dispatch strategy also should be developed when optimizing the hybrid system. Two dispatch types [4]; i.e. "Load following" and "Cycle charging".

- Load Following (LF): The diesel generator is switched on when required and produce only the required amount of power that cannot be produced by the renewable sources or battery bank to supply the load.
- Cycle Discharging (CC): The diesel generator starts when required and operates at its full capacity and excess energy is sent to the battery bank to charge the batteries.

4.4.4 Component costs summary

Table 4.1 : The summary of the costs of components and other relevant costs.

Component	Capacity	Capital cost $	Replacement Cost $	O & M Cost $
PV system	10kW	35000	25000	30/ year
Hydro system	20kW	40000	30000	800/ year
Battery	1156Ah	1200	1200	30/ year
Generator	10kW	7000	5000	0.5/ year
	15kW	8400	6000	0.6/ year
	20kW	9800	7000	0.7/ year
	25kW	10500	8000	0.8/ year
	29kW	11200	9000	0.9/ year
Inverter/charger	10kW	11370	11370	5/ year

5 Results

The optimal hybrid system is the one which can supply electricity needs at the lowest price or in other words, the system which is having the lowest total net present value, while supplying the electricity at the required level of availability. In this chapter we will discuss the results obtained from the HOMER simulations and the selection of the optimal system based on the simulation results. The chapter also discusses the performance of the optimal hybrid system, hybrid system design, economic viability of the project and a brief introduction to the energy management in the micro grid.

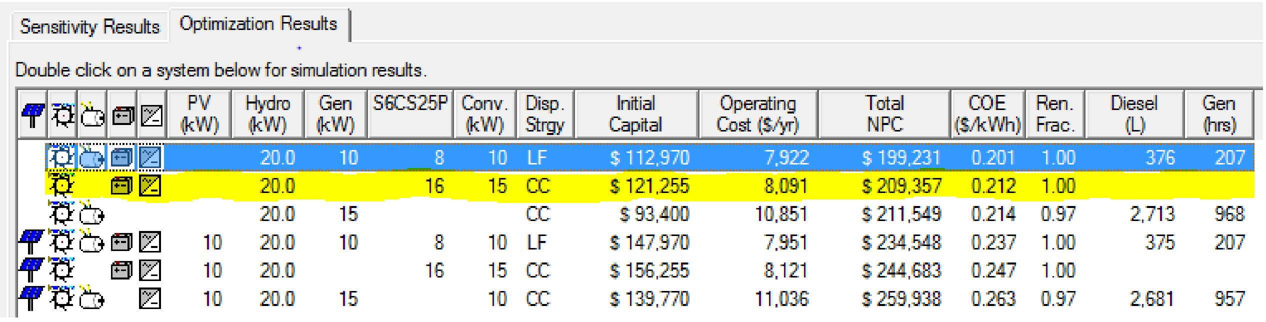
5.1 Optimization Results

For the off-grid electrification of a village in Burera, various combinations of hybrid Systems have been obtained with SPV, MHP, DG, batteries and convertors from the HOMER optimisation simulation. Figure 5.1 presents a screen shot containing the summary of simulation outcomes.
All possible hybrid system configurations are listed in ascending order of their Total net present cost. The best possible combination of MHP, DG, Batteries and Convertor is highlighted in blue, and the next best possible combination, is highlighted in yellow, includes the SHP, Batteries and Converter. The blue highlighted combination is able to fully meet Burera's load demands at the lowest possible total net present cost.
The optimal system configuration for our case study is 20kW MHP, 10kW DG, 8 Surrette 6CS25P batteries and 10kW Inverter with a dispatch strategy of load following.
There is no PV selected at this site as it can be seen on Figure 5.1.

As indicated in Figure 2.4 of the daily village load profile, the maximum demand will take cover in between 18h 00 and 21h 00 which is around 28 kW. But this power is changed to 38 kW due the random variability of 10 for both day to day and time step to time step as described in Figure 4.5. That is why, the system requires more source than the 20 kW from the micro hydropower plant. The reason behind, it is not feasible to increase the output power generated by this micro hydropower plant due to the limitation of design flow rate which cannot go beyond 280 litres per second. So, an additional sources to generate the excess of 18 kW which cannot be produced by the MHHP are required. The diesel generator and the batteries as shown in Figure 5.1 is optimized by the homer software. As it has been discussed in section 3.4 of chapter 3 that the diesel generators operate most efficiently when working near its full load, that is why, the diesel generator and the batteries. These two sources is used to generate the extra power of 18 kW required during the peak hours. The production Figure plots for the explanations of this configuration can be seen in the appendix D.

This system is considered at $ 1.3/l of diesel cost and 280 l/s of design flow rate for the MHP. The total net present cost, capital cost and the COE for such a hybrid system are $ 199,231, $ 112,970 and $ 0.201/kWh, respectively.

The COE of $0.201/kWh from this hybrid system is not cheaper than that of $ 0.2/kWh from grid connected as considered for this study.



Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	Hydro (kW)	Gen (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen (hrs)
	20.0	10	8	10	LF	$ 112,970	7,922	$ 199,231	0.201	1.00	376	207
	20.0		16	15	CC	$ 121,255	8,091	$ 209,357	0.212	1.00		
	20.0	15			CC	$ 93,400	10,851	$ 211,549	0.214	0.97	2,713	968
10	20.0	10	8	10	LF	$ 147,970	7,951	$ 234,548	0.237	1.00	375	207
10	20.0		16	15	CC	$ 156,255	8,121	$ 244,683	0.247	1.00		
10	20.0	15		10	CC	$ 139,770	11,036	$ 259,938	0.263	0.97	2,681	957

Figure 5.1 : Summary of HOMER optimization results in categorized way.

Table 5.1 : Optimal least cost hybrid system for the case study.

Cost summary		System architecture		Electrical		
Total NPC	$199,231	MHHP	20kW	Component	kWh/y	%
LCOE	$0.201/kWh	DG	10kW	Hydro Turbine	198,086	100
Operating Cost	$7922	Battery bank	8 Batteries	DG	843	0
Capital Cost	$112,970	Inverter	10kW	Total	198,929	100
		Dispatch Str.	Load Following			
		Renewable fraction	0.996			
		Capacity shortage	0			

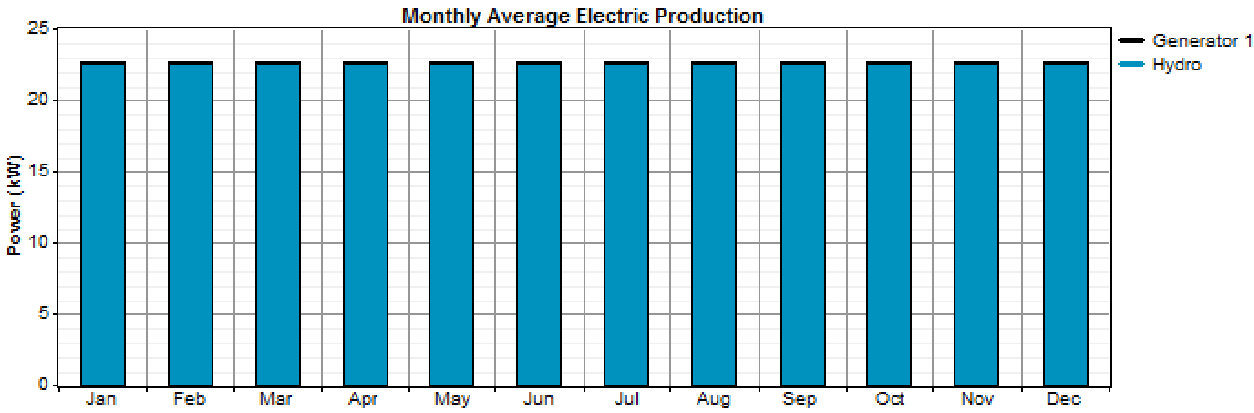


Figure 5.2 : Electricity production from the best system type.

As shown in the results from the above Figure 5.1, a micro hydropower and a diesel generator only system requires a small capital investment ($ 93,400) compared to hybrid systems. But due to the large O&M cost due in general to a diesel generator ($10,851), the lifetime NPC of the system ($ 211,549) is very much higher than the hybrid system ($ 199,231). Thus the LCOE is also becoming larger which is approximately 0.214 $/kWh.

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	Hydro (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
	20.0	16	15	CC	$ 121,255	8,091	$ 209,357	0.212	1.00
10	20.0	16	15	CC	$ 156,255	8,121	$ 244,683	0.247	1.00

Figure 5.3 : Optimization results when using only renewable resources.

According to the above observations we can see that the hybrid system which use both renewable sources and diesel generator is more economical than the system with only renewable energy sources, the letter is shown in the above Figure 5.3 where the optimal system configuration is 20kW MHP, 16 Surrette 6CS25P batteries and 15 kW Inverter with a dispatch strategy of cycle discharging.

But the important matter is the sizing of the hybrid components in a right way to reduce the energy cost or net present cost of the project. If sizing is not done properly then we may end up with a system having larger NPC than the base system was in concern.

The Figure 5.4 and Table 5.2 shows the cost flow summary for this project optimal system. The Capital cost of micro hydro power plant is about 35 % and the fixed capital cost for the system is about 40 % and the remaining share the capital cost of 25%.

About 84 % of the operation and maintenance cost goes to the monthly salary of an engineer charged to run and control the system.

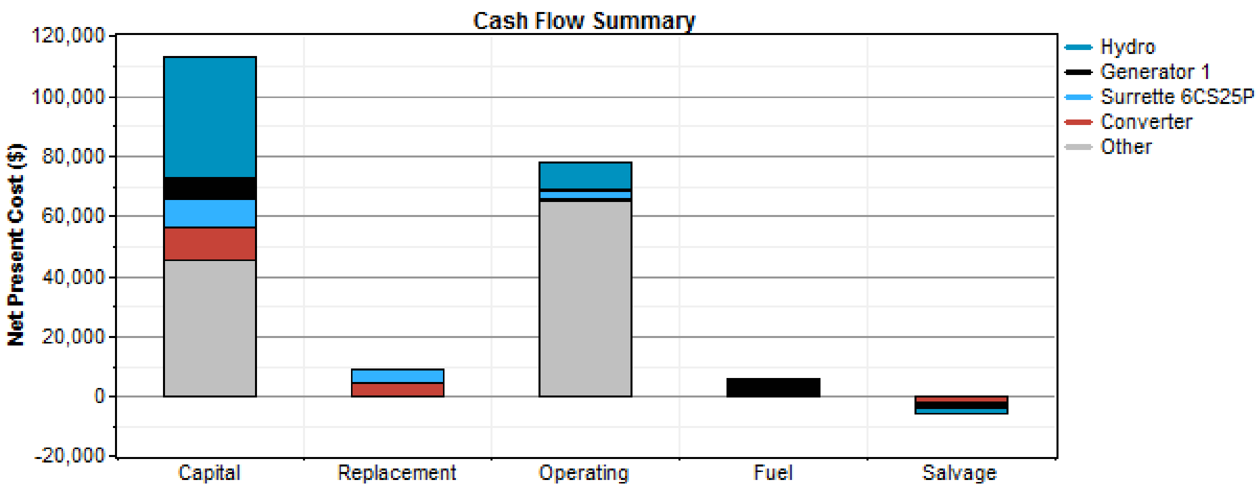


Figure 5.4 : Cost flow summary by cost type

Table 5.2 : Cost summary of the project based on the used component.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hydro	40,000	0	8,711	0	-1,656	47,055
Generator	7,000	0	1,127	5,325	-999	12,453
Battery	9,600	4,433	2,613	0	-883	15,764
Converter	11,370	4,329	22	0	-2,091	13,629
Other	45,000	0	65,331	0	0	110,331
System	112,970	8,762	77,803	5,325	-5,629	199,231

These costs are further illustrated in Figure 5.5 as a nominal cash flow of the project throughout 20 years. Here we can see, after 11 years battery replacement occurs, the same case for the converters, the letter will be replaced after 14 years. But the diesel generator replacement does not occur within 20 years lifetime of the project, because the hours of working for the generator during a year is about 207 this means the total working hours of the machine during the project lifetime is 4140 hrs which is less than the lifetime operating hours of the generator 15000 hrs.

