UNIVERSITY OF NAIROBI

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DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

INVESTIGATING RENEWABLE ENERGY POTENTIAL FOR RURAL ELECTRIFICATION IN RWANDA: TECHNICAL AND ECONOMIC VIABILITY

BY

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Declaration of Originality

I, **NISINGIZWE EMMANUEL**, hereby declare that this thesis is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

NISINGIZWE EMMANUEL **Date: ……………………………**

This thesis has been submitted with our approval as university supervisors:

1. **Dr Cyrus Wekesa Wabuge**

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2. **Prof. Maurice K. Mang'oli**

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Dedication

I dedicate this thesis to my dad Edouard HABINEMA, my mother Spéciose MUKAMUYENZI, my Uncles and Aunts and grandmother Thérèsie MUKARUSINE for their prayers and inspiring me to work hard in my academics. To my brothers and sisters for their prayers and encouragement provided. I really appreciate all of you and I love you so much. Last but not least, I thank God for everyday blessing.

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Finally, I am grateful to my lecturers and students in the Department of Electrical and Information Engineering at the University of Nairobi for their moral, valuable advice and academic support.

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List of Abbreviations:

ARES: Autonomous Renewable Energy Systems

BGR: BundesanstaltfurGeowissenschaften und Rohstoffe (Germany Institute for Geosciences and Natural Resources)

BRALIRWA: Brasserie et Limonaderie du Rwanda

BRGM: Bureau de RecherchesGéologiquesetMinières (French Bureau of Geology and Mines)

CFL: Compact Fluorescent Lights

DRC : DemocraticRepublic of Congo

DVD: Digital Video Disc

EDCL: Energy Development Corporation Limited

EDPRS: Economic Development and Poverty Reduction Strategy

EUCL: Energy Utility Corporation Limited

EWSA: Energy and Water Sanitation Authority

GDP: Gross Domestic Product

GoR: Government of Rwanda

HOMER: Hybrid Optimization Model for Electric Renewables

HySim: hybrid energy simulation model

ICT: Information and Communication Technology

IHOGA: Improved Hybrid Optimization by Genetic Algorithm

INSEL: Integrated Simulation Environment Language

IPP: Independent Power Producer

IPSYS: Integrated Power System

ISOR: Icelandic Geo Survey

IT: Information Technology

ITER: Spanish Institute for Technology and Renewable Energies

KenGen: Kenya Electricity Generating Company

LACE: Levilized Avoided Cost of Energy

LCOE: Levilized Cost of Energy

MEPS: Minimum Energy Performance Standards

MHPP: Mini/Micro-Hydro Power Plant

MINEDUC: Ministry of Education

MININFRA: Ministry of Infrastructure

MW: Mega Watt

ORINFOR: Office Rwandais de l'Information

PPA : Power Purchasing Agreement

PV: Photo-Voltaic

RAPSIM: Remote Area Power Simulator

RBA: Rwanda Broadcasting Agency

RE: Renewable Energy

REC: Rwanda Energy Company

REFIT: Renewable Energy Feed In Tariff

REG: Rwanda Energy Group

RET: Renewable Energy Technology

RIG: Rwanda Investment Group

RURA: Rwanda Utility and RegulatoryAuthority

SOMES: Simulation and Optimization Model for Renewable Energy Systems

UNEP: United Nations Environment Program

USD: United State Dollar

VAT: Value Added Tax

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ABSTRACT

Rwanda is a country with many hills, thus expansion of electricity is expensive. Hence no wonder that at the present, the major energy resource used in Rwanda is fuel wood biomass where the current national electrification is estimated to be 23% mostly concentrated in towns. So, most of rural villages are not electrified. The aim of this study is to investigate the feasibility of renewable energy technologies, technically and economically; focusing on two renewable resources (solar and wind) to come up with hybrid system to electrify Kinyana village in Kayonza District as this district has been found to have the strongest Wind in Rwanda and then all the collected data were analyzed using HOMER software tools.

The wind data was collected from the installed weather stations in different parts of Rwanda while the solar data were provided internally from the HOMER software and RET Screen. These data are the following: The maximum wind speed at 40 m of height is found at wind mast of Kayonza District and the horizontal solar radiation of 5.13kWh/m^2/day was also measured in Eastern province. This is also proven by a solar power plant in this region that is already connected on national grid. The selected village has a typical daily load of 265.14 kWh/day, with an estimated maximum load of 29.2 kW that has been observed during the evening hours from 18:00 hrs to 21:00hrs.

With the simulation in HOMER; Hybrid System (Solar-Wind-diesel generator) composed of 40 kW PV panels, 4 wind turbines with 10 kW rated capacity each; 15 kW diesel generator; 40batteries of 1, 156 Ah each and the inverter of 20 kW has been selected for this village. This system was chosen due to its low cost of energy which is $0.339 compared to the remaining ones. With 20 years of lifetime considered for this project; it is showed that the required initial capital investment for this project is $ 268,000. Then, the Net Present Cost (NPC) needed for this project is $ 850,480 with a total O&M cost of $ 21,376for the whole system. This has mainly increased by O & M of the diesel generator, batteries and wind turbine. The obtained results show that the system can satisfy the demand at a Levilized Cost of Energy (LCOE) of 0.339 $/kWh with renewable fraction of 56% as found in simulated results.

Keywords: Renewable Energy, Rural Electrification, Solar and Wind Energy, Hybrid System, HOMER Simulation and Feasibility Analysis.

CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

Rwanda gets its electricity from hydro, methane gas, thermal and solar energy sources. The Rwanda Energy Group (REG) is the only utility mandated to sell power to consumers and it continues to install diesel generators to meet the increasing rural demand for electricity. It is estimated that 85% of the Rwandan population lives in rural villages [1]. Current national electrification is estimated to be 23%; and mostly concentrated in towns. Most rural villages are not electrified.

In most of rural areas connecting to the national grid or even to expand the power system is expensive due to the geographical situation of Rwanda. The country is made up of so many hills that building distribution lines becomes expensive and slow to undertake. Hence, renewable energy resources could be the best choice, given that these energy resources are found in the environments in which the energy is to be consumed and hence require minimal transmission and distribution lines.

There is exploitation of renewable energy in Rwanda such as micro hydro and solar energy to provide electricity to communities, especially in Northern Rwanda (Hydro) and solar in Eastern province where there is a solar plant producing 8MW. Renewable energies have advantages in terms of their environmental impact due to the fact that energy cannot lead to depletion and is also friendly to the environment.

In most villages, however, diesel generators are used for basic electricity services such as lighting and cell phone charging. The motivation for this research is to study techno-economic viability of using solar-wind hybrid system and the design of this hybrid power system as most of researches done for Rwanda electrification focus on using stand-alone system.

1.2. Problem Statement

In Rwanda the largest energy consumed is not electricity but biomass energy in form of low-efficiency application of firewood and charcoal. Rwanda still faces significant challenges in achieving the industrialized middle income target. The major challenges include, limited electricity infrastructure that supports economic development and low levels of access to safe and clean energy for the majority of the population. With current national electrification estimated at 23% and mainly in towns, and with 85% of the whole population living in rural villages, it will not be possible to reach middle income status unless there is affordable electricity to all Rwandans. The Rwandan Government seeks to increase electricity access to 70% of the population by 2017. However this is not easy to achieve [1].

Many households in rural areas in Rwanda, like in many African countries, do not depend on electricity in cooking, heating and lighting. They instead depend on traditional fuels (wood fuel, crop residues and charcoal), kerosene and candles. Thus, the majority of population is therefore, excluded from the benefits of national development that comes with access to electricity. This is extremely costly and cause high electrical loss to provide electricity to rural areas through conventional means, such as through electrical grid extension or diesel generation. High cost is due to remoteness and low population densities which disallow for economies of scale in the provision of electricity services [2].

Compared to urban electrification programs, rural projects are challenged with many factors such as: low levels of demand; the consumers that are scattered and it means the population density is low; low loading factors; high levels of power loss and low paying capacity of consumers. Therefore it is necessary to analyze the potential of renewable energy in Rwanda to meet the government policies especially by facilitating cost-effective electrification of rural areas. This entails doing a techno-economic analysis of using renewable energy technologies for rural electrification in Rwanda.

1.3. Research Gap

Even if the authors described above used HOMER as an optimization tool for their studies, the hybrid system set ups were studied using different load demands and the applications, location of studies as well as climatic data's they used were different. Every hybrid power system has to be designed in a different way for the site based on the available climatic data's, number of households, service centers and consumer load profiles. This thesis has been also employed the same software to design and optimize the off-grid hybrid power system besides the electricity to be provided has to be supplied for community of households which has to be applied for lighting, communication, water supply, irrigation supply, school, health service and small commercial business. Hybrid power systems implementation did not started yet in the country and even very limited studies in master's level has been undertaken for limited resources. However this thesis differs from the related studies in terms of application, load demand, climatic data, and location of the area.

1.4. Research Objectives

The overall objective of this study is to investigate the potential contribution of renewable energy in Rwandan rural electrification, focusing on solar-wind hybrid power systems through a technical-economic analysis.

The specific objectives are:

i. To evaluate the renewable energy potential for a sample site in Rwanda mostly for two resources: solar and wind;
ii. To estimate energy demand in order to design a system of electrifying a typical rural village.
iii. To establish renewable energy resource (solar and wind)viability in Rwanda; this addresses technical viability;
iv. To determine economic viability of exploiting renewable energy resources to meet the demand.

1.5. Justification for the Study

Due to the target of Rwanda Government about Economic Development and Poverty Reduction Strategy part II (EDPRS II) the number of population connected to the grid will increase from 23% to 70% by 2017 especially to develop the rural electrification sectors. This study will play a big role by investigating the potential of Hybrid system of solar and wind for rural electrification. Despite that there is a way of using different renewable energy technologies to provide illumination to the population living in those areas there are still many rural areas without electricity while different sectors like schools; health centres; business centres and administrative offices need electricity for fast development. Then, we end by designing a system to electrify Kinyana village located in Kayonza District.

1.6. Assumptions and Limitations

The scope of this study is limited to determining the feasibility of Wind-Solar hybrid system 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 designed power system is not specifically located. It will be the optimal structure for other locations with the same considered parameters as at sample site. The same process can be applied for other communities in Rwanda by following the same procedures as it is used in this Thesis.

For this research, the limitation is for optimizing the size of components of a hybrid system used to supply electricity to the selected village of Rwandan, and we look at the system performance and the cost of the system.

To achieve this analysis we have considered the following assumptions:

i. The variations of solar radiation occurs the same throughout the project lifetime.
ii. The users of this power system live according to an unchanging daily life; resulting to the same load variations every day. This is because summer and winter are not presenting a big difference for summer or winter for the selected location as the temperatures seem to remain unchangeable throughout the year.
iii. By considering that the rate does not changing during the lifetime of the project for all types of costs. The considered costs are: cost of fuel, maintenance and labor costs.

The limitations for this designed system are that we do not discuss the stability and control of this Hybrid system. The only considered renewable resources are solar and wind to know their potential contribution in electrification of Rwanda.

1.7. Organization of the Thesis

This thesis is organized in five chapters.

Chapter one deals with the background and motivation, problem statement, goals and objectives, research method, assumptions and limitations and finally gives the thesis organization.

Chapter two reviews the related works and it includes the renewable energy sources available in Rwanda. Generally it discusses the country overview in terms of energy, focusing on Renewable resources, it also deals with the further explanation of main components used in PV-Wind Hybrid System technology. It explains the essential characteristics of the system components. It also gives solar and wind data in Rwanda.

Chapter Three discusses the other different input data used, cost values of all components, economic inputs, constraint inputs, sensitivity and the displaying of the hybrid system in HOMER; it reviews also load profile of the village.

Chapter Four gives the model and presentation of the results obtained from the simulations in HOMER.

Finally, Chapter Five makes the conclusions through the results obtained, the beneficiaries of this research work, the recommendations and the proposed future works for expanding this Thesis.

CHAPTER 2: LITERATURE REVIEW

2.1 Country Overview: Rwanda

Rwanda is a small land-locked country with 26,338 km^2 in area and a population of 11,689,696 people [3]. It borders with Burundi in the South, Democratic Republic of Congo in the West, Tanzania in the East and Uganda in the North. It is a densely populated country in comparison to other African countries as it is shown with Figure 2.1. In 2014, GDP was 643 USD/capita. The economy Rwanda has been growing at an annually average rate of 8.3%. Government’s target is to raise it up to an average growth rate of 11.5% with EDPRS II period (2013-2018)[4]. Ensuring that every Rwandan accesses to affordable and modern sources of energy as it is one of essential point for achieving the EDPRS II objectives for sustainable development.

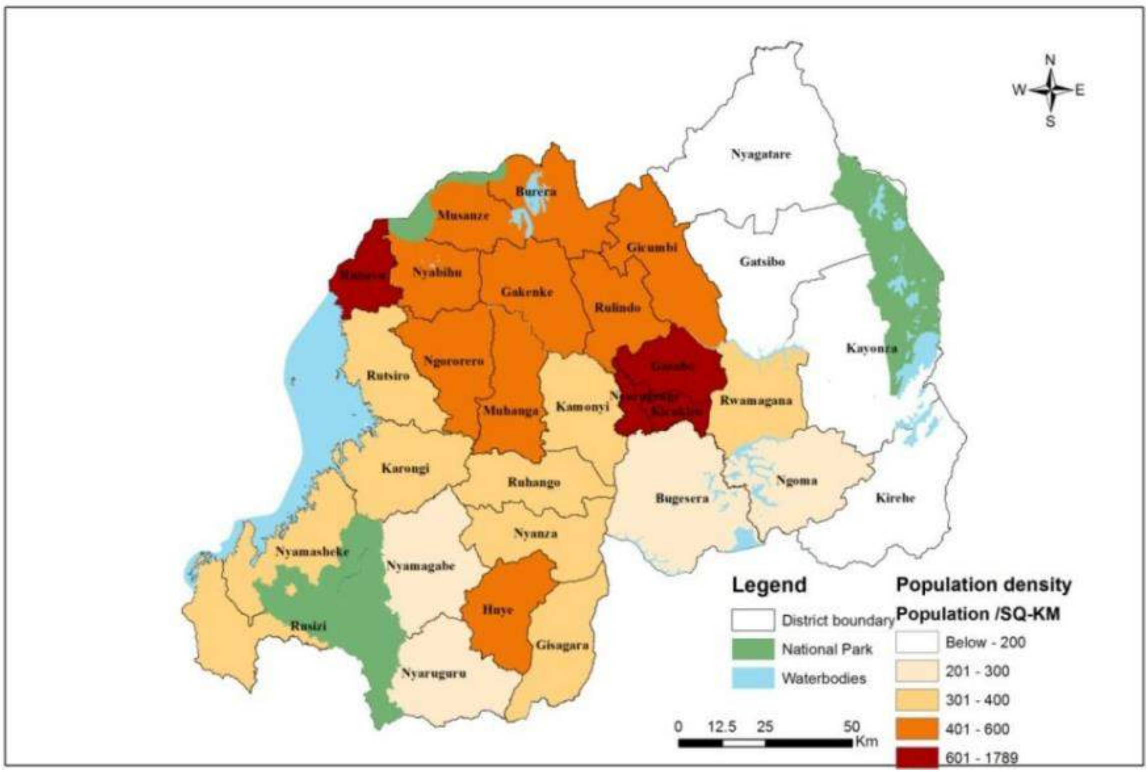


Figure 2.1: Map of Rwanda [3]

2.2 Energy Sector Institutional Framework in Rwanda

The following Figure 2.2 shows how the energy sector institution in Rwanda is structured:

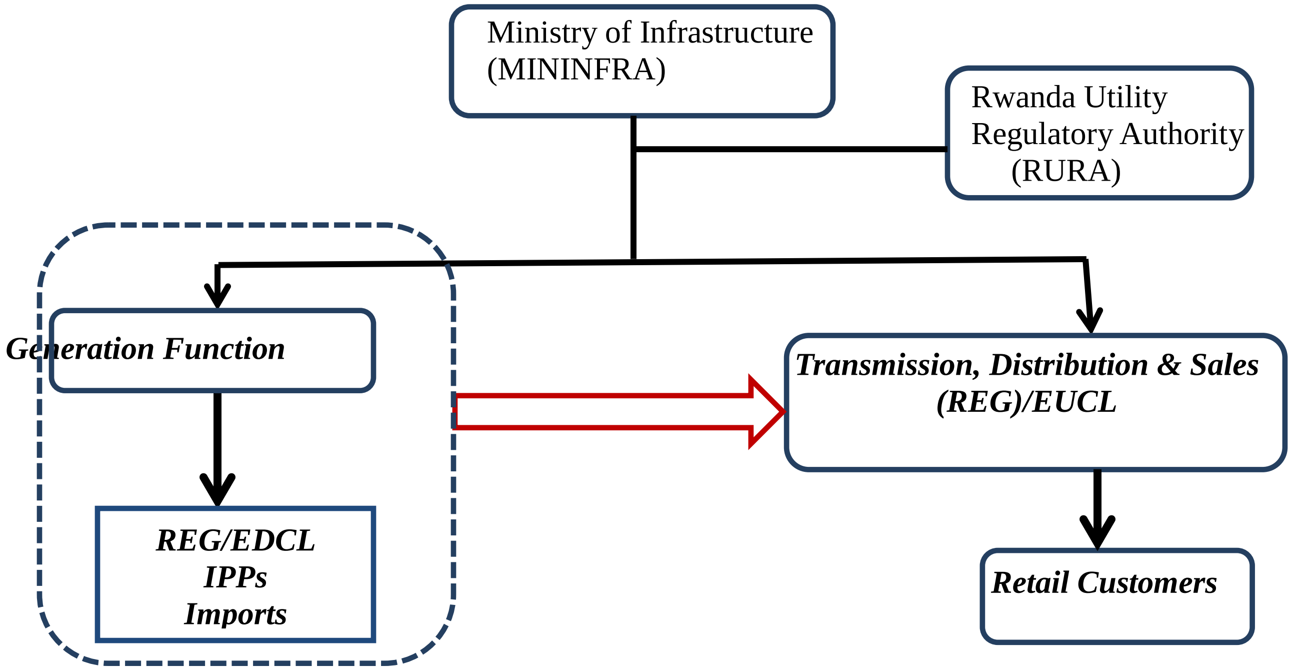


Figure2. 2: Energy sector institutional structure in Rwanda [1]

The Ministry of Infrastructure (MININFRA) has the primary responsibility for setting the overall policy and strategy of the energy sector, and for coordinating the developments of the electricity sub-sector. Then Rwanda Energy Group (REG Ltd) with its two sub-branches EUCL (Energy Utility Corporation Limited) and EDCL (Energy Development Corporation Limited); is an independent body which is authorized to effectively execute and efficiently run the energy sector. It has also tasks of setting the tariffs, generation and distribution of energy.

There is also Rwanda Utility Regulatory Authority (RURA) which intervenes in the regulation of energy sector, the policy and strategic plan. It has also responsibility of regulating the cost tariff set by REG and technical regulation of electricity and the energy sub-sectors for both electricity and gas infrastructure. RURA is similarly tasked with the licensing of all Independent Power Producers (IPPs) licenses for generation projects or concession and all off -grid licenses where concessions were granted to companies and individuals, to generate transmit and distribute power within a specified area[1][5].

2.3 Review of Related Works

Many works done on renewable energy in Rwanda focus mostly on off-grid solutions that include both isolated distribution grids (mini-grids) with central power generation and individual stand-alone systems. There are no many researches done on Hybrid system for renewable energy in Rwanda, even if they are some done in the other countries but we need to study the case on Rwanda due to its climate data and geographical situation. Therefore, to gather reasonable data of renewable energy potentials of the country; hybrid energy systems and rural electrification techniques; the following authors were referred as they studied hybrid systems using the same software HOMER for simulation, but the studies carried out at different times, sites and different countries.

