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EVALUATION OF A HYBRID SOLAR PHOTOVOLTAIC-BIOENERGY SYSTEM FOR POWERING REMOTE DWELLING IN RWANDA

CASE STUDY OF KABASEGA VILLAGE

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Declaration

I, Gemma ITUZE, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material, and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics**.**

Gemma ITUZE

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Abstract

The use of energy has always been important to improve the living standard of human beings. Relying on energy generated from fossil fuels has resulted in the reduction of fossil-fuel reserves, the change of climate due to the pollution of the environment and to financial instability due to its cost fluctuation. From the presented challenges related to the use of fossil fuels, renewable energy resources have been thought as solutions. On the other side, because of the renewable source intermittent character, it is difficult and rare for one single renewable energy source to supply clean, reliable and cost-effective power. Thus, a combination of multiple power resources can be a good way to provide a solution.

The electricity access in Rwanda is still low; only 23% of the population has access to electricity. In remotes area, the situation is even worst; access to modern energy services is practically inexistent. The rate of electrification is extremely low. Renewable energy, by its availability and its adaptability to the remote areas, is the best way to get these regions out of the energy poverty and to improve the quality of life of their population.

The present work deals with this issue for the case of Kabasega Village in Gicumbi district Northern Province of Rwanda. An off-grid hybrid system based on renewable energy resources solar PV and biomass with a Fuel cell as a backup has been proposed. The target of this research has been first to evaluate the renewable energy resources in the chosen area in order to determine its potential in meeting the local energy needs. After that, a survey has been conducted to determine the village energy load demand. HOMER software has then been used to optimize a suitable system that meets the requirements.

To satisfy a primary load demand of 243KWh/day with a load peak of 49.3 kW, an optimum hybrid system is proposed. This system is made of a 25 kW PV, 45 kW biomass, 5 kW Fuel cell, 7 kW converter, 10 kW Electrolyzer and 3 kg hydrogen tank. For this system, the origin of the produced electricity is 27% solar, 72% biomass and 1% fuel cell. The Levelized cost is 0.144 $/kWh; which is competitive with the national grid tariff.

Keywords: Renewable Energy, off-grid power System, HOMER, hydrogen, fuel cell.

Résume

L'utilisation de l'énergie a toujours été importante pour améliorer le niveau de vie de l'homme. Le fait de dépendre de l'énergie produite à partir des combustibles fossiles a entraîné la réduction des réserves de combustibles fossiles, le changement climatique suite à la pollution de l'environnement et à l'instabilité financière en raison de la fluctuation du coût. Pour relever ces défis associés à l'utilisation des combustibles fossiles, le recourt aux énergies renouvelables sont considérés comme la solution. D'autre part, en raison du caractère intermittent des sources renouvelables, il est difficile et rare pour qu'une seule source d'énergie renouvelable fournisse de l'énergie propre, fiable et viable d'une façon adéquate. Ainsi, la combinaison de multiples ressources peut être un bon moyen pour apporter une solution.

L'accès à l'électricité au Rwanda est encore faible ; seulement 23 % de la population en a accès. Dans les régions enclavées, la situation est encore pire, accès aux services énergétiques modernes est quasi inexistante. Le taux d'électrification est extrêmement faible. Les énergies renouvelables, par leur disponibilité et leur capacité d'adaptation pour les régions éloignées représentent la meilleure façon de faire sortir ces régions de la pauvreté énergétique et d'améliorer la qualité de vie de leur population.

Le présent travail traite de cette question dans le cas du Village de Kabasega dans le district de Gicumbi province du nord du Rwanda. Un système hybride autonome basé sur les énergies renouvelables PV solaire et biomasse et sur une pile à combustible comme système d'appoint a été proposé. L'objectif de cette étude a été tout d'abord d'évaluer les sources d'énergies renouvelables disponibles dans la région choisie afin de déterminer son potentiel à répondre aux besoins énergétiques locales. Après cela, une enquête a été menée pour déterminer la demande de charge énergétique du village. Logiciel HOMER a ensuite été utilisé pour optimiser un système adapté qui répond aux exigences.

Pour satisfaire une demande de charge de 243kWh/jour avec un pic de charge de 49,3 kW, un système hybride optimal est proposé. Ce système est composé d'un PV de 25 kW, de biomasse de 45 kW, de pile à combustible de 5 kW, convertisseur de 7 kW, électrolyseur de 10 kW et d'un réservoir d'hydrogène de 3 kg.

Dans ce système, l'origine de l'électricité produite est à 27 % solaire, 72 % de la biomasse et a 1 % de la pile à combustible. Le coût économique est 0,144 $/ kWh ; ce qui est en concurrence avec le tarif de la grille nationale.

Mots-clés : Énergies renouvelables, système autonome, logiciel HOMER, hydrogène, pile à combustible.

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List of abbreviations

AC	Alternative Current
BMW	Bayerische Motoren Werk or Bavarian Motor
CHP	Combined Heat and Power
DC	Direct Current
EJ	Exa-joule
FAO	Food and Agricultural Organization
H_2	Hydrogen
CH4	Methane gas
CO2	Carbon dioxide
IEA	International Energy Agency
FC	Fuel cell
KWh/m²/year	Kilowatt- hour per meter squared per year
GDP	Gross Domestic Product
EDPRS II	Economic Development and Poverty Reduction Strategy II
kWh	kilowatt hour
MW	Megawatt
NDBP	National Domestic Biogas Programme
NPC	Net Present Cost
COE	Cost of Electricity
MATLAB	Matrix Laboratory
HOMER	Hybrid Optimization Model for Electric Renewable
EDPRS	Economic Development and Poverty Reduction Strategy

RMA	Rwanda Meteorology Agency
MININFRA	Ministry of Infrastructure
O&M	Operating and Maintenance
PAUWES	Pan African University Institute of Water and Energy Sciences (including climate change)
PV	Photovoltaic
BOS	Balance of System
Hd	Daily global solar radiation [kWh/m2]
$\dot{H}$d	Monthly mean value of the daily global radiation [kWh/m2/day]
Ni	Number of days
REG	Rwanda Energy Group
SSA	Sub-Saharan African (SSA)
TOE	Tonne of oil equivalent
TV	Television
US	United States of America
SWH	Solar Water Heater

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Chapter 1. INTRODUCTION

Outline

1.1 General Introduction

For the development of any country, energy always plays a very important role. For energy to be produced in an environment-friendly way, there must be an urgent need and understanding of shifting from existing fossil fuel energy based systems to one based on renewable resources. That change will result in a reduction of carbon dioxide (CO_2) emissions that cause harm to the atmosphere and human health as well, changing from fossil fuel to renewables will also help countries to achieve their sustainable goals by providing access to clean, secure, reliable and affordable energy through renewable energies [1].

the demand for power could exceed the limited reserves of the non-renewable energy resources; this could be a motivation for many countries to change from non-renewable to renewables resources [2]. While fossil fuels are unfortunately concentrated in a limited number of countries, renewable energy resources are not only available worldwide but their technologies are commercially well established; all could attract the world to focus on those replenished resources [3].

Though the mentioned advantages of renewable energy technologies, there are however some disadvantages related to renewables such as poor reliability and diffuse nature [4]. Some renewable resources like wind and solar depend also much on the weather condition which automatically affects their generation. It is difficult and rare for one single source of energy to supply clean, reliable and cost-effective power. The combination of multiple power resources can then be a good way to provide a solution [4]. A combination of one or more sources is also known as hybrid systems and those systems are important in achieving a cost effective and reliable power generation.

The socio-economic development of any country could be accelerated by the energy generated from replenished resources. The quality of life in both rural and urban areas is directly enhanced by the provision of many services to people which are associated with electricity or energy in general. World Bank energy group has shown that the access to electricity is still a problem in many countries of Africa where about 620 million of people do not have access to electricity and nearly 730 million of people use risky and inefficient forms of cooking [4].

That inaccessibility to modern energy is due to high prices for a supply that is both insufficient and unreliable. Practically the energy sector in sub-Saharan Africa is not yet capable to meet the needs of the citizens [2].

The energy situation in Sub-Saharan African (SSA) countries is a challenging issue to the development of the nations. The access to electricity is very low, and even the little accessible electricity is erratic and unaffordable. Fossil fuels and biomass used in a conventional way are the most used as a source of energy; they present though harmful effect [5]. However, Africa, especially sub-Saharan Africa, has low access to electricity; the continent itself has a good potential of renewable energy resources such as wind potential, solar irradiation, hydro potential, geothermal and biomass potentials [3].

Rwanda being one of the sub-Saharan countries, suffers also from very low access to electricity. However, it has undergone an increase in electricity access from 2 percent in 2000 up to 16 percent in January 2013 [6] and to 23 percent in 2015. The government is willing to expand that access. The country is expecting to continue electricity grid expansion by 2018 and expecting to generate 168.86 MW from hydro, 210 MW from peat, 253.6 MW from methane in Lac Kivu and 20MW from solar [6]. In Rwanda, the on-grid electrification serves mainly the urban areas while a large portion of the population lives in rural areas. Thus, enhancing and developing off-grid technologies can contribute to the rural areas access to clean energy. Once that is thought, some programs such as solar PV, biogas and energy efficiency can help achieve that development and contribute as well to the poverty reduction and reducing the reliance on fuelwood in those areas.

1.2 Rwanda description

1.2.1 Size and location

Rwanda also was known as the “land of a thousand hills” is among the small countries in the world; it has an area similar to the one of Netherlands of 10,169 square miles or 26,338Km^2. Rwanda is one among the fifty-five countries of Africa and is located in East Central of Africa between 1°04’ and 2°51’ south latitude, and 28°45’ to 31°15’ East longitude.

It has also an altitude varying from 900 meters to 4707 meters; which provides it with a moderated tropical climate [7]. Rwanda is bordered by Uganda to the north, Tanzania to the east, the Democratic Republic of the Congo to the west, and Burundi to the south. Landlocked, Rwanda lies about 1,200 kilometers from the Indian Ocean and 2,000 kilometers from the Atlantic Ocean [8]. The country is divided into five provinces, which are subdivided into thirty-one districts, which are further subdivided into sectors, cells, and villages at the low level. Figure 1.1 [9] shows the administrative map of Rwanda.

Figure 1.1: Administrative map of Rwanda

1.2.2 Country’s demography

Despite its small land, Rwanda’s population keeps on growing. The population growth rate in Rwanda was 2.6% since 1950 to 2015[10]. According to National Institute of Statistics of Rwanda, in 2012 Rwanda had 10,515,973 of residents, of which 52 percent was women and 48 percent were men. The same fourth census has shown that with one in two persons is less than 19 years which means that the population of Rwanda is young.

The median age of Rwandan population is 22.7 years. Women are many compared to the men by 23.5 vs 21.9. Only 3% of the resident population is people aged 65 and above. A big number of young adults live in urban areas compare to rural areas presumably for studies and work [11]. The population density in 2012 was 415 inhabitants per square kilometer. The fourth census conducted in 2012 has shown that 83 per cent of the population lives in rural areas [11]. In Rwanda, the average of 4.3 persons live in private households and in urban areas, it is a little bit smaller with an average of 4.0 persons. Figure 1.2[11] indicates number of people living in the rural and urban area of Rwanda by province.

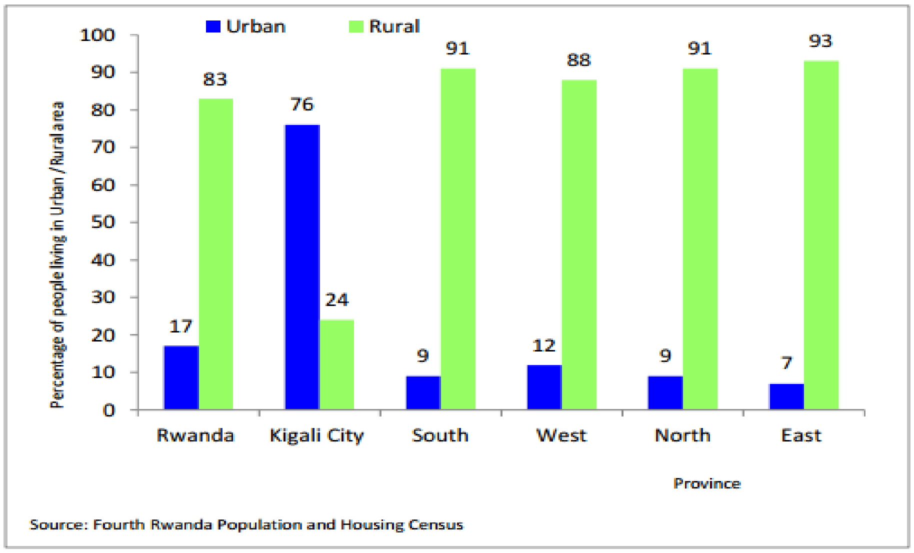


Figure 1.2: People living in urban and rural areas by Province in Rwanda

1.2.3 Country climate characteristics

Due to its high elevation ranging between 900m and 4507m, Rwanda experiences a tropical-temperate climate. The average annual temperature varies between 16°C and 20°C. in its high regions, the temperature ranges between 15 and 17°C and abundant rainfall. In east and southeast(the lowlands), the temperature is high and can go beyond 30°C in February, July and August [12]. The country has four main seasons where the period of heavy rains occurs over March, April and May and moderate rains occur in September, October, and November.

The long dry season occurs in June, July and August and lastly but not the least the short dry season occurs in December, January, and February.

1.2.4 Economy characteristics

The economy of Rwanda has known a steady growth of about 8 percent per year since 2001. The gross domestic product (GDP) per capita was $211 in 2001 and has tripled to $719 in 2014. Three main sectors that have been contributing to a significant extent to that GDP in that year are the service sector which contributed at 48 percent, the agriculture sector which contributed at about 33 per cent of which food crops cover 23 per cent of that sector and industrial sector with contribution of 15 per cent [8].

1.3 Problem statement

In most developing countries, exploding population growth and fast urbanization on one hand and wasteful energy consumption, on the other hand, are putting a lot of stress on the limited exploited energy sources. This has resulted not only in economic development hampering but also in the quality of life degradation. Rwanda, being one among those countries, is suffering the same problem. The electricity access in Rwanda is still low. Only 23% of the population has access to electricity. In the rural or remotes area, the situation is even worst; access to modern energy services is practically inexistent. The rate of electrification is extremely low. The actual energy system, by their centralized nature, is not adapted to these regions. Indeed, lack of access to modern energy services, electricity, modern telecommunications, clean water and other basic services are the consequences of their inaccessibility. Connecting them to the national electricity grid is then economically viable. Renewable energy, by its availability and its adaptability to the remote areas, is the best way to get these regions out of the energy poverty and to improve the quality of life of their population. The present work deals with this issue for the case of a remote village in Rwanda. A stand-alone renewable energy solution to its energy issue is proposed.

1.4 Objectives of the study

1.4.1 Main Objective

The objective of this study is to evaluate the hybrid system of solar and bioenergy for powering remote area in Rwanda considering a case of Kabasega village in Gicumbi district.

1.4.2 Specific Objectives

- ✓ Estimating the everyday load demand of the selected area based on their needs
- ✓ Studying the potential of RE resources in that selected area
- ✓ Describing the relevant renewable energy resources by means of solar and biomass for the proposed hybrid system
- ✓ Analyzing solar and biomass data of the chosen region using MATLAB
- ✓ Sizing the hybrid solar-biomass system that meets the energy need of the local area using HOMER
- ✓ Selecting the best option based on the COE (Cost of Energy) generation
- ✓ Analyze the results and conclude

1.5 Significance of the research

In most remote or rural areas of sub-Saharan Africa, grid connection is almost difficult and sometimes impossible in terms of cost and geographic location. The off-grid power generation is meant to supply those areas. Exploiting renewable energy resources in abundance by introducing hybrid power systems can offer the best solution by providing least-cost alternative means of energy for extending modern energy services to remote or rural communities. In the present work, a standalone system based on renewable energy is proposed as a mean to meet the energy needs of a remote village in Rwanda. The renewable energy sources considered for this system are the one that is abundant, namely solar and biomass.

1.6 Scope of the research

The research of evaluating the hybrid solar-bioenergy system for powering remote area in Rwanda will only cover the village called Kabasega in Gicumbi district in the northern province. This chosen district is among the areas in much need of electricity in Rwanda.

1.7 Research methodology

Energy situation and evaluation of energy needs data are collected through literature review but mainly through a survey carried out in the local population in the selected area.

Solar and biomass data are acquired; MATLAB has been used to analyze solar data to get the daily average solar radiation. A hybrid solar PV-biomass stand-alone is proposed as a mean to meet the local energy needs. HOMER has used to size this system.

1.8 Structure of the research

This report is subdivided into seven chapters. The first chapter includes an introduction to the topic, the problem statement, objectives, significance of the research and scope of the study, description of the country by means of size and location, demography, climate characteristics, economic characteristics, research methodology and the research structure. The second chapter covers a literature review related to the topic. The third chapter talked about hydrogen and fuel cells with related working principles, technologies, and applications. The next chapter discussed the details on the methods used for data collection, data analysis; and a detailed description of the chosen area for a case study. The fifth chapter includes evaluation and simulation of the obtained data. Chapter six gives the results and discussions. Finally, conclusions and recommendation

1.9 Summing up

This chapter has focused on the general introduction, country's description including its size and location, demographic, climate and economic characteristics. In Additional to that, problem statement, objectives of the study, scope of the research and research methodology have been detailed in this chapter and lastly not the least the structure of the research has been described there.

Chapter 2. LITERATURE REVIEW

Outline

2.1 Related work on hybrid power system

2.1.1 Introduction on hybrid systems

A combination of different technologies based on renewable energies to produce power is known as a hybrid power system, it may work either with a backup source or itself [4]. Usually, hybrid systems are a combination of photovoltaic with wind turbines and/or generators running on diesel or biofuel or biogas and or hydro. Some sources by means of those renewable energies are considered uncontrolled while others are controlled sources; solar is considered uncontrolled due to its availability totally dependent on the climate condition. Biogas, biomass and some other sources are considered as controlled ones because their power production can be controlled [4, 13]. The resultant hybrid system could offer an optimal solution at a considerably lower cost.

The new form of power generation (solar-bioenergy hybrid system) is able to modulate power out the function of demand. A hybrid power system could be one of the solutions for electrification of remote villages of Rwanda. Rwanda is willing to offer reliable off-grid and other solutions that energy sector needs for rural areas where powering critical loads are still a process. Using those renewables for power generation serves to decrease nonrenewable and imported fuel not only that but also to increase the livelihood of the population in rural or remote locations.

2.1.2 Advantages of hybrid systems

There are a lot of benefits of using a hybrid system based on renewable energies sources over a standalone system, by using the former that could result in improved reliability and continuous power due to the ability of a hybrid system to provide a backup power. The improved energy services, reduced emissions and noise pollution are benefits of hybrid systems since they adopt environment-friendly technology [14]. Those systems offer reduced cost due to the cost- effective way of generating electricity and lower maintenance cost associated with the use of renewable energies. They are efficient to use due to the fact that renewable energy could be configured to meet with base load [14].

2.2World energy situation

Nowadays, in most of the countries worldwide in their agenda objectives, the words energy security, sustainability, and equity are dominating in order to developer energy sector in those countries because energy is a critical factor for the economic growth of any country. However, development of that sector differs from country to country based on the available resources and economic status of that country. The priorities in the way energy is being developed depend on the countries as well. European countries, what matters on top is energy security while for sub-Saharan countries what matter most is how energy is accessible and affordable by means of energy equity [15].

According to the IEA world energy outlook, in 25 years, the world's primary energy supply has increased by 58% from 7.2 billion TOEs in 1980 to about 11.4 billion TOEs in 2005. The projection shows about 48% of the increase is expected over 25 years from that of 2005 to about 17 billion TOEs in 2030 [16]. Worldwide, the deployment of renewable energy sources has been increasing rapidly in recent years where total power capacity of 25.4GW of renewable has been installed in 2013 and it is expected that in the medium to long-term, renewable energy sources are being economically competitive with conventional energy sources for electricity generation. Figure 2.1 [16] shows the generated power capacity in all renewable resources.

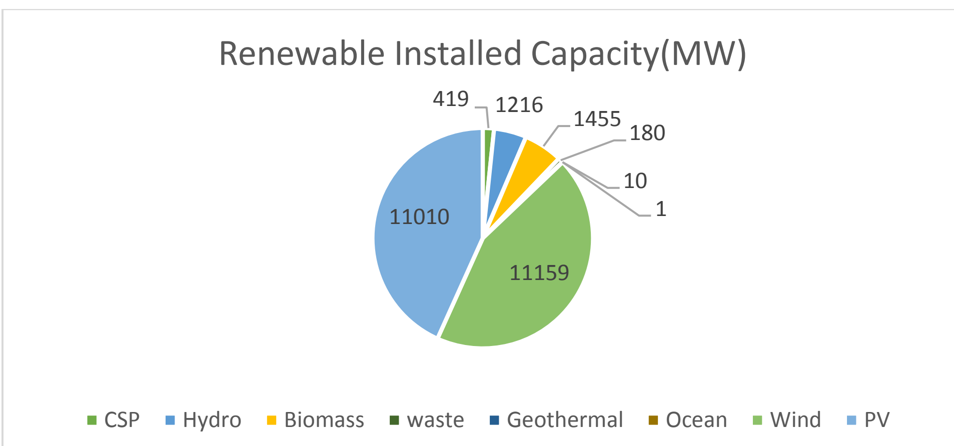


Figure 2.1: Shares of new renewable power capacity installations in MW in 2013 (total 25450MW)

2.3 Sub Saharan Energy Situation

2.3.1 Overview of Energy situation in Africa

Around the world, the economic and social development of all the countries is based on energy. Though all depend on the way it is produced and used which may cause-effect locally, regionally and globally. In general, Africa has the landmass of an area of 30.3 million km^2equivalent to the combination of the ones of America, Europe, Brazil and Japan [17]. Africa has resources both fossil fuel and renewable energy resources but most of those resources are yet to be exploited which makes the continent to consume less energy. About seven percent of world's commercial energy is produced in Africa but almost more than a half of its production is exported and consumes only three percent [18]. In 2006, the British petroleum statistics have shown that Africa has about 9.5 per cent of oil, 5.6 per cent of coal and eight percent of natural gas of the world's global economic recoverable reserves [17].

Contrary, the continent is rich in renewable energy resources example of the excess of hydropower capacity that represents about thirteen percent of the global total with the estimated capacity of 1100 TWh/per from both large and smaller hydropower systems to be exploited economically [19]. Considering that hydro resource is available in most countries of Africa but the dominant resource is in eastern and central regions. Despite the hydro resource, the world's best solar resources are found in Africa and once that resource is exploited may serve in different activities like heating water, home lighting, drying crops and so many other activities. About 10 TWh per year is an estimated wind potential for Africa which is good.in most households of African countries, the source of heat is from firewood and charcoal [17]. In addition to those resources, Africa has peat and geothermal resources through their exploitation are still low.

2.3.2 Energy Potential in Sub Saharan Africa Region

This region like other countries of the continent has the abundant potential of both fossil and renewable resources. About 10000GW is the total solar potential available in the region and about 109GW of wind potential.

In addition to that this region in East Africa rift valley precisely has an estimated geothermal capacity of 15 GW [20]. This region has some of the big hydropower resources in the whole continent as well as in the world with an estimated of the exploitable capacity of 350 GW. In addition to those renewable energy resources, the region has oil, gas, and coal. The estimated potential of natural gas is about 400GW and 300 GW of coal resources are available in the region [21]. Figure 2.2[21] shows the abundant energy potential in the sub-Saharan region of Africa. Solar photovoltaic is the most dominant.