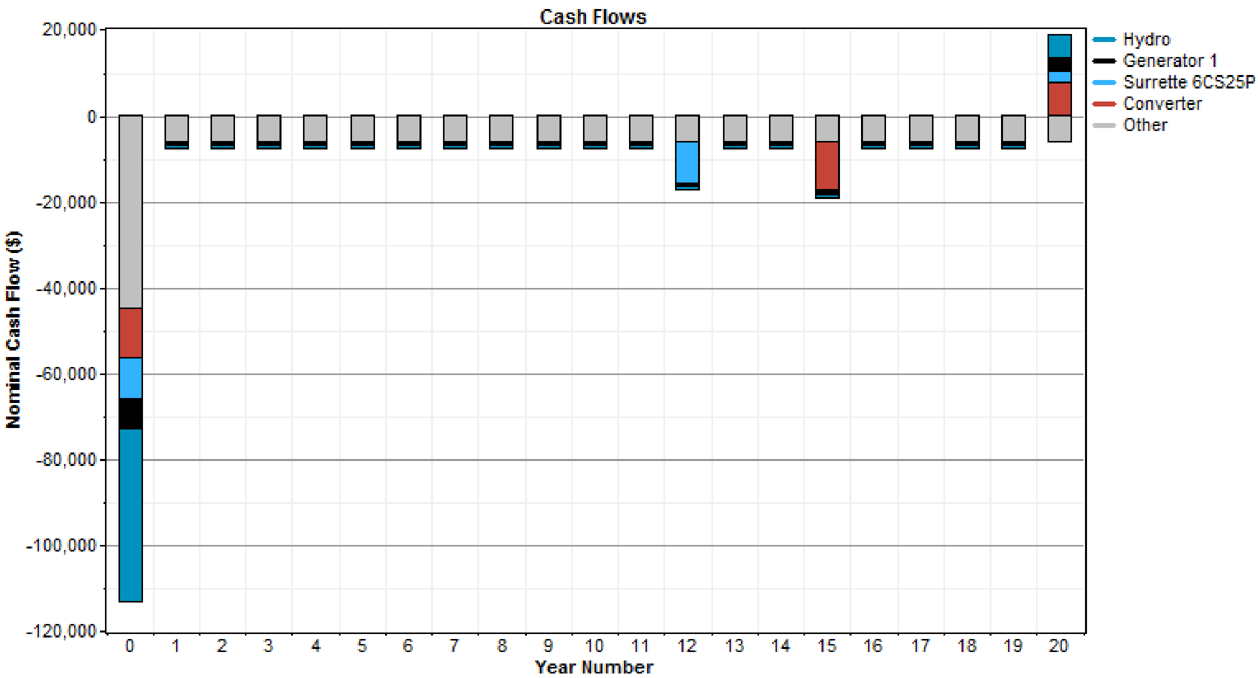


Figure 5.5 : Nominal cash flow of the project throughout 20 years.

Figure 5.6 shows the grid extension cost compared with the cost of a standalone system, it is clear that this standalone system will be more useful for a community situated at a distance greater than 8.3 km from the national grid, otherwise it will be better to use the extension of national grid because it is the one which will have less investment in terms of money. This decentralised RE hybrid system is a better option than the grid extension for a selected community, because this village is at 20 km from the transmission line of the national grid.

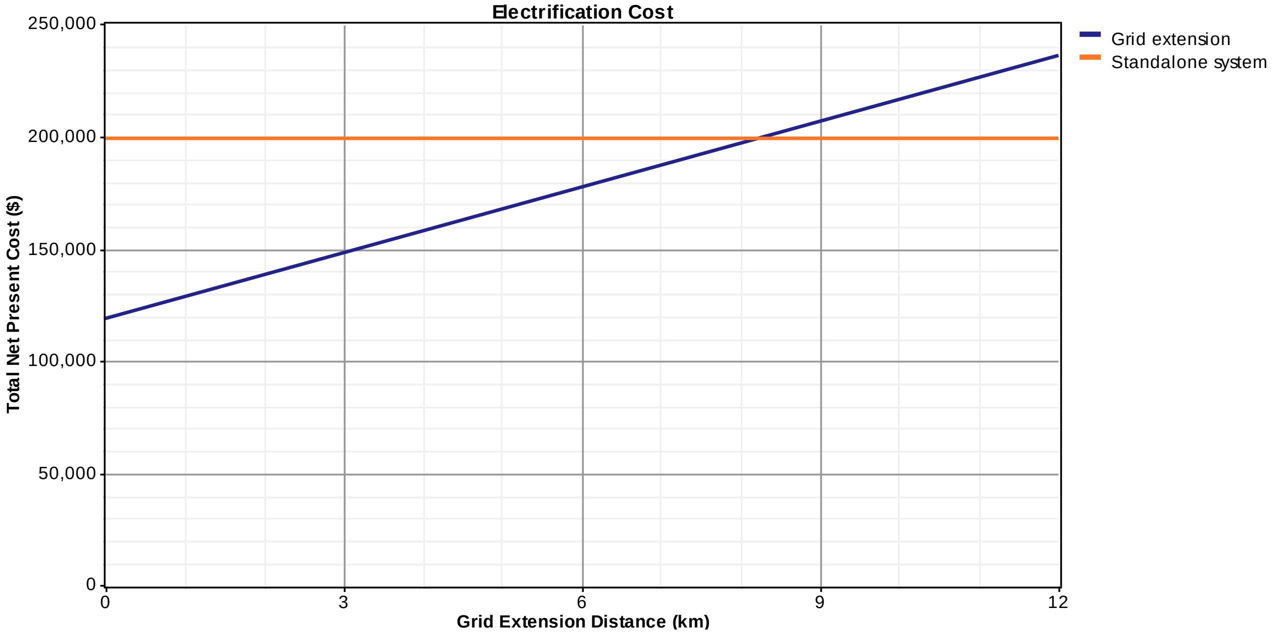


Figure 5.6 : Breakeven grid extension distance with its cost

The optimal hybrid system configuration obtained from the HOMER optimization algorithm is given in Table 5.1. However, finding the optimum hybrid configuration requires more analysis because the inputs given to the HOMER may not 100 % accurate. Especially the renewable resource inputs, solar radiation and water flow data. In this study these data have been obtained from the NASA surface meteorology and solar database. Therefor there may be little variations between these and the actual data. Moreover, there may be uncertainty in the cost inputs as well. Thus the sensitivity analysis is required to validate the results obtained from the optimization analysis by considering the sensitivities of the input variables.

5.2 Sensitivity Results

HOMER sensitivity algorithms is used to assess the effect of uncertainties in the input variables discussed in section chapter 4, in selecting the optimum hybrid system configuration.
Sensitivity analysis exclude all impractical configuration and ranks the feasible configuration by judging uncertainty of parameters [1]. HOMER allows taking into account future developments, such as increasing or decreasing load demand as well as changes regarding the resources, for example fluctuations in the river's water flow rate, wind speed variations or the biodiesel prices. Here, various sensitive variables are considered to select the best suited combination for the hybrid system to serve the load demand. I have analysed the uncertainties of the following variables when selecting the optimal hybrid configuration.

- Design flow rate
  It may have some fluctuation of water flow rate in the Rugezi catchment which will reduce the water in the reservoir shown in Figure 2.7 where the power plant is possible [1]. That is

why the sensitivity analysis has been done for the uncertainties of water flow rate in between 200 to 300 litres per second.

- Diesel price
  As there can be uncertainties in the estimated diesel cost of our generator, the sensitivity analysis has been done for the uncertainties of diesel cost in between $ 1.1 to $ 1.5 per litre.

The techno economic optimum configuration system capable to supply power to a community selected in Burera district in the northern province of Rwanda which its load profile has been approximated and indicated in Figure 2.4, has been found using the HOMER optimization analysis. The architecture of this system is given in Table 5.1.
As can be seen in the HOMER optimization and sensitivity analysis results given in Figure 5.7, both capital cost, total NPC and LCOE can be affected with the design flow rate and the diesel price. With the results of optimization and sensitivity analysis shown in Figure 5.7, the optimum configuration has the total net present cost, capital cost and the COE for such a hybrid system are $ 196,502, $ 112,970 and $ 0.2/kWh, respectively.
The COE of $0.2/kWh from this hybrid system is the same as that one from the national grid. But there is no difference between the energy costs of this system configuration and the system configuration ranked in the 1st place in the table 5.1 without sensitivity.

Sensitivity Results | Optimization Results

Sensitivity variables

Diesel Price ($/L) 1.5 Design Flow Rate (L/s) 300

Double click on a system below for simulation results.

PV (kW)	Hydro (kW)	Gen (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen (hrs)
	21.4	10	8	10	LF	$ 112,970	7,672	$ 196,502	0.199	1.00	201	112
	21.4	15			CC	$ 93,400	10,564	$ 208,420	0.211	0.98	2,260	822
	21.4		16	15	CC	$ 121,255	8,091	$ 209,357	0.212	1.00		
10	21.4	10	8	10	LF	$ 147,970	7,702	$ 231,829	0.234	1.00	201	112
10	21.4		16	15	CC	$ 156,255	8,121	$ 244,683	0.247	1.00		
10	21.4	15		10	CC	$ 139,770	10,783	$ 257,183	0.260	0.98	2,251	818

Figure 5.7 : HOMER optimization and sensitivity results in categorized way

The surface plot for the levelised COE is presented in Figure 5.8. The micro hydropower design flow rate is represented on the x-axis, and diesel price variation on the y-axis. In Figure 5.7 as the design flow rate increases, the power output from MHHP increases and consequently there is a reduction in the total NPC. As the total NPC reduces, the system's COE decreases as well. The same case happen for the diesel price but in reverse way, the total NPC increases in little way as well as the diesel price increases. Therefore, a hybrid system with MHHP proves to be the cheapest option compared to other RETs due to lower capital cost of a small hydropower plant.