The only work done on Rwanda about hybrid power system is by Odax Ugirimbabazi [6]Master Thesis in spring 2015 named Analysis of Power System Options for Rural Electrification in Rwanda to electrify one village of Burera District. The results obtained are: a micro hydro - power plant (MHPP) of 20 kW, the diesel generator of 10 kW and the battery bank of 55.5 kWh, 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. This helped to get the information about solar energy and status of electrification in Rwanda.

According to Solomon Teklemichel Bahta [7] wind turbine-photovoltaic-diesel generator-battery bank-converter have been simulated and optimized for the rural community of Haressaw among the sub-districts of Atsbi district in the regional state of Tigray, Ethiopia. Primary load demand of 1505kWh/day, peak load of 284kW, deferrable energy is about 17kWh/day, and deferrable peak load of 3.6kW was involved during optimization of the power system.

A research carried out by Boneya, Gelma [8] gave the detailed design of solar PV and wind turbine hybrid power system to generate electricity to a community of 100 households, health clinic and a school. The study was started firstly by investigating potential of solar and wind sources at the area taken as case study. The optimized results obtained after simulation, showed that PV/wind turbine/diesel generator/battery and convertor have been chosen to be a configured system. For this structure the total NPC and COE is $103,914 and 0.302 $/kWh respectively, for a renewable fraction of 84% and diesel fuel consumed is 1,955 liters per annum and it runs for 633 hours per year.

A feasibility study was conducted by Bekele, Getachew and Palm, Björn [9] for a standalone solar/wind based hybrid energy system to supply electricity for rural areas in Ethiopia. This paper presented the simulation of PV/wind/diesel and battery to supply electricity for 200 household's model community. The paper shows the most cost efficient combination from the hybridizing of diesel generator/battery and converter with no contribution of renewable sources fractions. It also presented other cost effective combinations of diesel generator/PV and converter; in this case the dispatch strategy applied was the cycle charging strategy. The conclusion of the author is viable to deploy the above stated power configurations in the areas where these resources are stated.

Thesis done by Kusakana Kanzumba and Vermaak, Herman [10] investigated the applicability of hybrid renewable power systems as a source of primary energy for mobile telephone stations in the Democratic Republic of Congo. The study was performed for three different areas which are not connected to the grid namely; Kamina, Mbuji-Mayi and Kabinda. The possible set-up options conducted by the authors are PV-wind turbine, diesel generator, pure PV and pure wind schemes were configured. Moreover, techno-economic and environmental effect were studied; for Kabinda the optimal hybrid system contains 2 wind turbines, 11kW PV, 82 batteries and 7.5kW converter, and the NPC and COE are $196,975 and0.372 $/kWh respectively.

According to the paper done by Ranaweera Udumbara and K.M Iromi [11] techno-economic optimum sizing of hybrid energy system rural electrification in Sri Lanka, rural village from the Siyambalanduwa region in Sri Lanka containing approximately 150 households which results in a daily electricity demand of 270 kWh with a night-time peak of 25 kW has been chosen as target. The Siyambalanduwa region receives an abundance of solar radiation with an annual average of 5.0 kWh/m^2/day. In addition, the annual average wind speed of this region is 6.3 ms^{-1}which results in a wind power density of 300 W/m^2 at a height of 50 m above the ground.

2.4 Renewable Energy Sources in Rwanda

Table 1 indicates a list of power plant and their generation capacity in 2015 and it is seems that such MW of electricity indicated is not enough for a country with almost 12 million people and need for development. This lack of infrastructure also becomes one of the main barriers for the economic development of the country in general.

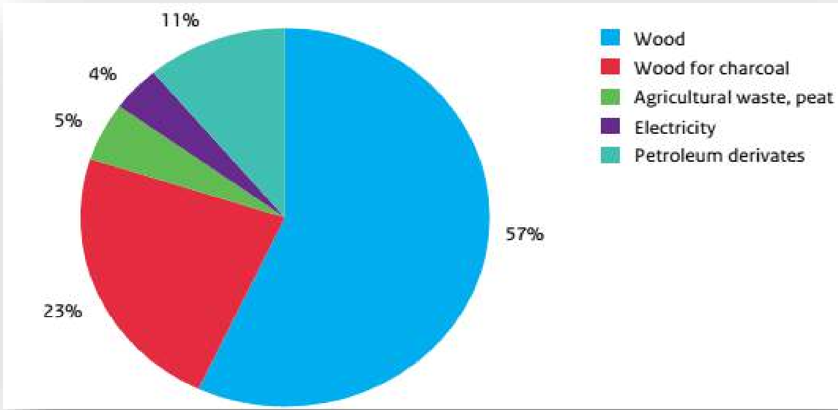


Figure 2. 3: Main energy sources in Rwanda **[1]**

In addition, the high level of diesel-powered generation in the energy mix means that Rwanda is dependent on imported diesel and fuel oil which places high demands on Rwanda's foreign exchange reserves. In addition, it means that Rwanda's economy is highly vulnerable to oil price spikes which are on the other hand very expensive and need to be reduced.

Table2. 1: List of Power Plants and their capacity in 2015**[12]**

N°	Plant name	Type	Year of operation	Installed capacity in MW
1	Mukungwa I	Hydro	1982	12MW
2	Ntaruka	Hydro	1959	11.5MW
3	Gisenyi	Hydro	1957	1.2MW
4	Gihira	Hydro	1984	1.8MW
5	Jabana I	Thermal	2004	7.2MW
6	Aggreko Gikondo	Thermal	2005	10MW
7	AggrekoMukungwa	Thermal	2012	10MW

8	Jali Solar	PV	2007	0.25MW
9	KP 1	Thermal	2008	3.6MW
10	Jabana II	Thermal	2009	21MW
11	Murunda	Hydro	2010	0.1 MW
12	Rukarara I	Hydro	2010	2 MW
13	Rugezi	Hydro	2011	2.2MW
14	Keya	Hydro	2011	2.2MW
15	Nkora	Hydro	2011	0.68MW
16	Cyimbili	Hydro	2011	0.3MW
17	Mukungwa II	Hydro	2010	2.5MW
18	Mazimeru	Hydro	2012	0.5MW
19	Rukarara II	Hydro	2010	9.5MW
20	Nyabarongo	Hydro	2014	28MW
21	KIVU Watt	Methane gas	2015	25 MW
22	Rwamagana solar	PV	2015	8 MW
23	Ngoma solar	Solar	2011	2.4MW
			TOTAL: 161.93 MW	

The analysis of supply and demand of energy in Rwanda as it is shown with figure 2.3 indicates that today about 85% of primary energy still comes from biomass, in the form of wood that is used directly as a fuel (57%) or is converted into charcoal (23%), together with smaller amounts of crop residues and peat (5%). Of the 14% of non-biomass primary energy, petroleum products account for 11% (use mainly in the transport sector) and electricity for approximately 4% [2], while Rwanda has variety energy resources such as: hydro, solar, methane gas, wind, peat and geothermal.

The following are seven renewable energy resources that are available in Rwanda and are discussed to see the current situation of renewable energy in Rwanda. This helps to analyze the potential of renewable energy in Rwanda in order to increase the generation through renewable energy and this leads to quality improvement of life especially in rural areas where there is a lack of access to electricity from the grid.

2.4.1 Hydropower

Rwanda is a country with favorable topography comprising numerous hills, the reason why it is so called a country of thousands hills and rivers which present large opportunities for the development of hydropower. The current installed hydro capacity is approximately 96 MW[1]

Therefore electrification through mini/micro hydropower plants (MHPP) can play an important role in increasing the generation capacity in Rwanda as well as promoting the socio-economic development of remote rural areas. Among Rwanda government plans on energy side, it has to develop around 70 MW of domestic Hydro projects by 2018. To achieve one of Government's objectives of increasing the installed capacity from the current 160 MW to 563 MW by 2017, the Government of Rwanda through the Ministry of Infrastructure and Rwanda Energy Group Limited (REG Ltd) is committed to utilize every means and resources to develop projects that will make this mile stone achievable [4].

In order to achieve this target, EWSA Ltd (currently REG Ltd) has selected around 69 potential micro and Pico hydro sites totaling approximately 15 MW of estimated total capacity (in the capacity of 500 kW and less). Feasibility studies for these sites are currently underway on a number of sites. For most of them are being developed by Private developers, they have already signed a power purchasing agreement (PPA) with REG. As part of Private Sector participation and encouragement in the energy sector activities, the Government of Rwanda through REG Ltd is planning to deliver some of its operational mini hydro power plants to private operators. Currently there is only one hydro power plant (Rukarara I with 9 MW), has been placed under private management [16].

Despite of having a favorable topography to produce hydro power, the low participation of private sector in the development and operation of the plants continues to be the main barrier to hydro power as it is facing also other renewable energy development and operation in Rwanda. To handle this, the Government has decided to develop and then transfer them to the private sector for operation; this motivation is expected to increase their participation as the involved risks will be minimized. Another issue now facing hydro is topography at the River banks where if there is a case of erosion the sediments reach the turbine and this damages the mechanical part of the system. To finish this problem, there is a campaign in the country to plant trees and grasses along the rivers in order to protect all river banks and also construction of terraces are required and encouraged in localized areas that have been identified through feasibility studies for hydropower production[17].

2.4.2 Solar

Rwanda is located in East Africa at approximately two degrees below the equator it is generally characterized by Savannah climate and its geographical location endows it to have a good solar energy potential, where the daily insolation is ranging from 4 to 5 KWh/m^2 and peak sun hours of approximately 5 hours per day [13]

The first solar power plant was constructed in 2008 where the government of Rwanda signed with German state Rhineland-Palatinate to construct own and operate a 250 kWp grid connected solar plant. It was funded by the German municipal power company Stadtwerke Mainz and installed by Juwi. The plant was constructed on the top of Mount Jali in Kigali City. Since its commissioning date, the plant has been operating successfully.

A public call for pre-qualification for the design, build, finance, own/operate a 10 MW solar power plant has been launched. The 25 hectares site is located in Eastern province of Rwanda in Nyagatare and Rwamagana districts. Access is made from main road that cuts through the land plot, 2.4 km long. Within the site there is a 30Kv transmission line and a 50KvA transformer that will be upgraded to evacuate the power generated from the 10 MW plant.[12]

The plant (10 MW Solar plant) has been constructed on an Independent Power Producer (IPP) basis and now is connected on national grid with contribution of 8.5 MW. The PPA (Power Purchasing Agreement) and a 25 years Land Lease Agreement will be signed between the investor and the Government of Rwanda. The followings are Government plans concerning solar energy exploitation:

- Rwanda has chosen a realistic track by focusing on the use of solar PV in two main areas: Electrification of clinics, schools and administrative offices in remote centers.
- Solar water heating, substituting biomass and electricity water heating, with significant environmental and recurrent cost savings.

The solar energy is mostly also used to produce electricity by reliable off-grid systems for rural institutions, especially located at far distance like over than 5 km from the national grid. As reported by MINEDUC in 2014 electrification in the schools was on rate of 20% and more than 2000 schools have no access to electricity due to the fact that are located far from the national interconnected grid. The lack of electricity in schools continues to be a very big challenge to ICT program in Education where government has planned a program of **'one laptop per child'** in primary schools.

Following the experience from the previous projects (like the on-going project of supplying and installing solar PV equipment in 300 rural schools located at distances greater than 5km from the national interconnected grid), solar energy can be used as a source of electricity required by "One Laptop per Child" program, in rural primary schools. It is in this regard, that the Government of Rwanda would like to electrify more schools with Solar PV systems as a part of a the current country wide campaign of achieving 100% electricity access[15].

To achieve this target, most of primary schools are equipped with a PV array of at least 2.5 kWp that provide sufficient electrical energy for IT equipment and lighting. Solar PV installation includes: PV modules, charge regulators, solar batteries, Inverters, lightening arresters, differential circuit breakers, junction boxes, compact fluorescent lights (CFL) and its accessories cables, plugs, switches, supports etc.

2.4.3 Methane gas

Lake Kivu is lying between Rwanda and DRC and it has been found that there is Methane gas. The 2,400 km^2 lake has been proved to have high concentrations of naturally occurring methane gas (CH_4) and carbon dioxide (CO2), with the highest concentrations at depths ranging from 270 m to 500 m; the gas pilot is used to produce electricity (see Figure 2.3). The resource is shared equally between Rwanda and the DRC. Rwanda wishes to utilize this resource to develop methane-to-power projects and other uses such as fertilizer and gas-to liquids projects.

Methane gas in Kivu Lake was firstly taped by Union chimique de Belge with a gas pilot plant at cape Rubona in 1963 to supply the BRALIRWA brewery, where; in place of using fuel oil, it turned its boilers to use gas and was supplied daily 5,000 cubic meters. The pilot plant was shutting down after operating over 40 years [18].

Figure2. 4: Methane gas pilot plant in Kivu Lake **[18]**

Currently Kivu-Watt is producing 8.5 MW and developing to produce a 100 MW, also a 45 MW plant developed by Government of Rwanda (GoR) is operating only about 1.5 MW since 2007 with plan to scale-up capacity to 50MW and REC (Rwanda Energy Company) is subsidiary of RIG (Rwanda Investment Group) undertaking a 3.6 MW plant project, is seeking new partners and investors to revive and scale up the project [18].

2.4.4 Biogas

The Biogas Program in Rwanda started in 2007 under the Ministry of Infrastructure and as well as the program of one cow per family. This should help more Rwandans to get benefits from the biogas program. In 2013, 103 biogas digesters were installed in households in 5 districts which include Ruhango, Gatsibo, Kamonyi, Rulindo and Gicumbi districts.

Most digesters are made from bricks and stones but a pilot project using more efficient fiberglass digester is implemented in Kirehe district where Chinese engineers are training technicians in installing the prefabricated digesters. As motivation Government of Rwanda sets technical assistance to households as well as a credit scheme in "Banque Populaire du Rwanda" specifically for the biogas program and there is also a worth of 230 USD per User to start the project [15]. This is to be done in the following sectors:

- **Domestic Biogas program**: The attention of the program was on capacity development, trains the technicians and entrepreneurs, awareness campaigns and promotion. As a result, by September 2012 biogas digesters had been constructed in the cited districts and over 200 masons were trained. The government is in the process of facilitating installation as stated above and constructing many more additional domestic Biogas digesters by 2017/18.
- **Institutional Biogas program:** Rwanda Government announced in 2008 a strategy of introducing biogas digesters in all boarding schools, big health centres and all institutions with canteens for a purpose of reducing the consumption of firewood. With this program, constructions of large biogas digesters have been started in several institutions in Rwanda. The biogas systems installed in the schools and prisons have reduced firewood usage closely to 60% and 40% respectively, along with an improved hygienic situations and revenue savings [15].

2.4.5 Peat

Peat is considered a promising alternative source of energy. Rwanda has considerable peat reserves in Gishoma (western region), with an estimated reserve of 10 bcm, and at Akanyaru (southern province). It is estimated at 1.5 bcm currently, Gishoma peat power plant is under construction with expected production of 15 MW to be completed end of 2017.

A first Peat master plan was developed in 1993 and indicates the potential to develop around 700MW of generation from Rwanda’s Peat resources; the master plan indicates that Rwanda has estimated reserves of 155 million tons of dry peat spread over an area of about 50,000 hectares. About 77% of peat reserves are near Akanyaru, Nyabarongo River and Rwabusoro Plains. However, the study was not detailed enough to allow the full understanding of the entire country’s peat resources. Thus, the detailed study to provide a detailed picture of peat reserves in Rwanda is ongoing [20][5].

2.4.6 Wind

Wind Potential in Rwanda has not been fully exploited for Power Generation, although potential wind power that Rwanda has in some areas may provide energy with possible solutions such as water pumping, windmill and electricity generation. A study of wind speed distribution has been made in the country in general and the following are the results obtained.

- Direction of wind varies from 11^0 to 16^0
- Wind speed varies from 2m/s to 5.5 m/s

The National Meteorological Service is the utility responsible of the Rwandan synoptic stations and supplies data summaries. The Rwanda National Meteorological Service uses 6 sites which are Kigali-Kanombe Airport, Cyangugu-Kamembe Airport, Nyagatare, Gisenyi, Gikongoro, and Butare) with hourly wind records.

Using the Weibull function to analyze the wind speed (wind speed frequency distribution is an important parameter for predicting the energy output of a wind energy conversion) the annual mean wind speed exceeds 2 m/s for these stations [13].

The analysis of the wind energy possible solution for energy supply in rural areas of Rwanda was undertaken to estimate the wind power potential. In total data from 4 stations (Kamembe, Butare, Nyagatare and Gisenyi) have been firstly analyzed by the National Meteorological Division in 1989. Once again, the data from 3 synoptic sites (Kigali, Butare and Gisenyi) is analyzed by the Weibull function. The considered data has been used to evaluate the annual frequency of wind speed and the direction of wind, yearly variation of the monthly average, annual and daily variation, and vertical profile of wind energy potential [5]. Nevertheless more detailed data is still required. In 2010 the only wind system was put in place to serve the Rwanda office of information ORINFOR (currently RBA) on Mount Jali overlooking Kigali and this is the same site for the 250KW solar system feeding to the grid [14].

2.4.6.1 Wind Turbine: Working Principles

The wind is an abundant, free, clean, sustainable and environmentally-friendly renewable energy source. It has served the human civilization for many centuries by propelling ships and driving windmills to grind grain and pump water, and nowadays also for electrical power production.

Wind is one of the renewable energy resources, which can be converted into the useful energy. Wind turbine converts the kinetic energy of wind into mechanical shaft power. If the mechanical energy is directly used by devices such as pumps and grinding stones, it is known as a windmill rather than wind turbine. If wind energy is converted into electricity, the machine is called a wind generator or wind turbine [37].

Wind turbine work at their best when working under unrestricted wind access to wind speeds. Currently, the wind power industry is experiencing a rapid growth in the world. The electricity can be produced continuously in areas, of high wind velocities. At the peak demand load, when the PV system is not able to meet the load, the wind turbine can be used in hybrid mode to meet the peak load. A hybrid system consisting of wind turbines and photovoltaic panels with diesel/generator or battery bank as a backup power supply are employed for stand-alone applications, especially in remote areas far away from the grid network.

2.4.6.2 Wind Power Generation Technology

To measure the wind potential of a given site is considered a particular wind flow passing through a cylinder with across $\boldsymbol{A}$, given by the diameter of a rotor as shown on Figure 2.12.

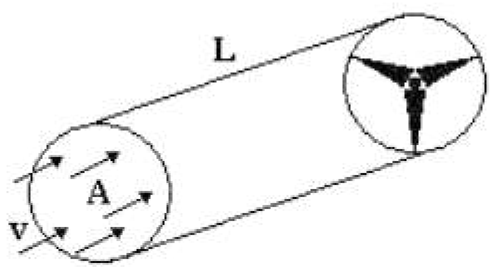


Figure 2. 5: Flow of wind through a cylinder/rotor of area (A) and length [38]

The formulas related to the above figure to calculate power density are the following:

$$\frac{P}{A} = \frac{1}{2}\rho V^3 \tag{2.1}$$

P/A: Power density [W/m^2]

The power density expressed in equation 3.8 is the power in the upstream of the wind turbine rotor.

The wind is considered as a vector defined by: the wind direction and wind speed. Wind direction is the direction from which the wind blows and is expressed in degrees. The wind speed is expressed in meters per second (m/s), kilometers per hour (km/h). According to the laws of physics, the rate of kinetic energy ***E***=***P*** of the air mass flow m with a speed **V** is calculated as:

$$P = \frac{1}{2} m V^2 = \frac{1}{2} (\rho A V) V^2 \tag{2.2}$$

Where m is the mass flow rate of the air, A is section area of a cylinder/rotor, ρ the air density (1.225 kg/m^3 at sea level) that depends on altitude and meteorological conditions - air pressure and temperature, both being functions of height above sea level.