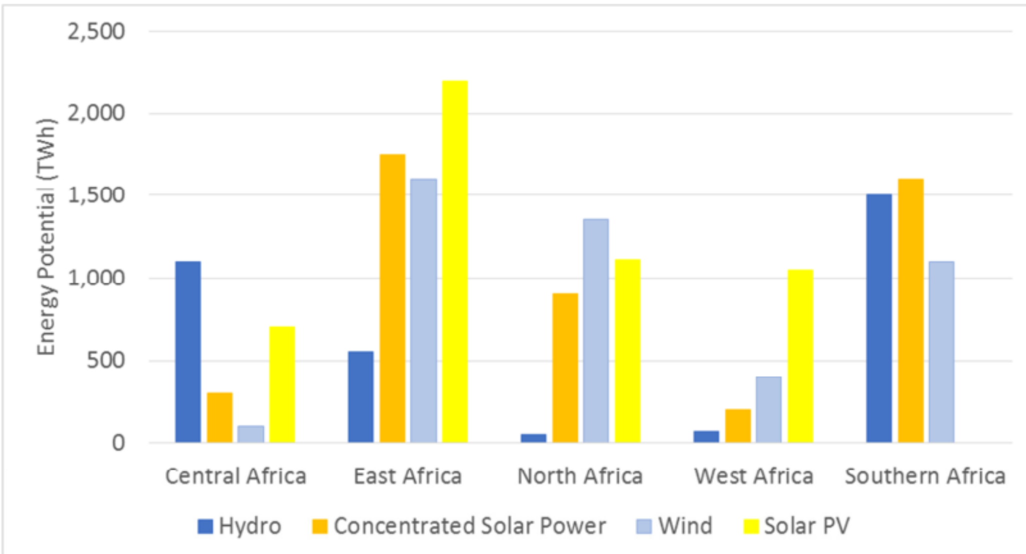


Figure 2.2: Abundant renewable energy potential in Sub-Saharan Africa

2.4 Rwanda energy profile

Rwanda is endowed with various energy resources, which include renewable energy like hydropower, geothermal, biomass (firewood and charcoal) and solar. It has also conventional energy like methane gas and diesel generators. However, there are still untapped resources and results in low electrification rate of 23% in 2015 [22]. The rural or remote areas are more affected with having low access to the electricity. Vision 2020, the guideline that Rwanda is following in implementing and evaluating the projects. Rwanda is targeting to increase its access to 75% from 23% in 2015, and reducing the use of wood from 90% up to 50% of the national consumption [23].

Approximately 85% of Rwanda primary energy is from biomass in the form of wood that used directly as fuel at 57% or converted into charcoal by 23%; with smaller amounts of crop and peat by 5%. Non-biomass counts15% of that primary energy which includes 11% of imported petroleum products mainly used in the transport sector and the other 4% used for electricity [24].

2.4.1 Rwanda electricity profile

2.4.1.1 Electricity generation, access, and consumption

Rwanda as other countries in Sub-Saharan region of Africa is suffering the low access to electricity though the region is rich in energy resources. Among 915 million people living in sub-Saharan Africa, only 290 million have access to electricity [25]. In Rwanda, at the end of 2012 only 4% of primarily consumed was electricity. Up to 2015, the electrification access rate was 23% with 160MW of capacity generation of which 60% was from hydropower and 40% from diesel powered generators. That 23% of electricity access was shared in the way that 51% was consumed by households mainly using that electricity for lighting purpose. Apart from households, 42% was consumed by industrial sector that uses electricity for motor-drives and lighting purpose mainly where cement, mining, textile factories and agricultural sector by means of tea estates are the major companies in the industrial sector. Lastly but not the list comes public sector with the rate of 6%. That amount of electricity used in public sector is mainly for a public building, street lighting and water pumping [3]. Though the electricity generation is still low in Rwanda, the government has set the policy that targets the generation capacity of 563 MW and to increase the access to electricity up to 70% by 2017/2018[6]. Table 2.1 [6] and 2.2 summarize the current and targeted access to electricity and the generation roadmap to achieve 563MW respectively.

Table 2.1: Current and targeted access to electricity in Rwanda

Outcome	**Indicators**	**Baseline2013/14**	**March 2015**	**High-Level Targets**			
				2014/15	**2015/16**	**2016/17**	**2017/18**
563 MW of electrical power capacity	MW of electricity system (domestic generation+ imports)	119	160	185	245	427	563
70% of households to have access to electricity with 48% on-grid and 22% off-grid	% of households on-grid connections	20%	22%	23%	29.9%	42.8%	48%
	% of households, off-grid connections	N/A	N/A	1.5%	8.6%	17.3%	22%

Table 2.2: Generation roadmap to achieve 563MW

Year	**Project**	**Capacity(MW)**	**Total Capacity(MW)**
2013/14	Installed capacity		
2014/15		**70.5**	
Hydro	Mushishito HPP (Rukarara V) (Phase 1)	2	**119.6**
Hydro	Nyabarongo I EHP	28	**190.1**
Thermal	Rental (Thermal Power Plant)	4	
Solar	Rwamagana Solar Power Plant	8.5	
Methane	KivuWatt Methane PP (Phase I)	25	
Peat	Gishoma Peat Power Plant	15	
Hydro	Mukungwa I HPP	-12	
2015/16		**65**	
Hydro	Mushishito HPP (Rukarara V) (phase II)	3	
Hydro	Mukungwa I HPP	12	**255.1**
Hydro	Micro Hydro (IPPs)	10	
Solar	Rwinkwavu Solar Power Plant	10	
Import	Interconnection(Ethiopia-Kenya-Uganda-Rwanda)	30	
2016/17		**58**	**313.1**
Hydro	Micro Hydro (IPPs & REFIT)	12	
Thermal	Kigali Special Economic Zone (KSEZ) HFO	40	
Solar	Nyagatare Solar Power Plant	10	
Thermal	Rental (Thermal Power Plant)	-24	
Import	Interconnection(Ethiopia-Kenya-Uganda-Rwanda)	20	
2017/18		**251**	**564.1**
Hydro	Ntaruka B HPP	5	
Hydro	Micro Hydro (IPPs & REFIT)	14	
Solar+ Bioenergy	Solar Bioenergy (REFIT)	12	
Methane	Symbion Methane PP	50	
Peat	Hakan Peat PP (Phase I net Output	70	
Import	Interconnection(Ethiopia-Kenya-Uganda-Rwanda)	100	
Total Generation and import capacity End EDPR II		**564.1**	

2.4.1.2 Electricity from on grid system

Developing countries as a whole represent 1200 kWh per capita electricity consumption rate while sub-Saharan countries represent an average of 478 kWh. Rwanda one of the small countries in the world is also considered to have a lowest electricity consumption rate of 42 kWh per year per capita. In 2015, around 20 per cent of households in Rwanda were connected to the grid, the tariff was about $0.24c/kWh [6] which was relatively high compared to the other countries in the region, due to the country's topography and dispersed settlement patterns.

However, the government has addressed some measures like having a proper network planning and operation in order to minimize the losses that result in transmission of power from the generation source to the end-user(consumer). Aditionionally, the government has thought about increasing the productivity looking at renewable energies technologies.

2.4.1.3 Electricity from 0ff grid system

An off-grid system also called a standalone system is generally considered as a power system exclusively responsible for providing power to meet external load demands and that system is not connected to the main grid. Those systems are commonly utilized in remote locations where connecting to the grid is found expensive. Those systems have a variety of application like in telecommunications where can serve as a back-up and UPS systems for the mobile network [26]; and in agriculture also for water pumping purpose and mainly can serve as power generation for remotes communities [27].

In 2015, the tariff of electricity in Rwanda was relatively high as described in the previous section, as consequences, the number of people having access was low only 23%. In rural areas, kerosene and candles are mostly used for homes lighting. From that time, up to now the use of other sources like solar PV, biogas, and LPG is still limited. Off-grid which is a way of accessing electricity without being connected to the grid, is one of the solutions for any country having resources preferably renewables in order to reduce capital cost which contributes a lot the high price of electricity.

In that case, the government of Rwanda plans to ensure that 52% of households benefiting from grid systems [28].

2.4.1.4 Electrification in remote and rural areas in Rwanda

The electrification rate in Africa is still low and most African people live in rural areas. This affects more those living in rural areas. The fast development of any country could not be achieved without considering how its rural area could have access to sustainable energy [26]. The electrification rate in Rwanda of households for lighting purpose has been doubled nationally from 11% to 20% as indicated in the report of the National Institute of the statistic of Rwanda of2010-20111 to 2013-2014.

However, that electrification rate is predominantly high in Kigali city the capital of Rwanda where it has risen from 56% to 73% compared to 9% to 15% for the remaining part of the country. All have happened in the same period of the statistic of 2010-20111 to 2013-2014. The report shows that the electrification in an urban area was in the range of 58.2 to 71.8percent while in a rural area was about 2.5%to 9% [6]. The government is willing to provide all facilities for finding a solution. Through the rural electrification program with the help of donors, 150 schools in remote areas are connected with 1.7kW by solar solution and 300 other schools, 46 health centers are in progress of being connected. Lantern kits of 5kw have been served to 15 rural settlements and other 400 solar kits of 300W have been distributed into 4 rural settlements [6].

2.4.1.5 Electricity tariff in Rwanda

The electricity generation in Rwanda is low though the consumption does not exceed the available generated. The access in Rwanda is still low due to the high cost of electricity per unit which makes it not affordable to every citizen and the fact that electricity is still generated from on imported fossil fuel that affects its cost in many ways. Table 2.3 [29] summarizes the current electricity tariff excluding the value-added tax.

Table2.3: Electricity tariff in Rwanda

Customer	**Consumption(kWh) block/month**	**US cent/kWh**
Residential	0-15	0.11
	15-50	0.22
	> 50	0.23
Non-residential	0-100	0.23
	>100	0.24
Medium Industries		US cent/kVA
17H00- 23H00, Peak	0.4 kV<V≤15kV/month	12.5
08H01'16H59', Shoulder		6.69
23H01' – 08H, Off-Peak		2.26
Customer Service Charge	US cent/customer/Month	3.74
Large industries		US cent/kVA
17H00- 23H00, Peak	15 kV<V ≤ 33 kV/month	8.60
08H01'- 16H59', Shoulder		4.80
23H01' – 08H, Off-Peak		1.30
Customer Service Charge	US cent/customer/Month	3.74

2.4.2 Conventional energy resources in Rwanda

Non-renewable natural resources also known as conventional resources are the resources which are available in finite quantity and once used cannot be replenished. Up to now Africa, in general, relies heavily on those resources as her main source of energy. The consumption of those resources is high compared to its reproduction which makes fear to the world [30]. Those conventional resources are classified into fossil fuels (coal, gas, and oil) and minerals (metals and non-metals) and these contribute significantly to the economies of resource-rich African countries [31]. On the other hand, the sub-Saharan African has known the economic growth due to extraction and export of conventional resources [32]. It is estimated that about 30% of the world's minerals are in sub-Saharan Africa and more than 20% of the world's undiscovered crude oil are also estimated to locate in this region [33].

For Rwanda, the non-renewable resources available are thermal fuel, methane gas, peat (under development) and imported petroleum. Table 2.4 [3] summarizes the installed plants from the mentioned non-renewable resources

Table 2.4: Installed capacity from non-renewable resources in Rwanda

Thermal/diesel power plants		**Thermal/methane gas power plants**	
Plant Name	Installed capacity (MW)	Plant Name	Installed capacity (MW)
Jacana1	17.8	KP	5
KESZTPP	11	Kibuye Gas Methane	25
Jacana2	20.5	Total	30
Total	38.8		

2.4.2.1 Methane Gas

The methane Gas has been found in Lake Kivu which is located in African rift zone between Rwanda and DRC. The lake has the size of about 2,400$km^{2.}$ It contains the reserves of that gas of an estimated capacity of 55 million $m^3$of which 39 billion are economically exploited, meaning the equivalence of 32 million of PET (petroleum equivalent tone). Methane and carbon dioxide are the gases that are occurring in high concentration in the lake. The highest concentrations occur at depths ranging from 270 meters and 500 meters [34]. Annually, from 120 to 250 million m^3 of methane is estimated to be generated from there [35]. In the year of 2016, A pilot methane electricity plant has been commissioned by the Government of Rwanda [36]. 700 MW of electricity is the estimated capacity estimated to be generated from the methane in Lake Kivu over 55 years.

2.4.2.2 Peat

Rwanda is known to have peat potential and the followings sites have been identified to have peat: Rwabusoro, Akanyaru, Murigo, Gihitasi, Mashya, Gishoma, Rucahabi, Cyato, Cyabararika, Nyirabirinde, Kageyo, Kaguhu, Mashoza, Gasaka, Bahima, Bisaka, Rwuya, Nyabugongo, and Rugeramigozi [37]. Over 50000 hectares of land cover 155million tons of dry peat with an estimated power capacity of 700MW[38].

2.4.2.3 Petroleum

Through Kenya and Tanzania, it's from these neighboring countries where Rwanda imports all her petroleum products. It is estimated that the demand for petroleum products is growing at the rate of 10 per cent from 2010 up to 2020. At the time about 25 per cent of import costs was for oil products and around 55% was the proportion of export revenues spent on oil products [39]. The domestic storage of oil and gas is 30 million liters that cover in case of shortage, and there is a target of increasing the storage capacity up to 150 million liters by 2017 [40]. Table 2.5 [39] summarizes the status of imported petroleum in the period of 2011-2012. It is obvious that diesel and petrol have dominated the imports. The diesel mainly was used in electricity generation while petroleum was for transportation.

Table 2.5: Petroleum products importation 2011/2012

Petroleum Product	Volume (Liters)
Diesel	103,624,633
Petrol	74,025,910
Kerosen	12,006,010
Jet Fuel	1,044,002
Heavy fuel oil(HFO)	31,433,859
Other heavy fuel Oil(HFO)	2,770,187
LPG	240 tonnes

2.4.3 Renewable Energy Resources in Rwanda

Energy generated from renewable resources is called renewable energy those renewable resources are those replenished naturally and fast as they are being used. As discussed in the previous sections, Rwanda and other African countries have renewable resources through their exploitation is still low. Some of those resources are hydropower, sunlight, and biomass, geothermal and low potential of wind.

2.4.3.1 Hydropower

Since the 1960s, Hydropower has generated the bulk of electricity in Rwanda. Within the estimated 15000 MW of the total energy resources on power generation, 313 MW of them is from hydro power where approximately 130MW are considered to be domestic hydro and 183MW are regional hydro resources [41]. The domestic hydro consists of 32.7 MW operational capacity and 77.2 MW additional capacity of potential from both small and medium-sized hydropower and a larger number of mini and micro-hydro sites with 4.5 MW of operational and 8MW additional potential capacity. The latter refers to hydro resources on the border with neighboring countries by Rusizi on the border with DRC and Rusumo on the border with Tanzania [41]. The Rusizi 1 is in four phases where the first two phases have been developed and are operating with a capacity of 15.5MW. Rusizi III has of MW and Rusizi IV of 98MW is under active consideration. On the other side Rusumo could provide 20.5MW of capacity but still, it is at the early stage of feasibility study [41]. Table 2.6 [3] indicates some of first on grid hydropower plants with their installed capacity.

Table 2.6: Hydropower plants connected to the grid

Plant Name	Installed Capacity(MW)
Ntaruka	11.5
Mukungwa 1	12
Nyabarongo	28
Gisenyi	1.00
Gihira	1.8
Murunda	0.1
Rukarara 1	9.0
Rugezi	2.4
Keya	2.4
Nkora	0.6
Cyimbili	0.3
Mazimeru	0.5
Nshili	0.4
Musarara	0.4
Mukungwa 2	2.5
Rukarara 2	2.4
Giciye	4
Total	79

2.4.3.2 Geothermal energy

Besides to the hydropower sources, Rwanda has a geothermal potential capacity of about 700 MW. The main areas where it can be found are Karisimbi with an estimated size of 320MW, Gisenyi with 200 MW, Kinigi and Bugarama have a capacity of 200 MW and 20 MW respectively, and other areas counts 20MW [22]. Those resources are in form of hot springs. The country is conducting exploration of economically viable sites.

2.4.3.3 Wind energy

Being located close to the equator impacts the wind potential of the country and makes it low. In the year of 2011, there has been a rapid wind energy resources assessment in five locations of the country. The indications from the analysis of wind energy measurements on the field have shown that the country is not well placed for wind energy [42].

2.4.3.4 Solar energy

2.4.3.4.1 Current status of solar energy sector in Rwanda

Rwanda is geographically around the equator and has a sufficient sunshine with an estimated average daily global solar irradiation on the tilted surface of 5.2 kWh per m^2[6]. From 4.8 kWh per m^2 to 5.8kwh per m^2 per day has recognized as the long-term range of monthly average global irradiation [3] and that indicates the sufficient and good potential for solar energy. Figure 2.3[43] shows the global solar horizontal irradiation of Rwanda.

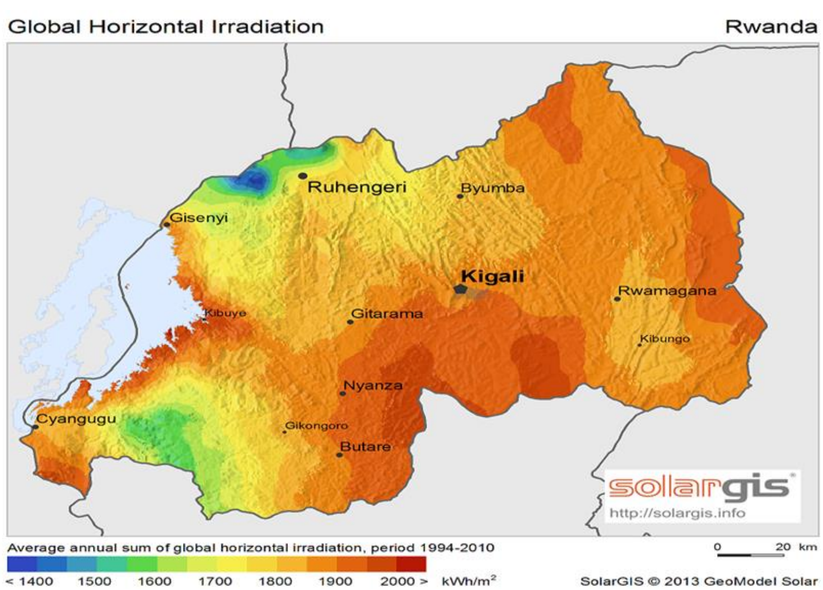


Figure 2.3: Rwanda global horizontal irradiation

With that sufficient potential of solar radiation, in Rwanda, there is a significant solar energy development and two technologies solar PV and the solar water heater is currently taking place. The former is more used to generate electricity either as on grid-connected or off-grid to supply communities in remote areas where government buildings, schools, and health institutions are more benefiting.

The government, donors and private sectors are all contributing to that development. In Rwanda, in Rwamagana district Agahozo - Shalom Youth Village, there is an 8.5 MW solar power plant and is the first utility scale farm in east Africa. This plant uses 28.360 PV panels and is 20 hectares of land. It produces 6% of total electricity supply of the country [22]. Table 2.7 summarizes the current solar power plants installed in Rwanda with their capacity and time of completion.

Table 2.7. Rwanda installed solar PV power plants

Plant name	Location	Installed capacity(MW)	Completion time
Jali	Gasabo	0.25	2007
Ndera	Gasabo	0.16	2013
Gigawatt	Rwamagana	8.5	2014
Nasho	Kirehe	3.3	2016

Apart from those installed power plants, there are some ongoing projects mostly to be off-grids systems, an example of Greenfield 10MW grid-connected solar plant in Nyagatare district in the eastern province [44]. Besides solar photovoltaic being used in Rwanda, also solar water heating technology is there now understudies as a solution for households. In some urban areas of Rwanda, electricity is used for heating water and that cost a lot the users. Solar water heaters have been used in Rwanda before 1994 genocide but now with the effort of the government and different partners provide loans and subsidies to former EWSA customers to afford SWHs [22]. Nowadays, through SolaRwanda Program, there are a number of solar water heaters that are being installed all over the countries.

2.4.3.4.2 Solar energy technologies

Background of solar energy

Solar energy is the energy from the sun. It is called renewable energy because it is generated from a natural source which is the sunlight and this source is replenished by natural process. The sun radiates more energy in one day than what the world uses in one year. The sun is considered to be the source of virtually all energy on the earth due to the fact that this energy is indirectly harnessed in many different ways [45]. Examples are human beings, animals and plants all rely on the sun on food and warmth, air currents created by solar heated air and the rotation of the earth are used in wind energy system. Hydroelectricity is another example where it is derived from the evaporation of water from the sun and then its subsequent return to the earth as rain to provide water in dams, thus make solar energy the largest available form of renewable energy.

Solar energy can be converted into electricity, heat and chemical energy. The solar energy is directly converted into electricity using devices called photovoltaics (PV). When the solar light is converted into heat, the application is called solar thermal energy. Mainly the heat is used in the industrial sector like facilitating chemical processes and in residential sector for heating and warm water supply. Apart from generating electricity and heat from sunlight, it can also be converted into chemical energy and it is referred to solar fuels [45]. This research will further go in details of solar Photovoltaic because its aim is based on power generation through sunlight available in the chosen area.

Solar Photovoltaic technologies

Figure 2.4 [45], shows the exponential growth where more than 40% of solar cell production has increased yearly by considering the annual production. This means the total produced power capacity at the maximum power that a PV module can deliver once illuminated.

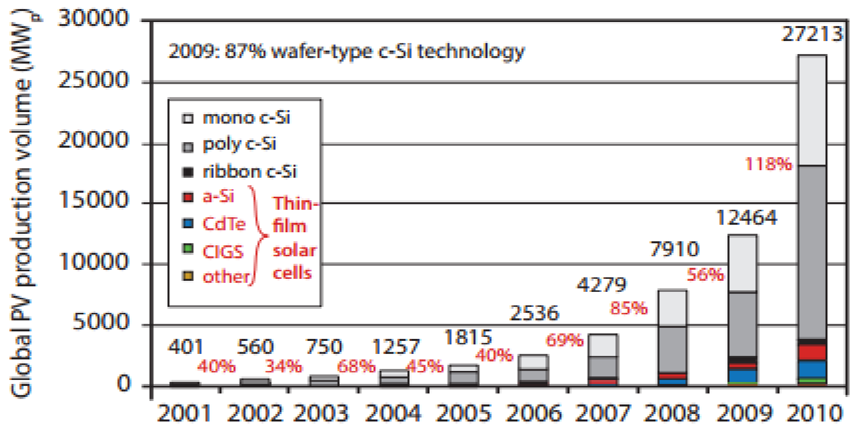


Figure 2.4 Global PV production volume in recent years

Some theories show that the solar electricity is growing faster than the other technologies; some causes are behind that. It is considered to grow faster because everywhere on the earth, solar radiation is available and in great abundance; also, because PV systems have an advantage compared to nuclear and hydro electricity generation systems. PV systems are decentralized on every roof and that can help houses and homes to generate their own required electricity and consequently that reduces their dependence on the electricity market. However, that does not mean that solar electricity cannot be in large parks. Additionally, in large part of the world, the price of electricity generated by PV systems is cheaper than from the grid [46].

For hydropower and nuclear, the electricity generation technologies are more centralized where big dams are needed for hydropower plants and nuclear as well not only big plants required for those technologies but also large amounts of investments. Lastly but not the least, helping people to be aware of those advantages of solar technologies will contribute to its faster growth in the coming years. As discussed in the previous sections, for sunlight to be converted into electrical energy there is a need of a semiconductor called the solar cell. Multiples PV cells wired together and sealed form a solar module and multiple solar modules also wired together in one structure to produce an amount of power from a solar array.

Depending on the efficiency, the solar cell is between one and four watts, the solar module is between ten and 320 watts and operates at six to 36 DC volts while at up 600 DC volts, a solar array can operate [47]. Having in mind that solar cells are named depending on the semiconductor that is made of and is classified into three categories depending on the generation of cells. The first generation is made of crystalline silicon. This generation is also called conventional, traditional or wafer-based cells besides that it is a PV technology that is commercially predominant. The second one is a generation of thin-film solar cells that are commercially significant in the small stand-alone power system, building integrated photovoltaics or utility-scale PV power stations; this generation includes amorphous silicon, CdTe, and CIGD cells [48]. The third generation of solar cells includes thin-film technologies and most of them are still under research and development phase and not yet commercially applied.

Generally, the efficiency of solar cells depends on temperature, the former decreases as the latter increases, by increasing one-degree Celsius results in 0.5 percent decrease in the Crystalline's output. To avoid that, the PV module should be kept in a cool place and preferably use amorphous silicon cells in hot condition as their output decreases only 0.2 percent for the increase of one degree Celsius. Thus, compare to the thin films cells, the crystalline cells are more sensitive to the heat [49]. Different primary types of PV cell and their applications are described below.

a. Monocrystalline solar cells

Monocrystalline solar cells are the first-generation technology as its name indicates these cells are made from single crystalline solar cells and due to its dark black color, they are easily recognized. They are made of silicon ingots and its shape is cylindrical [50]. They are most efficient and commonly used for residential solar installations. They also find application in limited space. Though more electricity can be converted from solar energy but these cells are costly. Figure 2.5[51] shows an example of monocrystalline PV cell.