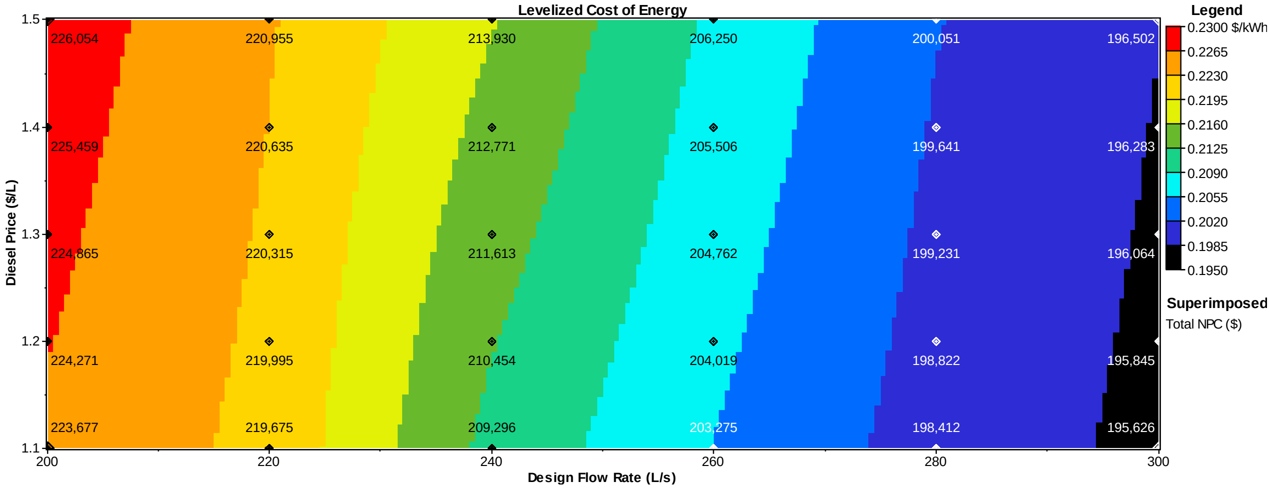


Figure 5.8 : Surface plot of cost of electricity from hybrid system.

Figure 5.9 shows the result for the breakeven distance for grid extension or Economical Distance Limit (EDL). It shows that the distance varies from 7.5 km to 11 km depending on the total NPC and levelised COE. For the hybrid configuration for this study as shown in Figure 5.9, the total NPC line comes out be a lower value than the breakeven distance for grid extension at a distance of 10.2 km, meaning that a decentralised RE hybrid system is a better option than the grid extension for a community village which is at a distance greater than 10.2 km far from the national grid. It is clearly evident from the line graph that as the design flow rate increases with a diesel cost at a fixed value of $ 1.3/L, the total NPC of the system decreases. At 225 L/s of design flow rate the EDL comes out to be 10.2 km, and at 300L/s the EDL comes out to be 7.9 km of distance. Hence, the total NPC and levelised COE of a system determine the EDL with respect to the input parameters.

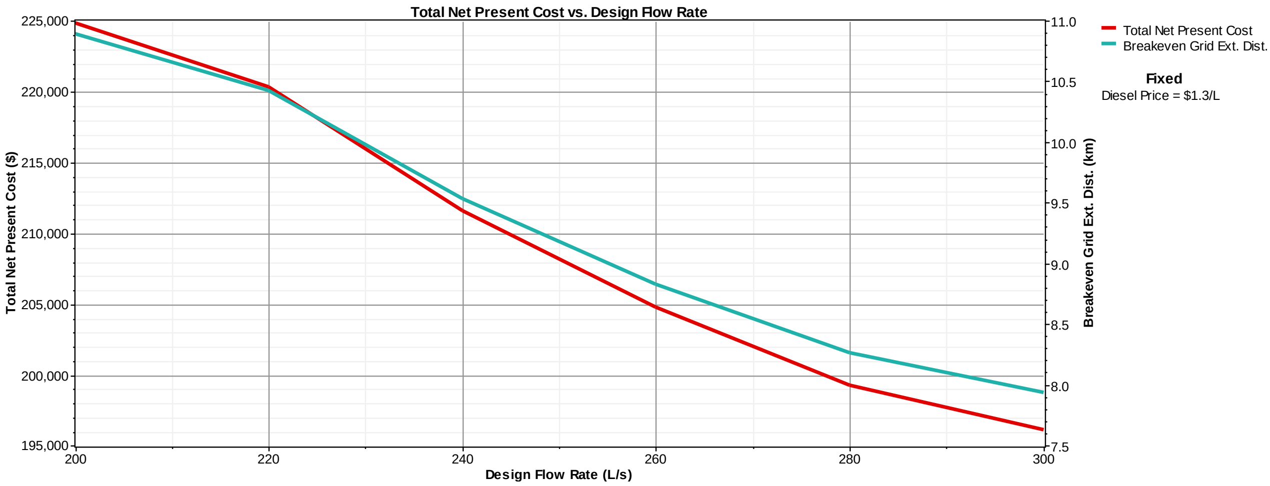


Figure 5.9 : Line graph for total NPC vs. design flow rate and breakeven grid extension distance

The Figure 5.10 which shows how the number of batteries can be affected by the design flow rate, it is clear that the batteries increases with the increase of water flow rate, but the variation of fuel price do not affect the battery bank for the hybrid system. The same case happen for the Converter capacity as shown in Figure 5.11 this capacity of converter increases with the increase of water flow rate and this capacity do not vary with the variation of fuel price.

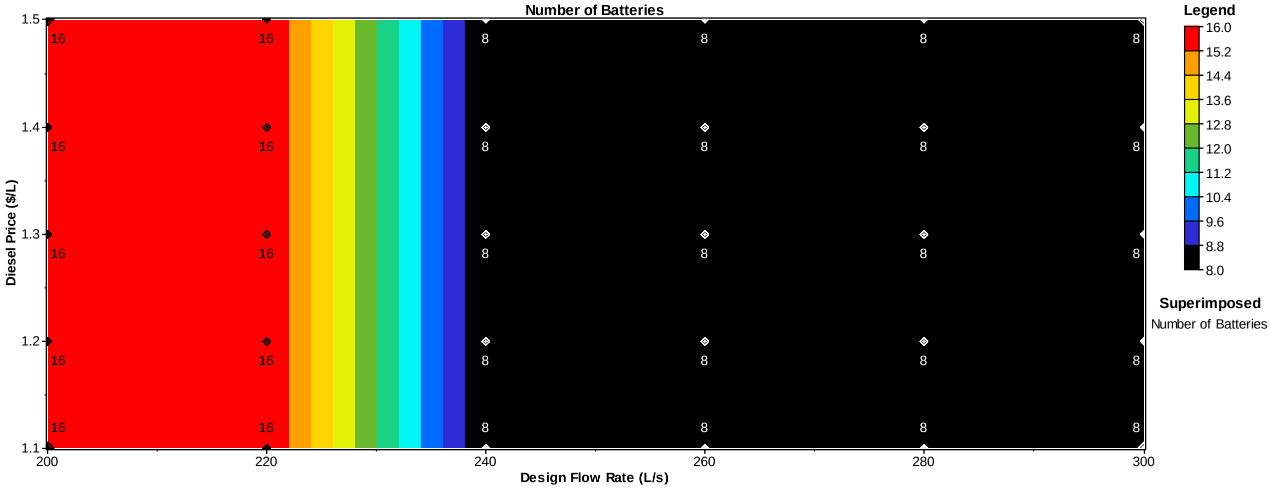


Figure 5.10 : Number of batteries vs the water flow rate.

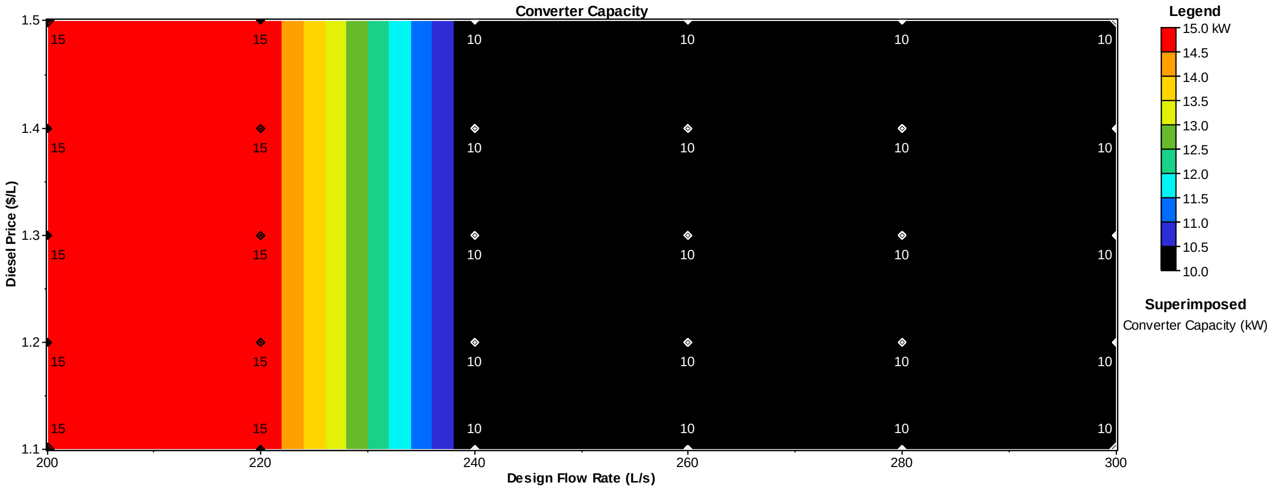


Figure 5.11 : Converter capacity with respect to the water flow rate.

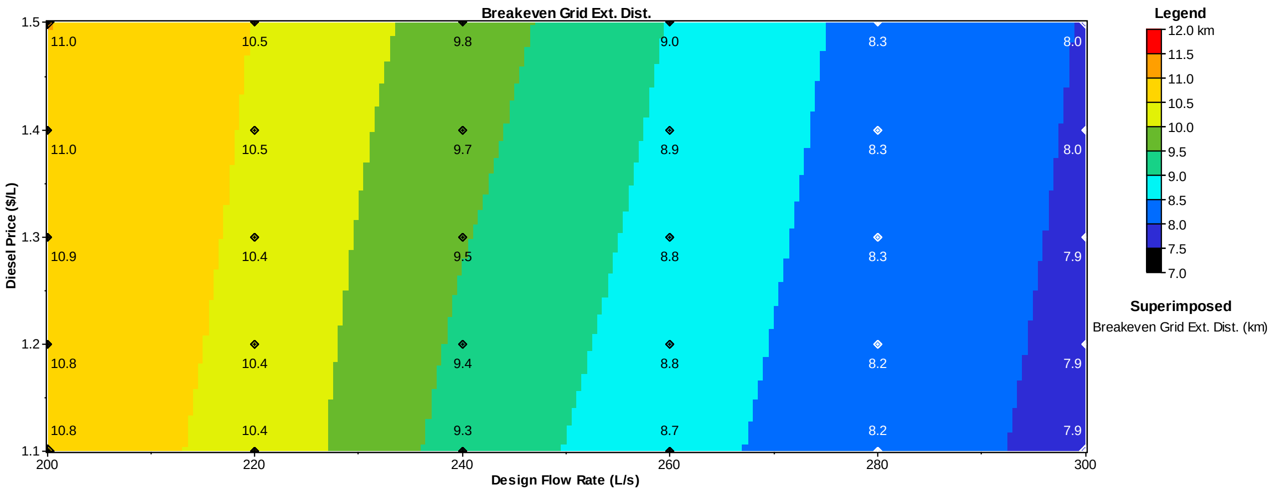


Figure 5.12 : Breakeven grid extension distance with respect to hybrid system

According to Figure 5.13 we can see that the LCOE decreases as the design flow rate increases. But for the case of diesel price as it shown in Figure 5.14, the COE increases due to increase in the fuel cost [15]. The decrease in the COE for the variation in design flow in the range of 200 Litres – 300 Litres is approximately \$ 0.035/kWh (25 frw/kWh). But the change in the cost is not as high as in the case of fuel price variation. It is not significant, see the Figure 5.14. The increase in COE for the variation in diesel price in the range of \$ 1.1 – \$ 1.5 is approximately \$ 0.0017/kWh (1.2 frw/kWh) which is negligible.