Considering a wind turbine placed inside of the cylinder, and part of the wind power will be transferred and used by this wind turbine, then the power output 'P' extracted by the rotor will be

$$P = \frac{1}{2} c_P \rho A V^3 \tag{2.3}$$

C_p is a constant, dimensionless power coefficient or Betz limit, and is a measure of the efficiency of the wind turbine in extracting the kinetic energy content of a wind stream that may be converted into mechanical work; A is the rotor swept area [39]. It has a theoretical maximum value of 0.593, i.e. Np=16/27=0.593=59%.

Due to mechanical or transmission and generator losses, power generated by the electrical generator is less than the power extracted by the turbine blades. Mechanical power available for the load machine is obtained by multiplying with the efficiency of the drive train.

$$P_m = \frac{1}{2} \rho A V^3 C_p \eta_m \tag{2.4}$$

Electrical power of the wind turbine is expressed mathematically as:

$$P_{el} = \frac{1}{2} \rho A V^3 C_p \eta_m \eta_g \tag{2.5}$$

P_{el}: wind turbine electrical power [kW]

P_m: wind turbine mechanical power [kW]

η_m: The mechanical (gear box) [%]

η_g: Electrical generator efficiencies [%]

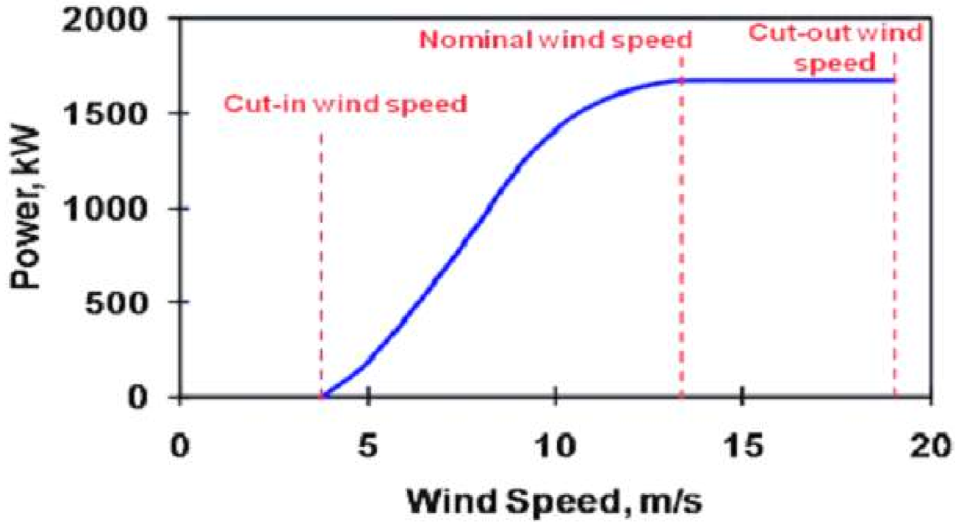


Figure 2. 6: Characteristic Curve of Typical Wind Turbine [40]

The above figure is the general characteristic curve of a wind turbine and that exhibits wind turbine power output variation with wind speed. Though, these characteristics curve of any wind turbine the following three parameters are to be considered in a special way:

- **Cut-in Wind Speed**: This is wind speed that Wind Turbines start to generate power and is between 3-5m/sec. Wind machines will not produce any more power below this wind speed.
- **Cut-off Wind Speed**: This is the highest wind speed at which wind turbine is not able to produce power. The cut off speed for most wind turbines is 25 m/s [41]. The cut-out point is more important; it denotes how fast the turbine can go before wind speeds get so fast that it risks damage from further operation.
- **Nominal or Rated Wind Speed:** This is the wind speed at which the maximum power is produced. This speed is the very important one because it determines the power curve. For most turbines the rated wind speed is between 11.5 to 15 m/sec; beyond this wind speed higher power generation is also possible but with special control to the power output in order of reducing rotor blade stress. Power curves having lower rated speed produce more energy because it will produce more energy between cut-in and rated wind speed [41],[42].

Other important parameters to be considered here are ***Survival Speed*** and ***Rotor swept area***, and these parameters are defined as follow:

- **Survival speed:** is when wind turbine machine will not be able to resist wind speed beyond the cut out wind speed, it is not actually part of the power curve but it is necessary to specify the design wind speed of the turbine. The range of survival speed is between 50 to 60 m/sec [41].

This theoretical power that is available in the wind could not be realized at all due to the decrease of kinetic energy of the wind which would not be dropped to zero level. The amount of energy from the wind that results in torque development of the turbine depends on the following three parameters [39][43].

- **Rotor swept area:** This is the area that is created when the turbine blades are rotating and is determined by length of the turbine blade, additionally it increases with the increase of blade length [44]. As rotor diameter gets higher the lager the power output of the turbine. The rotor swept area is expressed mathematically as follow:

$$A = \frac{\pi D^2}{4} \tag{2.6}$$

A: The rotor area [m^2]

D: The rotor diameter [m]

The vertical axis wind turbine rotor swept area can be approximated as is given in [43]

$$A = \frac{2}{3} W_r h_r \tag{2.7}$$

W_r: Rotor width [m]

h_r: Rotor height [m]

Air density: The heavier the air, more energy harnessed by the turbine. Density is mass per volume and kinetic energy is a function of the two air flow parameters. This is also affected by the variation of air temperature and pressure of the location.

$$\rho = \frac{P}{RT} \tag{2.8}$$

ρ: Air flow density [kg/m^3]

P: Air pressure [pascal]

R: Gas constant [287 J/kg°k]

T: Absolute temperature of air [^{0}k]

But the air temperature as well as humidity of air is not controllable factors at all. The air density magnitude at sea level is 1.25kg/m^3. Having this value as a reference, air density is modified for site specific and of course the pressure and temperature varies with altitude. So the combined effect of these parameters is expressed by the following formula; and applicable up to 6000m of elevation above sea level.

$$\rho = \rho_0 - 1.194 * 10^{-4} H_m \tag{2.9}$$

With:

H_m: Site elevation [m]

ρ_o: Air density at sea level [kg/m^3]

Another important point to be considered is Wind Speed Variation with Height above Ground; with Table 3.8 it can be realized that the speed of wind is proportional to the height above the ground. The height's effect on the wind speed is mostly depends on the roughness of surface of the earth. This cited effect is defined by equation 2.17 [45].

$$v(h) = v(h_1) \frac{ln(\frac{h}{z})}{ln(\frac{h_1}{z})} \tag{2.10}$$

h_1: Anemometer height

h: The height of the wind speed to be calculated *z*: Surface roughness

v(h): The wind speed to be calculated

$v(h_1)$*:* The wind speed at the anemometer height

2.4.7 Geothermal

Geothermal energy is defined as a clean and consistent source of energy and it is not affected by short-term variations of weather or the prices of oil. Once this energy is producing, it has a very low maintenance costs and high availability. Geothermal energy is independent on weather, day or night as it is the case for solar or wind energies.

Currently there is no electricity generation from geothermal in Rwanda despite that some areas as shown on Figure 2.7 were investigated on Rwanda geothermal resources which started in 2006 with a view of diversifying energy sources for electricity generation and meet the electricity demand in the country. Surface exploration studies to prove the resource have been carried out in several phases. In 1983, the French Bureau of Geology and Mines (BRGM) identified Gisenyi and Bugarama as potential sites for geothermal energy with estimated reservoir temperatures of over 100°C [15].

In 2006, Chevron carried out geochemistry studies in Bugarama and Gisenyi geothermal prospects and estimated the geothermal reservoir temperatures to be more than 150°C.

In 2008, the Germany Institute for Geosciences and Natural Resources (BGR), in collaboration with the Kenya Electricity Generating Company (KenGen), the Icelandic Geo Survey (ISOR) and the Spanish Institute for Technology and Renewable Energies (ITER) carried out surface studies in the Gisenyi, Karisimbi and Kinigi areas. The results from this study concluded that a high temperature geothermal system (>200°C) may exist on the southern slopes of Karisimbi volcano and that a medium temperature geothermal system may exist around Lake Karago (150-200°C) [19].

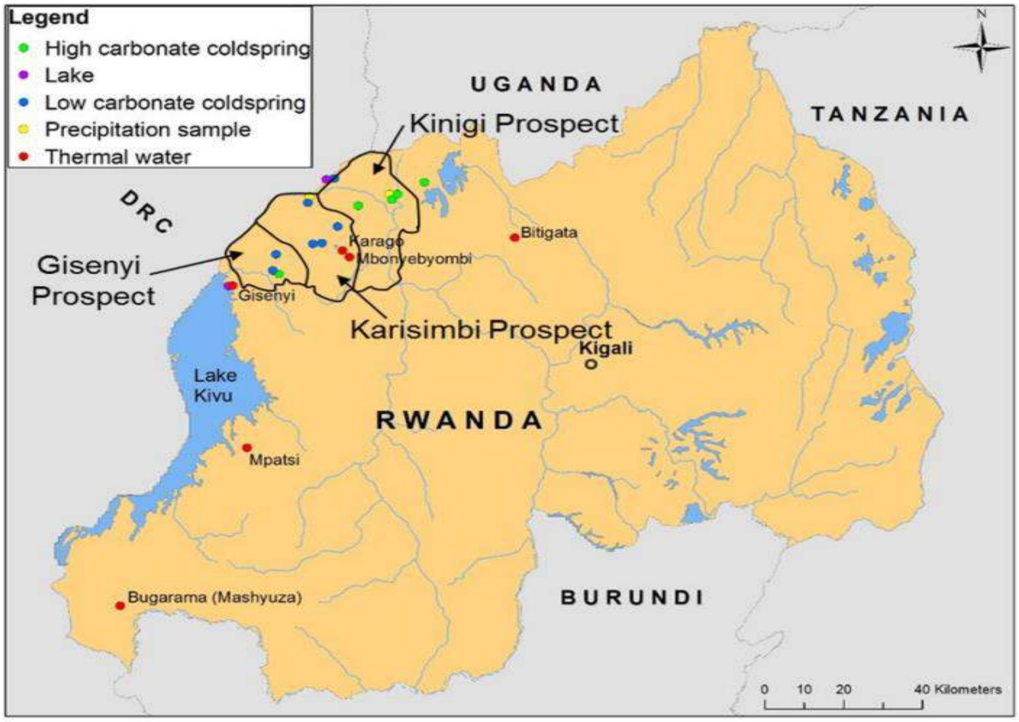


Figure 2. 7: Geothermal Resources Prospect in Rwanda **[19]**

2.5 Current Electrification in Rwanda

Total installed electricity generation capacity is currently 160 MW, of which almost 60% comes from hydrological resources and less than 40% from diesel-powered generators and other sources [1]; as it was in September 2015 it was estimated that 23% of the whole population has access to electricity supplies mostly concentrated in towns. Rwanda has a very pronounced peak demand load and hence supply is occasionally unable to match demand in these peak hours. The cost of electricity is currently not cost reflective and heavily subsidized. The diesel fuel and heavy fuel oil required to run petroleum-based power plants represents a large share of the total national import load, and is one factor driving the high cost of electricity and currency depreciation.

The following is current retail tariff (excluding VAT) as announced by RURA in September 2015 [21]:

- Industries: 0.12 USD/kWh: Off peak hours (23 h00 - 07h00)

  0.15 USD/ kWh: Mid peak hours (07 h00 - 17h00)

  0.2 USD/ kWh: On peak hours (17 h00 - 23h00)

- Residential consumption: 0.22 USD/ kWh

Electricity access in Rwanda has been exponentially increasing as shown on Figure 2.6 with number of households connected from 2008 to 2013 even if it is still low. In September 2015, it was estimated that 23% of the whole population has access to electricity supplies. Despite this lack of access to electricity, the high retail tariff for electricity is an obstacle to the growth of electricity demand in the country, but to this problem the government plans to increase the generation where it will even import electricity from neighboring countries such as 30 MW from Kenya and 20 MW from Ethiopia [15].

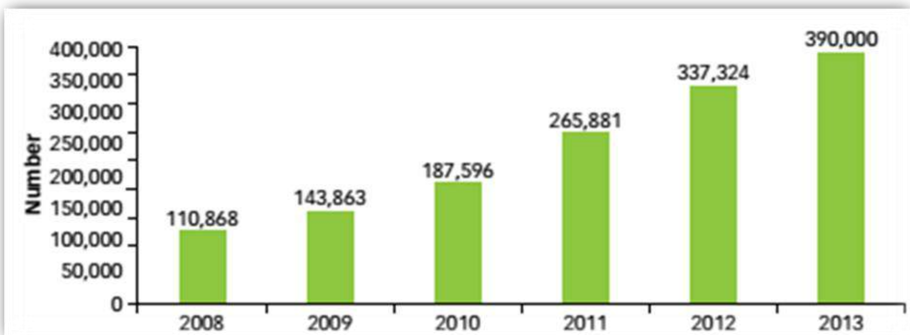


Figure 2. 8: Electrification in Rwanda 2008-2013 **[4]**

The government's target is to raise installed capacity up to 596 MW by 2018 and the priority is for studying the feasibility of using different generation sources. This has advantages of increasing the economy to the country but also improving the lifestyle of the population. The Government supports programs for ensuring that 100% of households get access to electricity through grid and off-grid solutions by end of 2017. This will be achieved through:

i. **Grid Connections:** Government plan to connect 48% of households to national grid, by expanding the network of electricity where possible across the country. Even if expansion of grid is expensive due to many hills in the country, the national grid will be extended across the possible part of the country and by connecting commercial consumers will raise the economy of the country.

ii. **Off-grid installations:** Households that located in far distance from national grid far and those ones getting insufficient electricity will be advised to use off-grid solutions such as solar PV solutions and mini grids. To this aspect, the proposed plan is that once 100% of electrification is reachable 52% of households electricity might come from Off-grid. This technology will be focusing on rural electrification [16]. Figure 2.7 shows the increment of electricity generation from 2009 and how it is expected to be in 2017[22].

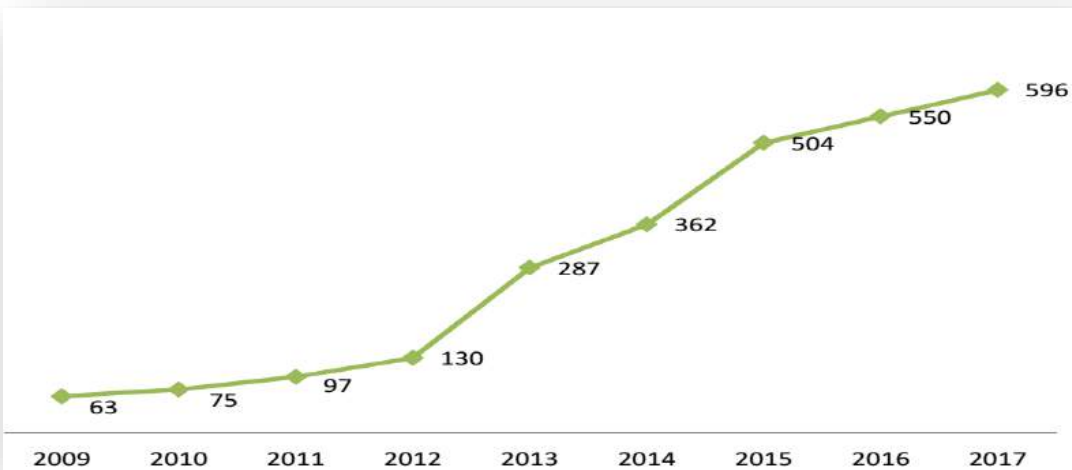


Figure 2. 9: Electricity capacity demand forecasts for 2009-2017, in MW [16]

In Rwanda, electrical power is transported at high voltage at 110 kV and the transmission lines are covering a total distance of 412 km to reach the various distribution substations. Rwanda high voltage system is made up of fifteen 110 kV major buses, five for generation and ten for loads to serve the entire national supply [23].

2.6 Renewable Energy Feed-in Tariff in Rwanda

Table 2.2 shows a feed-in tariff applicable to the hydro power plants published by RURA on 9th February, 2012. This regulation is applied to any person intending to construct and operate any hydro power plant that produces a minimum of 50Kw up to 10MW but this does not apply to those off-grid power developers. The regulation also applies to projects located 10km away from the grid therefore; in this case the transmission operators distant 10km to the grid negotiate for discounts.

Table 2. 2: Hydro Power Plant FITs in Rwanda **[25]**

Hydro	∈/Kwh	CAD/Kwh	USD/Kwh
50 KW	0.131	0.169	0.166
100 KW	0.127	0.164	0.161
150 KW	0.120	0.155	0.152
200 KW	0.113	0.146	0.143
250 KW	0.107	0.137	0.135
500 KW	0.102	0.131	0.129
750 KW	0.097	0.125	0.123
1 MW	0.093	0.120	0.118
2 MW	0.075	0.097	0.095
3 MW	0.069	0.089	0.087
4 MW	0.062	0.080	0.079
5 MW	0.057	0.073	0.072
6 MW	0.056	0.072	0.071
7 MW	0.055	0.071	0.070
8 MW	0.054	0.070	0.069
9 MW	0.054	0.069	0.068
10 MW	0.053	0.068	0.067

The feed-in tariff range from USD cent 16.6/KW for a plant of installed capacity of 50Kw to USD cent 6.7/KWh for a plant installed capacity of 10 MW. The tariffs for other sources of energy are fixed through negotiation process. In order to maintain a regional competitive tariff, Government plans to remove the subsidies to the tariff by 2016 [24].

The Rwanda Utility and Regulatory Authority reserves the right to review these REFITs in the second year anniversary of these Regulations, provided that only upward revisions and adjustments would be considered and shall be applicable to the projects falling under the scope of application of these regulations.

2.7 Solar Photovoltaic System

2.7.1 Introduction

The sun's energy is the source of life on the planet. It reaches the Earth in the form of radiation. It provides heat which can be collected and can be converted into electricity. Energy emitted by the sun is in form of electromagnetic radiation and after reaching the earth surface it is converted to other types of energy sources and used for many purposes.

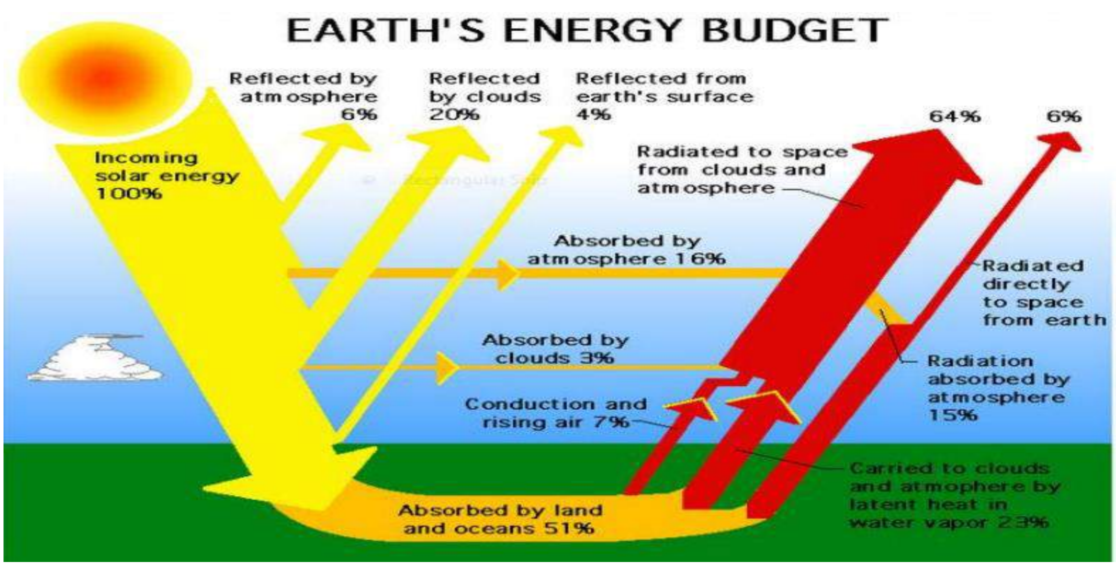


Figure 2. 10: Schematic of Earth's energy budget [27]

Most of the energy the sun emits does not reach the earth. When measured at the top of the earth's atmosphere, the average solar irradiance is 1368W/m^2[27].The incident solar energy (shortwave) may be reflected and absorbed by the Earth's surface or the atmosphere and Earth's surface and atmosphere also emit the radiation (long wave) as it is shown on Figure 2.8.