Figure 2.5: Monocrystalline PV cell

b. Multi-crystalline solar cell

The multi-crystalline solar cell also known as the polycrystalline solar cell is made of multiple small silicon crystals hence the name. These cells are not uniform like monocrystalline; they are light and dark blue color. These cells are less expensive compared to monocrystalline but occupy more surface area to produce the same amount of energy and they have low efficiency [47]. Figure 2.6 [51] shows a Multiycrystalline solar cell.

Figure 2.6: Multiycrystalline PV cells

c. Amorphous thin film solar cells

Amorphous solar cells are non-crystalline cells that are very flexible and easy to fit on any shape of the substrate. These cells are good for mass production and are cheaper than crystal type though their efficiency is low in normal sunlight more efficient in low light conditions compare to crystal type and they have a shorter useful life. These cells are used where space is enough and in the areas with high temperatures and anticipated shade. The elements of these cells are more resistant to damage [47].

Advantages of photovoltaic technology

Compare to other technologies, PV system presents several advantages including being reliable. That means capable of working even in harsh conditions, its modules are guaranteed for 25 years with production even after that period. This technology requires low maintenance cost mostly only periodic and occasional maintenance are required [52]. Additionally, the system is a free fuel use in power production and is environmental friendly with less sound pollution only from pumped and tracked system. To increase the power output, PV modules can be added due to its modularity. Lastly but not the least the system is independent as it can be a stand-alone system with no grid-tied components.

2.4.3.4.3 Factors affecting PV system

A PV system can be affected both positively and negatively by several factors either internal factors or external ones. Some of those factors are irradiance, temperature, losses, wind load, temporary shading, corrosion, grounding schemes and so many others.

a. Solar Irradiance

As explained in the previous sections, all energy except geothermal and nuclear energy is originally derived from the sun and that makes it be the best source of energy as its potential exceeds other resources. The energy reaching the earth’s surface from the sun is approximately 10000 times the energy that the world requires. Human’s energy need covers only 0.01 per cent of that total energy [53].

The earth's atmosphere, shadowing, latitude, season and daily time are the factors that may affect solar radiation on the earth. The yearly average extra-terrestrial solar irradiance is about Go=1.367W/m^2. The solar irradiance is one and amost important parameter that affects the output of PV system, where once it decreases that reduction happens to the current as well. Figure 2.7 [54] shows the dependence of current and voltage on solar irradiance once the temperature is kept constant.

Using ground sensors or satellite can be a way of measuring solar radiation. PV based sensors and typical pyranometers are used as ground sensors in addition to that photodiodes can also be used in solar radiation measurement. PV based sensor is composed of crystalline silicon cells and it delivers the voltage proportional to the measured irradiance. Compare to the pyranometers, PV based sensors have many benefits including the low-cost and fast response. The other takes a long time during measurement due to thermal transients. However, there are some limited disadvantages like spectral sensitivity and higher inaccuracy compares to pyranometers [55].

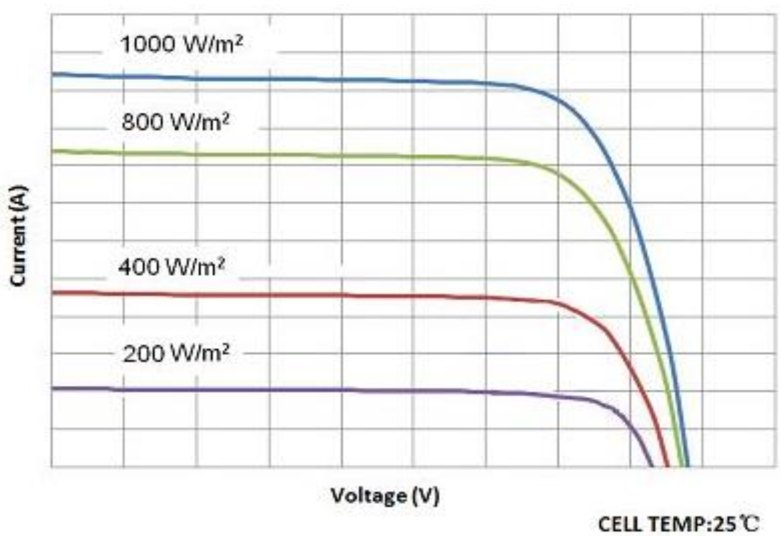


Figure 2.7: I-V curve at different irradiance levels and a fixed cell temperature

b. Temperature

The output of a PV system is mostly affected either by the available solar irradiance or the ambient temperature.

Once the latter increases above 25^0C that will decrease the voltage as well and the results the power output will also decrease. Vice versa phenomenon happens when the temperature is below that mentioned degrees. Figure 2.8 [54] shows how increasing the temperature at a fixed solar irradiance decreases the voltage as well.

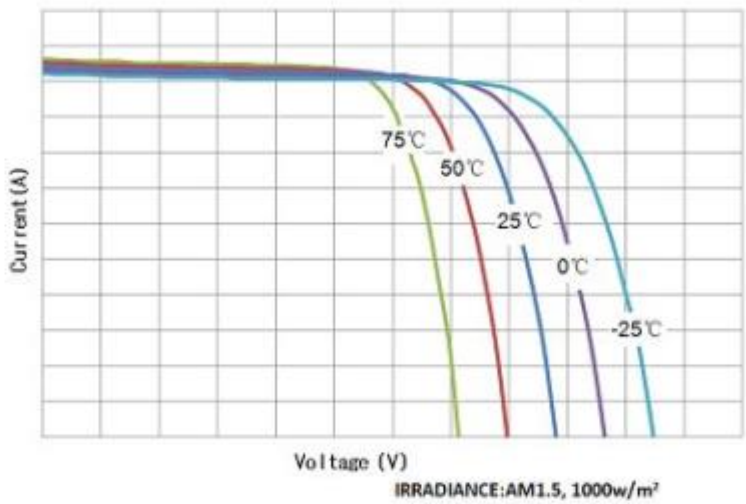


Figure 2.8: I-V curve at different temperature levels and a fixed irradiance

c. Voltage Drop along the cables

There is always a loss in voltage as the electric current flows through the wire. That loss is referred to the voltage drop. It is also defined as the loss of voltage in the cable due to resistance and that loss causes the loss in power output. It is expressed as $P=I^2R$. The voltage drop is given by Wire resistance times the current (E=IR). The total resistance is dependent on many parameters such as the cross-sectional area of the conductor, resistivity and the length of the wire as well. From Australian standard, the voltage drop is specified to be less than 5% [56]. The voltage drop is met in sizing of cables. In DC cable sizing, the voltage drop is calculated using the following equation:

$$V_{DropDC} = \frac{2.L_{DC\ cable}.I_{DC}.\rho}{A_{DC\ cable}} \quad 2.1$$

Where: $L_{DC\ cable}$ stands for the length of m of the DC cable of one way, I_{DC} is the DC current in the cable at the worst-case scenario, ρ is the wire resistivity expressed in (Ω.mm^2/m) and $A_{DC\ cable}$ is the cross-section of the DC conductor expressed in (mm^2).

d. Temporary Shading

It is obvious that PV systems generate electricity based on the amount of sunlight they are receiving. The typical temporary shading may come from nearby trees or surroundings, snow and bird droppings. The shading on PV panels reduces the system performance significantly. Shading one panel can reduce the performance of the array once PV panels are connected in series which means that shading one panel of PV system connected in series affect the output of all panels as if they are all shaded [57]. Practically shading cannot be avoided completely but looking the way to reduce it as much as possible. There are two ways in which the shading effects can be estimated. The first one is by looking at the percentage of the sky blocked by the nearby obstacle. The second one is looking at the spatial movement of shadow from the surrounding or obstacle as it moves across the panels during the day [57].

e. Corrosion

More than 25 years in the field is the time that PV modules are designed to operate for and mounting PV systems, there is a need for mechanical fittings which are more exposed to different weather conditions. In the fittings, low steel quality and a combination of different metals may increase the risk of corrosion [55]. The location of the PV systems plays an important role on the exposition of the system to the corrosion. Several types of corrosion are available but the galvanic corrosion has been found mostly affecting PV plants [58]. This type of corrosion happens between two pieces of different metallic elements. Mostly on a PV system, fixing points is more affected by corrosion but there are some proposed guidelines that may prevent that effect such as [59] choosing metals to close together and avoiding threaded joints for elements in the galvanic series when mixing metals; between dissimilar metals, the contact area should be minimized and coating or insulation should be applied to dissimilar metals.

f. Grounding

Ensuring the safety of the public during the installation's decades-long life, PV power system should be grounded properly. Even though for that period of time, all components of the PV system may not fully be functioning but to avoid any danger that may result from produced currents and voltages proper grounding is required. In electrical and PV systems, there exist two types of grounding such as equipment grounding and system grounding [60].

Equipment Grounding

Apart from the United States, the rest of the World defines equipment grounding as safety grounding or protective earthing. In United States, the equipment grounding system bonds all exposed non-carrying metal parts of the electrical system together and then connect them to the ground [60]. Once that bonding is properly done, the potential difference reduces to near zero between the earth and conductive surface.

System Grounding

In the system grounding type, the current-carrying conductors also known as a grounded conductor is bonded to both equipment grounding system and earth. This grounding is also known as a functional grounding in the rest of the world apart from United States [60].

2.4.3.5 Biomass Energy

2.4.3.5.1 Status of Biomass in Rwanda

In Rwanda, talking about biomass energy easily one may understand cooking energy and boiler fuels. In another form, it is understood as a source of power generation and transport fuel but to a lesser extent. In Rwandan households and some industries, biomass resources are exploited in form of firewood, charcoal or agricultural residues mainly for cooking purposes. The use of biomass resources is more in rural areas of the country [15].

In Rwanda, the vast majority of rural households about 99.5% (firewood dominant by 82.41% of households and charcoal 14.77%) have been reported using traditional wood fuel and or its derivatives as a source of energy for cooking [61].

It is estimated that a rural-based family consumes an average of 1885 kg of fuelwood annually while the charcoal consumers stand to 565 kg per family yearly. For urban families, the annual consumption of fuelwood is 1891 Kg while charcoal use stands at 771 Kg yearly per one family. Countrywide biomass consumption was about 4,754,871,603 Kg equivalent to 4,755 Million of tonnes or 6,792,674 m^3 [61].

About 80% of the country's firewood and charcoal comes from privately operated plantations of the type of eucalyptus trees and a small agroforestry programs [28]. There are a big number of farmers that dedicate a small portion of their land to eucalyptus trees for self-consumption and it has been noticed that much of that wood is mostly used for construction than as energy. The use of charcoal is more found in households of urban areas in Rwanda. Due to the increase in biomass consumption, the government is putting much effort into looking at other forms biomass such as papyrus, rice and coffee husks and biogas by promoting the program of "one cow per poor family" [28]. Not only that but some other measures have been put in place to reduce and prevent the cutting of trees.

I. Improved cooking stove technologies in Rwanda

According to the survey conducted in 2012, it has been indicated that an average of 72.6% of rural households use improved cookstoves where the use of improved wood stoves counted 21.9%, use of improved mud stoves counted 30.3%, 8.5% use of single metal charcoal stove and 2% use of canmakeivuguruye [61]. 27.4% of the households in the rural area are still using three stone cooking practice. 26.93% of urban households use single pot metal charcoal stove, 20% use fixed improved mud stove, 2.20% use portable improved mud stove and 2.03% canmakeivuguruye. The survey indicated that the use of LPG stove is 1.42% in urban area, 0.47% use of kerosene stove while the use of electric stoves is at 0.63% [61]. For the case of Kigali, the main fuel for cooking is charcoal at the rate of 65% followed by 32 % of fuelwood and 0.9 % of electricity and 1.4% of LPG be used.

Three districts of Kigali namely Kicukiro, Nyarugenge and Gasabo use the above-mentioned fuels differently. Kicukiro and Nyarugenge use charcoal dominantly by 81% and 72% respectively while Gasabo accounts 41% use of that fuel. Outside of Kigali, the capital city of the country, the other urban towns in the country use charcoal at 50.8% and wood fuel at 45.9% which is higher compared to the Kigali one. While in those towns the use of electricity and LGP stand to 0.1% and 0.8% respectively [61].

II. Biogas

The market of biogas in Rwanda is estimated to 150000 households where rural customers are dominating. Household, schools, and prisons are the more targeted by the government for disseminating biodigesters. Through the National Domestic Biogas Programme (NDBP), 11 out of 14 prisons in Rwanda are currently using biogas for cooking. In addition to that 3687 domestic biogas digesters have been installed in households and 68 institutional biogas digesters have also been installed in schools and prisons [28]. The program continues and the government is subsidizing biogas technologies at the rate of 50%. That installed biogas in schools and prisons has reduced the use of firewood by 60% and 40% respectively.

III. Biofuels

In Rwanda, there are land shortages and the trade-off between bio-crops for fuel and food production challenges and growing bio-crops require enough area of land for a significant output to be produced. Biofuel has could play an important role by reducing the imported petroleum products by replacing that imported fuel with fuel produced from domestically harvested crops [28].

2.4.3.5.2 Worldwide biomass energy background

The energy that is quickly obtained from wood, twigs, Straw, dung and agricultural residues is known as biomass energy. It can be burned for heat purpose and electricity generation [62]. Additionally, it can be fermented to alcohol fuels; anaerobically digested to produce biogas, and high-energy gas through gasification technology.

Biomass is a multiple purpose dependence summarized in six “fs” such as food, feed, fiber, fuel, feedstock, and fertilizer [62]. Worldwide, the biomass fuels find applications in so many things like being used in households, some institutions, bakeries, restaurants, and industries for cooking. Biomass energy serves 35 per cent of the world’s population energy needs to its three to quarters in its traditional forms. In developing countries, it still dominates between 60 to 90 percent compared to the other source of energy [62]. Some basic definitions from [61] that anyone should understand before detailing biomass energy are:

a. **Agrofuels** is a term that covers biomass materials derived from fuel crops and agricultural, agroindustrial and animal by-products. "FAO definition".
b. **Animal waste:** manure from animals such as dung, feces, and slurry.
c. **Bagasse** is defined as fibrous residue obtained after the extraction of juice from sugarcane. It has application in electricity generation, production of ethanol, paperboard, pulp and paper and so many. By weight, it constitutes 50 per cent of cane stalk and it varies from 6.4 to 8.60 GJ/T of calorific value.
d. **Biofuels** is a term used to indicate any product produced organic matter directly from plants or indirectly from commercial, industrial, domestic or agricultural wastes. That product could be solid, liquid or gaseous.
e. **Biogas** is fuel produced in the absence of oxygen from the microbial decomposition of organic matter. It mainly constitutes with a mixture gaseous of methane and Carbone dioxide.
f. **Biomass** is the organic material that is derived from biological systems. Although fossil fuels originate from biomass-based sources they are not included in biomass. Biomass is in two categories, woody biomass, and non-woody biomass.

There is no clear difference between those two categories but trees and Forest's residues excluding leaves are called woody biomass. It includes also shrubs, bushes and agricultural crops by means of cassava, cotton and coffee stems while non-woody biomass mostly agricultural crops, shrubs, and herbaceous plants.

g. **Bioenergy or Biomass Energy:** a term covering all forms of energy derived from biofuels or organic fuels of biological origin used for energy production. It can either be biomass energy potential or biomass energy supply.
h. **Woodfuels:** cover all types of biofuels directly or indirectly derived from trees and shrubs that have grown in the forest and non-forest lands. Biomass-derived from

silvicultural activities, harvesting, and logging by means of tops, roots and branches and industrial by-products from primary and secondary forest industries are all included in woodfuels. Fuelwood or firewood, charcoal, black liquor and other all the compositions of woodfuels.

a. Worldwide biomass potential

Biomass resources are the world largest and most sustainable energy source. Additionally, biomass is an infinite potential and renewable resource. The complex nature of biomass production and use, the large range of conversion technologies, as well as ecological, social, cultural and environmental considerations, are the factors that make quantifying the biomass potential so difficult. Despite all those factors and others, some researchers had come up with an estimated biomass potential [63]. The estimated annual biomass primary production is of 200 dry tonnes or about 45000 petajoules (EJ). The estimated annual bioenergy potential is about 2900 petajoules (EJ), that potential includes approximately 1700 petajoules (EJ) coming from forests, 850 petajoules (EJ) from grasslands and 350 EJ from agricultural areas [64]. Theoretically, the energy farming in the current agricultural land could contribute over 800 EJ without affecting the world’s food supply [64].

b. Bioenergy classification

Based on FAO, bio energy is classified into three main groups such as wood fuels, agrofuels, and urban waste-based fuels. While biomass is classified into two groups such as traditional bioenergy that includes firewood, charcoal and residues and modern biomass that includes industrial wood residues, energy plantations and use of bagasse. Table 2.8 [62] summarizes the biofuel types. The term ‘by-products’ used in the 2.8 table includes solid, liquid and gaseous by-products derived from human activities.

Table 2.8: Biofuel classification scheme

Production side, supply	**Common group**	**Users side, demand examples**
Direct wood-fuels	Wood fuels	Solid: fuelwood (wood in the rough, chips, sawdust, pellets), charcoal
Indirect wood-fuels		Liquid: black liquor, methanol, pyrolytic oil
Recovered wood-fuels		Gases: products from gasification and pyrolysis gases of above fuels
Wood delivered fuels		
Fuel crops	Agrofuels	Solid: straw, stalks, husks, bagasse, charcoal from above biofuels
Agricultural by-products		
Animal by-products		Liquid: ethanol, raw vegetable oil, oil diester, methanol, pyrolytic oil
Agro-industrial by-products		Gases: biogas, producer gas, pyrolysis gases from agrofuels
Municipal by-products	Municipal by-products	Solid: municipal solid waste(MSW)
		Liquid: sewage sludge, pyrolytic oil from MSW
		Gases: landfill gas, sludge gas

c. Bioenergy applications

Traditionally, biomass is used in its natural state ("raw"), though the traditional use presents some disadvantages. Some are inefficient, wasting much energy and significant negative impacts on the environment and the users as well. It has been estimated that depending on the source, the use of biomass traditionally varies from 700 Mtoe to 1200 Mtoe. In many developing countries such as Burundi, Ethiopia, Mozambique, Nepal, Rwanda, Sudan, Tanzania and Uganda, about 80 to 90 per cent of energy comes from biomass [65]. Between the year of 1980 and 1997, the consumption of traditional bioenergy has been increasing in both industrial countries and developing countries due to many factors [62].

Deliberating policies supporting renewable energies and lower growth in energy demand have increased the mentioned consumption in industrial countries. Low energy consumption, the desire to move from traditional bioenergy and rapid energy demand has contributed to that increase of bioenergy consumption in developing countries. Modernization use of biomass is based on technologies such as gasification, pyrolysis, and combustion. And that find applications in the household example of the improved cooking stove, use of biogas and ethanol; brick-making, bakeries, ceramics, and tobacco curing in small cottage industrial applications and CHP and electricity generation in large industrial applications [65]. The World counts over 40 GW of installed electricity generated from biomass and is still growing where China and India are leading [66]. Transport sector plays an important role in rapidly increasing applications due to ethanol and biodiesel use. Those biomass by-products are the best alternatives to petrol and diesel highly dominate that sector.

2.4.3.5.3 Assessment of Biomass method

Bioenergy plays an important role in the daily living of people in different ways; there is a big problem in measuring the consumption and supply of biomass. Those problems are due to some causes such as multiple uses of biomass, difficulties in measuring biomass physically and use of many units for biomass measurements. Avoiding pitfalls during biomass assessment, there are general considerations to note down depending on the purpose for which the data are intended, the detail required and available information for a particular country, region or local site [62]. The following are the steps to follow during biomass assessment: clearly Defining the purpose and objectives, identifying the audience, determining the level of detail, classifying biomass type, identifying critical areas in biomass supply and demand, quantifying existing data through literature, determining methods of measurements either by volume, weight or length, etc.

2.5. Fuel cell and hydrogen

For the 21st century, fuel cell and hydrogen are being seen as key solutions that enable the clean efficient production of power and heat from a range of primary energy sources. In Europe, both hydrogen and fuel cells technologies were initiated in 2002 by many Mr. Philippe Busquin, the vice president of the European commission, Loyola de Palacio, Commissioner for energy and transport, commissioner for research [72].

2.5.1 Fuel Cell

A fuel cell is a device that directly converts chemical energy into electricity by electrochemical reaction with water and heat as its by-product. A fuel cell is like a battery though as long as the hydrogen and oxygen are the sources and by using an external supply of chemical energy. A fuel cell can run indefinitely while a battery discards and recharges by using an external supply of electricity to drive the electrochemical reaction in the reverse direction [72]. Generally, the source of hydrogen is referred as a fuel and hence gives the fuel cell its name. It could play a role in accelerating the transition from established world to the new, clean and more efficient technology thus it is viewed as a disruptive technology.

Fuel cell systems operate at different temperature levels from room temperature up to 1000^{o}C. Apart from hydrogen also other fuels such as natural gas or methanol can be used as sources of fuel cells. They have a wide range of applications from small portable electronic devices to large stationary applications and have application in the transport sector as well. There are benefits associated with fuel cells such as low or zero emissions, high flexibility and reliability and ease of maintenance. Though they are not yet fully commercial and much effort on fuel cell is more needed in research, development, and manufacturing for reduction of current high costs [72]. A fuel cell is available not only for large power plants producing megawatts but also for tiny devices that produce few watts of electricity. By its design, a fuel cell is made of two electrodes separated by a solid or liquid electrolyte that carries electrically charged particles between them. To speed up the reactions, a catalyst is used.

The nature of the used electrolyte determines the type of fuel and each type requires particular fuel and materials and is used for different applications.

2.5.1.1 Working Principal of Fuel cell

A fuel cell is a device converting chemical energy stored in gaseous molecules of fuel and oxidant into electrical energy. The process is the reverse of water electrolysis. During the electrolysis process, hydrogen and oxygen are produced when an electric current is applied to water while the reverse process, those gaseous hydrogen and oxygen are combined to produce electricity, water, and heat. The hydrogen or any other hydrogen-rich fuel is fed to the anode with catalyst separates hydrogen's negatively charged electron from positively charged ions or protons. In some cases, at the cathode side, oxygen combines with electrons and with species such as protons or water which results in water or hydroxide ions respectively [74]. Figure 3.1 [73], shows a block diagram of a fuel cell. The movement of electrons via an electrical circuit to reach the other side of the cell is an electric current. The type of fuel cell, the cell size, operating temperature and the pressure at which the gases are supplied to the cell are the factors that determine the amount of power produced by a fuel cell. The half-cell reactions occurring at anode and cathode are:

$$H_{2=}2H^{+} + 2e^{-}$$

$$1/_2\, O_2 + 2H^{+} + 2e^{-} = H_2O$$

The overall combustion reaction is given by a combination of those two half-cell reactions

$$H_2 + 1/_2\, O_2 \rightarrow H_2O$$

The two half-cell reactions must be insulated electrically in a strict sense by an electrolyte which is both good proton conductor and electric insulator by allowing the ionic passage of protons produce at the anode to the cathode side and combine them to form a molecule of water.

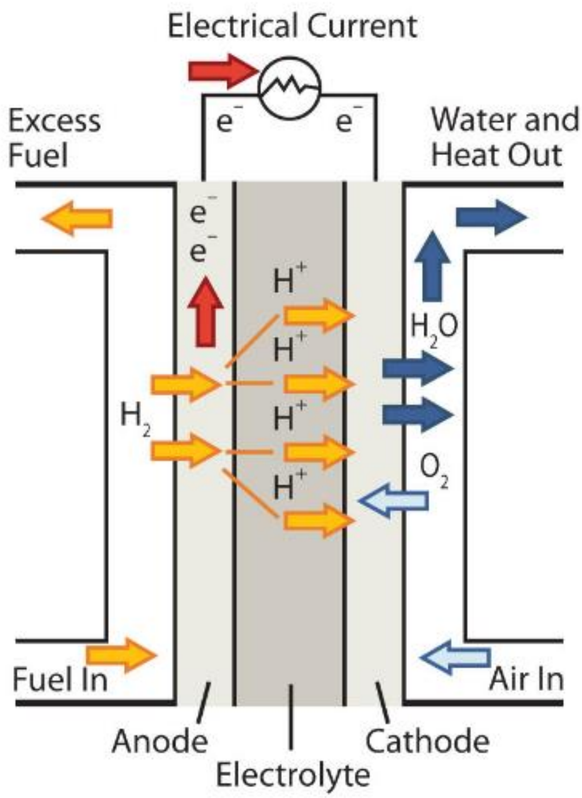


Figure 2.9 Block diagram of a fuel cell

2.5.1.1 Applications of Fuel cells

Fuel cells have an advantage of being flexible in sizes that could be used in applications with a need for wide range of power. As described in above section, fuel cells find application either in systems of few watts or megawatts.

a. Portable applications ranging from 0.1 up to 100W

This sector holds the future markets of fuel cells. The use of fuel cells could power portable devices for longer amounts of time as long as the fuel is supplied. Those devices include laptops, video recorders, iPods, cell phones etc. Compare to the battery technologies in today's portable devices, fuel cells present significant improvements. They have a higher energy density than batteries, which helps to provide more energy per unit of weight up to five times more with equivalent power.