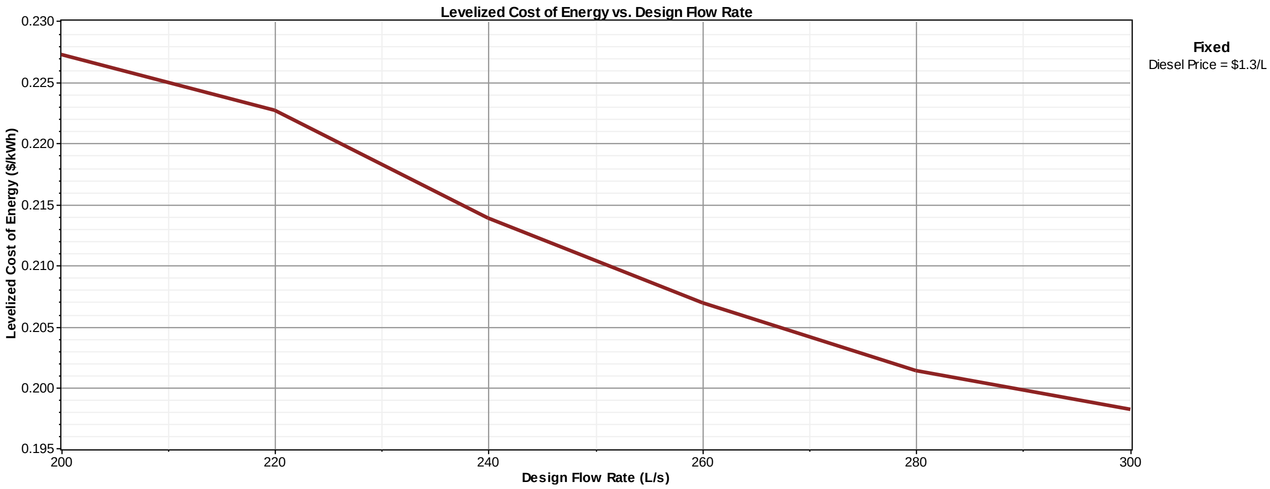


Figure 5.13 : LCOE at different design flow rate.

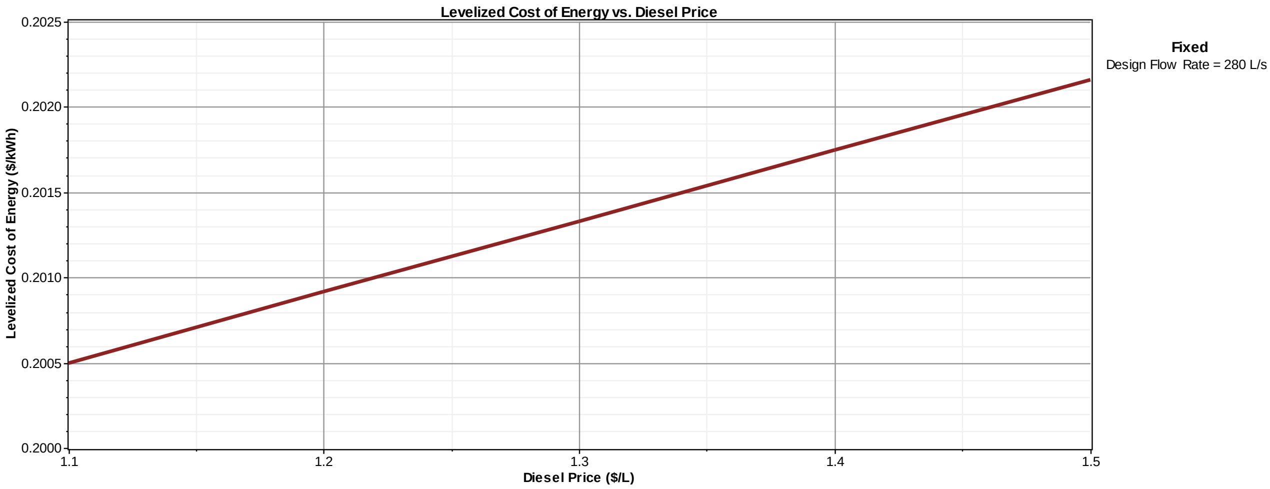


Figure 5.14 : LCOE at different diesel price.

5.3 Futures Connection of the Hybrid System to the National Grid

The selected rural community in Burera district in the northern province of Rwanda for this project has not yet been electrified by the national grid. The government of Rwanda has a target of having the electrification of 70 % of its citizens connected to the national grid. That is why, I assume that the selected community will be included so that in the future the government may invest money for the extension of the national grid to this remote village as well. But the time that will be taken to accomplish this task is uncertain.

However, if the grid is extended to the selected rural village during the lifetime of the hybrid system, then it will affect the cost returns of the project. It can influence either positively or negatively, because once the grid is available, the community will buy electricity from the national grid. On the other hand all the energy generated by the hybrid system can be sold to the grid. Therefore it is important to analyze the cost returns of the project if the national grid is available in the future.

For this analysis I have made the assumptions that the community will have access to the electricity from the national grid after any time and the hybrid power system is developed and operated by an Independent Power Producer (IPP). Under these assumptions, the community will buy electricity from the micro grid based on RET or in other words from the Independent Power Producer during the first time and then from the national grid. Hence the IPP can sell the electricity generated by the hybrid power system to the community during the period where national grid is not available. Once the national grid is available, the hybrid system can be connected to the grid and all the energy generated by the hybrid system can be sold to the national grid. When the hybrid system is interconnected to the national grid, the generator and the battery bank will not be required any more, thus they can be decommissioned. Then the hybrid system will consist only renewable system that is, a MHPP with the capacity of 20 kW.

From the homer simulation results, the LCOE for the hybrid system is $ 0.201 and the COE from national grid is $ 0.2, the difference in between to energy cost is $ 0.001 (0.7 frw/kWh) which is negligible. From the cost above, it is clear that the project will run and earn the cost returns of the project as it has been designed, but by selling all the energy generated by the hybrid system to the national grid, this will benefit to the IPP because even the excess of electricity will be purchased, which was not the case for the off grid system.

5.4 Design of the Hybrid System

According to the HOMER simulations it has been found that the following hybrid configuration is the optimal hybrid configuration which can supply the electricity at a lowest cost with an accepted level of availability to the selected one village from Burera District in the northern province of Rwanda.

Micro Hydropower plant capacity	20 kW
Diesel Generator capacity	10 kW
Battery bank/Number of 1156 Ah batteries	55.52 kWh/8
Capacity of the bi-directional inverter	10 kW

The connection diagram of components is indicated in Figure 5.15. An AC coupled hybrid configuration is used in designing the system. In this connection, all sources are connected to the AC bus. As the batteries generate DC electricity, they are connected to the AC bus via bi-directional inverter. Since the generator and the alternator from the micro hydropower plant give the AC power, they are connected directly to the AC, see Figure 5.15.

A power house for micro hydropower plant will be used with all necessary equipment. Like; Hydropower Gilkes Turgo turbine of 20kW, the butterfly valve motor drive unit, laptop for monitoring the top of falls water intakes, the Dump load controller to dumps the excess of electricity, Ethernet/communication box, capacitor bank for power factor correction and proportional valve control.

The battery bank consists of 8 Surrette 1156 Ah, 6 V flooded lead acid deep cycle batteries connected in series. The selected voltage of the DC bus is 48 V. Therefore 8 batteries have been

connected in series to obtain the nominal voltage of the DC bus of 48 V. one set of series connected batteries resulting in nominal capacity of the battery bank of 55.5 kWh.
A one SMA Sunny TriPower Island–10 kW inverters have been used as the bidirectional inverter.