2.7.2 Types and operation of Solar PV Cells

PV cells are made in different materials such as: Silicon (Si), Germanium (Ge), Indium Phosphide (InP), Gallium Arsenide (GaAs), Cadmium telluride (CdTe), etc. but we limit on Silicon PV due to its availability; high efficiency and commercial applications. But another reason also is that some of these materials like InP, GaAs are not abundant in the earth [28].

SC is a junction of two types of materials, i.e. the n and p types of semiconductor materials; when these are linked together, free electrons in the n-type material move to the p-type material and also free holes from p-type material move to n-type material resembling the flow of electric charges, creating the so-called diffusion current[29]

When the charge carriers (electrons and holes) move from one side to another, they leave behind both donor and acceptor ions on their previous material. Those left ions create spatial charges and, consequently there is an electric potential given by the following expression:

$$V = \frac{KT}{q} ln \frac{n_n}{n_p} \tag{2.11}$$

n_n is the electron concentration and n_p is the holes concentration, K- Boltzmann constant ($1.38*10^{-23} J/K$), q- Electron charges ($1.6*10^{-19} c$) and T is the absolute temperature given in [^{0}K]. And electric field is the gradient of electric potential; so it yields to the following expression [30].

$$E = \frac{KT}{q} \frac{1}{n} \nabla n \tag{2.12}$$

E is the Electric field given by Newton / Coulomb

The electric field due to the existence of spatial charges on a p-n junction, leads into the drift current “diffusion force” on holes with opposite direction to the diffusion current (“diffusion force” on electrons).

2.7.3 Equivalent Electrical Circuit of PV Cell

Simplified diagram of an equivalent circuit of an ideal Silicon Cell is presented in the Figure 2.9 in which is taken into account that there is no voltage and current drop [31]

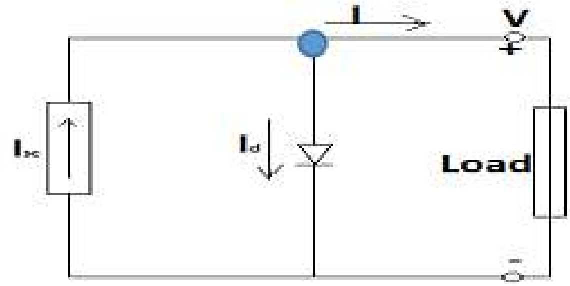


Figure 2. 11: Equivalent Circuit of Silicon Cell [31]

By applying the Kirchhoff's law to the blue node of the equivalent SC in the Figure 3.2, the short-circuit current is given by:

$$I_{SC} = I + I_0 \left(e \left(\frac{q^v d}{mkT} \right) - 1 \right) \quad (2.13)$$

Where I_0 is the diode reverse saturation current; V_d is the voltage across the junction; m is the diode ideality factor. The current flowing across the diode I_d in figure 3.2, then by calculating the open circuit voltage V_{oc} will help to get the output power.

$$V_{OC} = \frac{mkT}{q} ln \left(\frac{I_{SC}}{I_0} + 1 \right) \quad (2.14)$$

The open circuit voltage Vos and short circuit current Iss are parameters given by the manufacturer and are very important to draw the I-V curve, given in Figure 2.10, which is used to predict the SC's performance at various temperatures, voltage loads and level of insolation [32].

2.7.4 Electrical characteristics of PV cells

As it is shown in Figure 2.10; the power produced by the cell is given by the equation P = IV and if connecting in shunt a diode and the current source, this allow to find a perfect solar cell. The cell generates the maximum power at a voltage V_{MPP} and current I_{MPP} and it is also convenient to define the characteristic called "fill factor"FF.

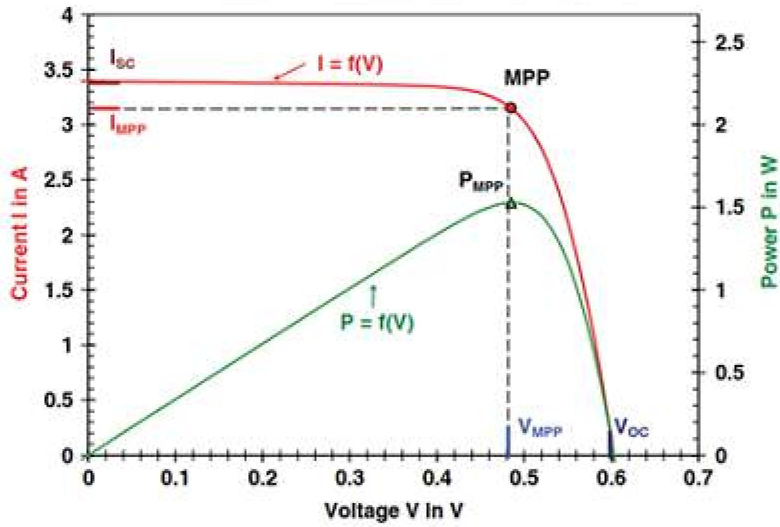


Figure2. 12: I-V and P-V curves of a solar cell [30]

The main important point to be observed in the above figure is M_{PP} (maximal power point) and it is defined as the point in which the module produces the greatest power, it is always found where the curve begins to bend and this allow to define the outputs of the module which are V_{MPP} – Voltage at maximum power point and I_{MPP} – Current at maximum power point. Then the output power at any other point is less than the power at maximum power point (P_{MPP}) [30].

However, there is another parameter that describes the deviation of the I-V curve in relation to the ideal, called the Fill Factor (FF). The fill factor is the ratio of the maximum obtainable power to the product of the open-circuit voltage; short-circuit current and is given by:

$$FF = \frac{I_{MPP}.V_{MPP}}{I_{SC}.V_{OC}} \qquad (2.15)$$

The conversion efficiency (η) of SC is the power density delivered at the operating point as a fraction of the incident light power density Ps and is given by the equation [31]:

$$\eta = \frac{FF.I_{MPP}.V_{MPP}}{P_S} \qquad (2.16)$$

2.7.5 Factors that Influence the Operation of a Solar Module

There are four major factors that can affect the solar cell performance namely:

i. The cell material: depending on the material and manufacturing method used, solar cells can achieve different conversion efficiencies of light, for instance the efficiency of amorphous silicon ranges from 5% to 7%, for the polycrystalline silicon, its efficiency does not exceed 12% and for the mono crystalline silicon the efficiency is over 12% and not exceeding 18% [33].

ii. The radiation intensity on module output: the current output is proportional to the radiation intensity, increasing the light intensity, the current also increases but the voltage does not change significantly at I-V curve above [31].

iii. The heat on module output: The output voltage of the module is affected by increasing the temperature of the module. At increasing temperature the voltage decreases considerably, however, the current does not change significantly. According to[31], the variation of temperature during the operation of a solar module may be explained by the equation below:

$$T_c - T_a = (NOCT - 20)\frac{G}{800} \quad (2.17)$$

G is the solar irradiance [W/m^2], T_c and $T_a$are the cell and ambient temperatures respectively, 'NOCT' is the Normal Operating Cell Temperature, its value is usually given by the manufacturer, and ranges between 44–54^{0}C for a conventional module, under the following conditions at open circuit: G_{NOCT}=800W/m^2 of solar irradiance, Ta =20^{0}C, air mass of 1.5 and Wind speed is 1 m/s.

iv. The shading effect on module output: If a module or part of module (cell) is shaded, may partially produce or even not produce electricity, and if it happens can also cause hot spots heating. However, this fact can be mitigated installing bypass diodes[34]

2.7.6 Solar Energy Potential in Rwanda

The solar data entered into HOMER software is the average horizontal radiation and the average monthly solar radiation data displayed in below table 2.3; so to get the amount of power generated by the solar PV it is important to record solar resources data in units of kW/m^2.

Table 2. 3: The average of monthly daily irradiance incident on a horizontal surface in Kayonza

Month	**Clearness Index**	**Daily Radiation (kWh/m2/d)**
January	0.557	5.52
February	0.569	5.23
March	0.525	4.74
April	0.515	4.55
May	0.542	4.84
June	0.516	4.72
July	0.49	5.22
August	0.483	5.69
September	0.507	5.9
October	0.464	5.1
November	0.477	4.98
December	0.51	5.12
Average	**0.513**	**5.133**

The solar resource information used for the selected village was found from the NASA Surface Meteorology [35], these might also be accessed through RET Screen International, HOMER itself and compare to some found from meteorology-Rwanda for past years (2012 & 2013) [13].

The obtained information is annum solar radiation that was found of an average of 5.13 KWh/m^2/day and average of the clearness index was found as 0.513.

The above monthly averages of the daily radiation in Rwanda are presented by Figure 2.11. The clearness is defined as a measure of the fraction of the solar radiation that is transmitted through the atmosphere to the earth's surface [36].

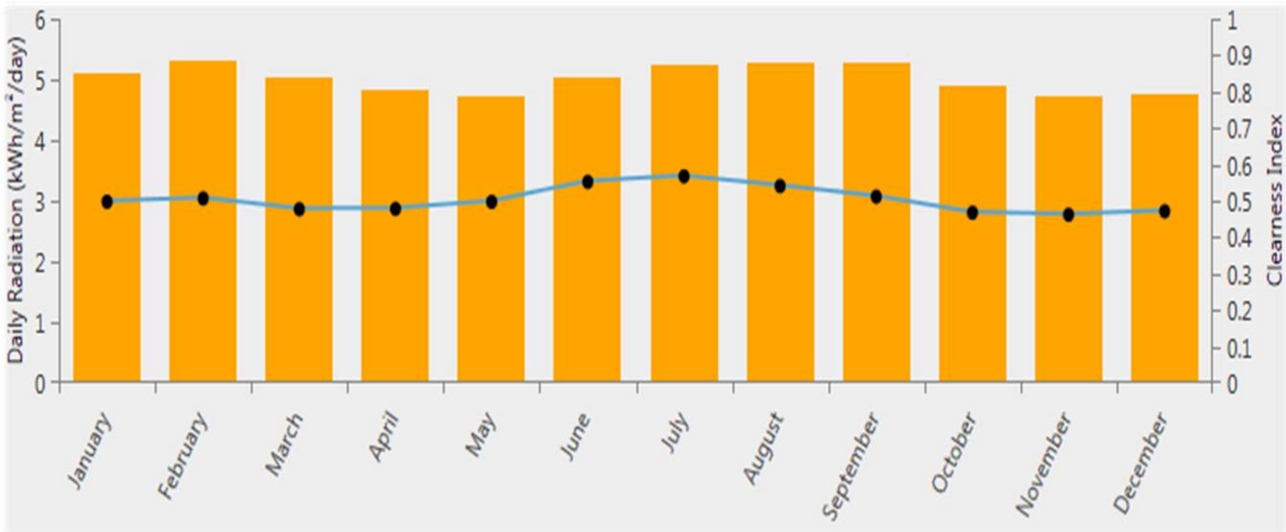


Figure 2. 13: Daily Radiation and Clearness in Kayonza District in Kwh/m^2

2.8. Wind Energy Potential in Rwanda

The wind speed data used in this paper is a two years and recent data, which was measured in 2012 and 2013[13]. These data were recorded over 24 hours for the whole two years through cup anemometer. They were obtained at 40 meters; 30 meters; and 10 meters of height wind mast; the data considered in this study are for the 40 meter height. The following are the data taken for 6 wind sites in Rwanda and leads us to choose Eastern Rwanda- Kayonza District to be good location of our Hybrid system as it is where we found strong wind and as well as good insolation.

Table 2. 4: Average Monthly Wind Speed at Mast 1: NGOMA (South East) [14]

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Aver
Wind speeds m/s	3.3	3.5	3.2	3.2	3.5	4	4.1	4.5	3.9	3.8	3.6	3.1	3.6
Air density kg/kg^3	0.997	0.997	0.998	0.999	0.998	0.998	0.997	0.993	0.997	0.997	0.998	1.001	0.998

Table 2. 5: Average Monthly Wind Speed at Mast 2: KAYONZA (East)

Months	Jan	Feb	Marc	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Aver
Wind speeds m/s	3.5	4	3.7	4.3	4.8	5.3	5.3	5.1	4.4	3.9	3.7	3.2	4.2
Air density kg/kg^3	0.962	0.953	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.99	0.996	0.964

Table 2. 6: Average Monthly Wind Speed at Antenna 1 MTN at 40m: North at Bicumbi

Months	Jan	Feb	Marc	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Aver
Wind speeds m/s	3.3	3.1	3.1	3.7	3.6	3.8	4.0	4.2	3.5	3.2	3.4	3.3	3.5
Air density kg/kg^3	0.912	0.912	0.914	0.915	0.917	0.919	0.918	0.914	0.915	0.913	0.913	0.915	0.915

Table2. 7: Average Monthly Wind Speed at Antenna 2 MTN at 54m: West at Nyabihu

Months	Jan	Feb	Marc	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Aver
Wind speeds m/s	2.2	2.2	2.2	2.3	2.3	2.4	2.8	3.3	2.6	2.4	2.3	2.1	2.4
Air density kg/kg^3	0.961	0.96	0.962	0.963	0.963	0.965	0.964	0.959	0.963	0.961	0.963	0.963	0.962

Table2. 8: Average Monthly Wind Speed at Antenna 3 MTN at 35m: South Nyamagabe

Months	Jan	Feb	Marc	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Aver
Wind speeds m/s	3.1	2.9	2.8	3.2	3.3	3.7	3.9	4.3	3.8	3.5	3.1	3	3.4
Air density kg/kg^3	0.966	0.966	0.968	0.967	0.968	0.97	0.969	0.964	0.967	0.965	0.968	0.969	0.967

Table2. 9: Average Monthly Wind Speed at Deutsche-Welle Mast at 60m at Kigali

Months	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Aver
Wind speeds m/s	2.4	2.3	2.1	2.1	2.0	2.1	2.2	2.5	2.5	2.4	2.2	2.0	2.3
Air density kg/kg^3	1.015	1.014	1.018	1.017	1.018	1.018	1.018	1.013	1.017	1.016	1.019	1.02	1.017

Table 2. 10: Summary of average annual wind speed in Rwanda

Sites	Height (m)	Average speed (m/s)
Mast 1	40	3.6
Mast 2	40	4.2
Antenna 1 MTN	40	3.5
Antenna 2 MTN	54	2.4
Antenna 3 MTN	35	3.4

According to Table 3.8, the strongest wind in Rwanda is found at Mast 2 which is in eastern Rwanda- Kayonza District and is characterized by more frequent wind speed than other areas. This contrast is related to the thermal effect and the low roughness of the water surface in the area where is relatively stable throughout the year with higher intensity between the months of September to November.

2.9. Identified solutions for rural electrification

Some factors and decisions have to be considered during the selection of rural electrification technologies, this is in order to get an appropriate system and technology to avoid the failure of a rural electrification project.

Once the area to be electrified has already been chosen, the first thing to do is to decide which technology is most appropriate based on availability of energy potential and a pre-feasibility study from the area according to the local grid conditions whether existing or not.

The technological choice should take into consideration information on potential customers and their expected load, the projected demand, productive potential, ability and willingness to pay among the various sectors, their requirement of reliability of supply, information on distance to existing grid and availability of local energy resources.

For these areas that are far from the grid connection or are not planned to be covered by the national grid in the next 5 years, off-grid solutions that includes both isolated distribution grids (mini-grids) with central power generation and individual stand-alone systems are more preferred. The most identified challenges in off-grid systems are the local operation and maintenance arrangements as well as the local marketing for the appliances.

2.9.1 Isolated grid solution

The production technology will depend on available local resources (small hydropower, diesel generator, hybrid diesel-renewable, or other renewable technologies). The final choice of technology must be based on the recipient country's overall strategic priorities, where the customer base is relatively strong and a feasible local energy resource is available, an isolated grid network with local power generation should be considered taking into consideration that in the isolated grid is not connected to national transmission grid.

2.9.2 Stand-alone solution

Rwanda has so far implemented stand-alone systems based on solar PV in rural areas and it is found as a good initiative for energy supply. Stand-alone systems are power supply systems that only cover the needs of one single user such as household, farm, etc. where the customers are living dispersed and little or no productive use of electricity, stand-alone systems should be considered. Solar PV systems are often considered the most feasible alternative. However, the electricity from PV systems is normally limited to household lighting and other simple applications, and it is not sufficient for productive uses requiring high power or much energy.

Other technologies such as small-scale wind power may be relevant. Where water resources are available Pico/micro hydropower and solar pumping systems should be considered for small communities.

2.9.3 Combined solution

Hybrid systems are another approach towards decentralized electrification, basically by combining the technologies presented above. They can be designed as stand-alone mini-grids or in smaller scale as household systems [24].

2.10. PV- Wind Hybrid Power System

Hybrid energy system is defined as a combination of two or more renewable and even non-renewable energy as main sources of energy generation so that the capacity shortage of power from one source will substitute by other available sources to supply sustainable power. It is appropriate means to provide electricity from locally available energy sources for areas where grid extension is capital demanding, geographically isolated places for which electricity transmission from centralized utility is difficult as case of Rwanda. Naturally gifted renewable sources can be connected to generate electricity in a sustainable way to provide power and make comfortable the living standard of people. There are different advantages and disadvantages of using only renewable sources for electricity generation in rural villages, among advantages we may state like fuel cost, fuel transport cost is high, issues of global warming and climate change. The disadvantages of using renewable sources as off-grid/standalone power systems is that, it makes difficult to regulate the power output to manage with the load required. To make sure for the reliability and affordability of the supply, combining conventional diesel generator with non-conventional energy generators can solve the problem visible while operating individually [43].

Hybrid standalone systems have power control flexibility, and are friendly to environment than diesel generator alone. Hybrid systems can expand its capacity when load demand is getting higher in the future, from renewable systems, diesel generator rated power or both of them. Some of the components produce DC power and others AC power directly with no use of converter. Figure 2.14 below describes the PV-Wind hybrid power system components as it is our considered case study with limitation on solar and wind resources.