Portable fuel cell systems with fuel container can be designed smaller and lighter compare to portable with batteries. For portable fuel cells, no time-consuming recharge and associated logistics also have less degradation of the components [75].

b. Transport applications

For vehicles such as passenger cars, light-duty vehicles, and buses, hydrogen is generally considered the most likely fuel for fuel-cell powered electrically. Without compromising comfort fuel cell vehicles could have very low fuel consumption. Using fuel cell in transport could further reduce emissions annually. Compare to the vehicles powered by other fuels, the fuel cell vehicles allow a range of power use in smaller vehicles and have the ability to be more fuel-efficient. Compare to the other fuel vehicles, fuel-cell vehicles are immature technology and more expensive though with studies conducted by car manufacturers, there will be a cost-competitivity for mass production manufacturing techniques [75].

c. Stationary applications

Stationary applications are the most diversified category among fuel cell applications. This category ranges from kW to multi MW and several types of fuel cells are eligible and a large spectrum of fuels is available. Large stationary fuel cells are used to produce electricity for powering a house; business or selling it back to the grid. Under this category, Phosphoric Acid Fuel cells (PAFC) were the first fuel cells tested on-site and about 200 kW modules have been commercialized by UTC fuel cells in Japan, USA, and Europe since the 1990s. While other types of fuel cells are under late stage development in the stationary sector [75].

2.5.1.2 Fuel cell types

Classifying the fuel cells mostly depends on the type of electrolyte used and that determine the chemical reactions taking place in the cell. Additional to the electrolyte, other factors that determine the fuel types are the catalysts required, the operating range temperature, type of fuel required and etc. Table 2.10 [76] summarizes the types of fuel cells based on the type of electrolyte.

Table 2.9: Fuel cell types based on electrolyte type

Fuel cell Designation	Electrolyte type	Temperature Range(C)	Cell Efficiency (partial load)	Type of applications
Alkaline Fuel cell (AFC)	Aqueous KOH	60-90	50-60	Mobile, stationary
Polymer Electrolyte Fuel cell (PEFC)	Polymer electrolyte Membrane	50-80	50-6	Mobile
Direct Methanol Fuel Cell (DMFC)		110-130	30-40	Stationary
Phosphoric Acid Fuel cell (PAFC)	H_3PO_4	160-220	55	Stationary
Molten Carbonate Fuel cell (MCFC)	Alkaline carbonates	620-660	60-65	stationary
Solid Oxide Fuel Cell (SOFC)	ZrO_2	800-1000	55-65	Stationary

Apart from the mentioned types of fuel cell-based on electrolyte types, there are the ones based on fuel type and oxidant including hydrogen (pure)-Oxygen (pure) fuel cell, hydrogen-rich gas-air fuel cell, ammonia-air fuel cell, synthesis gas-air fuel cell and hydrocarbon (gas)-air fuel cell [74].

2.5.2 Hydrogen

Hydrogen is an energy carrier like electricity. Chemically its symbol is H, and it is considered as the simplest element on earth. An atom of hydrogen is constituted with one proton and one electron. Hydrogen exists as a gas at standard temperature and pressure. Each molecule of hydrogen gas has two atoms of hydrogen and commonly expressed as “H_2”. It is also found as part of other substances such as water, natural gas, and biomass. Hydrogen is odorless, tasteless, colorless and lighter than air [77]. Initially, it is produced using existing energy systems based on different conventional primary energy carriers and sources hence Hydrogen is not considered a primary energy source like coal and gas.

It has potential to provide clean, safe, affordable and secure energy from existing domestic resources. Figure 2.10[78], shows the life cycle of Hydrogen by considering renewable energy sources as a primary source of hydrogen.

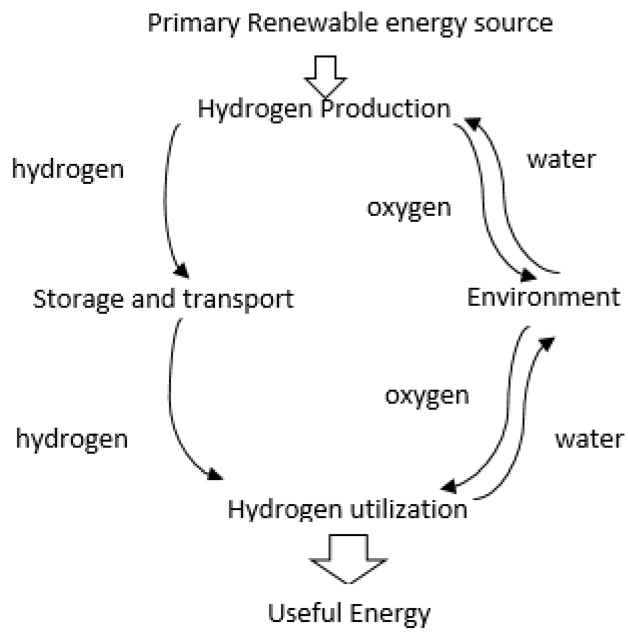


Figure2.10: Hydrogen life cycle

2.5.2.1 Hydrogen production

The hydrogen makes about three-quarters of all matter. On the earth's surface, there is about 0.14 percent of hydrogen and mostly resides in a chemical combination with oxygen and form water [79]. The sources of hydrogen are hydrocarbon (fossil) fuels ($C_x H_y$) and water (H_2O). Currently, the hydrogen is produced from fossil fuels such as natural gas, oil, and coal. Only for space program hydrogen is directly used as an energy carrier or a fuel. In 1996, the total production of hydrogen worldwide was about 40 million tonnes equivalent to 5.6EJ. Ten percent of that production was supplied by industrial gas companies while the rest were produced at consumer-owned and operated plants [79]. As mentioned above, large-production of hydrogen finds its logical source in water which is abundant on the Earth. Generally, hydrogen production technologies are classifying into three categories including thermal, electrolytic and photolytic processes [78].

Thermal processes include natural gas reforming, gasification, renewable liquid reforming and high-temperature water splitting while photolytic processes include photobiological water splitting and photoelectrochemically water splitting. Electrolysis, direct thermal decomposition or thermolysis, thermochemical and photolysis are the different methods for hydrogen production from water [79]. Hydrogen can be produced by photosynthesis or photoconversion process using the sunlight directly [80]. Figure 2.11[80] describes the principal production of hydrogen.

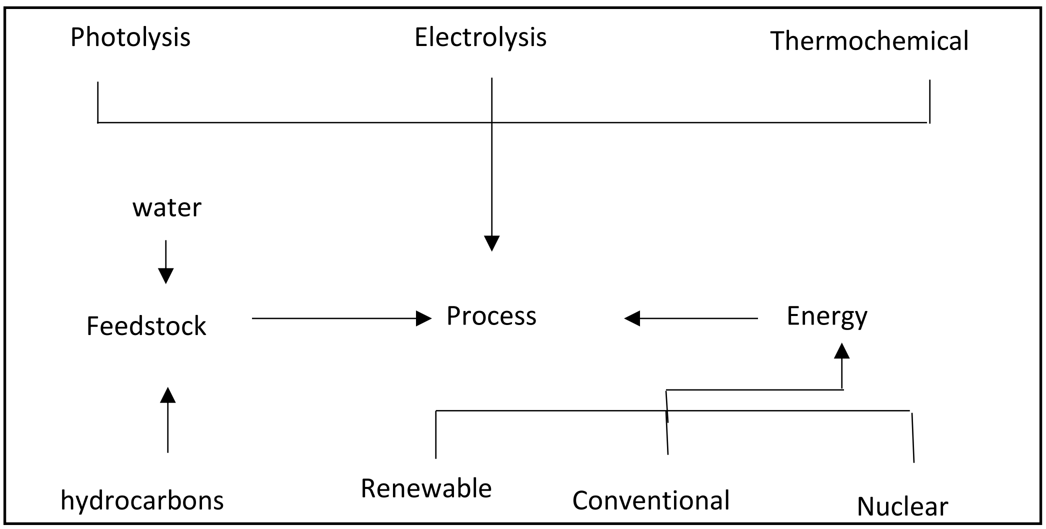


Figure2.11: Principle of hydrogen production

a. Electrolysis

In a post-fossil fuel era, this method is the only developed to date and can be used for large-scale hydrogen production. This technology uses electricity to split water into hydrogen and oxygen in an Electrolyzer unit and this is considered as a mature technology, very efficient and does not involve moving parts. The following are the reactions happening at the electrodes of an electrolysis cell using an aqueous solution of KOH or NaOH or NaCl the suitable electrolyte [81].

Cathode reaction:

$$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$$

Anode reaction

$$2OH^{-}(aq) \rightarrow {}^{1}\!/_{2}\, O_2(g) + H_2O(l)$$

Overall reaction

$$H_2O(l) \rightarrow H_2(g) + O_2(g)$$

At standard conditions, the reversible decomposition potential of the above reaction is 1.229V. Theoretically, the water decomposition potential is 1.480V which corresponds to hydrogen's enthalpy. Including the electrical resistance and due to the irreversibility processes occurring at cathode and anode, the potentials always vary from 1.75 to 2.05V and that corresponds to 72-82 per cent of efficiencies [79]. Advanced Electrolyzer technologies that are being developed include alkaline electrolysis which improves efficiency up to 90 percent from employing materials for membranes and electrodes [82-81]; solid polymer electrolytic process(SPE) employing a proton-conducting ion exchange membrane as electrolyte and as membrane separating the electrolysis cell [79,83] and temperature steam electrolysis operating at temperature ranging from 700 to 1000^{o}C and employs oxygen ion-conducting ceramics as electrolyte [83]. Electrolysis plant makes an interesting couple with renewable energy sources especially Photovoltaics (PV) as the latter generates a low voltage direct current which exactly fits with electrolysis process requirement and further studies have been performed on photovoltaic-Electrolyzer systems [79].

b. Thermolysis

The thermolysis process is also known as thermal decomposition of water. At a temperature above 2000K, this process thermally splits water and the following is the dissociation reaction of water [79] which gives the mixture of gaseous as a product at extremely high temperatures. When the hydrogen is produced thermally at lower temperatures, the process is called thermochemical process.

$$H_2O \rightarrow aH_2O + bOH + cH + dO + eH_2 + fO_2$$

c. Photolysis

Direct extraction of hydrogen from water using only sunlight as an energy source is known as photolysis. The process can be accomplished through the employment of photobiological systems, photochemical assemblies or photo electrochemical cells [84]. Research activities are ongoing for photo-conversion into hydrogen.

d. Hydrogen production renewable energy

Apart from conventional and nuclear energies, hydrogen can be produced with any type of renewable energy which may be a solution to problems related to use of conventional energy [85]. Figure 2.12 [80] presents the methods and processes for producing hydrogen using renewable energy. For supplying power for electrolysis and pumping water needed by the Electrolyzer, the wind can be used as an energy vector [80]. Additionally, Electricity generated from geothermal can be used as a source of hot water for Electrolyzer. By a pyrolysis or gasification processes, hydrogen can be obtained from biomass [86]. By oxidizing and decomposing biomass, a product consisting of hydrogen, methane, CO_2, CO, and nitrogen is produced. Except for the unit for pretreatment of biomass and the design of the reactor, the system is much similar to a coal gasification plant. Compare to coal, the calorific value per unit volume of biomass is lower thus the processing facility is larger [79].

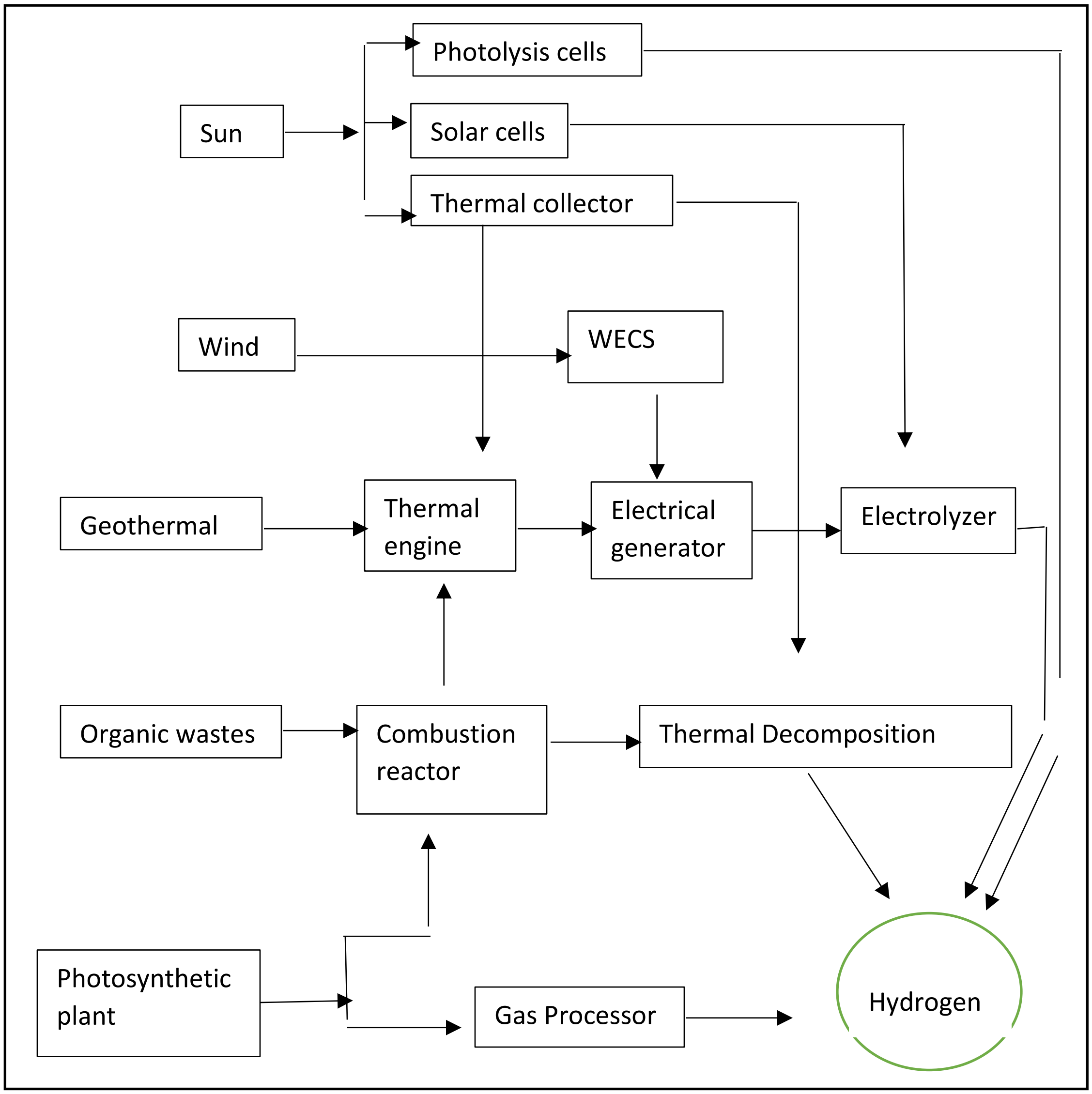


Figure 2.12 Principal techniques for hydrogen production using renewable energy

2.5.2.2 Hydrogen Storage Technologies

The hydrogen is an energy carrier that needs to be stored to overcome daily and seasonal discrepancies between the available energy source and the demand. There are different types of storage depending on their size and applications. Storage devices are at the production site at the start or end of the pipelines and transportation pathways known as stationary large storage systems.

The stationary small storage system is in the distribution or final user level, mobile storage systems for transport and distribution for both large-capacity devices. Additional to those mentioned types, there are vehicle tanks for storing hydrogen to be used as fuel for road vehicles [79].

a. Gaseous hydrogen storage

This storage method is a traditional way of storing hydrogen. Basically, hydrogen behaves very much like an ideal gas in the ambient temperature thus it satisfies the following ideal gas law: PV=nRT where n is the amount of hydrogen in moles and R being the gas constant [73]. This technology stores gases in pressure vessels up to 300 bars (30 MPa). The expansion during the filling process of a pressure vessel from a reservoir and compression are of thermodynamic interest and methods of this technology. This technology is also applicable in tank systems and high-pressure infrastructures.

b. Liquid Storage

Liquid hydrogen (LH_2) also referred as cryogenic hydrogen is denser than gaseous hydrogen and has higher energy content on a per-unit volume basis. Its volumetric density at normal boiling point (-253^{O}C) is of 70.8 kg/m^3, at that boiling point gaseous hydrogen can be converted to a liquid and must be stored in insulated pressure vessels to minimize hydrogen loss through evaporation or boil-off [77]. For the system to be cost-effective and energy-efficient the energy requirement for hydrogen liquefaction is high and must boil-off must be eliminated or minimized. Liquefaction, thermodynamic analysis, tank systems and distribution facilities are the methods under this storage technology [86]. Due to its high volumetric density of 70.8 kg/ m^3 hydrogen in a liquid form is widely used as a principal fuel in space programs and has been demonstrated in commercial vehicles particularly by BMW [74].

c. Storage in materials

Hydrogen atoms or molecules are tightly bound with other elements in a compound or storage material that makes possible to store larger quantities in smaller volumes at low pressure and near room temperature.

Within the structure or on the surface of certain materials as well in the form of chemical compounds undergoing a reaction to release hydrogen, the latter can be stored [78]. Storing hydrogen in materials occur via absorption and adsorption in which hydrogen is directly absorbed into the storage media and stored on the surface of storage media or chemical reaction respectively. Metal hybrids, carbon-based materials or high surface area sorbents, chemical hydrogen storage and new materials and processes are the general categories by which grouped the mechanisms that materials used for storing hydrogen could employ [77]. Table2.11[87] summarizes the six possible methods that can be used in order to reversibly store hydrogen. The following symbols are to mean: ρ_m stands for gravimetric density, ρ_v stands for the volumetric density, T is for the working temperature, P for pressure and RT stands for room temperature (25^{o}C).

Table 1.10 Basic hydrogen storage methods and phenomena with their characteristics

Storage method	ρ_m(mass%)	ρ_v(kg H_2m^{-3})	T(^OC)	P(bar)	Phenomena and remarks
High-pressure gas cylinders	13	<40	RT	800	Compressed gas (molecular H2) in lightweight composite cylinder (tensile strength of the material is 2000 MPa)
Liquid hydrogen in cryogenic tanks	Size-dependent	70.8	-252	1	Liquid hydrogen (H_2). continuous loss of a few % per day of hydrogen at RT
Adsorbed hydrogen	≈2	20	-80	100	Physisorption (H_2) on materials. E.g. carbon with a very large specific area, fully reversible
Absorbed on interstitial sites in a host metal	≈2	150	RT	1	Hydrogen (atomic H) intercalation in host metals, metallic hybrids working at RT are fully reversible
Complex compounds	<18	150	>100	1	Complex compounds ($\|AIH4\|^-$ or $\|BH4\|^-$), desorption at elevated temperature, adsorption at high pressures
Metals and complexes together with water	<40	>150	RT	1	Chemical oxidation of metals with water and liberation of hydrogen, not directly reversible

2.5.2.3 Applications of hydrogen

Hydrogen has application in industry as a chemical product and in the energy sector as a source of energy.

a. Hydrogen in industry

Almost the entire application of hydrogen is found in chemical and petrochemical industry needs. More than 95% of available hydrogen is used in the production of ammonia and oil refining [88]. While the rest is shared in various applications including: glass industry, manufacturing of semiconductors, welding, and food industries.

b. Hydrogen in energy

In the energy sector, the use of hydrogen is still at prototype and experiment stages but it is being used as a sole fuel in aerospace propulsion [80]. In industrial and transport sectors, hydrogen can be used in thermal engines. Hydrogen and fuel cells are used in energy storage and energy generation respectively.

2.6 Introduction to software

This work of evaluating of a hybrid solar-biomass system for powering remote area in Rwanda will need the use of MATLAB and homer software for data computation and design purposes.

2.6.1 Introduction to MATLAB software

The word MATLAB stands for Matrix Laboratory. It is a programming package that specifically designed for quick and easy scientific calculations and Input/output. It handles also simple numerical expressions and mathematical formulas [67]. Worldwide, it is now considered as a standard tool for universities and industries and commercially available since 1984 [68]. MATLAB has literally hundreds of built-in functions for a wide variety of computations and many toolboxes designed for research disciplines such as statistics, solution of partial differential equations, data analysis and optimization [67]. Some factors such as sophisticated data structures that contain built-in debugging tools, editing and supports object-oriented programming make MATLAB an excellent tool for teaching and research. Compare to conventional computing languages like C, FORTRAN, MATLAB has many advantages for solving technical problems [68].

2.6.2 Introduction to HOMER software

The word HOMER stands for Hybrid Optimization Model for Electricity Renewables. It is a free software application developed by the National Renewable Energy Laboratory in the United States (NREL). It was developed in 1993 to understand the tradeoffs between different energy production configurations for the use of internal Department of Energy (DOE). The use of this software is to design and evaluate the options for both off-grid and grid-connected power systems for remote areas, stand alone and distributed generation applications both technically and financially [69]. HOMER simulates different configurations renewable energy sources (RES) and scales them on the basis of net present cost which is the installation and operating total cost of the system over its lifetime [70].

2.6.2.1 HOMWER working principle

In the year, each of the 8760 hours, HOMER stimulates the operation of a system by making energy balance calculations. It performs these energy balance calculations for each system configuration that the designer or the user wants to consider. After that HOMER helps to determine the feasibility of a configuration by means of meeting the electric demand under the specified conditions lastly but not the least over of the project's lifetime, it estimates the cost of installing and operating the system [71].

2.5.4.2 Advantages and disadvantages of HOMER

Table 2.11[71] summarizes the advantages and disadvantages of HOMER software.

Table 2.11: Advantages and disadvantages of HOMER

Advantages	**Disadvantages**
Homer stimulates a list of real technologies as a catalog of available technologies and components.	Quality of input data is needed(sources)
HOMER provides detailed results for analysis and evaluation	Detailed input data and time are needed
It determines the possible combinations of a list of different technologies and its size	Experienced criteria are needed to converge to the good solutions
It is fast to run many combinations	HOMER will not guess the missing key values or sizes
You can learn from the results and optimize	You can lose yourself if you don't set the adequate questions

2.7 Summing up

This chapter has focused on Rwanda energy profile where the electricity profile has been detailed in its electricity generation, access and consumption, on and off-grid electricity status, rural electrification in Rwanda and the electricity tariff. Conventional energy resources and renewable resources have been discussed in this section, it also focused on the renewable of the chosen hybrid system by means of solar and biomass. This chapter also described the working principle, applications and different types of fuel cell, the hydrogen and its life cycle based on renewable primary resources, hydrogen production, hydrogen storage technologies and its applications are also part of this chapter. The last but not the least introduction to HOMER and MATLAB softwares have been discussed in this chapter.

Chapter 3. METHODOLOGY

Outline

3.1 Data collection

During this research, both primary and secondary data were collected from various sources. Rwanda meteorological agency provided solar radiation data from Rulindo station. Interviewing the family owned in kabasega village and the literature review.

3.1.1 Primary data collection

The primary data collected include the electrification status of the village, daily energy needs and the main activities of the village inhabitants. The latter helps to determine the type of biomass available in the village. All of those data have been collected through a conducted site visit. The questionnaires used are attached in the appendix section, appendix A.

3.1.2 Secondary data collection

This method was used to get solar radiation of the selected area that has been provided by Rwanda Meteorological station through Rulindo sub-station. Those data are collected each 10 minute daily, detailed data are attached in the appendix section, appendix B. Literature review was used to obtain secondary information such as consumption of specific appliances to determine the load profile of the village. It has been also used to extra information relevant to the study by reviewing reports, academic journals, and other scientific publications.