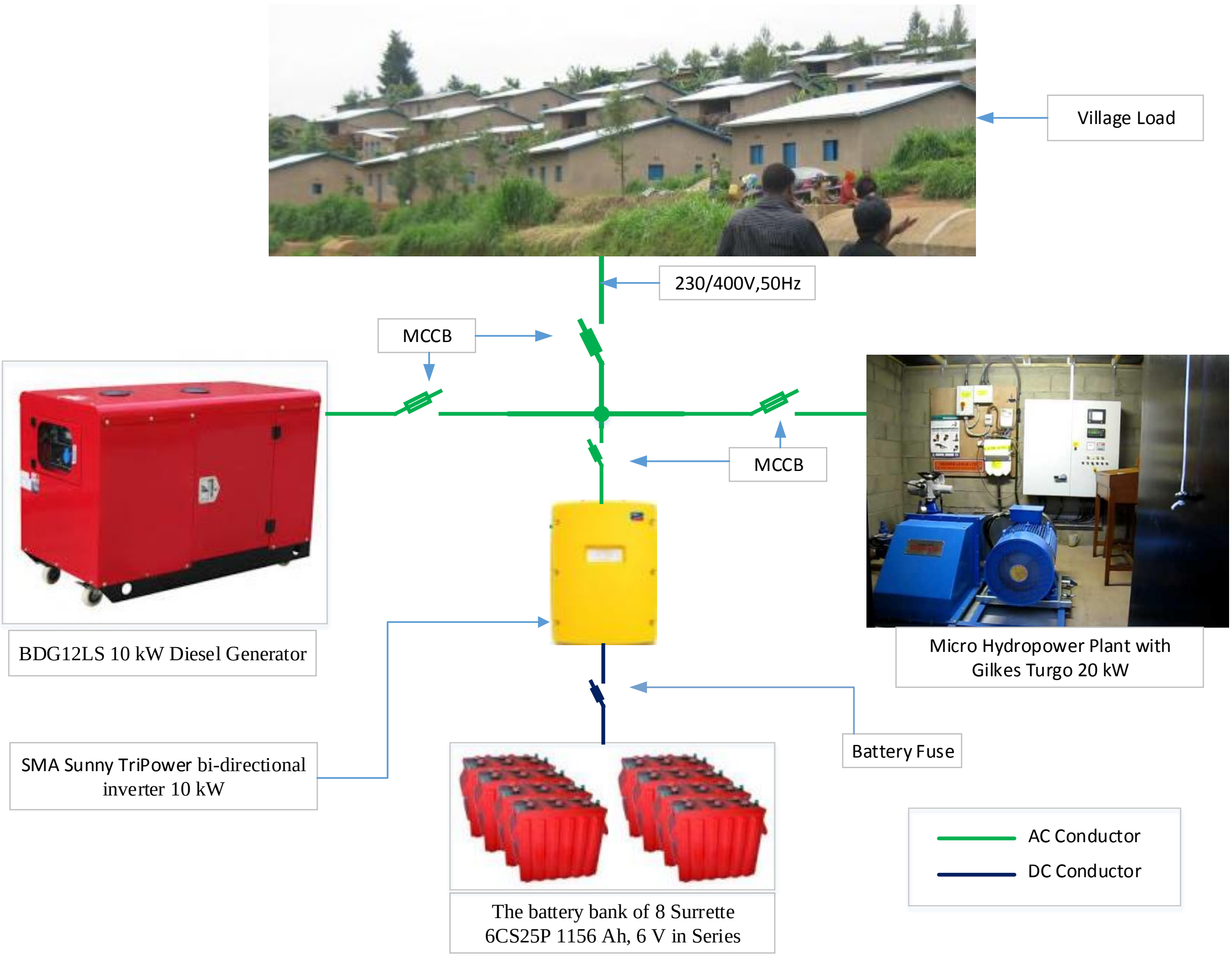


Figure 5.15 : Single line diagram of the hybrid system

Fuses, Miniature Circuit Breakers (MCB) and a Moulded Case Circuit Breaker (MCCB) are employed in the system to protect the equipment and conductors from overload and over current conditions. A MCCB is used to limit the total load of the micro grid to the required level and also to protect the equipment from over currents created due to faults in the micro grid. Since the maximum power of the village is about 38 kW. MCCB with a nominal rated capacity of 60 A is used. The thermal release setting (for overload) and magnetic release setting (for over current) can be set with respect to the nominal rated capacity in the MCCB.
In order to maintain the proper operation of the hybrid system by maximizing the energy utilization generated by the renewable sources and minimizing the operating hours and fuel consumption by the diesel generator, the collective operation of the individual components should be controlled by an intelligent hybrid management system. Energy Management System (EMS) can be either automatically or manually operated. A manually operated system requires well trained operator for

controlling the system operation. On the other hand automatic system does not require human involvement. However, the design of the energy management system of the hybrid system is not in the scope of this thesis.

5.5 Economic Viability

Development of a rural electrification scheme based on a renewable hybrid power system in Burera district requires an initial capital investment of approximately $ 113,000. This system can feed approximately 150 households including public utilities and several small businesses. This type of rural electrification schemes can be implemented either private sector based, utility based or as a combination of private sector and utility based. However, the government contribution will be essential to make the service affordable to the end users and to ensure the sustainability of the system even though the project is developed in either way, because the levelized cost of electricity (0.201 $/kWh) is basically equal to the average price of the electricity from the national grid. In reality, the electricity price of rural electrification schemes cannot be equalized with the national grid tariff which already incorporates subsidies, particularly in developing countries. Nevertheless, development of proper tariff structure is a crucial factor in the design stage of the project in order to attract the private sector investors. Simultaneously, sustainable financing for O & M of the system must be ensured by the regulated purchase tariff.

Generally the basic rule in the electrification project is that the tariff structure must cover at least the capital and the lifetime O & M cost of the project [4]. The LCOE is the indicator that represents the flat electricity tariff that can cover the capital and the O & M cost of the project during the project lifetime [4]. Table 5.3 illustrates how the levelized cost of energy can be brought down with the capital donation from the government or Non-Governmental Organizations (NGO). Other than capital investment based subsidy, several subsidy schemes are available. Different schemes can lower the energy cost by different amounts. As showed in Table 5.3, the LCOE can be reduced by 0.133 $/kWh if subsidy is available for covering 60 % of the capital cost.

Table 5.3 : Effect of subsidies on the electricity price.

Donation as percentage of capital cost (%)	0	15	30	45	60
LCOE ($/kWh)	0.201	0.184	0.167	0.15	0.133

In contrast to the financial scheme, proper O & M scheme must be developed to ensure the sustainable operation of the rural electrification project. Local people can be trained for doing basic maintenance of the system and even for collecting the monthly fees from the consumers. O & M cost can be brought down by incorporating well trained local people. However, the service of skilled technicians will be required for major maintenance activities especially in the micro hydropower plant for turbines and alternator and the diesel generator. Table 5.4 illustrates how the costs can be brought down by involving local trained people for maintaining the system. Training local people for monitoring the system operation and doing routine maintenance of the system will avoid the necessity of employing a full time technician thus reduces the administrative cost.

Table 5.4 : Effect of system fixed O & M cost on the electricity price.

System fixed O&M cost ($/year)	6,000	5,000	4,000	3,000	2,000	1000
LCOE ($/kWh)	0.201	0.19	0.179	0.168	0.157	0.146

If the annual fixed O & M cost can be brought down approximately to $ 1000 then the energy cost drops from 0.201 to 0.146 $/kWh, and with the capital subsidies of 60 %, the energy cost can be brought down approximately from 0.201 to 0.133 $/kWh. This is an acceptable and affordable price for the rural consumers.

5.6 Efficient Use of Electricity in the Micro grid

Efficient use of electricity is a key issue in rural electrification systems which are based on the hybrid power systems, because, the rated capacity of the generating systems is increasing as the peak demand of the community increases which then increase the capital cost substantially. To reduce the capital investment, the peak and the average load must be minimized as much as could be [1]. Therefore, the inhabitants must be educated about the energy efficiency measures. At the same time, people should aware about their responsibilities and the system limitations. Usually in rural communities, lighting loads make the largest contribution to the total load. Thus people should be educated about the energy efficient bulbs (LED) and their long lifetime to eliminate purchasing cheap low efficient incandescent bulbs. In addition people should be given an understanding about the right time of using the certain electrical appliances such as electric irons and water pumps. By operating them during off peak hours the peak demand can be reduced. In addition, people must be encouraged to iron cloths of few days and avoid daily ironing. Further, suitable water pumps must be selected according to the pump lift and flow rate. All these can be done by conducting awareness programs for the inhabitant in the village. So, awareness programs also should be a part of the micro grid development scheme.

On the other hand an alarm system can be designed to avoid unwanted tripping of the main circuit breaker due to increase in load above the rated capacity of the hybrid system. For this, the village load should be continuously monitored and as it is about to reach the limits, a siren horn can be activated to encourage the people to switch off some electrical appliances for clipping the peak load. The people may give positive feedbacks on these alarms, because they know otherwise they have to face supply interruptions.

5.7 Comparison of Electricity Prices

Solar Home Systems (SHS) provide huge benefits to the people in rural communities where national grid electricity is not available. These products are accessible from 10 Wp – 100 Wp and the prices are proportional to the size and the complexity of the system [1]. However the costs of these systems are typically higher and cannot be afforded by low income rural inhabitants for a one-time payment. Therefore, several loan schemes are available to make these systems viable for rural low income families in Rwanda. The cost of energy generated by these systems typically lies in the range of 0.28 – 0.30 $/kWh which is higher than the energy price of the micro grid based electricity (0.201 $/kWh). In comparison with SHS, micro grid based electricity offers several benefits to the consumers. SHS can power only limited number of appliances including few CFL/LED bulbs, radio and a television. If users need to power many appliances then a system having a large capacity PV system and a battery must be purchased and they are high cost, thus rarely affordable.

6 Discussion

The objective of this thesis was to explore the best renewable energy-based hybrid configuration for powering a selected village in Burera District. That village from Burera District in the northern province of Rwanda comprising around 150 families including several small businesses and public utilities was selected for the analysis. The average daily load of this village is 249 kWh/day and an approximate maximum demand of 28 kW has been observed during the evening between 18:00 – 21:00 PM. A constant load profile listed in Figure 2.4 has been assumed throughout the year because the region is not affected by seasonal variations and the day length does not vary significantly because Rwanda is located close to the equator.

The selected region receives an abundance of rain with an annual average of 98.6 mm. Consequently hydropower system was used as the main resources for power production in the hybrid system, but, due to the fact that the power need in some instances is more than what can be gained from the available water discharge also the diesel generator and battery bank had to be used to assure at best the supply of the peak demand. Subsequently, simulations was done for a certain number of hybrid system configurations, and the NPV of the lifetime cost and the LCOE of each configuration have calculated for 20 years, due to the latter parameters the lowest cost option is obtained.

Diesel powered micro grids seem to be economical based on the initial capital investment, because they require a very small capital investment when compared to renewable energy based hybrid systems. In contrast, hybrid systems entail a large capital investment, but lower O & M cost. Thus the lifetime cost analysis clearly shows that the hybrid systems are more economical than diesel powered micro grids. According to the results, the lifetime cost of a certain hybrid configuration greatly depends on the type of generating systems involved and their rated capacities. However, the least costly option that can meet the community's electricity demand under the specific requirements is the optimum solution. The decision concerning the final selection of the optimum configuration has been made based on both optimization and sensitivity analysis, which has not been done in most of the previous studies on hybrid system optimization using HOMER. The optimum configuration derived here is a function of the load profile of the village and the potential of renewable means on the site, thus this result is only valid for this site and should not be extrapolated to other communities. According to the simulation results, the following hybrid system configuration is found to be the optimized solution.

Micro Hydropower plant capacity	20 kW
Diesel Generator capacity	10 kW
Battery bank/Number of 1156 Ah batteries	55.52 kWh/8
Capacity of the bi-directional inverter	10 kW

The renewable fraction of the optimized hybrid system mentioned above is 0.996, hence the diesel generator is required to supply only 843 kWh which 0.4 % of the entire load. The micro hydropower plant generate annual energy of 198,000 kWh which is the highest percentage (99.6 %) from the overall energy generated. This system can meet the load with an availability of around 100 %

resulting in only around 0 hours of power outage during a year, however this excludes the power interruptions caused due to natural hazards or shut-downs for plant maintenance.

The optimal dispatch strategy of the diesel generator has been found to be "Load following" and the generator should therefore be operated only for direct supply of the load in case of unavailability of the renewable generation and depleted battery bank. According to the simulation results, generator's operating hours during one year is approximately 207 hours, this is equal to 4140 hours in 20 years of project. The lifetime operating hours of the generator are 15000 hours more than the operating hours of the diesel generator during the entire project. Therefore, while it is not required to replace the diesel generator within the project life span, the battery bank should be replaced after 11 years, a procedure which costs around $ 4,430. The same case for the converter should be replaced after 14 years, a procedure which costs around $ 4,330. The lifetime cost analysis of the system showed that the project requires a capital investment of $ 113,000. The NPV of the lifetime fuel cost is $ 5.300 while the total O & M cost for the whole system which primarily accounts O & M of the diesel generator, batteries and wind turbine is $ 77,800. For the complete system, the project is worth the NPC of $ 200,000 including the salvage values of the complex. According to the results, the hybrid system can fulfil the demand at a LCOE of 0.201 $/kWh.
One of the important point revealed by this analysis is that, developing this power production scheme in Rwanda requires government subsidies to make the service affordable to the customer. The present national grid electricity price for the domestic user lies in the range of 0.2 – 2.4 $/kWh with respect of how much kWh is consumed during one month. When compared with the latter price, it is clear that the electricity price from the hybrid system (0.201 $/kWh) is somehow good. However, in addition to subsidies, the active involvement of the local people to maintain the system is very important for reducing the operating and maintenance costs. As the results show, the energy costs can be lowered to approximately 0.13 $/kWh if the government funds become available for covering 45 % of the capital investment and by involving the local people to maintain the system, this can continue to decrease.