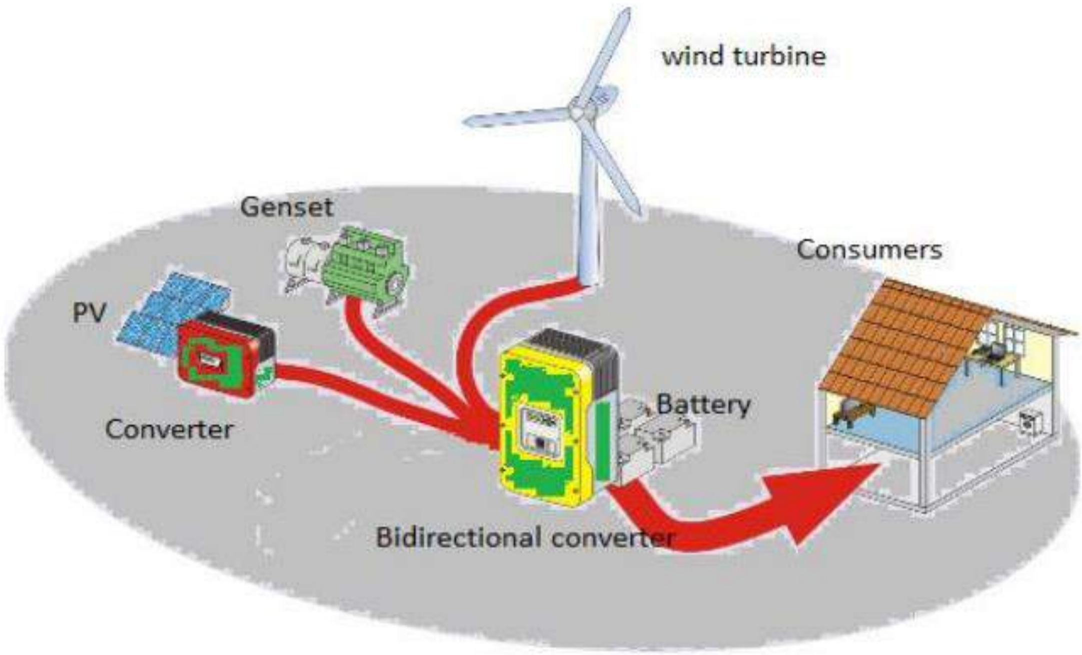


Figure 2.14: Working Principle of PV-Wind Hybrid system [43]

2.10.1 Classification of Hybrid Configuration

According to the type of voltage and the type of bus that will link the different components together, hybrid systems can be classified as follows [46]:

- DC coupled Hybrid system
- DC/AC coupled hybrid system
- AC coupled hybrid system

2.10.1.1 DC coupled hybrid system

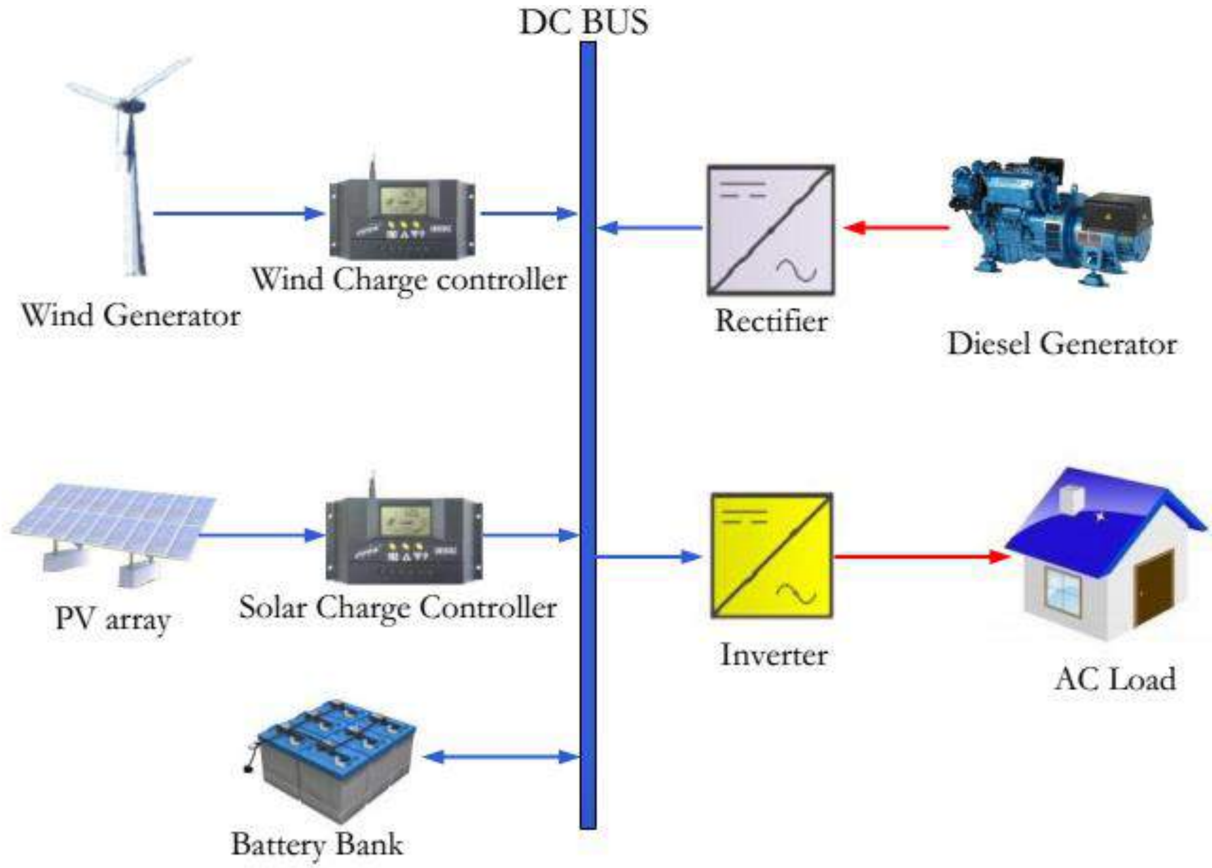


Figure 2.15: DC Coupled Hybrid System

Figure 2.15 demonstrates a DC coupled hybrid system. All components used to generate electricity in this model are connected on DC bus. Therefore, DC generating systems and AC generating systems with rectifiers is all equipped with charging controllers. In this DC coupled hybrid system, the power generated by the diesel generator is AC and is converted back after being rectified; this reduces the efficiency of energy conversion cause of several power processing phases. In addition to that the inverter cannot be operated in parallel with the diesel generator. So, the inverter must be sized in a way it supplies the peak demand. The failure of an inverter causes the interruption of power, except if the load can be supplied straight from the diesel generator in case of emergency conditions [46][47].

2.10.1.2 DC/AC coupled hybrid system

The generating components in DC/AC coupled system can be connected to DC or AC bus depending on the voltage generated. To link both DC and AC buses the system uses a bidirectional inverter that can be operated parallel with the diesel generator, hence inverter may not be sized to meet the peak demand. The operation of inverter in parallel with the diesel generator allows the generator to operate with optimization in the system and also the efficiency of the generator can be maximized.

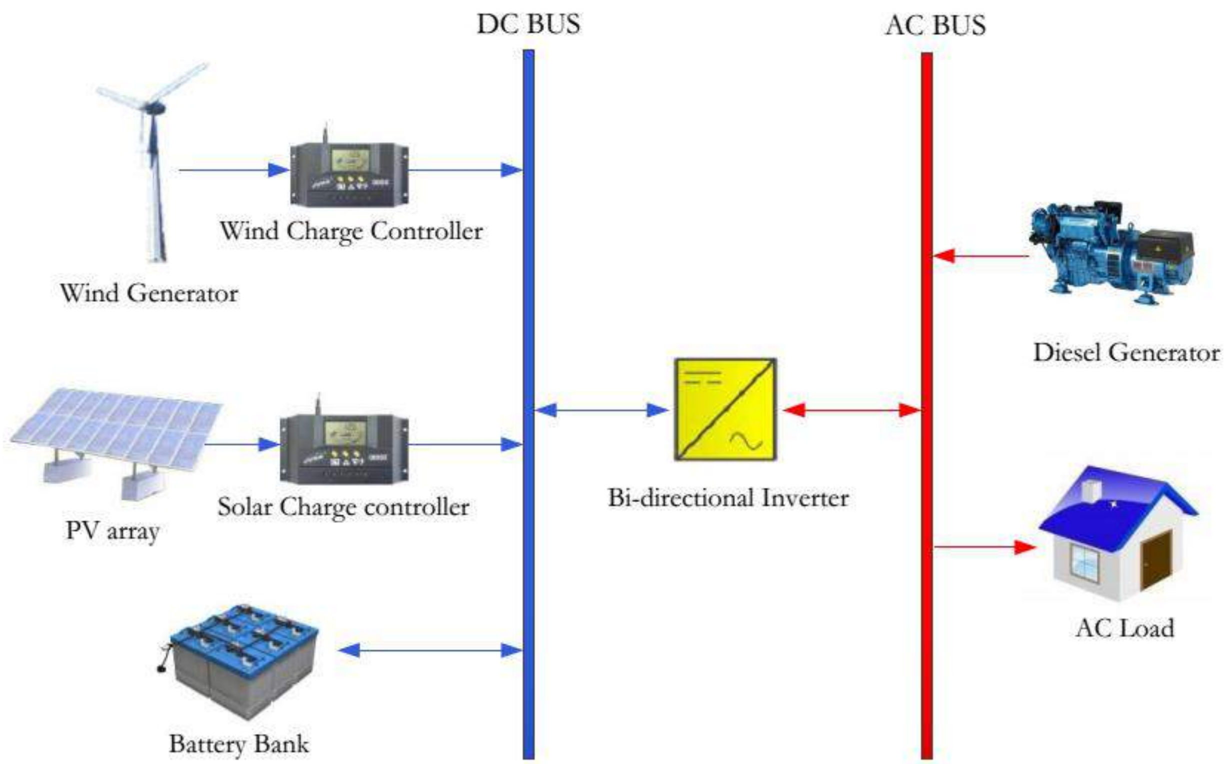


Figure 2.16: DC/AC coupled hybrid system

2.10.1.3 AC Coupled Hybrid System

In this system, all generating components of the system are connected to AC bus. Using the inverters, DC generating systems are connected to AC bus while AC generating components can be directly connected to the AC bus or sometime they may require an AC/AC converter to enable stable coupling. In this type of system, bidirectional inverter has an importance of controlling the energy supply for the battery bank. AC coupled systems are easily expandable and it provides the benefits thatdiscussed in DC/AC coupling hybrid system. Another advantage for this system, once the grid extends to the remote area in the future it is easy to connect the grid[46].

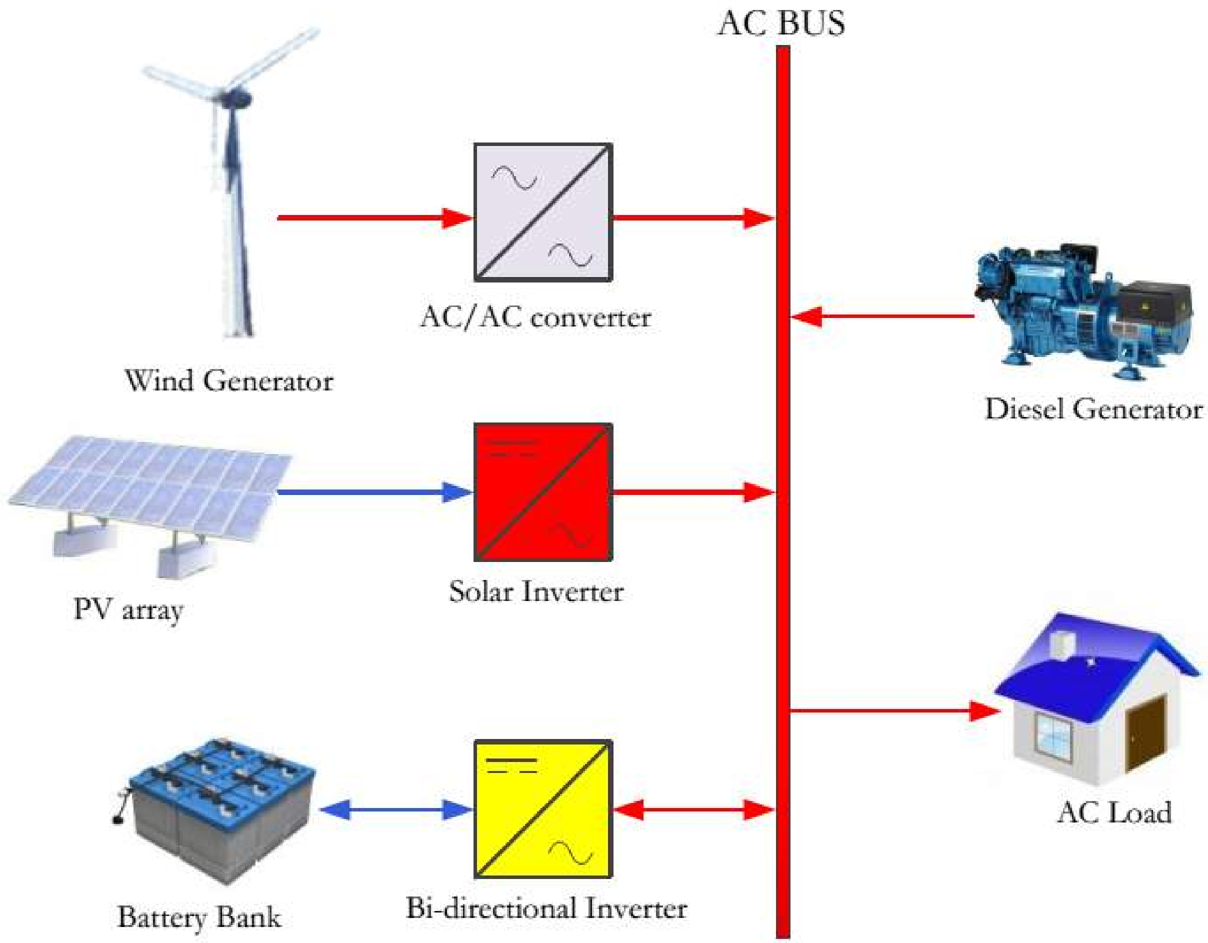


Figure 2. 17: AC coupled hybrid system

AC-DC configuration has been used in our study due to its advantage of presenting superior performance over the other configurations. Within this structure, a portion of the load demand is directly supplied by the renewable energy sources and the diesel generator, this resulting in higher general system efficiency. Both diesel generator and the inverter can either operate in standalone or parallel mode. So if the load is low, either the diesel generator or the battery can supply. However, during the peak hours both sources are operated in parallel mode. Due to this parallel operation the initial capacity of diesel generator and inverter can be reduced. In this configuration a controller is used to manage the operation of the system, selecting the most appropriate mode of operation to supply a certain load without power interruption [48]

2.10.2 Auxiliary Components of the Hybrid System

2.10.2.1. Diesel Generator

Diesel generators are very significant in the hybrid systems. This is for improving the quality and the readiness of the electricity supply. The diesel generators are mostly used as backup in Renewable systems. They intervene if extra load is needed, or in a case there is black-out and battery bank is not enough to feed the load.

Generally, initial capital for using a diesel generator is small comparatively to the initial investment for renewable resources solar or wind systems. The challenges come on maintenance and operating cost of diesel generator which is very high because it requires supplying the fuel continuously, regular maintenance and inspection of the engine during its operating life and all of these increase the cost.

In Rwanda and as it is mostly, the cost of available diesel generators is primarily dependent on the size of the generator and the kind 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. Therefore the cost of diesel generators does not vary linearly with the capacity of its output power.

To manage the good operation and to expand the operating life of the diesel generators it is necessary to follow all requirements of maintenance schedule [49].

2.10.2.2. Storage Battery

From the energy storage devices the selected and most common one used is lead-acid battery which is applicable for standalone systems due to its reasonable cost, maturity and high performance over cost ratio. It is available in different capacities like 6V, 12V and 24V terminal voltages. A battery life is affected with how much of their energy storage capacity is consumed at a time known as depth of discharge.

In unfavorable climatic conditions, the demand has to meet by the batteries, additionally if the battery is discharging deeper, the diesel generator provides the energy demand and at the same time charges the battery if the power controls mechanism could be cycle charging. Deep cycle batteries can discharge from 15-20% of their capacity, which means that it shows a discharge of 80-85%[50]. Some of the Factors that affect the sizing of battery system are the following:

- Daily energy demand
- Days of autonomy
- Maximum depth of discharge
- Temperature correction
- Rated battery capacity and battery life

To use part of the total stored energy of the battery it should be sized large enough and this is determined using the DOD. Energy generated from renewable energy conversion technologies has energy outages when there is no sun or wind blow, to avoid such shortfalls a battery bank should maintain days or hours of self-sufficiency. It is described mathematically by the following formulas [51][52].

Total capacity of the battery capable to supply the full load demand can be determined using the following mathematical expression:

$$C_B = \frac{E_L S_D}{V_B (DOD)_{max} T_{cf} \eta_B} \tag{3.18}$$

C_B: Capacity of battery [Ah]

E_L: The electrical load [Wh]

S_D: Battery autonomy [days]

V_B: Storage battery voltage [V]

$(DOD)_{max}$: Maximum depth of discharge of battery

T_{cf}: Temperature correction factor

η_B: efficiency of battery [%]

The state of charge of the battery depends on energy production by the solar photovoltaic, wind speed and the required load, therefore the state of charge can be determined using the equation below:

Battery charging state: During the charging, as the PV and wind generator output is larger than demand, the battery capacity at time t is given below in equation 3.19

$$SOC(t) = SOC\ (t-1)(1-\sigma) + \left[\frac{E_{L(t)}}{\eta_{inv}} - E_{gen}(t)\right] \tag{3.19}$$

$$E_{gen}(t) = E_{pv}(t) + E_{wg}(t) \tag{3.20}$$

SOC(t): State of battery capacity at hour (t) [Wh]

SOC(t-1): State of battery capacity at hour (t-1) [Wh]

σ: Battery hourly self-discharge rate. The manufacturer gives a self-discharge of 25% over six months for a storage temperature of 20°C [52][43]

EL(t): Load requirement at time (t)

η_{inv}: Inverter efficiency (in this paper assumed as constant, 90%)

η_B: Battery charging efficiency (during discharging the efficiency is equal to 100% and during charging is set from 65 to 85% depending on the charging current).

$E_{gen}(t)$: Total energy from wind and PV generated [kWh]

$E_{pv}(t)$: Energy generated from PV [kWh]

$E_{wg}(t)$: Energy generated from wind [kWh]

Battery charging:

$$S_O C(t) = S_O C(t-1) \times (1-\sigma) + \eta_B \left(E(t) - \frac{E_L(t)}{\eta_{inv}}\right) \tag{3.21}$$

Battery discharging:

$$S_O C(t) = S_O C(t-1) \times (1-\sigma) + \left(\frac{E_L(t)}{\eta_{inv}} - E(t)\right) \tag{3.22}$$

SOC(t): State of charge of the battery at time t

SOC(t-1): State of charge of the battery capacity at hour (t-1)

σ: Battery hourly discharge rate.

E_L (t): is the load demand at time (t)

E(t): is the total energy generated by the renewable systems

η_{inv}: Inverter efficiency

η_B: Battery charging efficiency

2.10.2.3. Inverter / converters

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

2.10.2.4. PV Controllers

The photovoltaic controller works as a voltage regulator. The primary function of a controller is to avoid the battery from being overcharged by a photovoltaic array system. A charge controller constantly monitors the battery's voltage. When the batteries are fully charged, the controller will stop or decrease the amount of current flowing from the photovoltaic array into the battery. The controllers average efficiencies range from 95% to 98%. For this thesis the efficiency that has been used for the analysis is 95% [30]. Charge controllers for PV system come in many sizes, typically from a few amps to as much as 80 amps. If high current are required, two or more controllers can be used.

When using more than one controller, it is necessary to divide the array into sub-arrays. Each sub-array will be wired into the same battery bank. There are five different types of PV controllers: shunt controller, single-stage series controllers, diversion controller, pulse width modulation (PWM) controller and the maximum power point tracking controllers (MPPT). In this thesis the one to be used are the MPPT controllers due to its additional 15-30% more power out of an array versus a PWM controller [30].