3.2 Case study

3.2.1 Description of the case study

The case study that has been selected for this research is the Kabasega village located in Gaseke cell, Mutete sector and Gicumbi district in the northern region of Rwanda. Gicumbi is one of the five districts of the northern province of the country. This district is bordered by Burera in its north, Gasabo, and Rwamagana in the south, Gatsibo and Nyagatare in East and Rulindo in Ouest [89]. The district is characterized by a relief with steep slopes and a mountainous topography character. Its geographical coordinates are coordinated are 1 °36'59’’south latitude and30° 7'16’’ in East Longitude.

The district has an area of 867 km^2 and is among most populated district with 367,871 of the population but with a low population density of 477 inhabitants/ km^2. The district is divided into 21 sectors, 109 cells and 630 villages [90]. Among those villages, Kabasega has been selected because it has the desired profile of being totally isolated with no connection to the electricity grid. All the population of the village lives in the rural area. The selected village has 892 inhabitants and 198 households.

3.2.2 Renewable energy resources in selected area

As mentioned in the previous sections the most available renewable resources in Rwanda are solar, hydro, biomass, and geothermal. The following is the case of Gicumbi District. In this district, there are rivers lying in the plains of floods in Mwange, Mulindi, Mutulirwa, Muyanza and Gaseke sectors. The last one Gaseke is the selected area of this research. Those streams or rivers some have permanent water flow that could allow irrigation once wetlands mastered the flow. Apart from hydropower resources the area has solar resources and biomass and the latter are the main composites of the proposed hybrid system, the more detailed are to follow:

3.2.2.1 Solar radiation potential of the selected area

For the case study, solar irradiation data were given by Rwanda meteorological agency. Solar radiation is the energy radiated from the sun in the form of electromagnetic waves, including visible and ultraviolet light and infrared radiation. Photovoltaic technology is used to generate electricity from that energy radiated from the sun. The given global solar radiation data were collected after 10 minutes daily and is expressed in W/m^2. From there, daily global radiation in $kWh/m^2/day$ was calculated using MATLAB. The latter is shown in the appendix section, Appendix B. Table 3.1 presents the monthly average global radiation calculated using the following formula:

$$H_M = \frac{\sum H_d}{N_i} [kWh/m^2/day] \qquad 3.1$$

Where H_M stands for monthly average global radiation, H_d: daily global radiation, Ni: number of days of the month.

Table 3.1: Monthly global radiation profile for the selected village

Month	**Average Solar radiation (kWh/m^2/day)**
January	4.01
February	4.45
March	4.93
April	3.9
May	4.32
June	4.58
July	5.05
August	5.42
September	4.73
October	4.84
November	4.17
December	4.99

3.2.2.2 Biomass potential of the selected area

About 94.8% of the population in the district relies on agriculture as the main activity. That dependency has contributed to nearly 85% of the total production in the district [90], thus biomass potential exists in abundant. The major crops in the area are wheat, sorghum, and maize as described by figure 3.1 [90]. In this Gicumbi District, about 65.9% households own farm animals. By considering the available resources, one can say that animal, human and agricultural wastes are in abundance in this area. For the case of Kabasega village considered as a case study its total population relies on agricultural where the main growing crops are sorghum and beans. Most of the family owns domestic animals mostly beef and goat and few of the families have chicken.

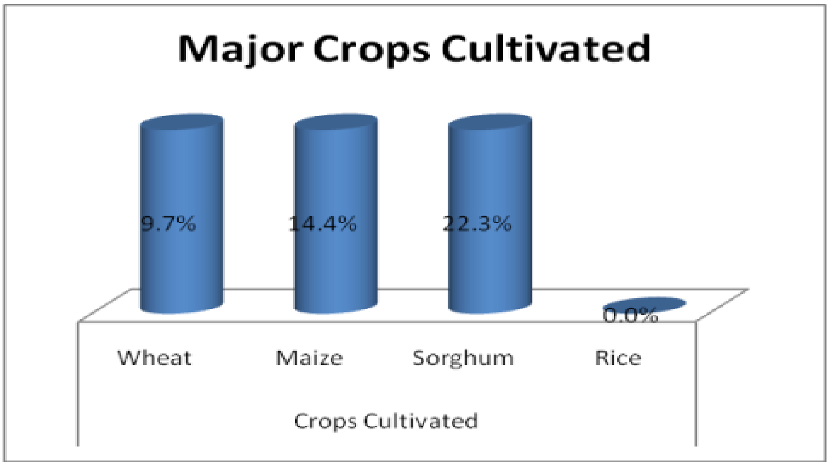


Figure 3.1: Main crops cultivated in Gicumbi District

The conducted survey in Kabasega village has come up with the estimated number of 150 beef, 70 goats, and 1000 chicken also known as poultry. By considering the residues of those domestic animals, the total biomass potential of the village is around 2 tonnes of dung per day and the volume of biogas is 90.74 m^3 which give daily electricity production of 194.1kWh by considering that 1m^3 of biogas generates 2.14 kWhel considering 35% of electrical conversion efficiency [91]. Table 3.2 details the daily manure production, which is the biomass potential of the selected village. Biogas (m^3/ kg) [92].

Table 3.2 Biomass potential for the selected village

Biomass source	Number (heads)	Daily manure production (kg/day)	Total available manure(kg/day)	Biogas (m^3/kg)	Volume of biogas (m^3)	Electricity (kWh)
Cattle	150	10	1500	0.04	60	128.4
Goat	70	2.6	182	0.07	12.74	27.26
Poultry	1000	0.3	300	0.06	18	38.52
Total			1982		90.74	194.18

3.2.3 Characteristic of load demand of the village

During the survey time, the whole village has been found isolated with no connection to the electricity grid and has no electricity.

50 households are using the solar home system for lighting purpose and each home cannot exceed 3 lamps. Other families use candles and torches for lighting their house. The survey helped to know the energy needs of the population of that village. Mostly their needs are classified in two categories such household load and public utilities consisting of nursery school, shops and hair salons. To determine the village load profile, the following are the assumptions 130 households will have access to electricity from the proposed hybrid system. 6 fluorescent lamps are considered (interiors and exteriors) and 2 cell phones per family. 80 televisions (19-inch color), 100 radios (clock radio), 10 fridges, 5 irons, 5 laptops are considered for the village. 2 hair salons with 1 lamp and 3 electric shavers each saloon and 5 small shops with 3 lamps each shop and a nursery school with 2 lamps. Table 3.3 summarizes the load profile of the village-based on their needs.

Table 3.3 Summarized Village Load Profile

Appliances	**Quantity**	**Pmax(W) AC**	**Total watts**	**Use (hr/day)**	**Use (day/week)**	**days of the week**	**Wattage (Wh/day)**	**kWh/day**
Television	80	100	8000	5	7	7	40000	40
Iron	5	1000	5000	0.14	1	7	100	0.1
Clock radio	100	2	200	6	7	7	1200	1.2
Laptop computer	5	100	500	3	5	7	1071.43	1.07
Electric shaver	6	20	120	4	6	7	411.43	0.41
Fridge	10	400	4000	24	7	7	96000	96
Cell phone charger	260	7	1820	3	7	7	5460	5.46
Lamp (interior)	665	20	13300	6	7	7	79800	79.8
Lamp(exterior)	135	20	2700	4	7	7	10800	10.8
Total			35640				243142.86	243.1

3.3 Solar PV system components

Generating electricity from energy radiated from the sun requires PV system and that system is generally constituted with panels or module, Charge Controller, Battery, and Inverter. The components vary depending on PV system types and those types are classified based on how the following questions one may know before choosing a system. It is important to know if the system will be connected to the utility's transmission grid, its output if it will either be alternating current (AC) or direct current (DC) or both. It is important also to know if the system needs a battery back-up or having diesel, gasoline or propane generator set as a back-up [93]. The present work considers fuel cell using hydrogen as a back-up no need of a battery.

Generally, PV systems are classified into two major groups such stand-alone system and grid-tired also known as utility-connected, grid-connected, grid- interconnected or grid-intertie systems. This research is focusing on a standalone system. This system is an isolated from electric distribution grid. The main components of this system are PV array, charge controller, inverter and battery bank as shown by figure 3.2[93]. Additionally, the generator could be considered to enhance the reliability when necessary, though the mentioned components may also be increased or decreased depending on the type of load to be served.

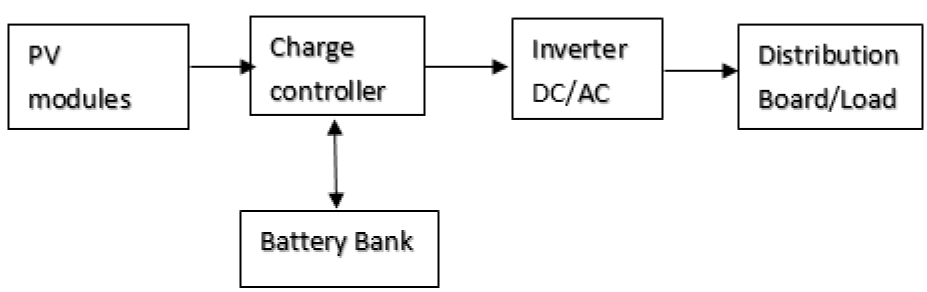


Figure 3.2: Stand-alone PV system

3.3.1 PV modules

A PV cell is the heart of a Photovoltaic system that directly converts the energy from the sun into electricity. As described in the previous sections, many photovoltaic cells electrically wired together by the manufacturer to form a solar PV module. The modules wired together in series form a string of modules and when the latter connected in parallel form an array for powering a wide variety of electrical equipment.

PV modules are manufactured with varying DC electrical outputs ranging from few watts to more than 100 watts [93]. Materials used for lamination, placement within the module and the efficiency of a cell all determine the overall efficiency of the module. A total irradiance of 1000 W/m^2 and an ambient temperature of 25^{o}C have defined as a standard Testing Condition (STC) to define module ratings. In crystalline technologies at STC, a typical module efficiencies range between 11% and 17% while a Thin-film module efficiencies range between 6% and 12% [95].

3.3.2 Charge controllers and balance of system components (BOS)

Charge Controllers control the current flow from the PV array to the battery in order to ensure proper charging and they are part of Balance of system components. Whenever energy produced exceeds the battery storage or load, these controllers disconnect the PV array from the battery and they extend the battery's life by stopping the flow when the loads have taken too much electricity from batteries until sufficient charge is restored to the batteries [93].

Commonly, for charge controllers to determine the depth of discharge, they monitor battery voltage, temperature or a combination of both. For residential and commercial installations, controllers are a safety requirement. Commercially, available controllers can achieve efficiency as high as 95% and can be adjusted to accommodate different battery types or built for specific battery technologies [93]. Charge controllers and other components all constitute a balance of system Components (BOS) and count 30 to 50% of total system costs. In order to properly install the PV system, it is necessary to consider all those elements [93].

3.3.3 Battery bank

Batteries store direct current electrical energy for later use. That means of electricity to be used during the night or meeting load requirements during the days when sufficient power is not being generated. Those days are called days of cloudy weather also known as “days of autonomy. Deep cycle batteries are required for a PV system to provide electricity over a long period. Types of batteries commonly used in PV systems are lead-acid batteries and alkaline batteries. The former is designed to discharge and recharge gradually by 80% of their capacity hundreds of times [94]. Sealed and flooded are two types of lead-acid batteries, flooded one is the least expensive though during normal charging process there is water loss and from there to replenish that lost needs to add distilled water at least monthly. Sealed batteries are more mostly used in grid-connected systems though require periodic maintenance [96]. Alkaline batteries are recommended for places with extremely cold temperatures from -50^{O}F or less and they are relatively high cost. Compare to Lead-acid, the former present advantages of tolerance for freezing or high temperatures, require low maintenance and have the ability of full discharged or over charges without harm [96].

3.3.4 Inverters

Inverters are required in AC systems for changing the produced DC electricity by PV modules and stored in batteries into AC electricity. Apart from converting DC into AC, inverters ensure the frequency of the AC cycles is 60 cycles per second, reduce voltage fluctuations. For grid-connected systems, inverters ensure that the shape of AC wave is appropriate for the application [96]. There are stand-alone inverters and grid-connected inverters. For proper operation, stand-alone inverters meant to operate isolated from the electrical distribution network and require batteries as they provide a constant voltage source at the DC input of the inverter. The grid-tied inverters operate coupled to the electric distribution network and must be able to produce perfect sinusoidal voltage and currents [93]. Load types and power requirements are the basis for choosing inverter type.

3.4 Biomass conversion technology

The end-user applications of the energy, physical condition of biomass and economics of completing process are the major factors determining an appropriate conversion technology. Direct combustion, thermos-chemical conversion, and biochemical conversion are three categories of biomass conversion technology [97]. Anaerobic digestion may be probably the best option when electricity and heat are the end use requirement by considering animal manures as feedstocks [98]. Though, gasification can be an option when electricity is the end use requirement. Figure 3.3[97], presents biomass conversion process.

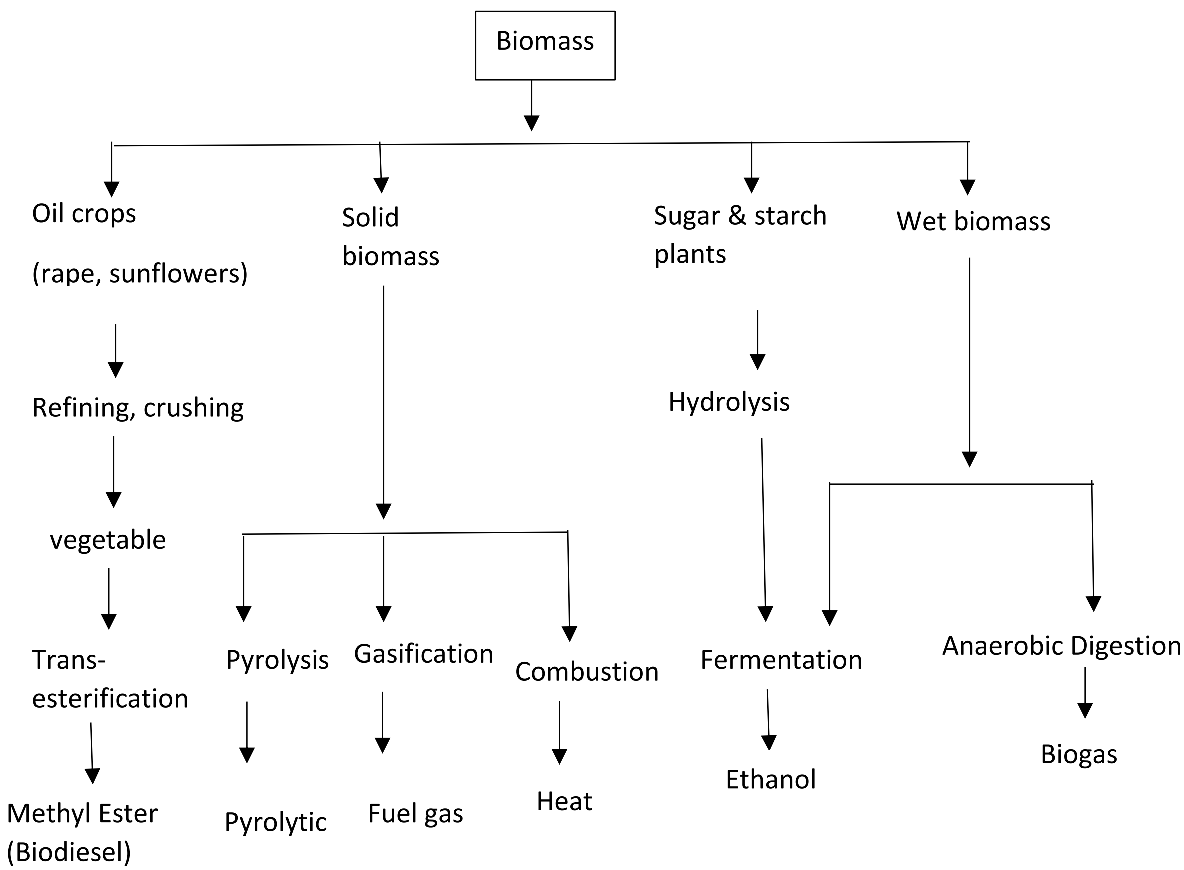


Figure 3.3: Biomass conversion process

3.4.1 Gasification

In this process, a combustible gas is produced by breaking down solid biomass using heat from outside of the system thus the reaction is endothermic. The produced gas is usually called “producer gas” [99]. H_2 and CO are the main combustibles gases and some small amount of methane, ethane, and acetylene.

The overall efficiency of gasification generally depends on the used gasifier, type of fuel and fuel physical property by means of its moisture content and geometry form [99]. The gas produced from gasification process can be used to produce heat, electrical or mechanical energy or being converted into methane and methanol substitutes. Figure 3.4 [99] summarizes the process of how electricity can be produced from biomass.

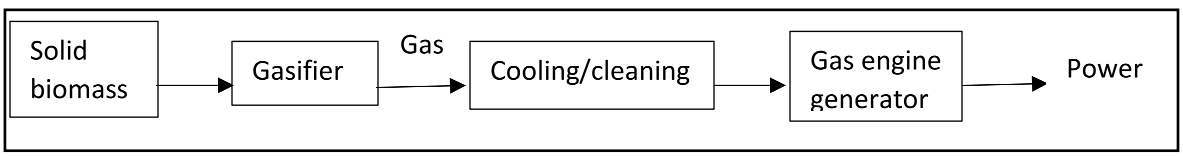


Figure 3.4: Biomass gasification process

Gasification conversion method presents advantages compare to another method including accepting various biomass materials as feedstock which makes it more flexible and its high thermos-chemical conversion efficiency of 70 % to 90% [99]. Per unit of output either heat or electricity requires a small area for gasification equipment and its output is a suitable fuel to all types of internal combustion engines at capacity derating to 15% up to 30% [100].

3.4.2 Anaerobic digestion

This method requires microbial digestion of biomass and the process takes place at a low temperature of 65^0C and at least 80% of moisture content [100]. The utilization of biomass with high moisture content up to 99% is one of the advantages of this process while its limitation is the dispose of a large quantity of wastewater after digestion. Typically, 30% up to 60% of the input solids are converted to biogas and byproducts including undigested fiber and various water-soluble substances during the anaerobic digestion. The produced gas could be used to generate heat and electricity at capacities up to 10MW(e).

An average of 0.2-0.3 m^3biogas is produced per kg of dry solids [99]. Any type of fresh manure with a solid content of less than 25% can be used in anaerobic digestion.

3.5 Hybrid system components specifications and estimated cost

By homer analysis, Solar PV and Biomass are considered the main resources and fuel cells will intervene for the emergency cases when those two sources are not supplying enough.

Hydrogen tank and the converter will be used for storing the excess of electricity and converting from one form of electricity to the other form (by means of AC and DC) respectively. The chosen hybrid system is AC coupled system where the generated DC from PV panel and FC are linked to the AC bus through inverter and AC sources are directed to the AC bus. This system can be easily expandable and is more flexible. For the optimization of cost results and design, the performance and cost of each component are so important.

3.5.1 PV Panels specification and estimated cost

As explained in the previous sections, PV is the heart of a Photovoltaic system that directly converts the energy from the sun into electricity. In this research, the derating factor and ground reflection considered are 80% and 20%. The panels have no tracking system and are modeled as the fixed latitude of the location with the slope of 1^0. The capital cost, replacement and operating and maintenance cost of PV panel took references [49], [101]. By default, the capital cost is equal to replacement cost. The costs are expressed in dollars. The lifetime of PV system has been set to 20 years.

3.5.2 Biomass generator specification and estimated cost

Through a gasification process, the biomass dung will produce biogas and that biogas will need a generator for electricity production. The initial capital cost of the biogas generator, its replacement cost and hourly operating and maintenance all in dollars. The rated intercept coefficient and slope output have been considered 0.0025 kg/hr kW and 0.852 kg/hr/kW respectively [49]. The expected lifetime considered is 40000 hours.

3.5.3 Converter specification and estimated Cost

A convert has an inverter and a rectifier for DC to AC conversion and vice versa. Its size is variable by referring to inverter capacity and rectifier capacity.The efficiency of converter considered 90% and a lifetime of 15 years. The capital cost and replacement cost in dollar took reference in [49]. The O&M was considered 1% of capital cost.

3.5.4 Fuel Cell specification and estimated cost

From the oxidation of fuel like hydrogen, a fuel cell can produce electricity. According to [102], the fuel cell is used for power generation ranging from five to 10 years and the system cost of 1kW varies from $ 1000-$2000. The capital cost of Fuel Cell in this research and its replacement cost all in the dollar were based on [101] and its O&M was estimated to 0.020$ per operating hour. Its lifetime is estimated to 35000hrs.

3.5.4 Electrolyzer specification and estimated cost

In this research, the function of Electrolyzer is to convert the excess of produced electricity in form of hydrogen to be stored for later use. The capital cost and replacement were estimated to $2000 and $1500 per 1kW respectively while O&M was set to $20 per year, its lifetime is estimated to 20 years and efficiency of 75%.

3.5.5 Hydrogen tank specification and estimated cost

This tank normally stores the hydrogen produced by Electrolyzer as indicated by its name thus must be of enough size. The capital and replacement cost per 1 kg were estimated to $1300 and 1200 respectively and O&M of $15 per year. Its lifetime is estimated to 20 years.

3.6 Summing up

This chapter has focused on the methodology used during this research. It mainly described the case study, methods used during data collection, the available renewable energy resources and then focus on solar radiation and biomass, detailing PV components for the standalone system and biomass conversion technology. This chapter looked into the hybrid system by their specifications and estimated the cost of each component.

Chapter 4. HYBRID SYSTEM MODELING AND SIMULATION

Outline

4.1 Hybrid system modeling with HOMER

4.1.1 Load input

4.1.2 Solar photovoltaic input

4.1.3 Biomass input

4.2 Economic inputs

4.3 Hybrid system simulation results

4.4 Summing up

4.1 Hybrid system modeling with HOMER

As described in the previous section a hybrid system is one of the best solutions for electrification of remote rural areas where the grid extension is difficult and not economical. A hybrid system combines two or several renewable energy resources. For this research, solar photovoltaic and bioenergy have been chosen as resources for powering one of the remote areas in Rwanda. That combination is performed using HOMER software where it helps to model a system's physical behavior, its life-cycle cost over its specified lifetime. HOMER also provides many different design options based on technical and economic aspects.

The evaluation of hybrid solar PV- bio energy system for powering remote area in Rwanda case of Kabasega village was modeled to power 130 households with an average of five persons per family-based on background and survey information discussed in previous sections. With HOMER, Figure 4.1 presents the stand-alone hybrid energy system designed to meet load demand.

The system is designed in such a way that Biomass and Solar are the main sources of energy. The electrolyzer and the fuel cell act as back up. Biomass electricity generator produces an alternating current that supplies directly the load. The energy produced by solar PV is a Direct Current that is first converted into AC by the converter and then supplied to the load. Electrolyzer generates hydrogen from the produced excess energy. The produced hydrogen is stored in hydrogen tank which is used by the thefuel cell to generate DC electricity in case of low production. HOMER inputs data and other parameters including other inputs such as a converter, fuel cell, hydrogen tank and Electrolyzer are presented in Table 4.1.