7 Conclusion

The crucial objective of this study was to find a best techno-economic of an off grid power system to supply a rural community in Rwanda. The work was started by describing the typical load profile of the selected community. Secondly, the identification of the possible renewable energy resources have been done by analysing past data on the annual variations of solar and water stream in the Rugezi catchment. Unfortunately, the wind system have not been considered because Rwanda is closed to the equator which mean zero wind.
Off-grid renewable energy-based power systems cannot provide a continuous supply of electricity without a storage medium. Consequently, batteries are added to the hybrid system. In order to ensure the continuity of the supply without putting severe stress on the battery bank for a reduced overall cost, a diesel generator are also incorporated. Further, while various component configurations for the system have been studied, the AC coupled hybrid configuration has been selected mainly due to its easy expandability and the maximized efficiency of the generator. After selecting the appropriate components and studying their characteristics, the hybrid system has been modelled in HOMER, and simulations have been made to determine the best system which can supply the village load with the required level of availability. The usefulness cost of all hybrid structure that can fulfil the continuous load demand has been calculated to determine the system which provides the lowest cost.

My development of a technically feasible and economically viable hybrid solution for power generation of one village in Burera district bring out a least-cost combination of a micro hydropower, diesel generator and batteries that can meet the demand in a dependable manner.
A micro hydropower plant, diesel generator and a battery bank hybrid system are found as the best option for the power system with the following capacities of 20 kW, 10 kW, and 55 kWh respectively. The estimated value of the levelized cost of energy obtained from the lifetime cost analysis is 0.201 $/kWh. It has been proved that the cost of energy can be further lowered approximately to 0.13 $/kWh (90 frw/kWh) with the reduction of O & M cost and with the help of the government donation. The energy cost of 0.13 $/kWh is acceptable and affordable for rural consumers.

Finally, I can conclude that this hybrid power system is excellent option solution and it make a difference to existing solutions which is more economical and attractive than grid electricity for electrification of the selected rural community in northern Rwanda under the condition of involving local trained people for maintaining the system and receiving some funds or donation from the government or non-governmental organizations, with the latter condition the cost of energy for hybrid system will be much lower than that from the national grid.

Before I propose a next steps or interesting focuses for the future work, let me first highlight a question that arises relates to financing of the investment. Let take the case of an investment of $ 113,000 will be required for a 30 kW system (or an average of $3,800/kW approximately). Even if this volume is not big either for any normal lender (such as banks) or for any utility shareholder, serious risks are involved in the financing. Firstly, a part of the investment is not re-deployable (e.g. the investment for MHHP). If the project does not succeed for any reason, the investment will be

lost for the shareholder and will represent a bad investment. Secondly, the electricity market is not good in the area and the assumptions related to the demand may not materialise, or may take longer to accomplish. This will negatively affect the cost return mechanism. Thirdly, the business domain may be troubled by administrative, managerial and politics objections, thereby altering such investments. Fourthly, there are reasonable obstacles (e.g. availability of professional manpower, govern supply logistics and bad transport means) that can attach to costs, slow up project delivery and minimize profitability of the projects. In such circumstances, appropriate motivations and support structure will be a paramount to attract investment and alleviate risks.
That is why the following may be an interesting focuses for the future work:

- Establishing an energy management system for the micro grid.
- Reinforcing a proper financial and business model by analyzing the economic condition in Rwanda as well as the selected rural community in Northern Province.
- Come up with a suitable operation and maintenance scheme which can ensure the sustainable operation of the system.
- Addressing the possibility of replacing the diesel generator in the hybrid system by locally generated biofuels.

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Appendices

Appendix A Survey form for Households Grid Connected

1. Form no:
2. Date:
3. Phase:
4. Number of persons in the household:

Age	Number of persons	Ubudehe Category (Richness classification)	
0-6		1 (Poor)	
7-13		2 (Low income)	
14-19		3 (Medium income)	
20+		4 (Wealthy)	

5. Size of household (number of rooms):
6. Total household income:
7. Electricity costs:
8. When did you get connected to the grid:
9. Electrical appliances:

Types	Number	Usage time (hour, min)	When during the day are they used?
Lamps			
Cell-Phones			
Radio			
TV			
DVD Player			
Computer			
Refrigerator			
Iron			
Water pumps			

10. Do you believe there is any difference between weekdays and weekend in your electricity consumption?
11. How often do you get blackouts?
12. How do they affect your everyday planning?
13. Are you satisfied with the electricity distribution?
14. Do you have any plans of buying new equipment?
15. If yes, which one?
16. How would you change your consumption if the price per kWh should increase?
17. Do you use any other energy sources (firewood, paraffin, batteries)?
18. If yes, for what purpose?

- Cooking
- Entertainment (radio, TV)
- Light
- Other

19. What's the monthly cost for these other sources?

Appendix B Detailed daily consumption for selected village

Domesticpurposes									
	Wealthy 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	660	05:00-06:00	18:00-22:00
2	Cell-Phones	2	5	10	2	20	100	05:00-07:00	
3	Radio	1	10	10	12	120	100	05:00-17:00	
4	TV	1	120	120	3	360	1200	18:00-21:00	
5	DVD Player	1	30	30	3	90	300	18:00-21:00	
6	Computer	1	100	100	2	200	1000	17:00-19:00	
7	Refrigerator	1	500	500	4	2000	5000	17:00-21:00	
8	Iron	1	1000	1000	1	1000	10000	09:00-10:00	
9	Water pumps	1	500	500	1	500	5000	08:00-09:00	
		Total				4620			
No.of houses						10			
Total for Wealth Families						46200			

	Medium income 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	1760	05:00-06:00	18:00-22:00
2	Cell-Phones	2	5	10	2	20	400	05:00-07:00	
3	Radio	1	10	10	12	120	400	05:00-17:00	
4	TV	1	120	120	3	360	4800	18:00-21:00	
5	DVD Player	1	30	30	3	90	1200	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				810			
No.of houses						40			
Total for Medium income families						32400			

	Low income 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	4400	05:00-06:00	18:00-22:00
2	Cell-Phones	2	5	10	2	20	1000	05:00-07:00	
3	Radio	1	10	10	15	150	1000	05:00-20:00	
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						390			
No.of houses						100			
Total for Low income families						39000			

Industrial/commercial/communitypurposes								
	Shops and Bars							
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	220	18:00-22:00
2	Cell-Phones	1	5	5	2	10	25	12:00-14:00
3	Radio	1	10	10	12	120	50	10:00-22:00
4	TV	1	120	120	10	1200	600	12:00-22:00
5	DVD Player	1	30	30	10	300	150	12:00-22:00
6	Computer	1	100	100	2	200	500	12:00-14:00
7	Refrigerator	1	500	500	10	5000	2500	12:00-22:00
8	Iron	0	1000	0	0.2	0		
9	Water pumps	0	500	0	1	0		
		Total				7050		
No.of houses						5		
Total for Shops and Bars						35250		

	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	44	18:00-06:00
2	Cell-Phones	2	5	10	2	20	20	05:00-07:00
3	Radio	0	10	0	12	0	0	
4	TV	0	120	0	3	0	0	
5	DVD Player	0	30	0	3	0	0	
6	Computer	2	100	200	4	800	400	08:00-12:00
7	Refrigerator	0	500	0	4	0	0	
8	Iron	0	1000	0	0.2	0	0	
9	Water pumps	1	200	200	1	200	400	08:00-09:00
		Total				1284	0	
No.of Post						2		
Total for Administration Post						2568		

	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	330	18:00-06:00	
2	Cell-Phones	5	5	25	2	50	25	09:00-11:00	
3	Radio	0	10	0	12	0	0		
4	TV	1	120	120	8	960	120	08:00-16:00	
5	DVD Player	1	30	30	8	240	30	08:00-16:00	
6	Computer	3	200	600	6	3600	600	08:00-12:00	14:00-16:00
7	Refrigerator	2	500	1000	24	24000	1000	00:00-24:00	
8	Iron	0	1000	0	0.2	0	0		
9	Water pumps	1	500	500	3	1500	500	05:00-08:00	
		Total				34310			
No.of Centres						1			
Total for Medical centres						34310			

	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	220	18:00-06:00	
2	Cell-Phones	0	5	0	1	0	0		
3	Radio	2	10	20	2	40	20	10:00-12:00	
4	TV	1	120	120	2	240	120	12:00-14:00	
5	DVD Player	1	30	30	2	60	30	12:00-14:00	
6	Computer	1	100	100	4	400	100	08:00-12:00	14:00-16:00
7	Refrigerator	0	500	0	4	0	0		
8	Iron	0	1000	0	1	0	0		
9	Water pumps	1	500	500	3	1500	500	05:00-08:00	
		Total				4880			
No.of Schools						1			
Total for Primary Schools						4880			

	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	440	18:00-06:00	
2	Cell-Phones	5	5	25	2	50	25	05:00-07:00	
3	Radio	3	10	30	3	90	30	05:00-08:00	
4	TV	1	120	120	3	360	120	18:00-21:00	
5	DVD Player	1	30	30	3	90	30	18:00-21:00	
6	Computer	4	200	800	4	3200	800	08:00-12:00	14:00-16:00
7	Refrigerator	0	500	0	4	0	0		
8	Iron	0	1000	0	1	0	0	06:00-07:00	
9	Water pumps	1	500	500	4	2000	500	18:00-22:00	
		Total				11070			
No.of School						1			
Total for Secondary Schools						11070			

	Community church							
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	132	18:00-06:00
2	Cell-Phones	2	5	10	2	20	10	05:00-07:00
3	Radio	1	10	10	3	30	10	09:00-12:00
4	TV	1	120	120	4	480	120	18:00-22:00
5	DVD Player	1	30	30	4	120	30	18:00-22:00
6	Computer	1	200	200	4	800	200	08:00-12:00
7	Refrigerator	0	500	0	12	0	0	10:00-22:00
8	Iron	0	1000	0	1	0	0	14:00-15:00
9	Water pumps	1	500	500	3	1500	500	05:00-08:00
	Total					4534		
No.of churches						1		
Total for churches						4534		

	Small manufacturing units							
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	99	18:00-06:00
2	3-phases motor	1	3000	3000	4	12000	9000	08:00-12:00
3	1-phase motor	1	1000	1000	3	3000	3000	13:00-16:00
4	TV	0	120	0	3	0	0	
5	Ceiling Fan	1	100	100	8	800	300	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						3		
Total for Small manufacturing units						48588		