CHAPTER 3: METHODOLOGY

3.1 Introduction

The research involves collecting local data as well as visiting some governmental institutions. The institutions visited are: Ministry of Infrastructure, Meteorology-Rwanda and also the national utility Rwanda Energy Group (REG Ltd) and this is known as primary data or first-hand data while the secondary data collection includes information, which already exists and is not gathered by the researcher. Secondary data is often represented in the form of publications like articles, reports or literature.

The research method use to achieve our objectives is as follow:

- Collect Wind and Solar data from the different institutions.
- Determination of village load profile by End-Use Analysis as Load forecasting methods.
- Studying component characteristics and costs to get the input parameters to our tool HOMER for modeling and simulation of the hybrid system for the selected village.
- Determination of Levilized Cost of Energy (LCOE) and Net Present Cost (NPC) for the system.

It is important to determine the daily load profile by considering the different parameters that are available in the village. The parameters that were taken into consideration are: number of households and community utilities; family revenue and willingness to buy electrical appliances and possible small businesses that can start if electricity is accessible. This helped in estimation of needed load for the village.

3.2 Modeling Software: HOMER

The technical details and major components of the hybrid system have been discussed earlier in Chapter 2. As clarified in problem statement the main objective of this study is to investigate the feasibility of hybrid configuration considering solar and wind resources in Rwanda for a purpose of supplying the electricity in rural community where expansion of national grid extension is with higher cost. For this project, it is required to consider combinations of RES (solar and wind) and diesel generator with different component capacities. All of these simulations are achieved by the software called HOMER.

International Renewable Energy Project Analysis Software called Hybrid Optimization Model for Electric Renewables (HOMER) is most widely used and it has developed by The National Renewable Energy Laboratory (NREL) in 1993 for both on-grid and off-grid systems, is a freely available and user friendly software[53]. The software is suitable for carrying out quick prefeasibility; optimization and sensitivity analysis in several possible system configurations. HOMER tool requires several inputs which mainly describe costs and specifications of the components of the system; the technology options and resources available in the study area.

There are many software tools like HOMER, RETScreen, HySim, HySys, SOMES, SOLSTOR, HYBRIDS, RAPSIM, ARES, IPSYS and INSEL used for renewable energy study but two of them (HOMER and RETScreen) are generally tools used than others due to their analysis capabilities of hybrid system over others. Amongst the above cited software tools, HOMER is found to be most widely used tool as it has maximum combination of renewable energy systems and performs optimization and sensitivity analysis which makes it easier and faster to evaluate many possible system configurations[54].

HOMER also helps with calculation of the NPV of installation and operating cost of the project during its lifetime and the total cost of energy based on the Levelized cost of energy [55]. After simulation, the best hybrid system to be chosen among the simulated results is the one with the least LCOE or the smallest total NPV of the whole.

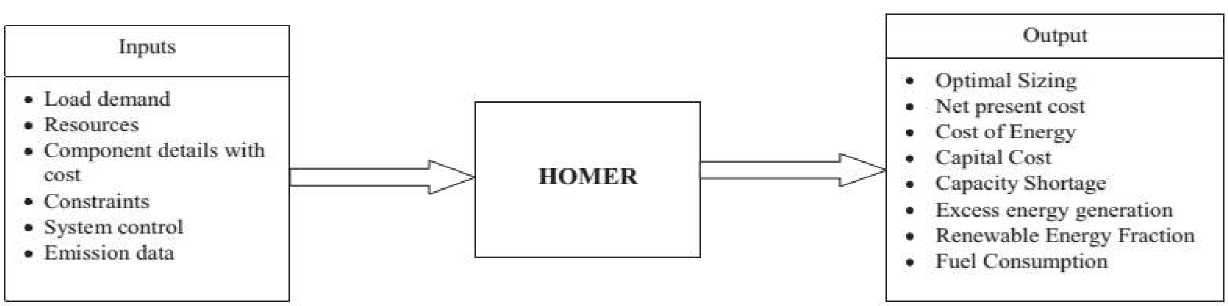


Figure 3. 1: Schematic Representation of HOMER

3.3 Village Load Estimation

The next step, after identifying that the potential area of wind and solar energy is in Eastern province we need to calculate the demanded electric load by estimating the population in the area. Rwanda is among the countries with highest population density so the electric load considered at this point is to satisfy the demand of 200 households which comprise a maximum of 1000 people in the selected site. A hypothetical model of rural village which contains 200 households has the following institution in addition to house electric appliance which demands a supply of electric load: One school (primary and secondary school) which has 1-8 grades, 7 mini-shops including 2 barbers, 1 Health post with 4 rooms, 1 milling house and 1 Government building which is used for office).

In addition to the total energy demand by the expected population, the peak hours have been estimated based on the experience of the people living style, when those electric appliances work most of the time in a day period. This is done by classifying the electric load in the division namely primary and deferrable loads. The primary load is the electric load that must be met at a specific time (example of lighting) and the deferrable load is the load that not need to be met within a specified time but should be met within a certain period (example of water pumping).

Therefore, the first step in determining the household appliance load by deciding where equipment are mostly used in a moderate family considering the current and near future economic development of the nation where the electric energy system is designing. Many households in rural Rwanda live below poverty line and no need of luxury appliances. But the current design of energy system considers a hypothetical model house which needs basic appliances for the better life.

The formula which can be used to estimate an appliance’s energy use:

- *(Wattage * Hours Used per day)/1000 = Daily Kilowatt-hour (KWh).*
- *Annual Energy Consumption by each appliance’s = (Daily KWh * Number of days that the appliance used)*; where [1 kilowatt (KW) = 1,000 watts].

3.3.1 Estimation of Primary Load

3.3.1.1 Domestic Load

In an individual household the electricity demand is proposed to apply for low energy compact fluorescent lamps (CFL), radio or cassette recorder and for TV. The peak load demands in the households normally happen in the weekends and holidays because TV and radio can be turned on for an extended period of time. During this time television would function for 14 hours from 8:00-22:00 and radio will be enjoyed for 6 hours from 6:00-12:00. The electricity load demand estimated for a single household for weekdays only is calculated as follows and is summarized in Table 3.1

Table 3. 1: Electric Appliances for single household and the running time

Appliances	AC/DC Watts	Number of equipment	Run time (hrs/day)	W-hr/day
Light bulb	20	5	6	600
Television	110	1	8	880
DVD Player	25	1	4	100
Radio	30	1	4	120
Total				**1.7 KWh**

The chosen appliances in Table 3.1 have main target of considering the low energy saving system and these are the minimum needs that could be possessed by the rural community and we consider rich families to have both of these equipment's, medium income and low income families have only light bulbs and Radio.

The studied village composed by 10 rich families, 140 medium income families and 50 low income families, the latter being excluded in this regards.

For good identifications of expressions of words used such as: rich, medium income and low income families, we refer to [56] where in Rwanda rich families are defined as the families that have big land and cows, and they normally have jobs where they can get income in terms of money, good housing, and generally have their own transport (motorbike or vehicle). Also the people who can do business with bank, so that they can easily get credit from the bank are in his case. Medium income families are differ to rich families that they have a small paying jobs, and can have access to health care and they do not have the transport and Low income families are the ones that have very small land and small house. Live on their own labor and even if they do not save but they can find something to eat, even if the food is not very healthful.

Therefore, peak load demand observed for household in the selected village is around 27.35kW and daily electricity usage for households in this community is around 153.8 kWh per day.

3.3.1.2 Commercial and Governmental Buildings Load

The main kind of electric appliances in commercial and governmental buildings are lighting lamps for shops and office, computer for administrative office work, refrigerator for some beverage, and coffee/tea machines for cafeteria and are presented in Table 3.2.

Table 3. 2: Electric Appliances for commercial, Government Buildings and the running time

Appliances	AC/DC-Watt	Number of Equipment	Run–time per day	Total energy [KWh/day]
Lighting bulb	15	20	6	1.8
Television	250	4	6	6
Computer	100	2	8	1.8
Radio	30	4	8	0.96
Refrigerator	200	2	8	3.2
Milling machine	12500	1	5	62.5
Printer	50	2	2	0.2
Others	200	2	4	1.6
Total				**78.06**

3.3.1.3. School Load

Due to Rwanda government strategic plan of 12 years basic education this area has 12 rooms for primary schools and 3 rooms for Ordinary Level. Furthermore, 3 administration offices with 2 units of 60W desktop computer, 2 units of 50W printer and with 1 unit of 15W CFL for each are required. The school has to be equipped with 2 toilet rooms for staff and 6 toilet rooms for students with 1 unit CFL and also equipment laboratory with 4 units each with 15W CFL. As noted above during the day time no need of electricity for the class rooms since the sunlight can provide light to the classes.

Therefore, most of the electricity demand is for computers and printer at day time which is very small. The largest load of the school will be recorded during the evening times when evening classes would be associated. Each of the class rooms are assumed to be installed with 1 unit of 15W compact fluorescent lamps (CFL), Moreover, 3 units of 40W CFL for surroundings lighting ofthe school is also proposed. The desktop computer is to be functioned for 8 hours from 8:00-

12:00 and from 13:00-17:00 and printer 50W is to be run for average of 1 hour from 15:00-16:00, following all typing will be completed. An assumption was taken that evening classes would conduct from 18:00-21:00 hours adding 1 hour in case there is no enough light from the sun. But the number of evening students would expect not to be more than three classes. The annual break of the academic year for schools in Rwanda is from end of September to midi January. The total daily electricity consumed by the school excluding annual break and semester breaks as shown in Table 3.3.

Table 3.3: School Electricity Consumption

Appliances	AC/DC-Watt	Number of Equipment	Run –time per day	Total energy [KWh/day]
Lighting lamps	15	30	4	1.8
Computers	100	2	8	1.6
Printer	50	2	1	0.1
External light	3	40	3	0.36
Laboratory Equipment	≈ 500	4	8	16
Total				**19.86**

The primary load calculated for school is19.86 KWh/day which comprises a peak load of 2.87 KW. This is the day time load only if the school will be required to use electricity during day time; otherwise the total load is only the demand for the three class rooms, for external lights and for toilet during the period of evening classes as well as computer and printer installations.

3.3.1.4. Health Clinic Load

Every group of communities needs an equipped Health clinic nearby to provide basic service centers with simple delivery services and minor illnesses to treat surrounding communities. The health center would expect to work as health clinic, which will serve stocking medicines, follow up of health condition of the residents including pregnant day to day health condition.

The same to the selected village both clinic and veterinary Centers are needed for the better life of the population. Currently in village there is only one healthy poste (poste de Santé) and as it is a village where almost every family has at least one cow; it is proposed another one veterinary Centre to help people. So, possible appliances which demand an electric power are lighting bulb, computers, refrigerator to store drugs and laboratory equipment's are summarized in Table 3.4

Table 3.4: Electric Appliances for Health Clinic and the running time

Appliances	AC/DC-Watt	Number of Equipment	Run –time per day	Total energy [KWh/day]
Lighting bulb	15	14	10	2.1
Computer	60	2	8	0.9
Microscope	1	20	5	0.1
Vaccine freezer	60	2	8	0.96
Printer	50	1	1	0.05
Television	110	1	12	1.32
Total				**5.43**

The total annual scaled average primary load of 265.14kWh/day, with peak load of 29.2kW and a load factor of 0.38are resulted from HOMER after simulation (see Figure 5.2 in chapter 5).

3.3.2 Estimation of Deferrable Load

Deferrable load is defined as the load that should be satisfied after the primary load demand is supplied except in especial cases such as when water tank left empty below the required level, regardless of the time. It is also known as secondary load, as it is not controlled with time to deliver. Some activities that use the secondary load are like water pumping, ice making and water heating. These Loads are really considered as deferrable due to the nature of the load they are associated with storage devices. The secondary load is prioritized after the fully satisfaction of the primary load. The storage capacity (kWh) of the pump is the electricity demanded to fill up the water storage tank because the electricity will be supplied for other activities when pumps are not operating.

3.3.2.1. Load for Water Supply

Daily life of human beings, clean water is among the basic needs; so in this thesis the supply of water was considered into a common central area to all households, meaning there will be no water pipe distribution to each household. The purpose for this load in our project is to supply water to the community water distribution midpoint, health clinic and school. As it is in thesis [57] and with own experience, it is identified that the minimum water requirement per household per day is $0.1m^3$. The quantity of water for both the health clinic and primary school is being $2.4m^3$per day; therefore to satisfy the quantity of water for the health center, school and households, the selection of pump's size would base on their power capacity and discharge rate. 2 units of pumps that draw electrical power of 150W with a discharge capacity of 10 liter/min operating for 4 hours per day was proposed to provide water for the community service centers (school and health centers). The total power drawn by the pumps is about 0.33kW. Community services was suggested for 3 days water storage capacity and electricity consumption drained by the pumps to fill the reservoir is about 3.6 kWh.

Water provision to the central distribution reservoir for household's usage would be pumped with 6 units of pumps with rating capacity of 550W that delivers 45litter/min of water. Pumps could run for an average of 7 hours per day. For our case water storage capacity for 3 days is also recommended. The energy storage capacity can be calculated as follows:

Energy storage capacity= N^o of pumps $\times$ rating capacity of pumps $\times$ storage days $\times$ running hours per day.

As the energy demand and power generation from renewable resources of the village can vary from time to time. During the rainy season (summer) delivery of water to distribution center with the aid of pumps is expected to decrease and to be shared by rain water, moreover, the amount of water to be covered by the rain water was assumed about 30% of the deferrable load[58]; Whereas inApril since it is the beginning month to the rainy season only 10% reduction is being suggested. Table 3.5 shows summary of household's water supply pumps characteristics.

Table 3. 5: Pump Power Consumption Characteristics for Household's Water Supply

N^o of Pumps	Capacity (Watts)	Running Hours	Energy Consumption (Kwh/day)	Peak deferrable (KW)	Energy storage capacity (Kwh)
6	550	7	23.1	3.3	**69.3**

3.3.2.2. Irrigation System Load

For maintaining the sustainability in farming of food crops and vegetables, using irrigation system have been encouraged to people and this enable people to be self-sufficient and to earn money by delivering to other consumers. The payback time of the electricity provider can be reduced due to the maximization of the load demand of the community for irrigation purposes. The electrical load required for this purpose is used to drive electrical water pumping to pump water to the farm land or reservoir for later use of watering. For this purpose of irrigation, 2 units of 550W pumps having discharge capacity of 45liter/min which delivers 43.2m^{3}per day was considered. These pumps runs daily for 8 hours and the electrical energy consumption would be 8.8kWh per day; especially for July, August and September where it is sunny season in Rwanda. But during the rainy seasons the deferrable load decreases, especially the irrigation pumps will be out of operation at all. So, the minimum load of the pumps has observed during the three months of March, April and May.

3.4 Other Inputs Parameters of the Hybrid System

3.4.1 Solar PV Size and Cost

Due to the advanced technology the price of PV solar panels has been reduced Cost of PV Solar panels has been significantly reduced in the past years and it is assumed that it will continue to decrease for the future, but also note that cost of solar panels is also dependently to the variable of place, time and scale of the solar panel installation.

According to [59] the prices for PV system installations that have been considered in this study and the current overall cost figures in recently updated prices are as follows:

- 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 qualified for conformity with the IEC61215 (Crystalline silicon terrestrial photovoltaic 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 Mono-crystalline Solar Panel SUNTECH STP250 is US $ 360[60][61]. 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 price of solar inverter is $0.435/Wp [62]this means that the cost of 10kW will be $ 4350, consider the transport of 20% and taxes of 18%, the total cost for 10 kW will be $6000.

Balance of System Cost

- The cost estimation of solar ground mounting system is considered to be $ 100 per module, with the module of 250 Wp has been selected, then the cost for the 10 kW that is 40 modules of 250Wp system is $ 4000.

- The estimated transportation cost of the equipment from Kigali to Kayonza is estimated to $ 500.

- The installation cost and other applicable cost were taken as $4500.

The total estimation cost for 10 kW PV solar system is around $ 35000. In comparison of other different technologies with movable parts, this solar system does not need a lot of maintenance work in comparison of other technologies with moving parts. Therefore the maintenance and operating cost of a PV system is comparatively small. The annual O&M cost of a 10 kW PV system has considered as $ 20.

3.4.2 Size and Cost of Wind Turbine

The selection of wind turbine depends on several factors like: availability of wind resource, application of wind energy and this leads us to select the size of wind turbine, reliability, warranty and proximity of operation, maintenance and transportation. For rural area off grid applications, the main issue comes in transportation of wind turbine components when selecting high rating wind turbines. Because higher rating wind turbines have blades with longer length which cannot be easily transported in rural areas. Thus, it is advised to use the small wind turbines for rural electrification.

The following wind turbine specifications are preferred in this project: Generic wind of 10 kW, rated power of 10 kW with startup wind speed of 3 ms^{-1}, rated wind speed is 10 ms^{-1} and working wind speed is ranged between 3 to 25 ms^{-1}. Generator efficiency is 85%, generator type is a permanent magnet alternator with blade diameter of 8.0 m.

The wind turbine was manufactured by the Viktor krogmann GmbH & Co.KG, Germany [63].

O&M cost of wind turbine was proposed about 2% of its initial capital. The total installation cost of wind turbines was estimated based on the installed wind turbines in Europe and China since 2012. The total installed capital cost was averaged from $1050/kW to $1350/kW in China and in Europe it was $1800/kW to $2050/kW [64][65]

Therefore; in this thesis installed cost was taken about $1800/kW. Replacement cost of the wind turbine is considered in this case to be 70% of capital cost after 20 year service life.

3.4.3 Cost and Size of Batteries

The batteries are much needed in an off-grid hybrid system to store the excess energy generated by the renewable sources for later utilization when required. A backup in the system is important for maintaining a constant voltage during peak hours or when deficit in generation capacity appear, therefore batteries can help [66].

Using batteries as storage technique is more familiar are the most known and common storage technique used in renewable energy system applications. A battery is defined as an electrochemical device which is able to store energy in form of electricity once placing different metals in an acid solution. At Rwanda market we only have two types of batteries that are primary batteries and Secondary batteries. Primary batteries are these ones which can be used only one time and these that are rechargeable are called secondary batteries and for renewable energy applications secondary batteries are used.

During charging and discharging state of the battery the voltage is not constant. Typically at the equilibrium conditions is known as the nominal battery voltage [67]. A 6CS25P-Surrette battery of 12V with a nominal capacity of 1,156 Ah (6.94 kWh) has been chosen for our study. This battery can be found on market with the price of $ 1200 with considering the approximated replacement cost and O&M costs for one unit to be $ 1200 and $ 10/year, respectively.

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 and this is depending on the proportion at which energy is withdrawn. A battery life time is mainly affected by operating condition (the range of discharge and the operating temperature). Depth of discharge is defined as the level at which batteries are discharged in a cycle before they are charged again. Typically this point is found in the product data sheet produced by the manufacturer. This specifies the nominal number of complete charge and discharge cycles as a function of the depth of discharge.

3.4.4 Diesel Generator Size and Cost

Table 3.6 show the cost of diesel generator used in this study but the replacement cost has been taken depending on working aspect [61].

Currently, in Rwanda the diesel price is approximately 800Frw ($0.75) and by considering transportation; the diesel will be transported from the urban areas (Diesel Stations) to the rural community. The considered values for the analysis are summarized in the below table 3.6.

Table 3. 6: Cost of Diesel generator

	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

3.4.5 Power Converter Size and Cost

This device is taken as a dynamic component in any solar system where the AC is needed. It converts the DC form of solar system or wind system into AC form for AC appliances. A hybrid system needs an inverter to convert DC voltage from the batteries to AC voltage required by the load. Some characteristic is needed to be considered when selecting an inverter for a certain application. The inverters applied in renewable systems can be divided into two categories which are: solar inverter and wind inverter [68].