Table 4.1: Additional inputs to HOMER

Options	Considered sizes	lifetime	Other parameters
PV	0, 25, 80 (kW)	20 years	Derating factor 80%
Biomass (biogas-generator)	0, 25, 90 (kW)	40000 hours	Minimum load ratio30 %
Fuel cell	0.25, 5 (kW)	35000 hours	Minimum load ratio 1%
Electrolyzer	0, 10, 20, 30 (kW)	15 years	Efficiency 80%
Converter	0, 7, 28, 45 (kW)	15 years	Inverter efficiency 90%
Hydrogen tank	0, 3, 18, 20 (kg)	20 years	Initial tank level 20%

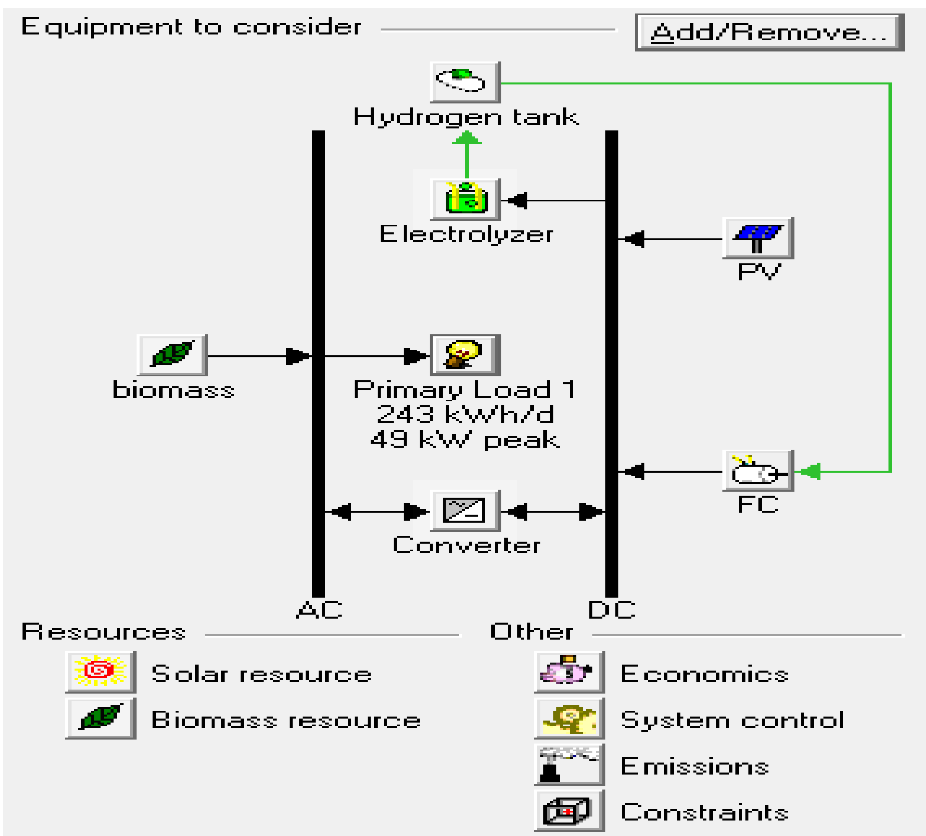


Fig 4.1: HOMER diagram for the hybrid PV -Biomass-FC set-up

4.1.1 Load input

The hourly demand for electric energy refers to the Load. According to the carried-out survey, the electric load in Kabasega village is assumed to be for lighting purpose and few home appliances. The village does not need electricity for water pumps as water is available, there is no health clinic and no schools expect a nursery school where they leave the village children daily. The table describing the detailed load profile of the village is attached in Appendix C. The daily average load demand of 243kWh/day with an average peak load of 10.1kW and peak load demand of 49.3kW has been determined using the data report in above table. The results are shown in Figure 4.2. This figure shows also the primary daily load profile and the seasonal load profile of the village-based on their electrical energy use.

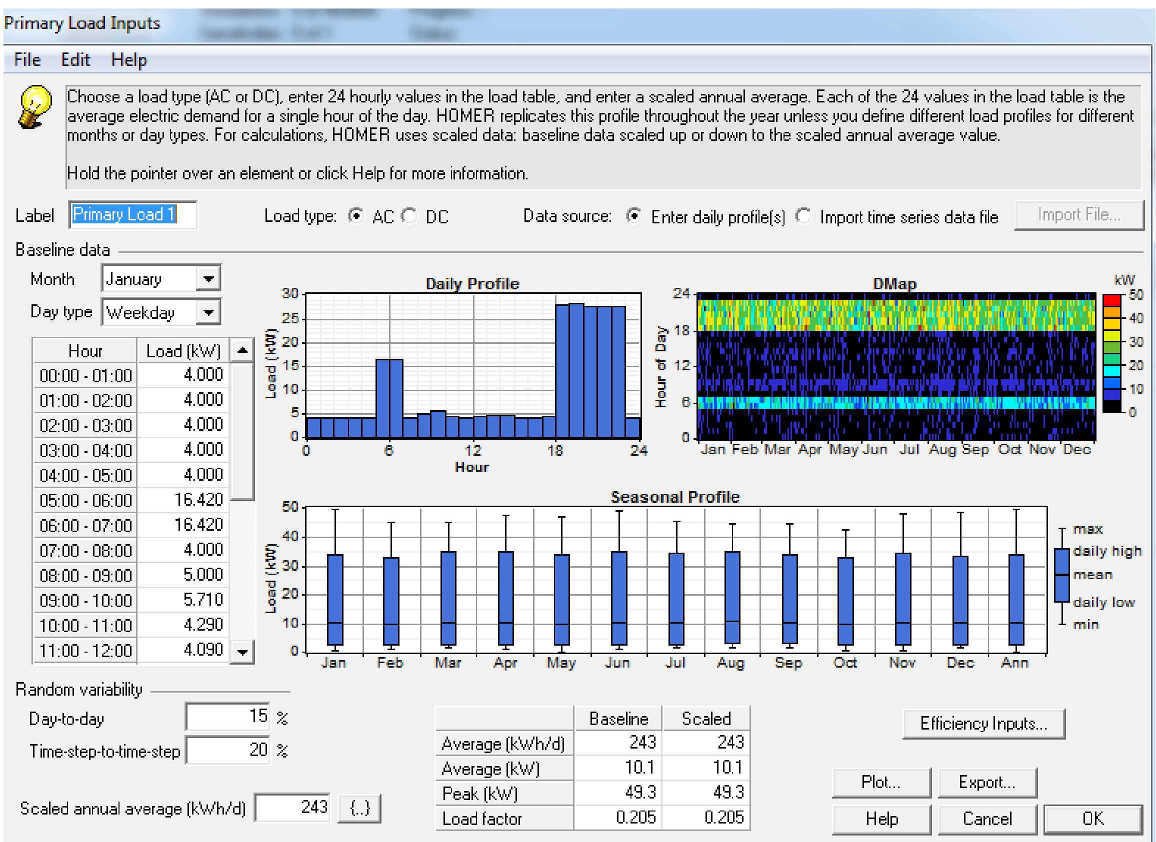


Fig 4.2: HOMER primary load input

4.1.2 Solar photovoltaic input

To model a system with a PV array, there is a need of solar data for the chosen location. For this work, the data used are the monthly average solar radiation on the horizontal surface determined using METEONORM data. Based on these data, HOMER provides the clearness index which is the measure of atmosphere clearness. Apart from solar data of the location, PV sizes and cost must also be provided for HOMER to optimize the system. About PV capital, replacement cost and all other specification have been discussed in the previous chapter. Figure 4.3 shows the monthly Global radiation profile for case study and Figure 4.4 shows the PV cost input.

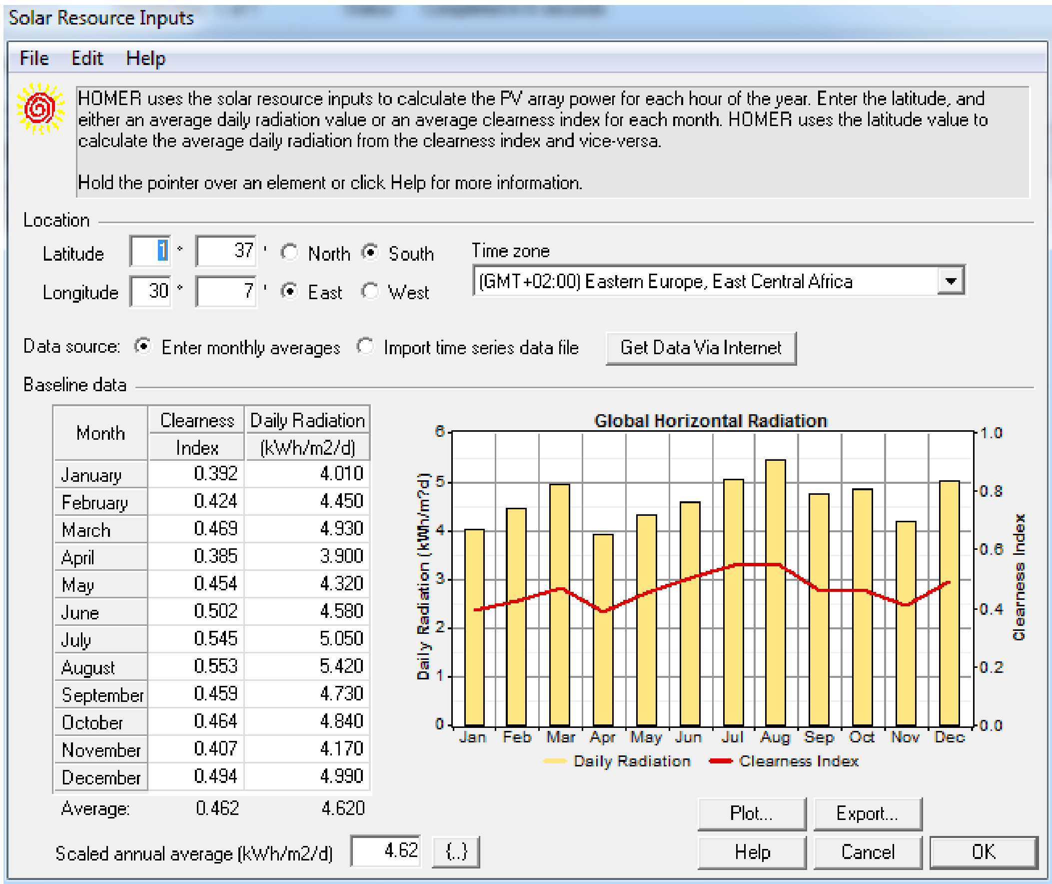


Figure 4.3: Monthly global radiation profile for the village

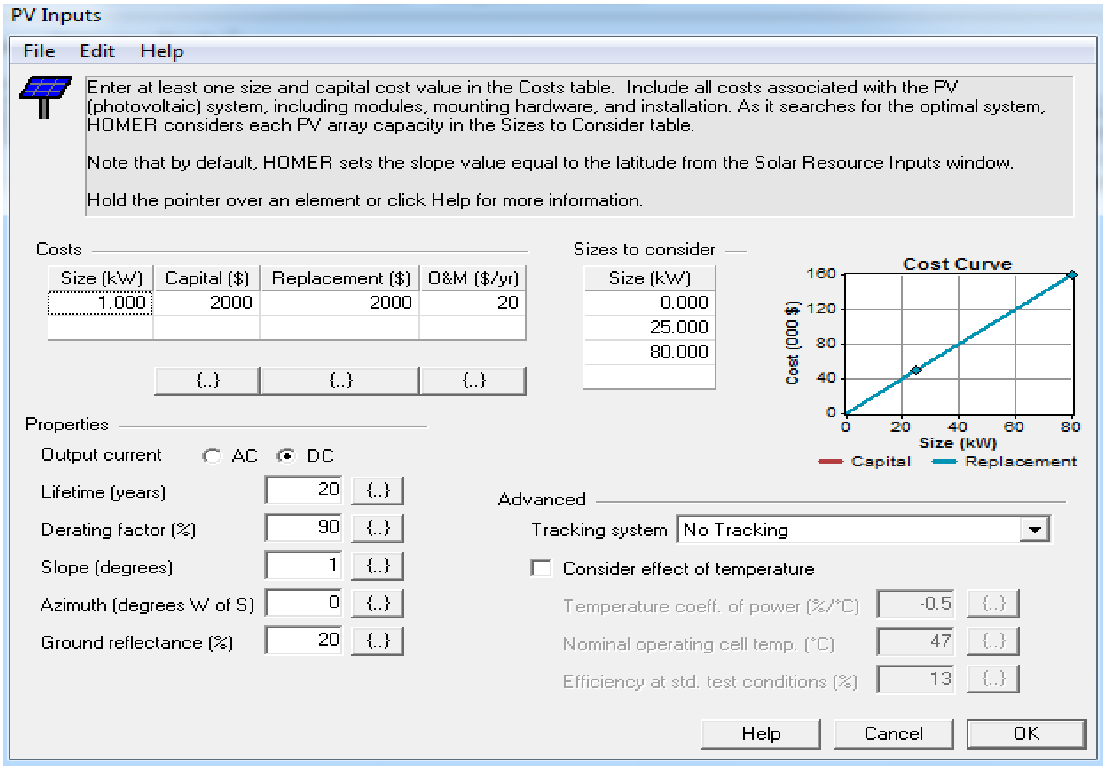


Fig 4.4: HOMER PV input

4.1.3 Biomass resource input

The generation of electricity from biomass needs a gas engine generator and other associated devices. The gas produced from anaerobic digestion or gasification process can be combusted for electricity generation. In the previous chapter, the biomass potential in the village has been calculated; two tonnes per day are available. By considering some losses in biomass collection and a small portion of biomass to be used for fertilization purposes, only 75% of the total biomass is considered for electricity production in the present study. The inputs of biomass resources and biogas generator are reported in Figures 4.5 and 4.6 respectively. The evolution of the biogas generator efficiency as a function of its percentage loading is reported in figure 4.7. All the costs have been discussed in the previous chapter.

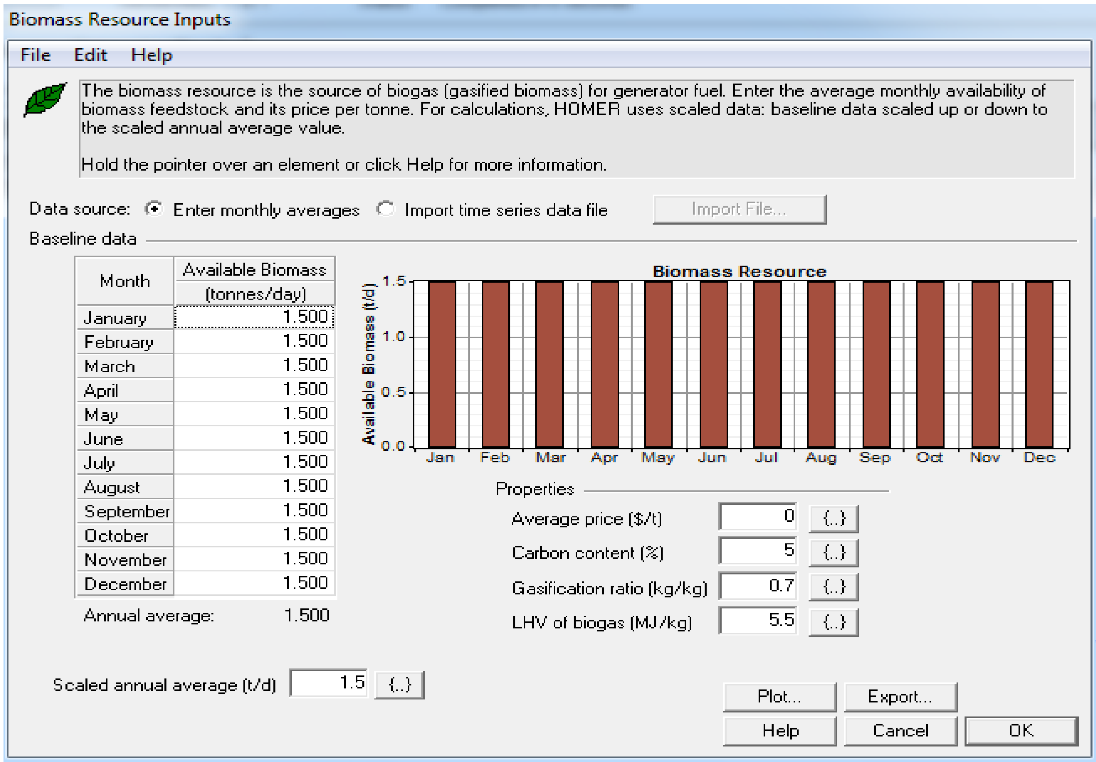


Fig 4.5 Biomass resource input

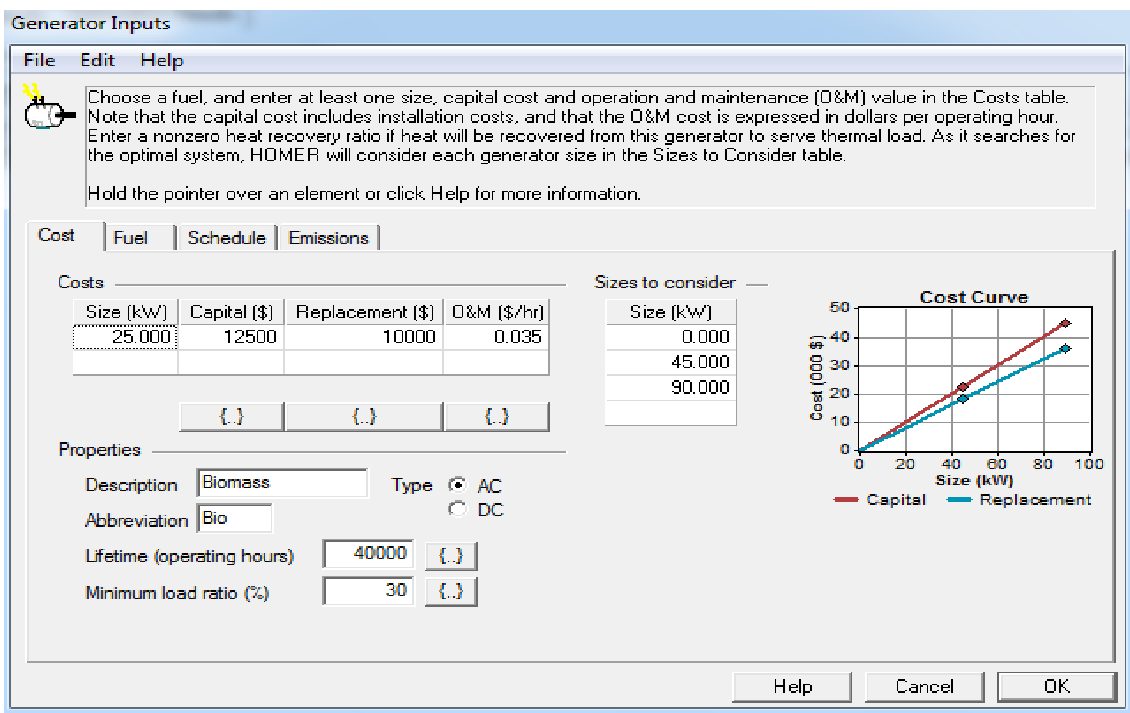


Figure 4.6 HOMER biogas generator input

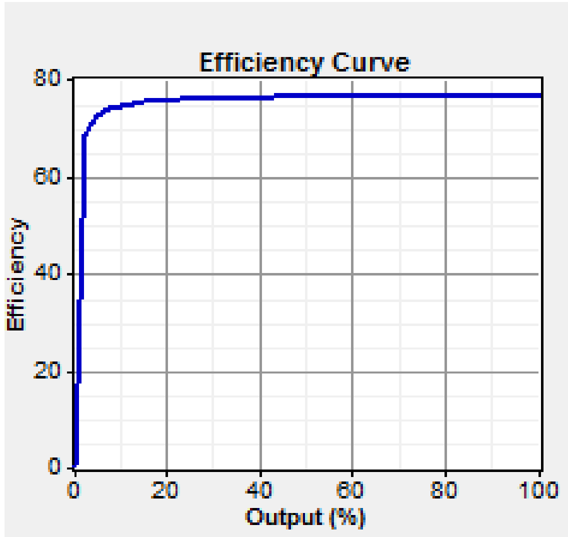


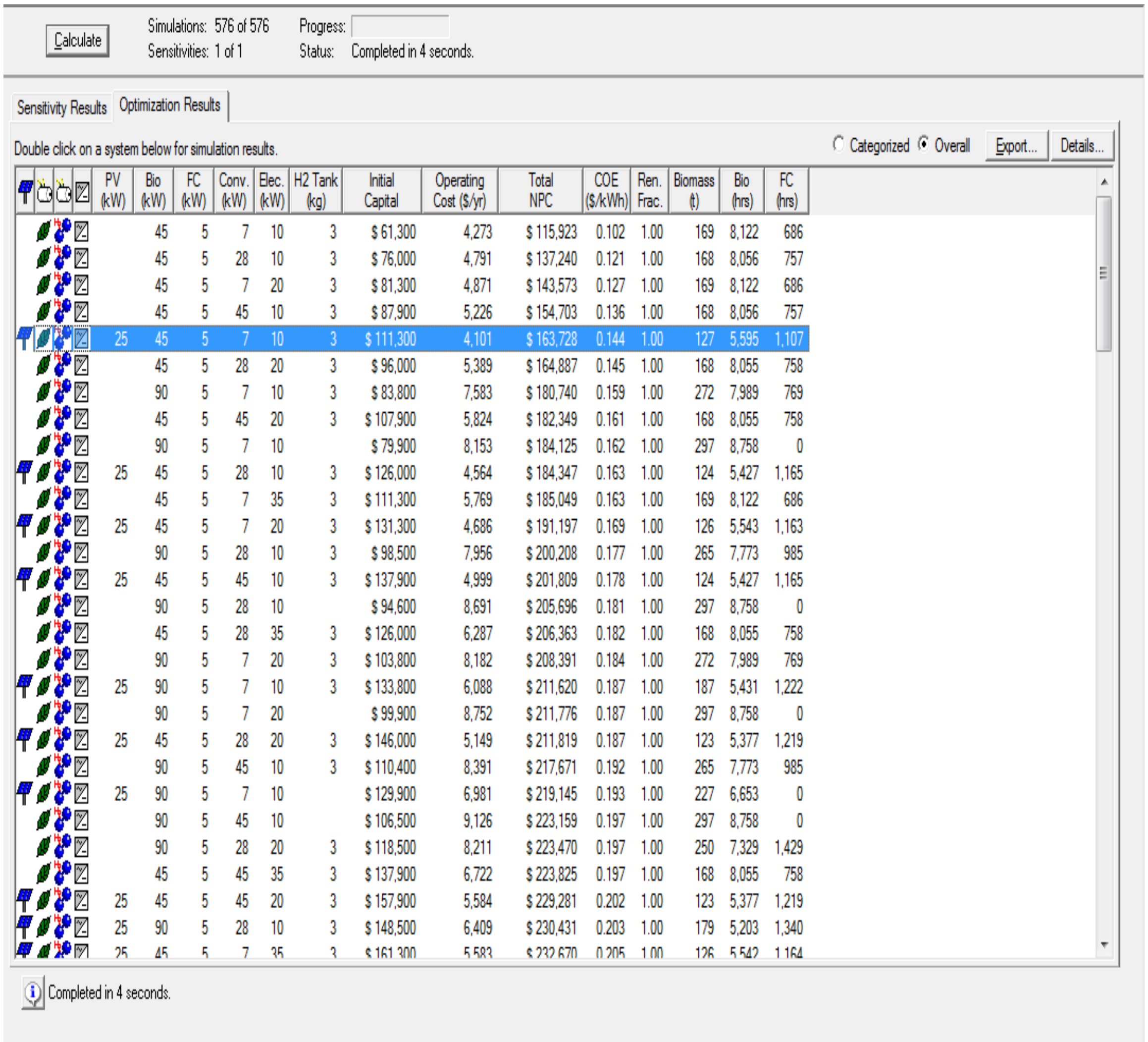
Fig 4.7 Biogas generator efficiency curve

4.2 Economic inputs

For HOMER to evaluate the economics of the hybrid system, the analysis is carried out based on the lifetime of the system rather than capital cost. For the present work, the considered project's lifetime is 25 years and the annual interest rate of 6%. The other economic inputs such as capital cost, system fixes, Operation and Maintenance, and capacity shortage penalty have been set to 0 in the present research. HOMER optimises the system by calculating the Net Present Value (NPV) of the lifetime cost of the project for each configuration and gives all possible configuration based on Net Present Cost and LCOE.

4.3 Hybrid system simulation results

The proposed hybrid system composed of PV-biomass-FC for electrifying Kabasega village was designed using HOMER software. The software simulates the inputs data and gives all the possible configurations. Figure 4.8 shows the HOMER simulation results in overall form. The overall gives all the possible configurations of the system according to the entered inputs.