Appendix C Daily power hourly distribution

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	00:00-01:0	01:00-02:0	02:00-03:0	03:00-04:0	04:00-05:0	05:00-06:0	06:00-07:0	07:00-08:0	08:00-09:0	09:00-10:0	10:00-11:0	11:00-12:0	12:00-13:0	13:00-14:0	14:00-15:0	15:00-16:0	16:00-17:0	17:00-18:0	18:00-19:0	19:00-20:0	20:00-21:0	21:00-22:0	22:00-23:0	23:00-24:00
	0	0	0	0	0	660	0	0	120	120	120	120	120	120	120	120	0	0	660	660	660	660	0	0
	0	0	0	0	0	1760	0	0	0	0	0	0	120	120	0	0	0	0	1760	1760	1760	1760	0	0
	0	0	0	0	0	4400	0	0	30	30	30	30	30	30	30	30	0	0	4400	4400	4400	4400	0	0
	0	0	0	0	0	500	500	500	0	0	0	0	500	500	0	0	0	0	220	220	220	220	0	0
	44	44	44	44	44	44	0	0	400	400	400	400	0	0	0	0	0	0	44	44	44	44	44	44
	330	330	330	330	330	330	0	0	600	600	600	600	0	0	600	600	0	0	330	330	330	330	330	330
	220	220	220	220	220	220	0	0	100	100	100	100	0	0	100	100	0	0	220	220	220	220	220	220
	440	440	440	440	440	440	0	0	800	800	800	800	0	0	800	800	0	0	440	440	440	440	440	440
	132	132	132	132	132	132	0	0	200	200	200	200	0	0	0	0	0	0	132	132	132	132	132	132
	99	99	99	99	99	99	0	0	9000	9000	9000	9000	0	3000	3000	3000	0	0	99	99	99	99	99	99
	0	0	0	0	0	100	100	0	300	300	300	300	300	300	300	300	0	0	1200	1200	1200	0	0	0
	0	0	0	0	0	400	400	0	0	0	0	0	0	0	0	0	0	0	4800	4800	4800	0	0	0
	0	0	0	0	0	1000	1000	0	0	0	0	0	600	600	600	600	600	600	600	600	600	600	0	0
	0	0	0	0	0	500	500	500	0	0	0	0	25	25	0	0	0	0	120	120	120	0	0	0
	0	0	0	0	0	20	20	0	0	0	0	0	30	30	0	0	0	0	120	120	120	120	0	0
	0	0	0	0	0	500	500	500	25	25	0	0	0	0	0	0	0	0	300	300	300	0	0	0
	0	0	0	0	0	25	25	0	0	0	0	0	0	0	0	0	0	0	1200	1200	1200	0	0	0
	0	0	0	0	0	10	10	0	0	0	0	0	150	150	150	150	150	150	150	150	150	150	0	0
	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	0	30	30	30	0	0	0
	0	0	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	0	30	30	30	30	0	0
	0	0	0	0	0	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	0	0
	0	0	0	0	0	0	0	0	0	0	20	20	0	0	0	0	0	1000	1000	0	0	0	0	0
	0	0	0	0	0	30	30	30	400	0	0	0	0	0	0	0	0	5000	5000	5000	5000	0	0	0
	0	0	0	0	0	0	0	0	5000	10	10	10	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	0	0
	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500	500	500	500	0	0
Watt	2265	2265	2265	2265	2265	13670	5585	4030	19475	14085	14130	14130	6925	9925	10750	10750	5800	11300	27905	26905	25905	13255	2265	2265
kWatt	2.265	2.265	2.265	2.265	2.265	13.67	5.585	4.03	19.475	14.085	14.13	14.13	6.925	9.925	10.75	10.75	5.8	11.3	27.905	26.905	25.905	13.255	2.265	2.265

Appendix D Plots of hourly power for different elements

The energy demand for the selected village community can go beyond 30 kW due to the random variability of the load as shown in the Figure D1 below.

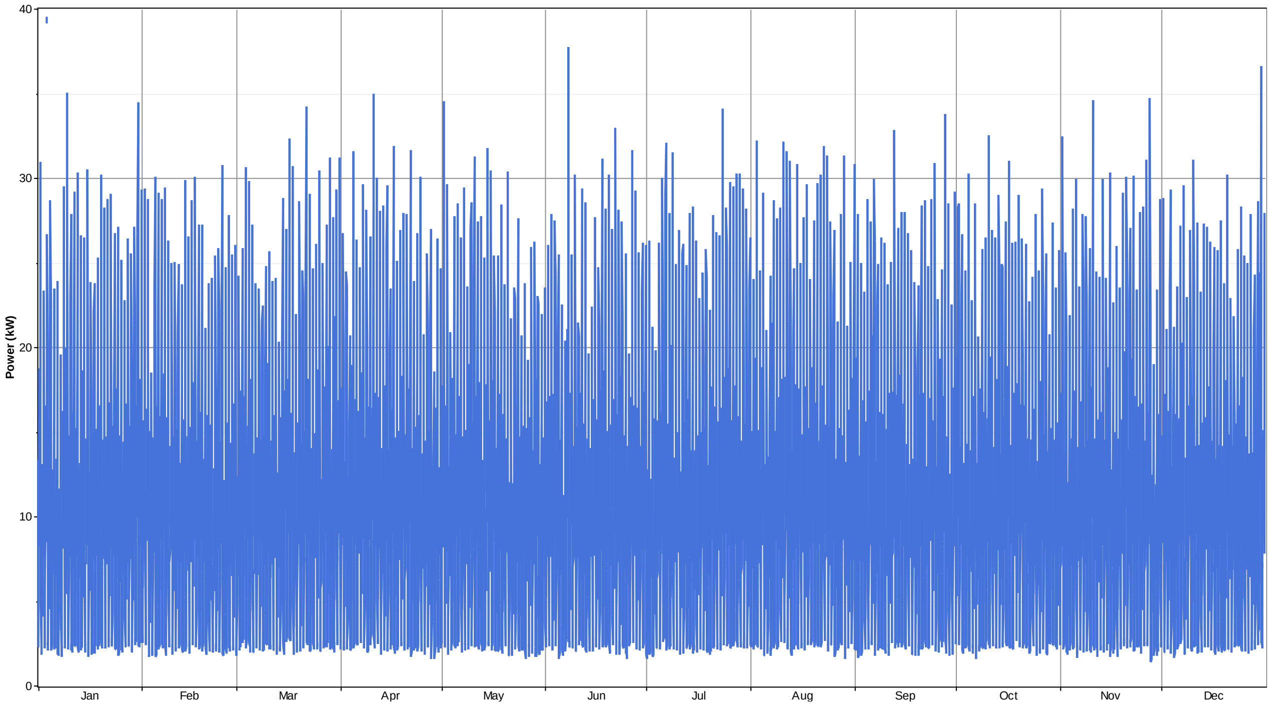

Figure D1: The hourly power consumption in kW for AC primary load over a period of 1 year.

The following Figure D2 shows that, the micro hydropower plant will give a constant output power of around 25 kW during a year.

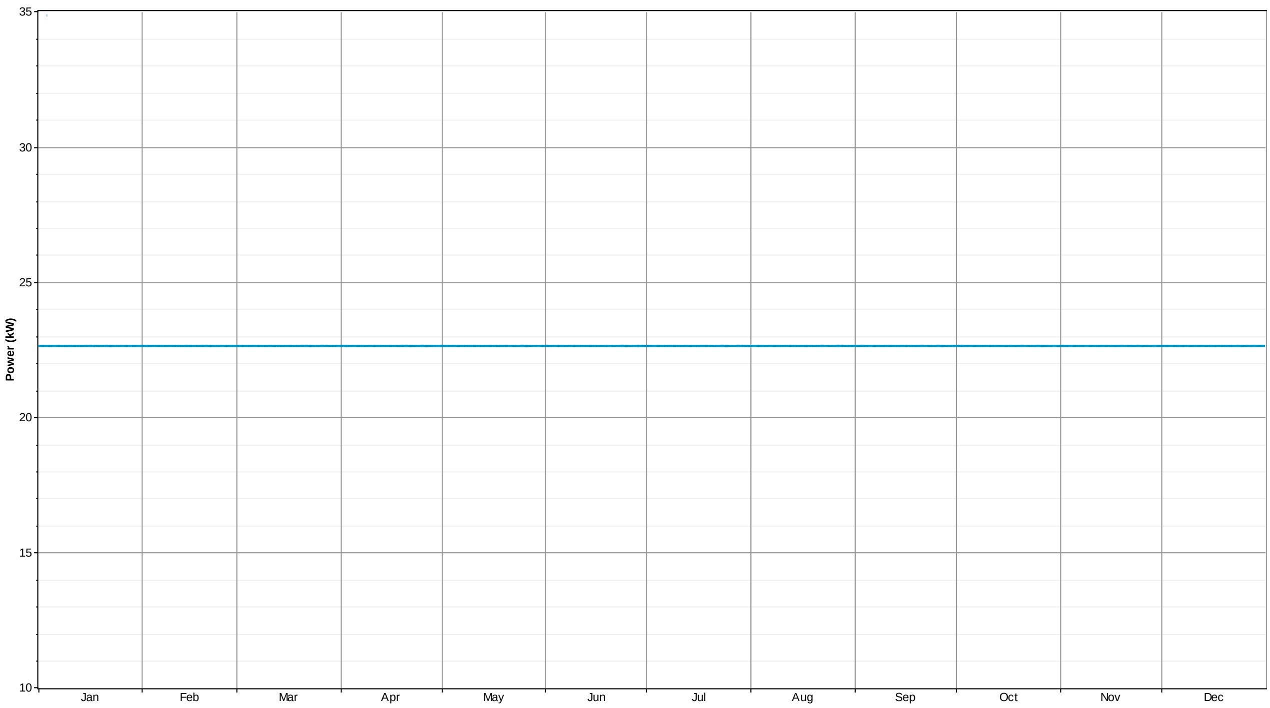

Figure D2: The hourly power production of a MHPP in kW over a period of 1 year.

The following Figure D3 shows that the diesel generator will produce roughly a constant output power of around 4 kW during a year. And let me remind that the diesel generator will be switched on when required and the latter will produce only the required amount of power that cannot be produced by the renewable sources or battery bank to supply the load.