Depending to the application of solar inverters, they are divided into four categories: stand-alone inverter (off-grid inverter), Grid connected inverter, hybrid power inverter and Grid interactive inverter. Among the cited inverters some are specifically designed for PV applications and they are integrated with Maximum Power Point Trackers (MPPT); some are bidirectional so that they can play double importance (inverting and rectifying). Within this study, we use hybrid power inverters for the fact that are good for the combination solar and diesel generator or with any other renewable sources. Nowadays, the efficiency of the inverters has been improved a lot, now the typical value of inverter efficiency is 90 % and above [69].

A 10kW bidirectional inverter price has estimated to $ 8, 240 and by taking transportation and tax at 36%, the capital for this used inverter becomes $ 11, 370. The cost of replacement, operating and maintenance has been considered as $ 11, 370 and $ 0.2 /year respectively. The specifications of the chosen inverter are summarized in Table3.7.

Table 3. 7: Inverter specifications [70] [71]

Solar inverter		Battery inverter
Brand	SMA Sunny Tri-Power	S-M-A
Rated Capacity	10 Kw	10 Kw
Maximum Efficiency	98%	95%
DC voltage	330V- 800V	41V- 63V
AC voltage	230/400 V, 50 Hz	230/400 V, 50 Hz
Price	$ 4345	$ 8, 240

And the size of converter considered are: 5, 10, 20, 30, 35, 40kW; Capital cost of converter is taken as $550, replacement cost is about $550 for a converter of 5KW, 48V, with an efficiency of 90% and the lifetime of the converter has taken to be 15 years.

A briefly summary of information that I entered into Homer are as follows:

- The load demand has an average value of 11.05 kW with peak load of29.2 kW and daily average demand of 265.14 kWh/d and the load factor of 0.38;
- The average value of solar irradiance is 5.13 kWh/m^2/d with the clearness index of 0.513and the temperatures have annual average value of 21.7°C;
- A Surrette 6CS25P batterywith nominal voltage 12V, and 1,156 Ah (6.94 kWh);
- Lifetime for the Diesel generator is 15,000 operating hours;
- A converter with efficiency of 98 %.

3.5 Other Inputs that Affect Power System Optimization

3.5.1 Economic Inputs

The factors considered which affect the optimization of this power system are: lifetime of the project, annual real interest rate; capacity shortage percentage and inflation rate. HOMER calculates the NPC of the system by inserting these economic inputs window. The other parameters are: capacity shortage penalty and fixed capital cost of the system which is defined as the involved cost during the beginning of the project implementation. However these values have an effect on the NPC of each simulated system and they do not the power system ranking reason why they were taken as zero for this project.

The difference which comes between inflation rate and nominal interest rate is called "Real interest rate". The way HOMER is designed, it discounts the capital cost into annual cost for each of the components of the power system. This is done by considering the real interest rate and compensating the lifelong time of the components. The software does not consider inflation; it only assumes that the prices will rise at the same rate during the life time of the project of the power system. To compare the economics of the power system configuration with renewable and non-renewable sources of energy, the modeling tool would consider the following additional inputs. The economic parameters put in software as inputs are lifetime of project taken to be 20 years and the annual real interest rate is taken as 5%which helps the software to calculate the NPC of the project. The followings are the important formulas used to calculate the different parameters that help us to decide the best configuration.

The total Net Present Cost

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

$$C_{NPC} = c\left(\frac{1+i'}{1+d}\right)^{n} \tag{4.1}$$

i': is the annual inflation rate (%)

d: is the nominal interest rate (%)

In order to get 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. The following equation is used to calculate the total annualized cost.

$$\textit{Total annualized cost (\$/year)} = \textit{Total NPC} \times \textit{CPF} \tag{4.2}$$

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

$$CPF = \frac{i(1+i)^{N}}{(1+i)^{N}-1} \tag{4.3}$$

N is the number of years and *i* is the real interest rate that is the discount rate used to convert one-time costs and annualized costs. 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 the following formula.

$$i = \frac{d - i'}{1 + i'} \tag{4.4}$$

Levelized Cost of Energy (LCOE)

Levelized cost of energy is measured in the cost per kWh of electrical energy such that the total NPC of the useful energy generated during the complete lifetime of the hybrid project is equal to the total net present cost of the project. The formula 4.5 shows how LCOE of the electricity generated by a hybrid system project can be calculated.

$$LCOE = \frac{Total\ annualized\ cost\ (USD/yr)}{Annual\ load\ served\ (Kwh/yr)} \tag{4.5}$$

3.5.2 Constraint Inputs

HOMER is also able to consider some sensitivity factor or constraints as it has been discussed above. In the constraint window the main parameters considered are renewable ratio and capacity shortage in which 30 to 70% (RF) and capacity shortage range for (8%, 9% & 10%) has been considered. Also diesel price which varies from $0.8/L to $1.5/L and an interest rate which varies from 6% to 10% are considered as sensitivity analysis. Then, HOMER simulates the proposed scenario based on these input sensitivity factors to find both technical and economical comprehensive energy system components.

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter discusses the modeling of the system and the results obtained from the simulations of the hybrid system in HOMER software, Thus technical and economic analysis have done.

4.1 Optimization and Modeling

As stated in chapter 3 the optimization model design process that was applied for the evaluation of the optimum choice for dimensioning of the hybrid system was the Hybrid Optimization Model for Electric Renewables (HOMER) version 3.7.6. The different obtained results are presented and discussed in this chapter.

4.1.1 Hybrid Energy System Configuration

Figure 4.1 presents the configuration of overall component of the designed system and its model in HOMER. The program set-up includes all the simulations and possible arrangements that were tested for solar PVs and wind turbines, for several sensitivity value ranges of generation capacity, financing costs, wind speed and solar irradiation as described in previous chapters.

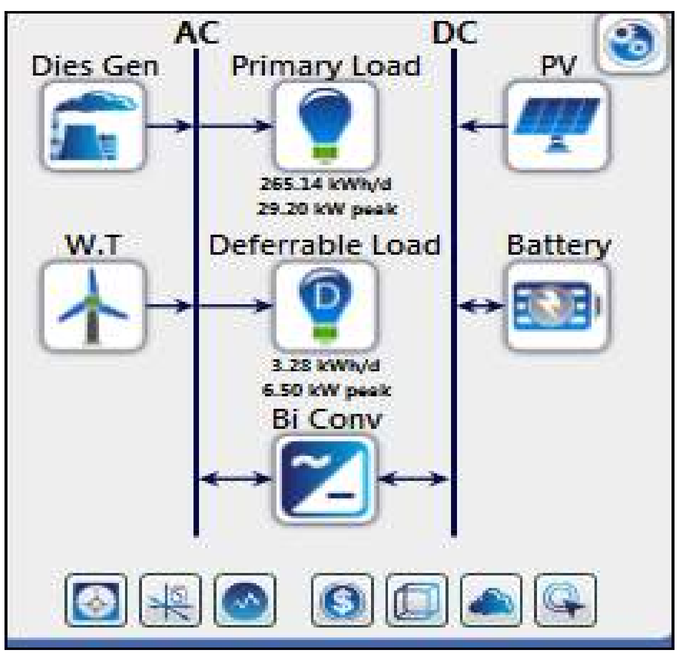


Figure 4. 1: Configuration of the System in HOMER

4.1.2 Seasonal Load Demand Profile

As it was proposed, the village load demand profile is categorized in DC charges for water pumping with a scaled annual average of 3.25 kWh/d and a peak load of 0.65 kW and AC charges for the remaining load with total scaled annual average of 265.14 kWh/d and a peak of 29.2 kW which are presented in the following Figure 4.2

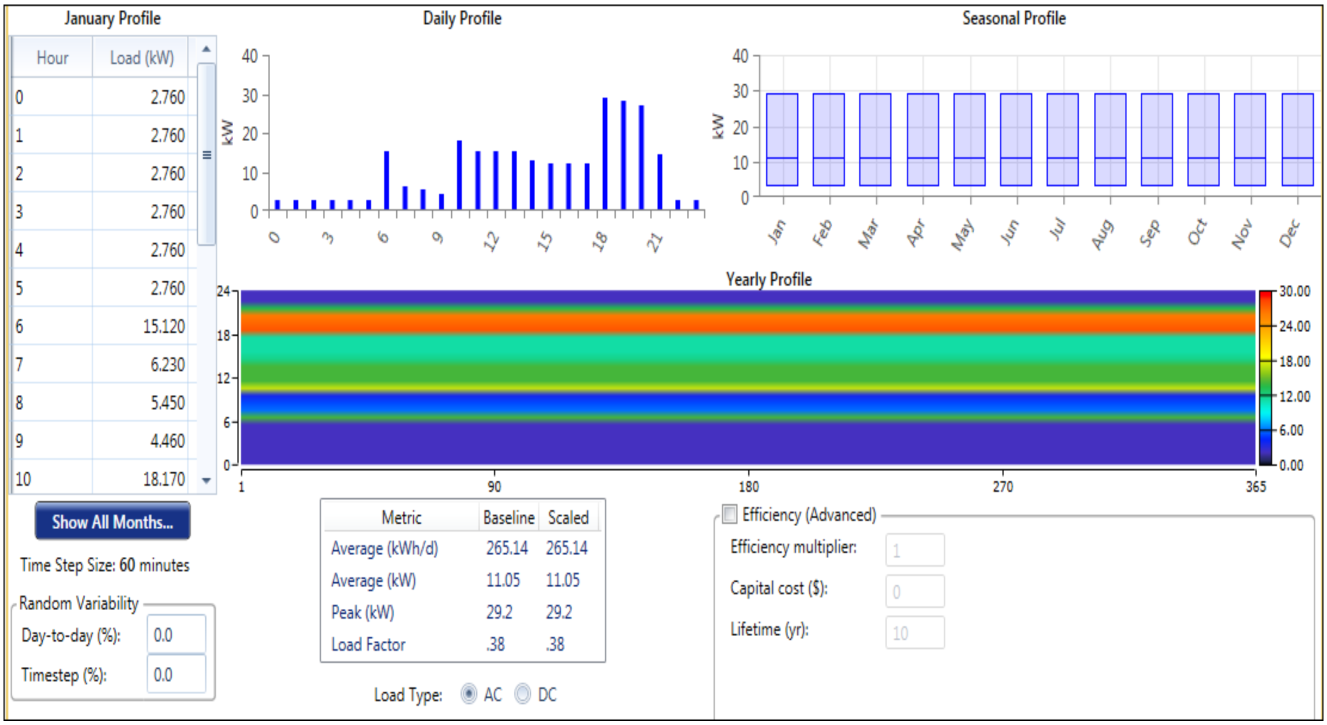


Figure 4. 2: Load profile for Kinyana Village locates in Kayonza District

4.1.3 Results Obtained in the Simulations

Table 4.1 summarizes the categorized results of the modeled system describing two main scenario variations (defined as SC1 and SC3) for electricity generation. Knowing that HOMER simulate the system for all proposed sensitivity variables as given in chapter 4, and the overall results are summarized in their entirety Appendix 1. However, at the end the values that best fit the system's proposed parameters - being the mean values for solar radiation (5.13kWh/m^2/d), wind speed (4.2 m/s) and the value of 40 meters for the hub height - were chosen as the representative ones for the main assessment criteria.

Table 4. 1: HOMER Simulation Categorized Results

Architecture						Cost				System
PV (kW)	W.T	Dies Gen (kW)	Batter	convert (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
40.0	4	15.0	40	20.0	LF	$0.339	$850,480	$21,376	$268,200	56
40.0		30.0	80	20.0	LF	$0.341	$913,046	$24,334	$250,200	45

Therefore, the above scenarios resulted from the simulations are described in details below:

- Scenario 1: Hybrid (Solar-Wind-diesel generator) system composed of 40 kW PV panels, 4 wind turbines with 10 Kw rated capacity each; 15 kW diesel generator; 40 batteries of 1, 156 Ah each and inverters of 20 kW. With simulated results, this has the best cost of energy which is $0.339 comparing to the second one.

- Scenario 2: Hybrid (Solar - diesel generator) system composed of 40 kW PV panels, a 30 kW diesel generator, 80 batteries of 1, 156 Ah each and inverters of 20kW with COE of $0.341.

For each case of the above two scenarios, the following parameters were obtained from the simulation procedures and helped us to make further analysis in the discussion section:

- Total net present cost (NPC[1]);
- Levelized cost of electricity (LCOE[2]); and
- Operating cost of electricity/expenditures (OPE[3]).

[1]NPC is the present value of all the costs of installing and operating the system over the project lifetime, minus the presentvalue of all the revenues that it earns over the project lifetime.

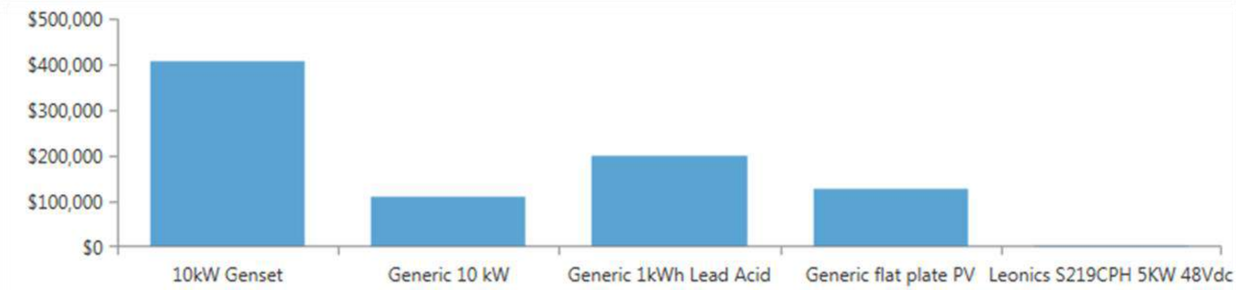
[2]LCOE is the average cost per kWh of useful electrical energy produced by the system if it should be paying back for itself in reasonable economy terms.

[3]OPE is the annualized value of all costs and revenues other than initial capital costs.

4.2 Techno-economic Analysis of the Results

In the techno-economic analysis of this thesis, each categorized scenario will be discussed in details regarding the technical and economy parameters resulting from the simulation procedures, and thereafter the best scenario that meets the demand at lowest costs will be chosen for further consideration.

4.2.1 Economic Analysis



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
10kW Genset	$6,000.00	$25,421.63	$43,066.41	$337,737.16	($6,197.52)	$406,027.68
Generic 10 kW	$72,000.00	$0.00	$39,225.57	$0.00	$0.00	$111,225.57
Generic 1kWh Lead Acid	$48,000.00	$205,701.66	$10,895.97	$0.00	($63,166.89)	$201,430.74
Generic flat plate PV	$140,000.00	$0.00	$21,791.98	$0.00	($35,133.31)	$126,658.67
Leonics S219CPH 5KW 48Vdc	$2,200.00	$2,915.86	$21.80	$0.00	$0.00	$5,137.66
System	$268,200.00	$234,039.15	$115,001.73	$337,737.16	($104,497.72)	$850,480.32

Figure 4. 3: Cost summary for the proposed system scenario

According to Figure 4.3 above, we can see that the hybrid system scenario SC1, presents low costs of O&M, LCOE and NPC compared to others.

The capital, replacement and operating costs of batteries from SC1 tends to be lower compared to SC2 however, the Scenario 1 salvage[4]is lower than other scenarios given its low storage capacity.

[4]Salvage is the remaining value in a component of the power system at the end of the project lifetime.

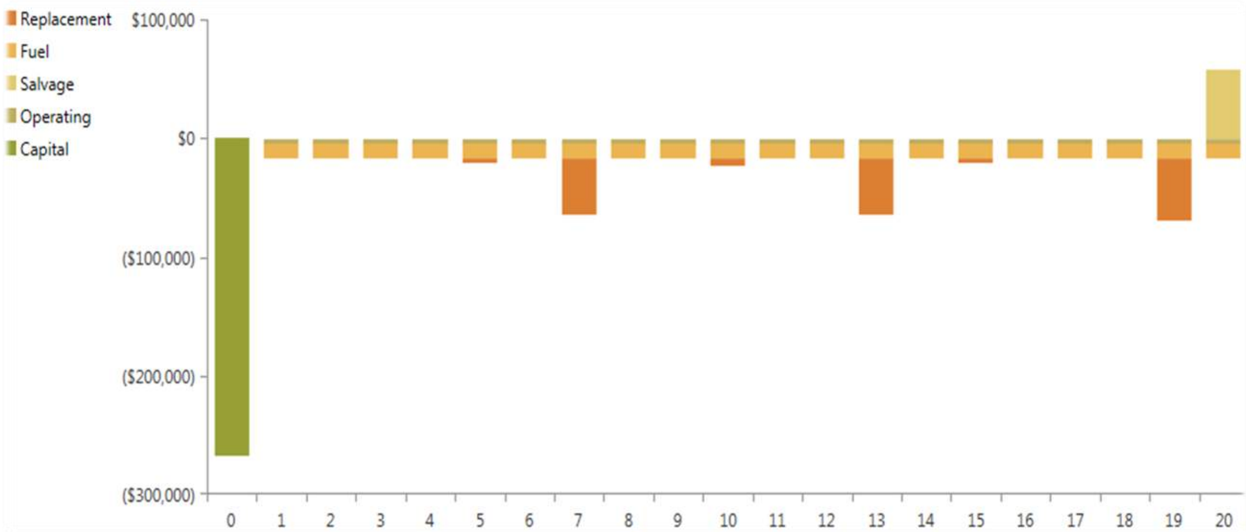


Figure 4. 4: Cash Flow Summary for the Selected Scenario

4.2.2 Technical Analysis

Additional analysis needs to be performed for the system feasibility and technical performance, such as the annual electricity production[5], consumption[6] and autonomy[7] parameters of each scenario, as shown in Figure 4.5. System autonomy is the ratio of the battery bank capacity to the electric load size.

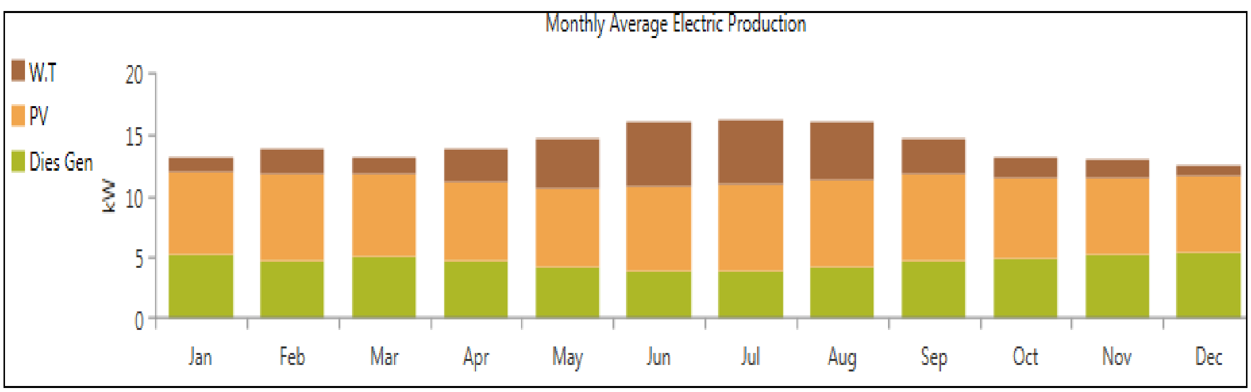


Figure 4. 5: Technical evaluation results

[5] The total electrical production is the total amount of electrical energy produced by the power system in one year. It is the sum of the electrical energy produced by all components of the system.

[6]The electricity consumption is the total amount of electrical energy that went to serve each of the system's electrical loads.

[7]The autonomy is the ratio of the battery bank size to the electric load.