PV (kW)	Bio (kW)	FC (kW)	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Bio (hrs)	FC (hrs)
	45	5	7	10	3	$ 61,300	4,273	$ 115,923	0.102	1.00	169	8,122	686
	45	5	28	10	3	$ 76,000	4,791	$ 137,240	0.121	1.00	168	8,056	757
	45	5	7	20	3	$ 81,300	4,871	$ 143,573	0.127	1.00	169	8,122	686
	45	5	45	10	3	$ 87,900	5,226	$ 154,703	0.136	1.00	168	8,056	757
25	45	5	7	10	3	$ 111,300	4,101	$ 163,728	0.144	1.00	127	5,595	1,107
	45	5	28	20	3	$ 96,000	5,389	$ 164,887	0.145	1.00	168	8,055	758
	90	5	7	10	3	$ 83,800	7,583	$ 180,740	0.159	1.00	272	7,989	769
	45	5	45	20	3	$ 107,900	5,824	$ 182,349	0.161	1.00	168	8,055	758
	90	5	7	10		$ 79,900	8,153	$ 184,125	0.162	1.00	297	8,758	0
25	45	5	28	10	3	$ 126,000	4,564	$ 184,347	0.163	1.00	124	5,427	1,165
	45	5	7	35	3	$ 111,300	5,769	$ 185,049	0.163	1.00	169	8,122	686
25	45	5	7	20	3	$ 131,300	4,686	$ 191,197	0.169	1.00	126	5,543	1,163
	90	5	28	10	3	$ 98,500	7,956	$ 200,208	0.177	1.00	265	7,773	985
25	45	5	45	10	3	$ 137,900	4,999	$ 201,809	0.178	1.00	124	5,427	1,165
	90	5	28	10		$ 94,600	8,691	$ 205,696	0.181	1.00	297	8,758	0
	45	5	28	35	3	$ 126,000	6,287	$ 206,363	0.182	1.00	168	8,055	758
	90	5	7	20	3	$ 103,800	8,182	$ 208,391	0.184	1.00	272	7,989	769
25	90	5	7	10	3	$ 133,800	6,088	$ 211,620	0.187	1.00	187	5,431	1,222
	90	5	7	20		$ 99,900	8,752	$ 211,776	0.187	1.00	297	8,758	0
25	45	5	28	20	3	$ 146,000	5,149	$ 211,819	0.187	1.00	123	5,377	1,219
	90	5	45	10	3	$ 110,400	8,391	$ 217,671	0.192	1.00	265	7,773	985
25	90	5	7	10		$ 129,900	6,981	$ 219,145	0.193	1.00	227	6,653	0
	90	5	45	10		$ 106,500	9,126	$ 223,159	0.197	1.00	297	8,758	0
	90	5	28	20	3	$ 118,500	8,211	$ 223,470	0.197	1.00	250	7,329	1,429
	45	5	45	35	3	$ 137,900	6,722	$ 223,825	0.197	1.00	168	8,055	758
25	45	5	45	20	3	$ 157,900	5,584	$ 229,281	0.202	1.00	123	5,377	1,219
25	90	5	28	10	3	$ 148,500	6,409	$ 230,431	0.203	1.00	179	5,203	1,340
25	45	5	7	35	3	$ 161,300	5,583	$ 232,670	0.205	1.00	126	5,542	1,164

Figure 4.8: HOMER simulation results in overall form

4.4 Summing up

This chapter has covered the HOMER model of the proposed hybrid system, the detailed Load input of the village, Solar PV and biomass inputs and economic input as well and finally the hybrid system simulation results.

Chapter 5. RESULTS AND DISCUSSION

Outline

5.0 Overall results

5.1 Cost summary of the hybrid system

5.2 Electricity production

5.3 Solar PV output Production

5.4 Biomass output production

5.4 Fuel cell output

5.5 Converter output production

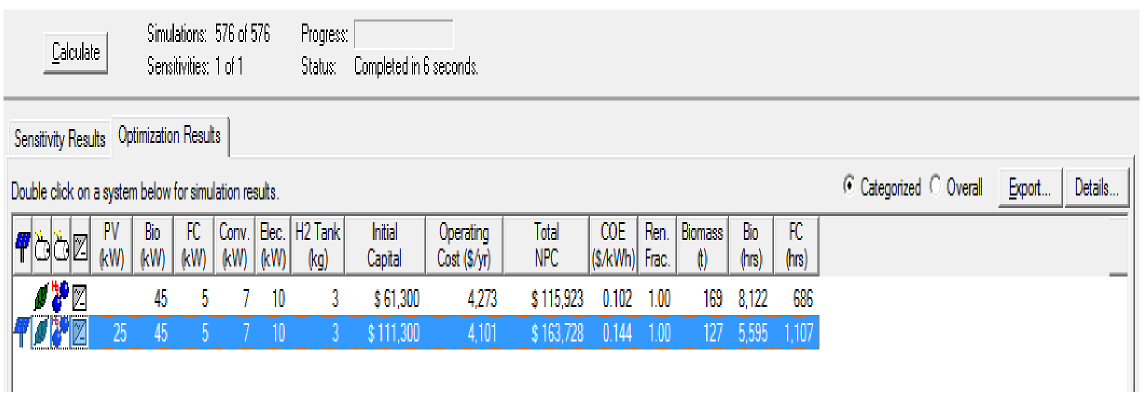
5.6 Hydrogen production

5.7 Emissions

5.8 Summing up

5.0 Overall results

As discussed in previous chapters, the simulation of hybrid solar PV-bio energy and Fuel cell as a backup has been conducted using HOMER software. HOMER provides all possible combinations based on the desired hybrid components. After simulation, the software displays the results in either overall form or categorized form, the former provides a list of all feasible system configurations based on their net present cost and the latter is only based on the most cost-effective configuration as presented in the previous chapter. By looking on the LCOE of all feasible which is important in the selection of the optimum system configuration, it ranges from $ 0.102 per kWh to $0.144 per kWh. Based on their monthly consumption, the electricity tariff in Rwanda is between $0.11 per kWh to $ 0.23 per kWh for residential customers. Figure 5.1 shows the optimum results in categorized form.



PV (kW)	Bio (kW)	FC (kW)	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Bio (hrs)	FC (hrs)
	45	5	7	10	3	$ 61,300	4,273	$ 115,923	0.102	1.00	169	8,122	686
25	45	5	7	10	3	$ 111,300	4,101	$ 163,728	0.144	1.00	127	5,595	1,107

Figure 5.1: Summary of HOMER simulation results in categorized form

Having a look at the above list, the results are remarkable. The most cost-effective system by means of a system with the lowest NPC is Biomass-FC-converter setup by means of one renewable source (biomass). Though this system has the lowest NPC and LCOE, it has a disadvantage of having high O&M cost compare to the other set up it also unmet the electric load demand at 0.01% while the other cost-effective system with PV-Biomass-FC-converter set up which uses both renewable sources met the electric load at 100% and its O&M cost is low. Though its LCOE is high compared to the first case it is still in the range of electricity national tariff thus the latter system configuration is the best.

Its total net present cost is $ 163,728, the energy cost (COE) is $ 0.0144 per kWh, it uses 127 tonnes of biomass. The biogas gas generator operates 5,595 hr per year and Fuel Cell operates 1,107 Hours per year. As said, the unmet electric load of this configuration is zero and low 0.09% while the excess electricity is 6.86% per year. The system configuration is 25kW PV, 45kW biomass, 5kW Fuel Cell, 7kW converter, 10kW Electrolyzer and 3kg hydrogen Tank. Table 5.1 summarizes the selected system.

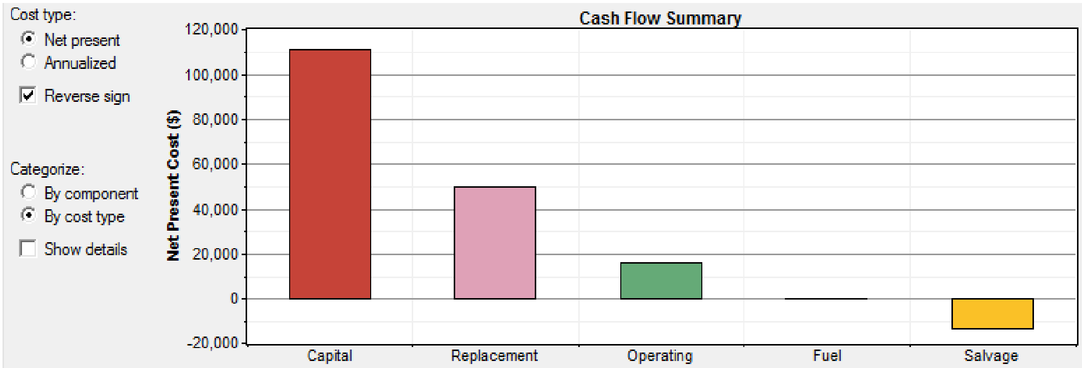
Table 5.1 system output summary

PV			**Biomass**			**Fuel cell**		
Quantity	**Value**	**units**	**Quantity**	**Value**	**units**	**Quantity**	**value**	**units**
Rated capacity	25	kW	Electrical production	103,442	kWh/yr	Elec. production	1,632	kWh/yr
Mean output	4.3	kW	Mean electrical output	18.5	kW	Mean electrical output	1.47	kW
Hours of operation	4,380	hr/year	hrs of operation	5,595	hr/year	hours of operation	1,107	hr/yr
Total production	37,900	kWh/year	Operational life	7.15	year	Operational life	31.6	year
Levelized cost	0.131	$/kWh	Bio-feedstock consumption	127	t/year	Hydrogen consumption	851	kg/year

Converter				**Hydrogen**
Quantity	**inverter**	**rectifier**	**units**	Total Electrolyzer production: 852 kg/year
Capacity	7	7	kW	Total hydrogen production:852 kg/year
Maximum output	6.36	7		Levelized cost of hydrogen: $15/kg
Hours of operation	3,492	3,094	hrs/year	Hydrogen generation: 852 kg/year Hydrogen consumption: 851 kg/year
				Hydrogen tank autonomy 9.88 hours

5.1 Cost summary of the hybrid system

Figure 5.2 and Figure 5.3 present the summary of cash flow by cost type of the optimal hybrid system. Figure 5.2 shows also the cost summary of the project based on the used component and nominal cash flow throughout 25 years of the project's lifetime.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	50,000	15,590	6,392	0	-8,737	63,244
Biomass	22,500	24,850	4,506	0	-2,110	49,746
FC	10,000	0	1,415	0	-488	10,927
Converter	4,900	2,045	626	0	-381	7,190
Electrolyzer	20,000	6,259	2,557	0	-1,165	27,651
Hydrogen Tank	3,900	1,122	575	0	-629	4,969
System	111,300	49,866	16,071	0	-13,510	163,728

Figure 5.2 Cash flow summary by cost type

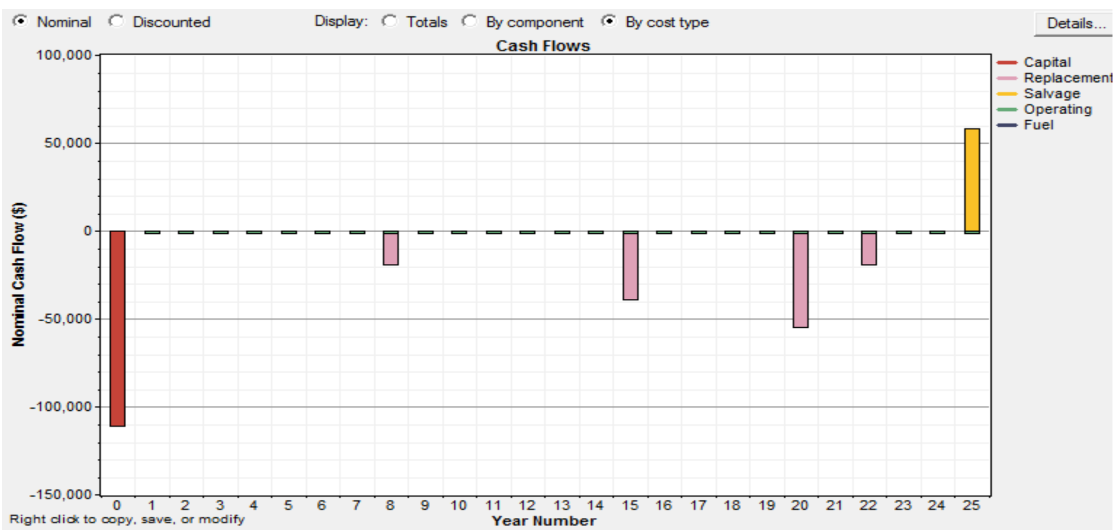


Figure 5.3 Nominal cash flow throughout 25years of the project

From Figure 5.3, it is observed that after 7 years, 14 years and 22 years there will be a replacement of biogas generator, this means 3 times in the project's lifetime. The same case scenario will happen for the converter after 14 years and PV and hydrogen tank after 20 years. The replacement of Fuel cell does not occur within 25 years of the project.

5.2 Electricity production

In the previous chapters, it has been shown that the primary load of the village is 243kWh/day with peak load demand of 49.3kW. Figure 5.4 shows the monthly average electric production from the optimum system configuration.

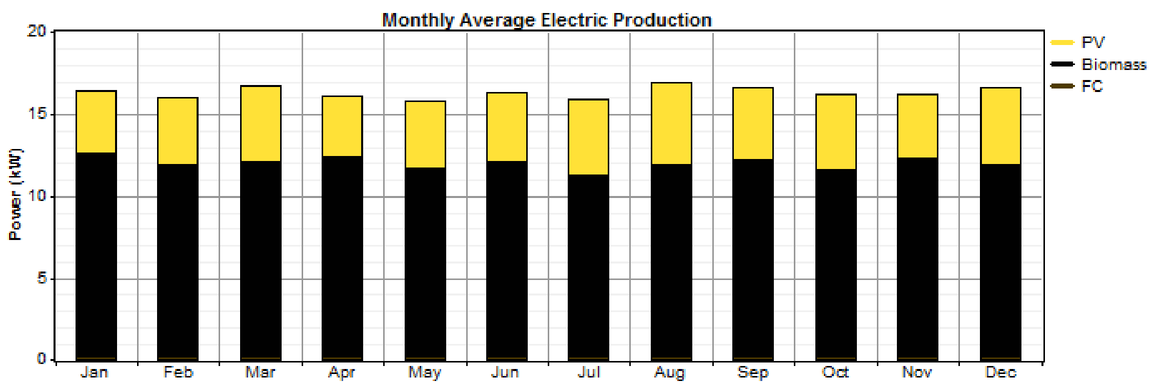


Figure 5.4 Electricity production of the selected system configuration

This figure shows the evolution of the monthly electricity production over the year. It is clearly shown that the highest PV electricity production occurs in the month of August. This could be explained by the fact that it is the month of the highest solar radiation. Concerning biomass, the highest produced electricity from this resource, is over the month April. This is due to the fact that solar radiation is at its lowest; therefore, there is a resort to the biomass resource. The power produced from the fuel cell is small compared to the other sources but still, it is necessary as it is the best way of ensuring the electricity availability. Table 5.2 shows the electricity production and consumption.

Table 5.2: Electricity production and consumption

Production			Consumption		
Source	kWh/year	%	Load type	kWh/year	%
PV array	37,900	27	AC primary Load	88,694	69
Biomass	103,442	72	Electrolyzer Load	39,515	31
FC	1,632	1	Total	128,210	100
Total	142,975	100			

5.3 Solar PV output production

Figure 5.5 shows the evolution of PV output over a typical day for the optimum system. This figure indicates that the PV panel starts generally producing around 7 AM and stops around 5 PM; which corresponds to the time going from sunrise to the sunset time. The mean output power of PV is around 4.3kW. It is obvious that there is no production from solar PV during the night.

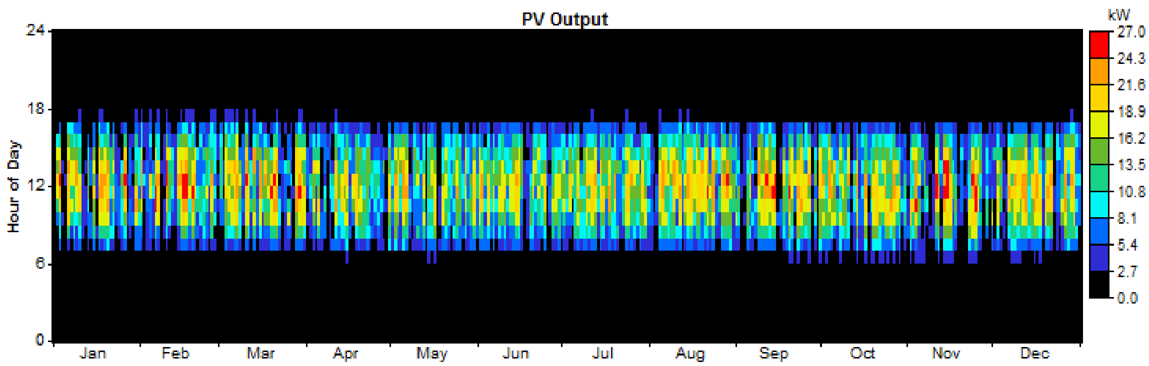


Figure 5.5 PV output production

5.4 Biomass output production

Figure 5.6 shows the output of the biomass generator. It can be seen that the production from biomass source dominated the production of the whole system. From this figure, it is observed that the production of power from biomass is quite low during the daytime from 7 AM up to 5 PM and quite high in the evening time from 6 PM up to 11 PM when the demand is high.

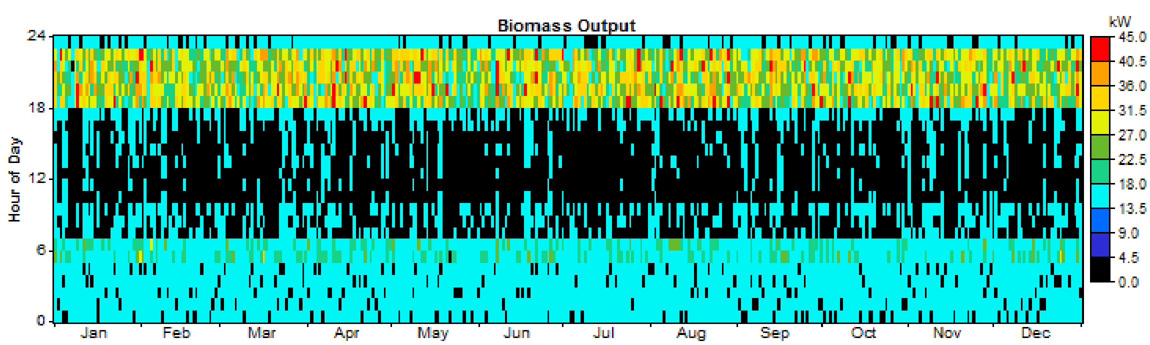


Figure 5.6 Biomass generator output production

5.4 Fuel cell output

Figure 5.7 shows the FC output production. Generally, it is seen that its production is relatively low below 0.5 kW but in some hours like from 11 PM up to 5 AM the production is around 4.5 kW although the mean electrical output power is low 1.47 kW.

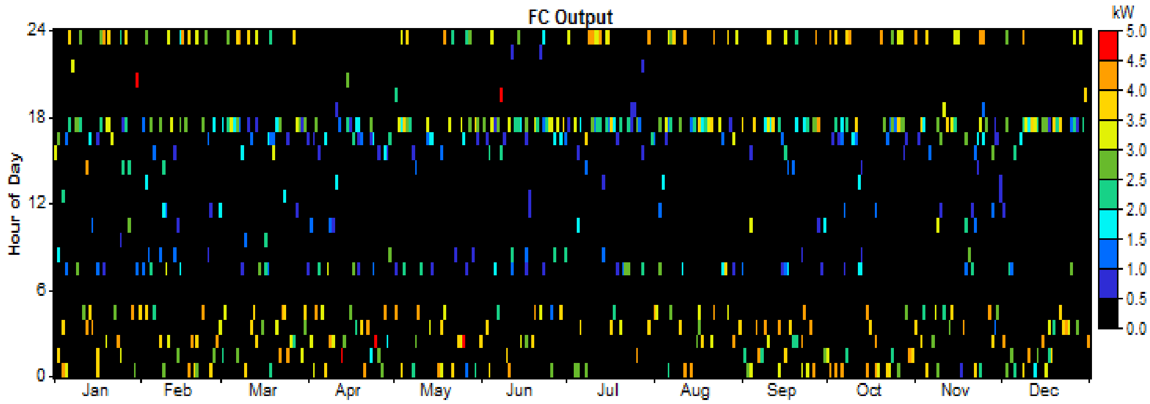


Figure 5.7: FC output production

5.5 Converter output production

Figure 5.8 combines two figures but both represent the Converter output, but their output figures are totally different. The inverter that performs DC to AC conversion mainly produce during the daytime from 7 AM to 6 PM which is the same time that PV is producing as it produces DC pow and its maximum output power is 6.36 kW. On the rectifier side that performs AC to DC conversion, it is clear that it produces at its maximum from 11 PM up to 5 AM the time when the biomass is producing and the load demand is low so the hydrogen is produced from excess produced from biomass. Its production is almost zero from 6 PM up to 11 PM when the biomass is producing at its maximum due to high load demand and no production from PV.

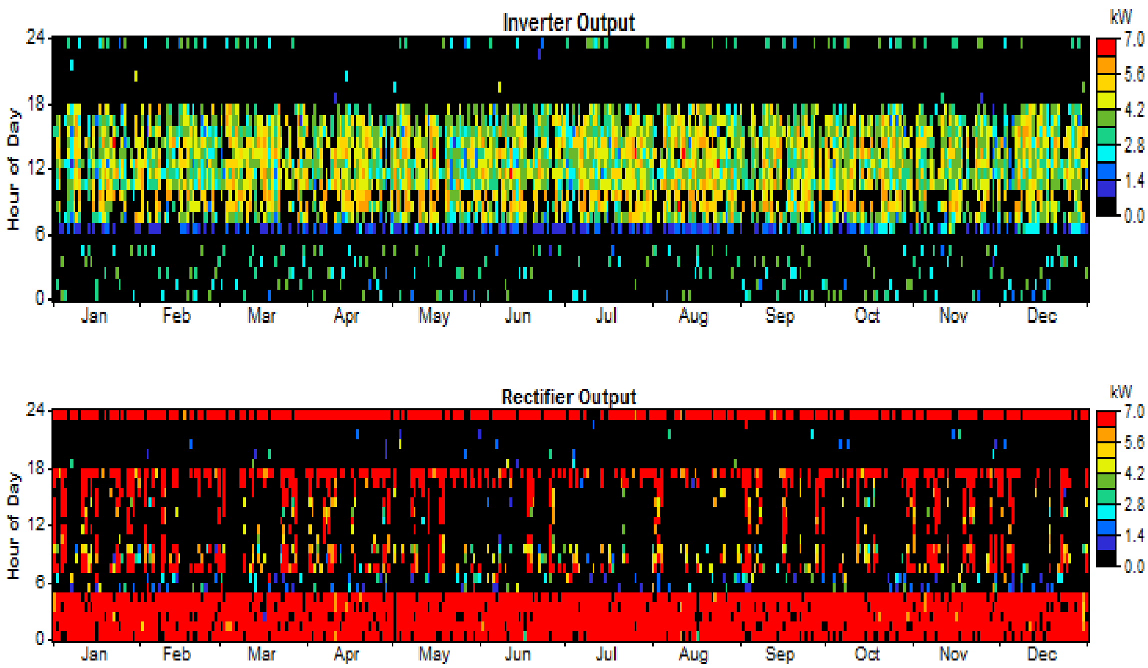


Figure 5.8 both inverter and rectifier output

5.6 Hydrogen production

The hydrogen is produced by Electrolyzer. Figure 5.9, Figure 5.10 and Figure 5.11show the produced hydrogen in Electrolyzer, the statistics of the hydrogen tank and hydrogen tank storage level respectively. From` Figure 5.9, it is observed that hydrogen production is high in January, March, and September. Figure 5.10 shows that the high daily mean is found in March, July, August and December the period where is high solar radiation. The last figure shows that the tank never goes to zero.