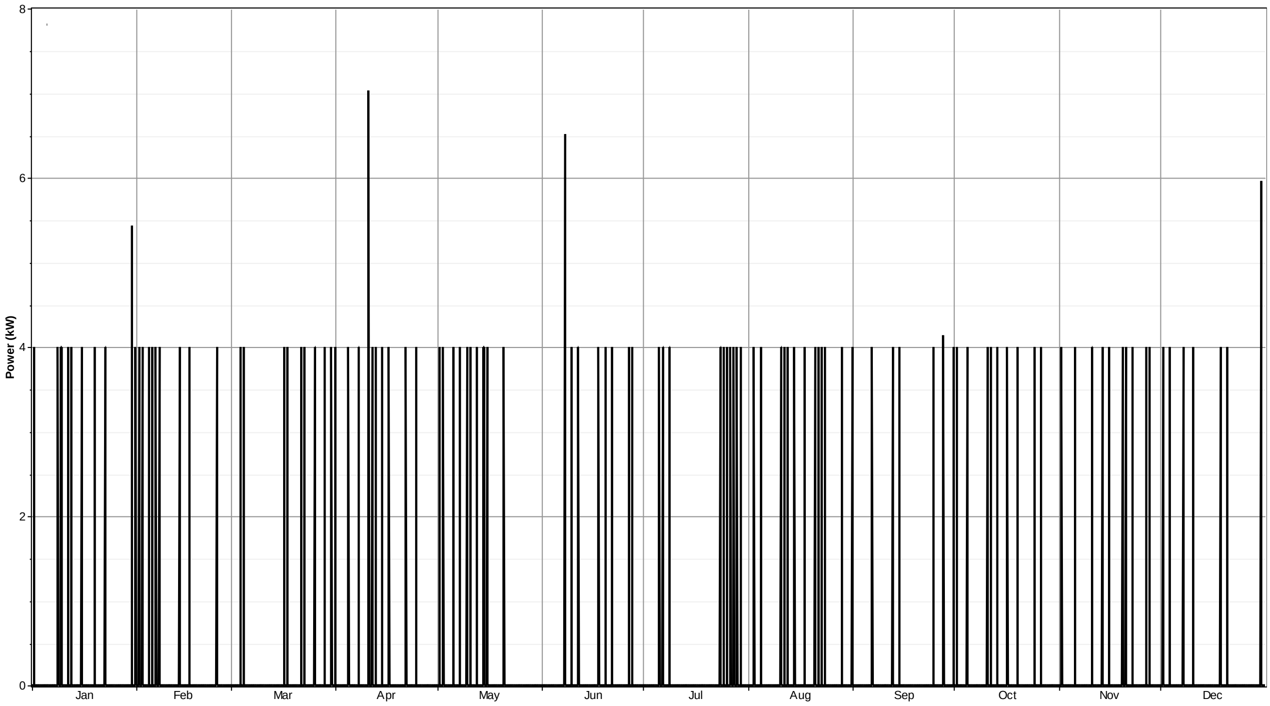

Figure D3: The hourly power production of a diesel generator in kW over a period of 1 year.

The Figure D4 shows the output power from the converter to the grid is around 4 kW, and this power is coming from 8 batteries in series of 1,156 Ah (6.94*8 = 55.5 kWh).

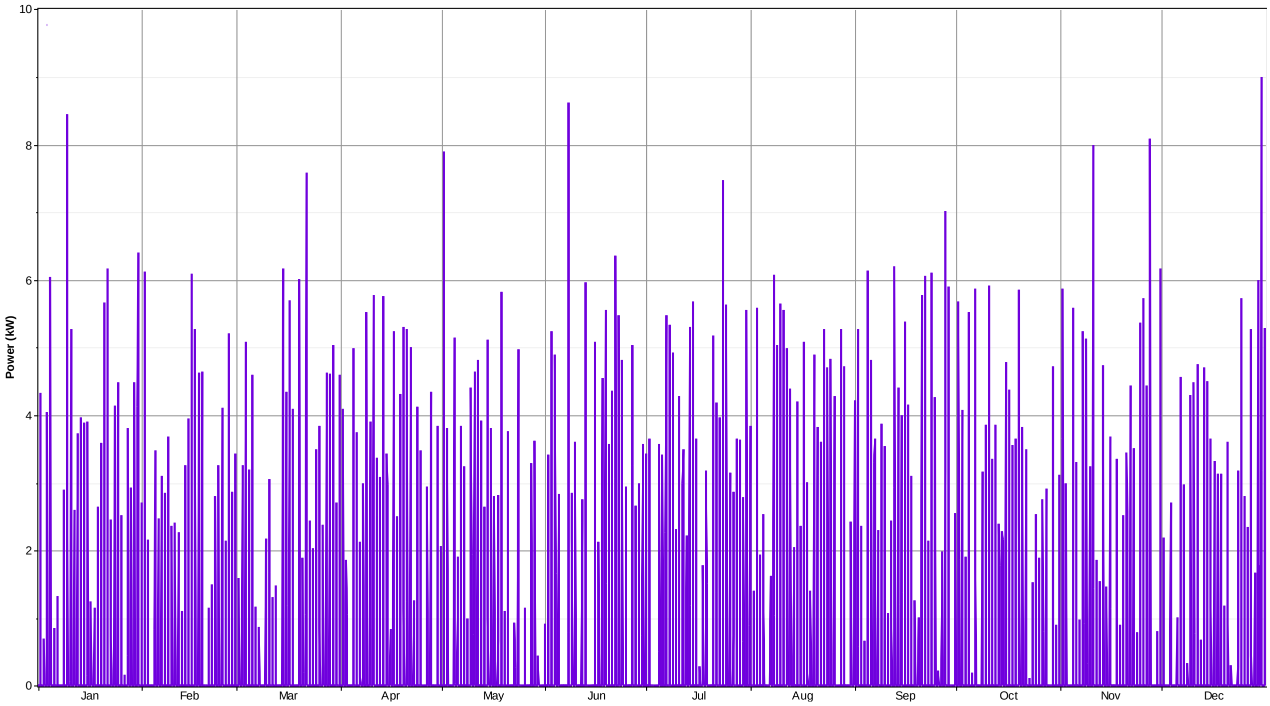

Figure D4: The hourly power production from the converter in kW over a period of 1 year.

The Figure D5 show that the power produced by the battery bank is equal to the power used for charging.

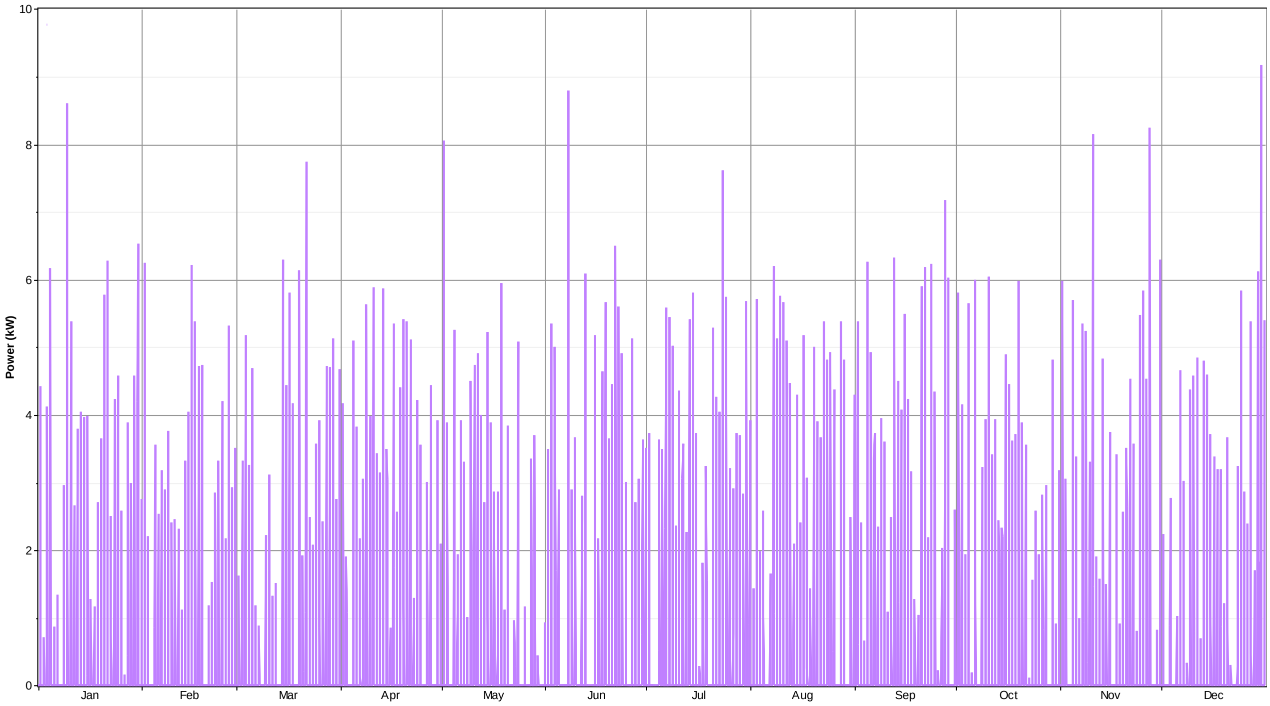

Figure D5: The hourly power used for battery charging in kW over a period of 1 year.

The Figure D6 here below shows that the batteries will be charged and discharged with an average of around 85 %.

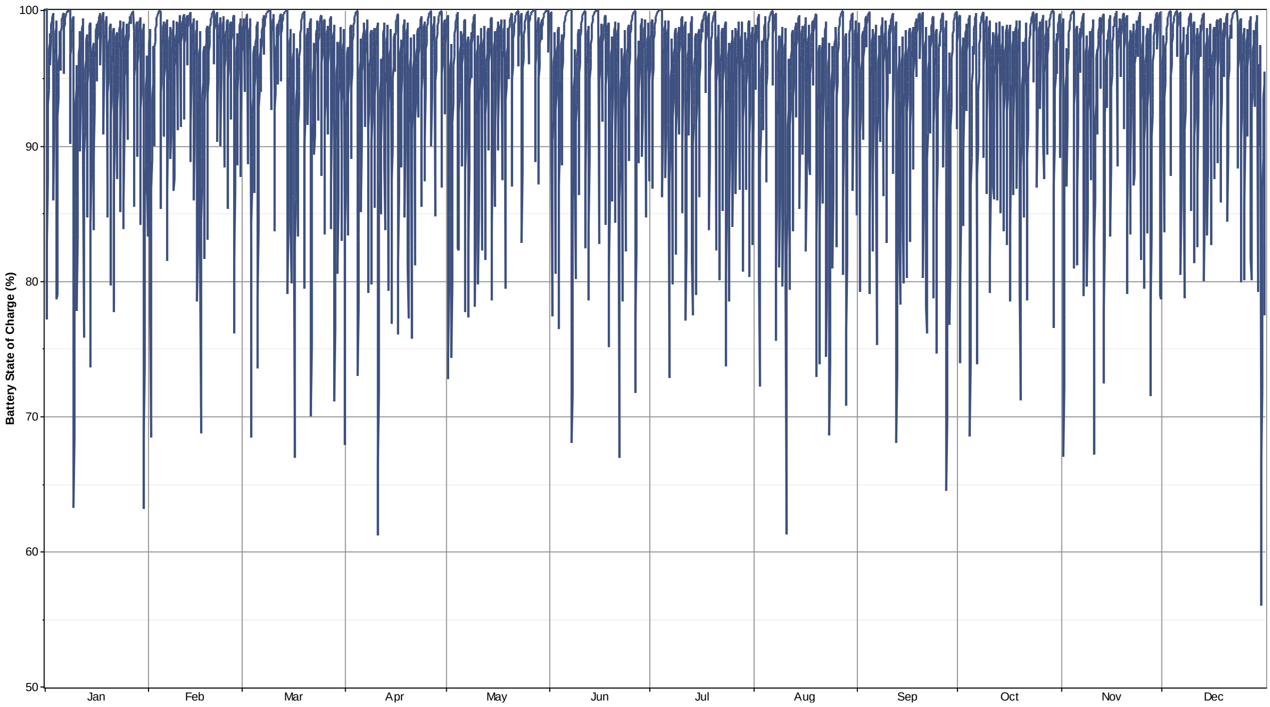

Figure D6: The hourly battery state of charging over a period of 1 year.