According to the overall results presented in Table 4.1, the hybrid scenario SC1 produces most electricity compared to SC2due to its combination of two sources of energy. However, SC1 presents a relatively low consumption compared to SC2given that during a greater period of the year, the energy produced by this system cannot be stored due to low capacity of the storage bank (fewer batteries) and this fact leads to higher unmet load[8] demand and a considerable capacity shortage[9]of the hybrid scenario.

Moreover, SC1 has been chosen for this project due to its larger amount of excess of electricity[10] and its lowest LCOE compared to other scenarios. The renewable contribution for the selected system has 56%. The details analysis of this combination is given in Appendix 1. So, as it is seen with Figure 4.5 the highest share of power production is from PV panel which contributes 58,597 kWh/year equivalents to 47.32% of the total electric production; while diesel generator is the second that contributes in the system with capacity of 40,923 kWh/year (33.04%) and the remaining is for Wind turbine with 24,323 kWh/year (19.64%) i.e. the total Electricity production for this system is 123,842 kWh/year. With the simulation results show, capacity shortage per year for this system is 9.9%; with excess electricity of 22.4% and unmet electric load is found to be 6.3%.

4.3 Discussion

This thesis work proposes the needs and performs a detailed feasibility study for implementing a hybrid power system of wind and solar resources for rural electrification in Rwanda; and the specific site considered in our study is Kinyana Village located in Kayonza District, Western province of Rwanda with 200 households; where the village classified into three categories: low income, medium income and Rich families, this is for load estimation purpose. The data used in this research are very recent and registered for two years 2013 & 2014and measured over 24 hours. The average monthly profiles and hourly data for both sources were analyzed using HOMER, and the result displays wind and solar energy potentials are certain to exploit for the

[8]The unmet load is the proportion of the total load that went un-served because of insufficient generation.

[9]The capacity shortage is a shortfall that occurs between the required operating capacity and the actual amount of operating capacity the system can provide.

[10]Excess electricity is surplus electrical energy that must be dumped because it cannot be used to serve a load or charge the batteries.

provision of electricity. The greatest wind speed and the global horizontal solar radiation were 4.27m/s and 5.13kWh/m^2/day respectively and for wind the data was measured at 40 m wind mast at Kayonza District. The average daily load of the selected village is 265.14 kWh/day where an approximate maximum demand of 29.2 kW has been observed during the evening hours between 18.00– 21.00 hrs.

The optimal dispatch “Load following” strategy of the diesel generator has gotten after simulation. It means that the diesel generator might be operated only for direct supply of the load in case the renewable generation and storage battery bank are not sufficient. Within the lifetime cost analysis of the system; it is showed that the required initial capital investment for this project is $ 268,200. Then the NPC for this project to electrify this village is $ 850,480and the total O&M cost for the whole system is $ 21,376. This O&M cost is for operating and maintaining the diesel generator, batteries and wind turbine. The simulated results show that this system can feed the demand at a LCOE of 0.339 $/kWh with 56% renewable fraction. Though, it is the Government responsibility to supply electricity to the citizens for helping them in development and lifestyle. So, for this kind of projects, Government of Rwanda and cooperating partners provide funds for implementation of rural electrification projects especially as Government of Rwanda’s goals; include the one which says that every Rwandan should access the appropriate energy by the ends of 2017 (which I do not find achievable); by considering the Government to fund 40% of the capital investment for this project, the energy cost can be minimized up to an approximately of 0.2 $/kWh and the local people involve in maintaining and controlling this power system.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This thesis work has been devoted to the design of an off-grid renewable hybrid power system for a community of 200 households in the rural village of Kayonza district. The average monthly profiles and hourly data for both wind and solar sources have found as 4.2m/s wind speed at 40 m of height at wind mast of Kayonza District, the horizontal solar radiation of 5.13kWh/m^2/day was also measured in Eastern province. These data found were analyzed using HOMER, and the result displays wind and solar energy potentials are unquestionable to exploit for generating electricity as hybrid system.

Electrifying rural areas has continued to remain a challenging assignment for developing countries like Rwanda. In Rwanda the current COE is lower than the value obtained from the off-grid hybrid system considered in this study ($0.339/kWh) for the reason that the main source of energy in the country is hydro-power but not available in all parts of the country for power generation.

As the studied area has no water to be used for electricity exploitation and also due to economic limitations and geographical situation of Rwanda; hydropower potential is not exploited fully to cover the electricity demand of the country and also electrical expansion might be also higher costly. By taking the special attention to the electricity shortage of the country, it would play a major role in many ways such as: improvement of life quality of the community living in the rural areas that is continuing to be major for many Rwandans, it will also improve the quality of education as Rwanda has a very wonderful program of one laptop per child, and this system is also friendly to the environment.

As Government's plan is that every Rwandan has to access affordable energy, this essential point has to be considered. For developing this power production system in Rwanda, it requires government supports. The present cost for domestic user of national grid electricity is in range of 0.24-0.3$/kWh, this depends on monthly energy consumption. Therefore, by considering Government subsidies and comparing the cost of energy obtained in this study (0.2 $/kWh) with the national grid users, the cost of Hybrid system is less than the price for using the national grid electricity.

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 Eastern 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.

5.2 Recommendations

Across different corners of the country there are renewable energy resources which varies from site to site, thus can be used for electricity generation either in grid or off-grid system. Electricity generation using off-grid systems form local renewables alleviates the country's electricity shortage. However, there will continue to face different challenges to implement such systems like: finance of the community, infrastructures, absence of awareness how to use renewable resources and risk taking decisions by investors and other related issues. To improve the energy deficiency at national and state level, grid and off-grid renewable energy technology systems has to be promoted using different mechanisms. Empowering the rural community’s income to grow renewable generated electricity purchasing power is also fundamental. If due attention is given for land degradation, environmental pollution and poor living standard of the rural community renewable sources hybrid should be implemented, however the current electrification trend of Rwanda’s government is by constructing large hydropower dams, exploitation of methane gas in Kivu Lake and peat energy. Additionally in a rare case PV standalone system for individual homes is also introducing but this system is not reliable and sustainable. Therefore, the implementation of other renewable energy sources like solar, wind energy power and hybrid systems can elevate the country’s electricity shortage and could be cost effective, provide a 24 hour quality electricity.

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Appendix: System Report of the Selected Configuration

A. System Architecture

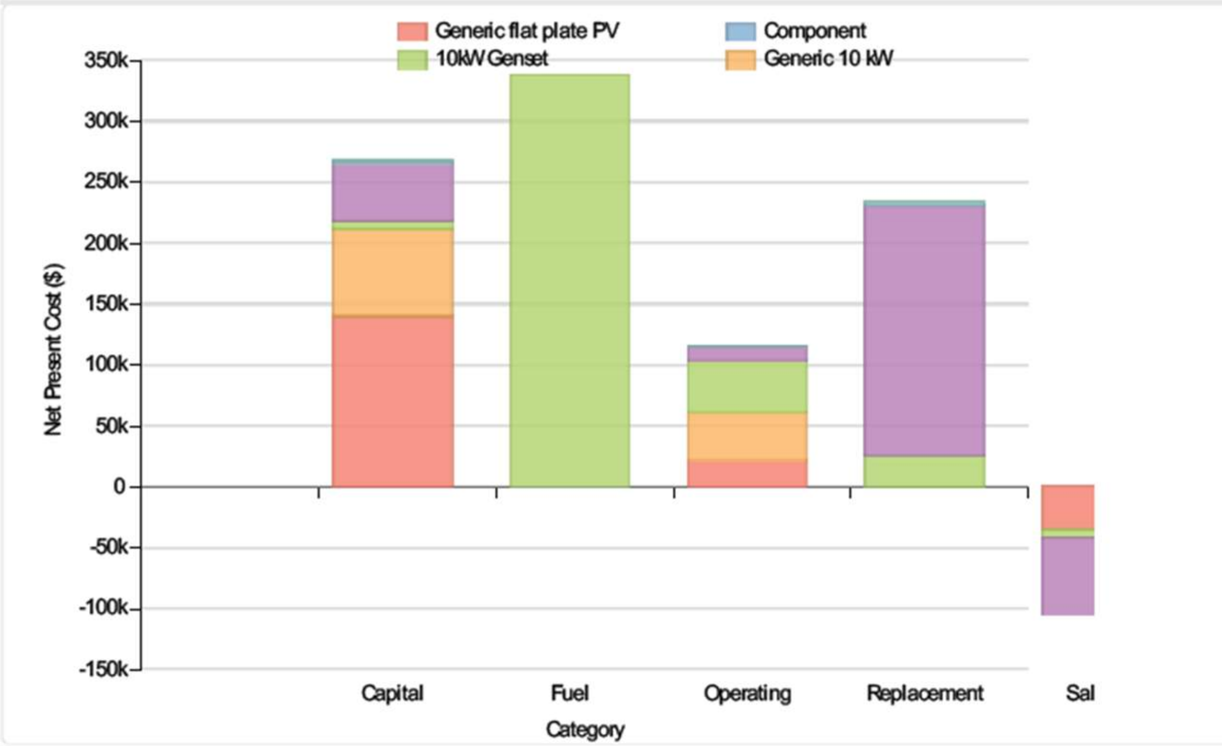
System Report

System architecture

PV	Generic flat plate PV	40	kW
Wind Turbine	Generic 10 kW	4	
Generator	10kW Genset	15	kW
Storage	Generic 1kWh Lead Acid	5	strings
Converter	Leonics S219CPH 5KW 48Vdc	20	kW
Dispatch Strategy	HOMER Load Following		

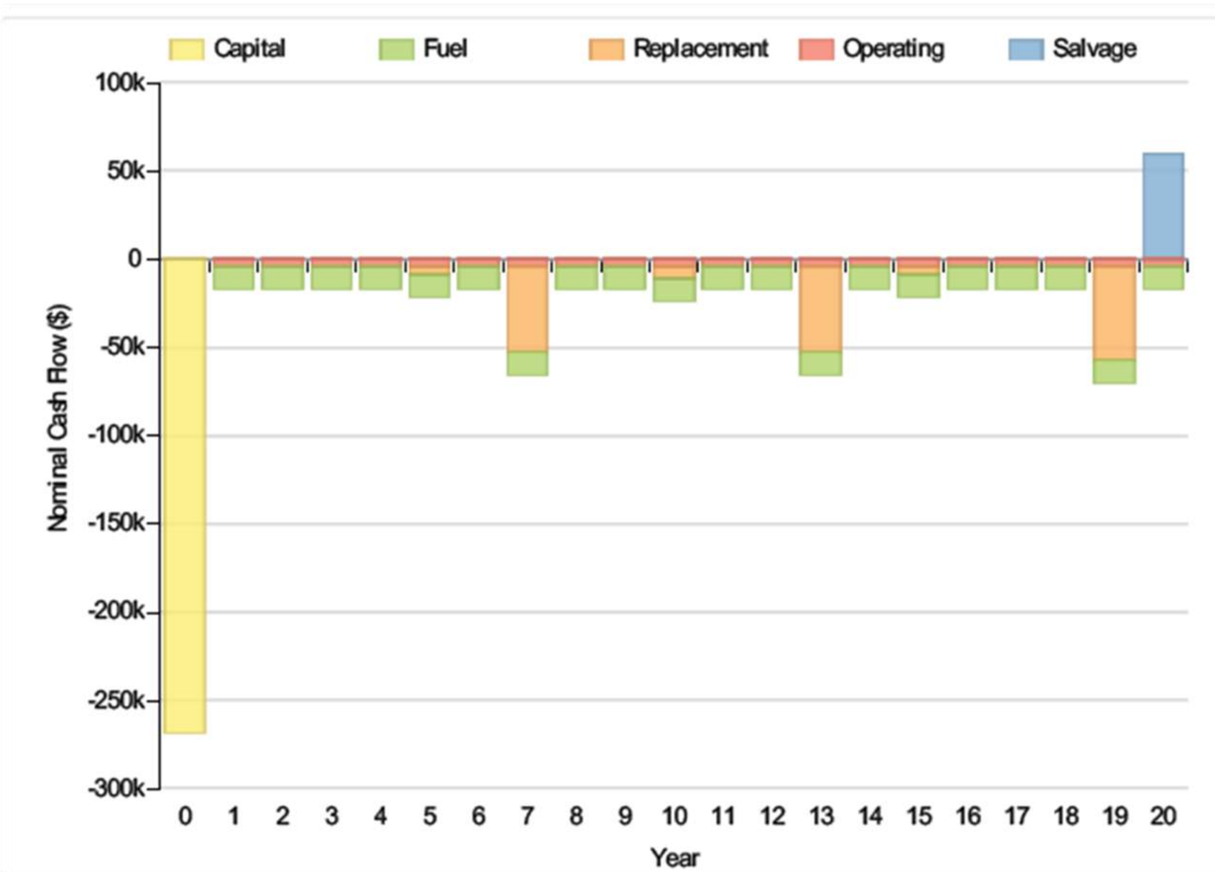
B. Economic Analysis

Cost summary



Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic flat plate PV	5,140	0	800	0	-1,290	4,650
Generic 10 kW	2,643	0	1,440	0	0	4,083
10kW Genset	220	933	1,581	12,399	-228	14,906
HOMER Load Following	0	0	0	0	0	0
Generic 1kWh Lead Acid	1,762	7,551	400	0	-2,319	7,395
Leonics S219CPH 5KW 48Vdc	81	107	1	0	0	189
System	9,846	8,592	4,222	12,399	-3,836	31,222



Cost Summary

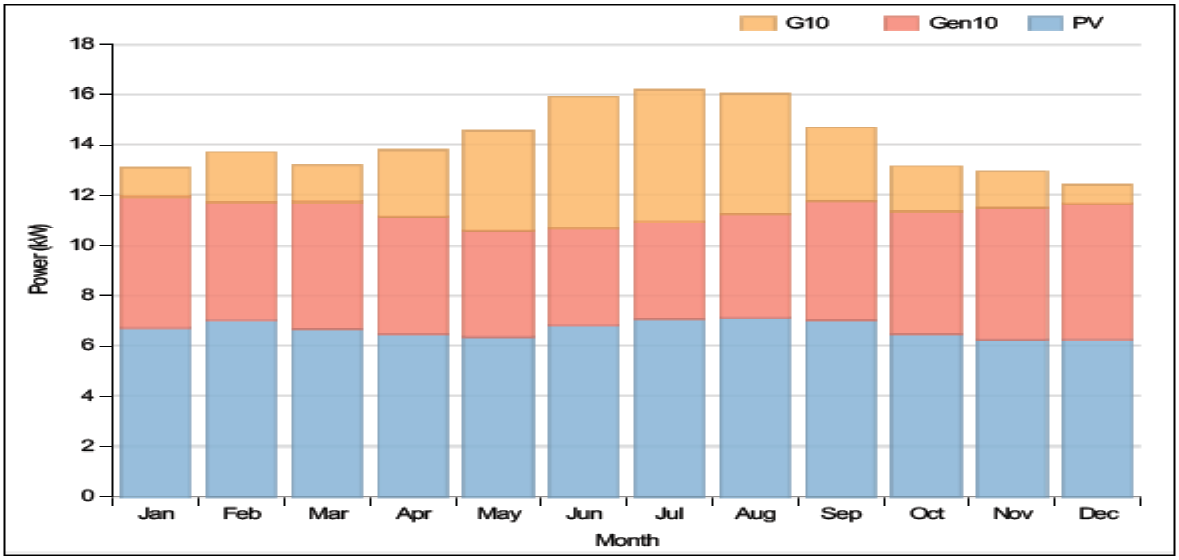
Total net present cost	850480	$
Levelized cost of energy	0.339	$/kWh

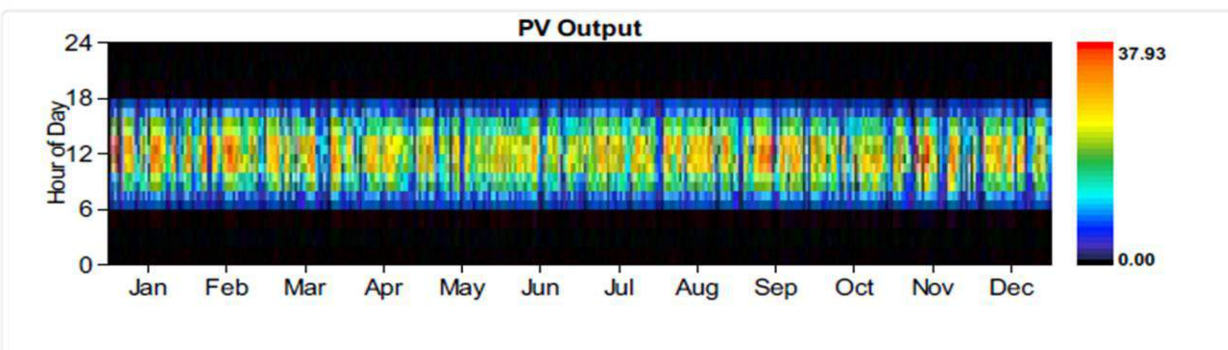
Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic flat plate PV	140,000	0	21,792	0	-35,133	126,659
Generic 10 kW	72,000	0	39,226	0	0	111,226
10kW Genset	6,000	25,422	43,066	337,737	-6,198	406,028
HOMER Load Following	0	0	0	0	0	0
Generic 1kWh Lead Acid	48,000	205,702	10,896	0	-63,167	201,431
Leonics S219CPH 5KW 48Vdc	2,200	2,916	22	0	0	5,138
System	268,200	234,039	115,002	337,737	-104,498	850,480

C. Electrical Analysis

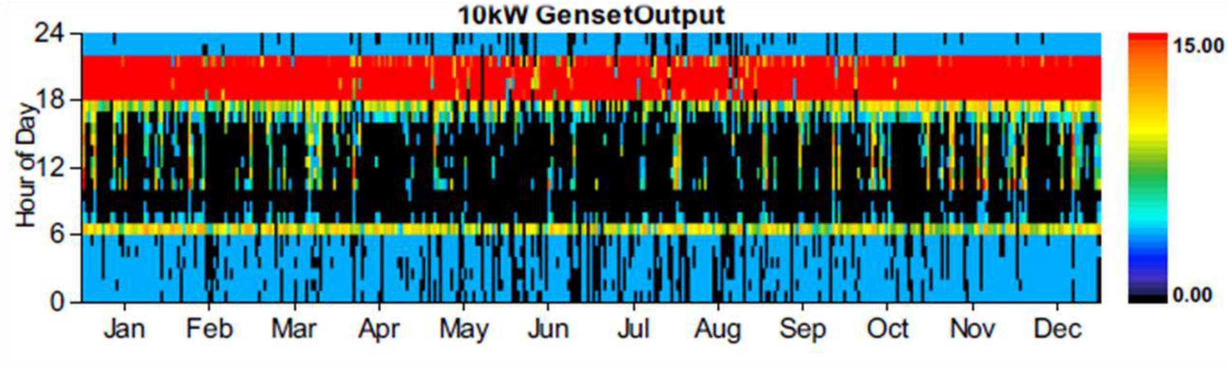
Component	Production(kWh/yr)	Fraction (%)
PV	58,597	47
Generator	40,923	33
Wind Turbine	24,323	20
Total	123,842	100





Generator:10kW Genset

Quantity	Value	Units
Hours of operation	5270	hrs/yr
Number of starts	685	starts/yr
Operational life	5	yr
Fixed generation cost	1.06	$/hr
Marginal generation cost	0.23	$/kWh
Electrical production	40923	kWh/yr
Mean electrical output	8	kW



PV:Generic flat plate PV

Quantity	Value	Units
Rated capacity	40	kW
Mean output	7	kW
Mean output	160.54	kWh/d
Capacity factor	16.72	%
Total production	58597	kWh/yr
Minimum output	0.00	kW
Maximum output	37.93	kW
PV penetration	60.42	%
Hours of operation	4380	hrs/yr
Levelized cost	0.079	$/kWh