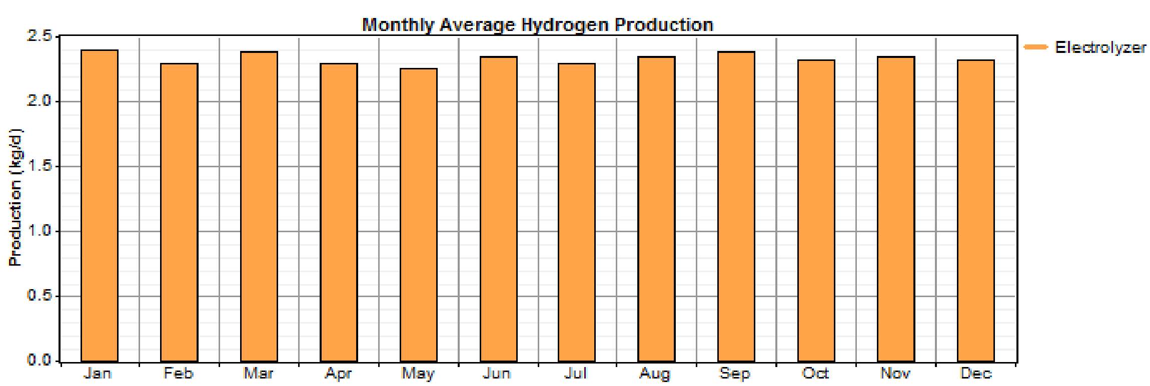


Figure 5.9: Monthly average hydrogen Production

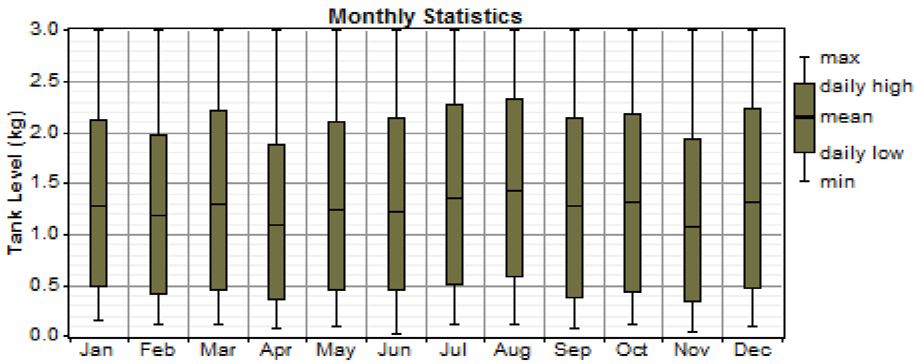


Figure 5.10: Monthly statistics of Hydrogen tank

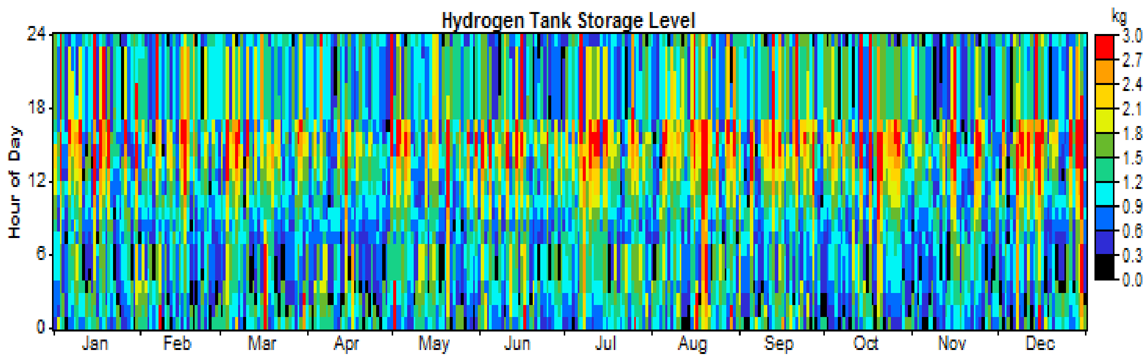


Figure 5.11 Hydrogen tank storage level

5.7 Emissions

Table 5.3 presents the emissions that could occur once the system is implemented. Compare to emissions from fossil fuels, the presented one in the table below is negligible.

Table 5.3 Emissions

Pollutant	**Emissions(kg/year)**
Carbon dioxide	13.2
Carbon monoxide	6.36
Unburned hydrocarbons	0.704
Particulate matter	0.479
Sulfur dioxide	0
Nitrogen oxides	56.7

5.8 Summing up

This chapter presented the results of the selected optimum system configuration after HOMER simulation. That includes the electric output from the system, output of each component by means of Solar PV, Biomass, Fuel Cell, converter and hydrogen, it also presents the pollutant and amount that could be emitted once the proposed system is implemented.

Chapter 6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The main objective of this research is to assess the potential of using a hybrid solar-bioenergy system for powering a remote area in Rwanda; Kabasega village in Gicumbi district, the Northern Province is taken as a study case. First, using the outcome of a survey, the work describes the load demand profile of the village-based on population's need for electricity. In this study, it has been found that, besides hydropower, the village has sizable energy potential in both solar and biomass resources. About 4.62 kWh/m^2 of average daily solar radiation and 2 tonnes per day of manure from cattle, goat, and poultry have been identified as the potential of chosen renewable energy resources.

Without storage system, renewable energy based power system could not satisfy the load demand adequately. Therefore, a system made up of an electrolyzer and a fuel cell has been added first as a mean of storing the excess electricity in the form of hydrogen then as a backup in case the production cannot meet the load. Using HOMER software, the hybrid system has been modeled and simulated to determine the optimum system meeting the village's load demand at low cost. This load demand is 243kWh per day with peak power of 49.3 wk. solar PV-biomass-fuel cell system with 25 kW PV, 45 kW biomass, 5 kW fuel cell, 7 kW converter, 10 kW electrolyzer and 3 kg hydrogen tank satisfy this load demand. The origin of the produced electricity is 72%, 27% and 1%from biomass, solar PV, and FC respectively. The Levelized cost is estimated at 0.144$/kWh. This cost is competitive with national electricity tariff in Rwanda for residential customers. The fact that the system is fully made of renewable energy sources leads to a reduction of the emissions of polluting agents.

6.2 Recommendation

I recommend this system to my government so that it could be implemented in many rural villages of the country where the lack of electricity is still a problem. Indeed, the system presents a lot of advantages compared to the grid-connection, including free and environment-friendly sources of energy, relative low zero capacity shortage and system well adapted to the remote area. This system could also be implemented in some other countries of Africa specifically where there are similar climate condition and biomass resource as well.

References

[1] Ali Heydari, Alireza Askarzadeh. (2016). Optimization of a biomass-based photovoltaic power plant for an off-grid application subject to loss of power supply probability concept. Applied Energy, 165 601–611.

[2] International EnergyAgency (IEA). (2014). Africa energy outlook: A Focus on Energy Prospects in Sub-Saharan Africa.

[3] Uwisengeyimana, J. de Dieu, A. Teke, T. Ibrikci. (2016). Current overview of renewable energy resources in Rwanda. Journal of Energy and Natural Resources. Vol. 5, No. 6, 20. (pp. 92-97).

[4] Kiranpreet Kaur, Gursewak Singh Brar. (2016). Solar-biogas-biomass hybrid electrical power generation for a Village (a case study). International Journal of Engineering Development and Research (IJEDR), ISSN: 2321-9939, Vol. 4, Issue 1.

[5] Agence Française de Développement. (October, 2013). Access to Electricity in Sub-Saharan Africa: Lessons Learned and Innovative Approaches.

[6] Rwanda Ministry of Infrastructure. (2013). Energy Sector Strategic Plan 2013/14 - 2017/18, 2015. Kigali, Rwanda.

[7] Rwanda Ministry of Disaster Management and Refugee Affairs (MIDIMAR). (2015). The National Risk Atlas of Rwanda. Kigali, Rwanda.

[8] National Institute of Statistics of Rwanda (NISR), Rwanda Ministry of Health (MOH), and ICF International. (2015). Rwanda Demographic and Health Survey 2014-15. NISR, MOH, and ICF International. Rockville, Maryland, USA.

[9] National Institute of Statistics Rwanda. Rwanda Provinces Maps. www.statistics.gov.rw. (Retrieved on 19th March 2017).

[10] Population Pyramids of the World from 1950 to 2100.Population Pyramids of the World from 1950 to 2100: https://populationpyramid.net/rwanda/2000/.(March,10, 2016).

[11] National Institute of Statistics of Rwanda (NISR), Rwanda Ministry of Finance and Economic Planning (MINECOFIN). (2012). Rwanda Fourth Population and Housing Census. Thematic Report: Population size, structure, and distribution. Kigali, Rwanda

[12] European Commission, Republic of Rwanda. (2006). Environmental Profile of Rwanda. Kigali.

[13] Amanpreet Singh. (2014). Design and Feasibility of Micro Hybrid Combined Solar Biogas Biomass Power Plant. International Journal of Research in Electronics and Computer Engineering (IJRECE). ISSN 2393-9028, vol.2, issue. (pp.78-80).

[14] Kamaruzzaman.S, Mohd Yusof.O, Mohd Azhar Abd. Rahman. (2005). the performance of a Photovoltaic Diesel Hybrid system in Malaysia. ISESCO Science and Technology Vision, Vol.1, May 2005. (pp 37-39).

[15] International Energy Agency (IEA). (2014). Africa Energy Outlook.

[16] J. Morales Pedraza. (2015). The Current Situation and Perspectives on the Use of Renewable Energy Sources for Electricity Generation. http://www.springer.com/978-3-319-16082-5.

[17] ICSU Regional Office for Africa Science Plan. (2007). Sustainable Energy in sub-Saharan Africa.

[18] Davidson O., Sokona Y. (2002). Energy path for African development-think bigger, act. EDRC/ENDA Tiers, University of Cape Town. Cape Town

[19] World Energy Council. (2005). Untapped Hydro Potential. in *The World Energy Book*, Issue 1. 24 – 25. London.

[20] Castellano, A., Kendall, A., Nikomarov, M., Swemmer, T. (2015). Brighter Africa: the growth potential of the sub-Saharan electricity sector.

[21] Avila, N., Carvallo, J. P., Shaw, B. and Kammen, D. M. (2017). the energy challenge in sub-Saharan Africa: a guide for advocates and policy makers: part 1: generating energy for sustainable and equitable development. Oxfam research backgrounder series.

[22] Ituze Gemma, Mwongereza Jean d'Amour, Abimana Colette, Rwema Michel, Chisale Paul. (2017). Energy Landscape of Rwanda and Institutional Framework. Science Research. Vol. 5, No. 3, 2017. (pp. 16-22). Doi: 10.11648/j.sr.20170503.11.

[23] United Nations Energy Programme (UNEP). (2014). Green economy sectoral study on energy – Rwanda.

[24] Ministry of Infrastructure. (2015). Energy Sector Strategic Plan 2013/14 - 2017/18". Kigali, Rwanda.

[25] The International Energy Agency (IEA). (2014). Africa Energy Outlook – a Special Report.

[26] Agbossou K, Chahine R, Hamelin J, Laurencelle F, Anouar A, St-Arnaud JM, Bose TK. (2001). Renewable energy systems based on hydrogen for remote applications. Journal of Power Sources. 96:168-72.

[27] Kanase-Patil AB, Saini RP, Sharma MP. (2010). Integrated renewable energy systems for off-grid rural electrification of the remote area. Renewable Energy. 2010; 35:1342-9.

[28] Rwanda Ministry of Infrastructure. (2013). Energy Sector Strategic Plan 2013-2018. Kigali, Rwanda.

[29] Rwanda energy group. Electricity tariff in Rwanda. http://www.reg.rw/index.php/tariff-publication. (Retrieved on 18th May 2017).

[30] Non-renewable energy resources.http://keydifferences.com/difference-between-renewable-and-not-renewable-resources.html. (Retrieved on 15th May 2017).

[31] African Development Report. (2007). Africa's Non-Renewable Natural Resources.

[32] World Bank. (2015). Africa's Pulse. vol. 11. (p 18).

[33] United States Geological Survey. (2012). an estimate of undiscovered conventional oil and gas reserves of the world. (p 3).

[34] Ministry of Infrastructure. (2014).sustainable Energy for All Rapid Assessment and Gap Analysis. Kigali: Republic of Rwanda. Kigali, Rwanda.

[35] Energy, Water and Sanitation Agency. (2012). Methane, Peat and Waste-to-Power Projects in Rwanda. Kigali: Republic of Rwanda. Kigali, Rwanda.

[36] Rwanda opens Methane Electricity Plant. http://www.dailymail.co.uk/wires/afp/article-3593418/Rwanda-opens-pioneering. (Retrieved on May 15, 2017).

[37] African Development Bank Group. (2013). Energy Sector Review and Action Plan, Rwanda.

[38] Ministry of Infrastructure (Mininfra).(2015). Rwanda Energy sector strategic plan. Kigali: Republic of Rwanda. Kigali, Rwanda.

[39] Rwanda Utilities Regulatory Agency (RURA). (2011-2012). Annual report. Kigali, Rwanda.

[40] Ministry of Infrastructure (Mininfra). (2015). Rwanda Energy Policy. Kigali, Rwanda.

[41] African Development Bank Group (AfDB). (2013). Energy Sector Review and Action Plan-RWANDA.

[42] Safari Bonfils. (2011). Modeling wind speed and wind power distributions in Rwanda. Renewable and Sustainable Energy Reviews.

[43] Global solar horizontal irradiation of Rwanda. http://solargis.com/products/maps-and-gis-data/free/download/rwanda. (Retrieved on 27th February 2017).

[44] Rwanda Energy, Water and Sanitation Authority (EWASA). (2012). Residential Solar Water Heating Program (SolaRwanda Program). Kigali, Rwanda.

[45] Klaus Jäger, Olindo Isabella, Arno H.M. Smets, René A.C.M.M. van Swaaij, Miro Zeman. (2014). Solar Energy Fundamentals, Technology, and Systems.

[46] V. Shah, J. Booream-Phelps, and S. Mie. (2014). 2014 Outlook: Let the Second Gold Rush Begin. Deutsche Bank, New York.

[47] Iowa Energy Center. (2016). Solar PV Energy Guide. 2521 University Boulevard.

[48] Askari Mohammad Bagher, Mirzaei Mahmoud Abadi Vahid, Mirhabibi Mohsen. (2015). types of solar cells and application. American journal of optics and photonics. Vol.3, No.5, (pp.94-113).

[49] Sisay Fitwi. (August 2014). Feasibility Study of Standalone PV/Wind/Biogas Hybrid System for Rural Electrification: (A Case Study of Midrwa community in Adigrat District). (Master thesis). ADDIS ABABA Institute of Technology.

[50] Shuvajit Sadat, Roy Raisa Sharmin, Tajkia Ferdous. (December 2014). Performance Analysis of Mono-Crystalline and Poly-Crystalline Silicon Solar Cells under Different Climatic Conditions: A Comparative Study. (Bachelor thesis). BRAC University.

[51] M. R. Abdelkader, A. Al-Salaymeh, Z. Al-Hamamre, Firas Sharaf. (November 2010). A Comparative Analysis of the Performance of Monocrystalline and Multi-crystalline PV Cells in Semi-Arid Climate Conditions: The Case of Jordan. Jordan Journal of Mechanical and Industrial Engineering, Vol 4, No.5, ISSN 1995-6665. (pp 543- 552).

[52] Gary L. Hawkins. (May 2013). Solar Power 101 the Basics of Solar Energy. The University of Georgia – Tifton.

[53] John Christer Sivertsen, Petter Soyland. (2014). Design and Installation of a Grid-Connected PV System. The University of Agder.

[54] Poly solar panels. http://www.tradett.com/product/u75356p682283/poly-solar-panels.html. (Retrieved on 5th June 5, 2017).

[55] The German Solar Energy Society. (2013). Planning and Installing Photovoltaic System. A guide for Designers, Installers, Architects, and Engineers. Routledge.

[56] G. H. Yordanov. (November 2012). Characterization and Analysis of Photovoltaic Modules and the Solar Resource Based on In-Situ Measurements in Southern Norway. (Ph.D. thesis). Norwegian University of Science and Technology. Trondheim.

[57] Frank Vignola. The shading on PV Systems: Estimating the Effect. Solar Radiation Monitoring Laboratory, University of Oregon Eugene, OR 97403-1274.

[58] J. Althaus, K. Strohkendl, S. Menzler, and G. Mathiak. (2013). PV mounting system corrosion by salt mist - Experimental study with full-size mounting systems. Proceedings of the 28th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC), (pages 2893– 2896).

[59] E. Weliczko. Galvanic Corrosion Considerations for PV Arrays. http://solarprofessional.com/articles/products-equipment/racking/galvanic-corrosion-considerations-for-pv-arrays?v=disable_pagination. (Retrieved on 5th June 5, 2017)

[60] John C. Wiles, Jr. (October 2012). Photovoltaic System Grounding. Southwest Technology Development Institute College of Engineering, New Mexico State University.

[61] Energy Water and Sanitation Authority (EWSA). (2012). Biomass Use Survey in Urban and Rural Areas in Rwanda" Vol 1, Survey Main Report, May 2012, Kigali, Rwanda.

[62] Frank Rosillo-Calle, Peter de Groot, Sarah L. Hemstock, Jeremy Woods. (2007). the Biomass Assessment Handbook/ Bioenergy for a Sustainable Environment. Earthscan, London.

[63] Hall. D. O, Rao, K. K. (1999). Photosynthesis. 6th edition, Studies in Biology, Cambridge University Press.

[64] Faaij, A. P. C., Schlamadinger, B., Solantausta Y. and Wagener M. (2002). Large Scale International Bio-Energy Trade. Proceed. 12th European Conf. and Technology Exhibition on Biomass for Energy, Industry, and Climate Change Protection, Amsterdam, 17–21 June 2002.

[65] Rosillo-Calle, F. (2006). Biomass energy. in Landolf–Bornstein Handbook, vol 3, Renewable Energy, Chapter 5 (forthcoming).

[66] Bhattacharya, S. C. (2004). Fuel for thought: The status of biomass energy in developing countries", Renewable Energy World, vol 7, no 6, (pp122–130).

[67] Linear Algebra with Application to Engineering Computations. (2006). A brief introduction to MATLAB. September 2006 or from

https://web.stanford.edu/class/cme001/handouts/matlab.pdf

[68] David Houcque. (2005). Introduction to MATLAB for Engineering Students. Version 1.2. Northwestern University, August 2005

[69] Areef Kassam. (2010). HOMER Software Training Guide for Renewable Energy Base Station Design. May 2010. Or www.gsmworld.com/greenpower

[70] Firincă S.D., Mircea I., Hiyasat A., Mircea P.M. (2015). Simulation of the Systems with Renewable Energy Sources using Homer Software", Journal of sustainable energy VOL. 6, NO. 2, JUNE, 2015

[71] Jorge Sneij, David Vilar. (2013). The HOMER Simulation Tool PROS & CONS.ECREEE Regional Training of Trainers Workshop: HOMER software for RE project design, June 2013

[72] Fuel cell basics

http://www.fuelcelltoday.com/media/1637138/fc_basics_technology_types.pdf. (Retrieved on June 28th, 2017).

[73] Block diagram of the fuel cell.

https://www.google.rw/search?q=block+diagram+of+fuel+cell&rlz=1C1AVNC_enUS619US619&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwj5jeqhwuLUAhVB1hoKHYIDAA4QsAQIHw&biw=1366&bih=613#imgrc=w4onvcfUUY5zbM. (retrieved on June 29th, 2017).

[74] Fuel cells,

http://www.srmuniv.ac.in/sites/default/files/files/NS%20316%20UNIT%20III%20and%20IV%20Supporting%20PPT.pdf. (Retrieved on June 29th, 2017).

[75] Prof. R. Natarajan. (2006). Prospects, Challenges, and Impediments in The Development of Biomass Gas Based Solid Oxide Fuel Cell (SOFC) in India. Seminar on Challenges in Fuel Cell Technology: India's Perspective Indian Institute of Technology-Delhi 1st and 2nd December 2006.

http://web.iitd.ac.in/~sbasu/seminar/presentation/8Prof.%20R.%20NatarajanVIT%20VelloreTamilnadu.pdf

[76] Fuel cell basics

http://www.pragma-industries.com/wp-content/themes/default/images/fuel_cell_basics.pdf. (Retrieved on June 30th, 2017).

[77] U.S. Department of Energy Hydrogen Program. Hydrogen & Our energy future.

[78] Hydrogen life cycle. http://www.need.org/Files/curriculum/Energy%20At%20A%20Glance/HydrogenAtAGlance_11x17.pdf.

(Retrieved on July 13th, 2017).

[79] Bonner M, Botts T, McBreen J, Mezzina A, Salzano F and Yang. (1984). Status of advanced electrolytic hydrogen production in the United States and abroad. Int J Hydr Ener, 9(4), 269-275.

[80] R. Boudries1. R. Dizène2, A. Khellaf, and M. Belhamel. (2010). Hydrogen as an energy carrier.2010 Nova Science Publishers, Inching: 978-1-61671-509-2

[81] S Asherif, F Barhir, TN Veziroglu. (2003). principles of hydrogen energy production, storage, and utilization. Journal of scientific and industrial research, vol.62, (pp 46-63). January-February, 2003.

[82] Dutta S. (1960). Technology assessment of advanced electrolytic hydrogen production" Int J Hydr Ener, 15(6), 379-386.

[83] Liepa M A and Borhan A. (1986). High-temperature steam electrolysis: technical and economic evaluation of alternative process designs. Int J Hydr Ener, 11(7), 435-442, 1986.

[84] Bull S R. (1988). Hydrogen by photo processes. Proc Int Renew Ener Conf (Honolulu, Hawaii). (Pp 412-426).

[85] Boudries, R. (2000). Evaluation du potential hydrogène- solitaire en Algérie rapport internet. CDER, Rapport RK-01 CDER-200, 2000.

[86] Michael Hirscher. (2010). Handbook of Hydrogen Storage: New Materials for Future Energy Storage. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

[87] Andreas Züttel. (2004). Hydrogen storage methods. Naturwissenschaften (2004) 91:157–172, DOI 10.1007/s00114-004-0516-x, 17 March 2004.

[88] SRI Consulting. (2001). Chemical Economics Handbook 2001, Menlo Park, CA, July 2001.

[89] Ministry of Finance and Economic Planning National Institute of Statistics of Rwanda. (2015). Fourth Population and Housing Census, Rwanda, 2012 District Profile, Gicumbi.

[90] Northern province Gicumbi district. District Development Plan (2013-2018). Rwanda.

[91] Charles Banks. (2009). optimizing anaerobic digestion: Evaluating the Potential for Anaerobic Digestion to provide Energy and Soil amendment. University of Reading, 25th March 2009.

[92] Sharmin Sobhan, Tanvir Ahmad, Md. Jakaria Rahimi, Md. Habib Ullah, Shaila Arif. (2016). HOMER Based Feasibility Study of Off-Grid Biogas Power Generation Model Using Poultry Litter for Rural Bangladesh. American Journal of Engineering Research (AJER), e-ISSN: 2320-0847 p-ISSN: 2320-0936, Volume-5, Issue-1, (pp-21-33).

[93] Stand-alone PV system. file:///E:/docc/Ch_5_PV_systems.pdf. (Retrieved on June 20th, 2017).

[94] Energy efficiency and renewable energy. (1997). Photovoltaics: Basic Design Principles and Components. March1997.

[95] Davidson J. (2001). The new solar electric home. 20th printing 2001.

[96] Solar Electric System Design, Operation, and Installation. (2009). An Overview for Builders in the U.S. Pacific Northwest. October 2009.

[97] Vinay Shrivastava, (May 2012). Design and development of downdraft gasifier for operating CI engine in dual fuel mode. (Master thesis), Rourkela (India).

[98] Midwest Energy Research Center. Turning manure into gold: converting agricultural waste to energy. 337 South Main Street, 4th Floor, Suite 5.

[99] H.J. Veringa. (2009). Advanced Techniques for Generation of Energy from Biomass and Waste. Energieonderzoek Centrum Nederland.

[100] Doaa M. Atia, & Hanaa T. Elmadany. (2015). Optimization and Economic Evaluation of Biomass Gasifier Based Hybrid Energy System in Egypt's: 978-1-61804-301-6.

[101] Donald Chung, Carolyn Davidson, Ran Fu, Kristen Ardani, and Robert Margolis. (2015). U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems. National Renewable Energy Laboratory, September 2015.

[102] Frank de Bruijn. (2011). PEMFC Lifetime and Durability an overview. Thessaloniki, September 21, 2011.

APPENDICES

Appendix A: Household Survey Format for Energy Use

Name of interviewer: Ms. ITUZE Gemma

Date of Interview: 12th May 2017

I. Household Profile

Village name:

1. Name of Respondent:

2. Sex of Respondent:

3. Age of Respondent:

4. have you attended school?

a) No

b) Yes (which level is your education) ……………………………………………….

5. Do you have a job?

a) No

b) Yes (specify)

6. Are you a Head of the Household?

a) **Yes**

b) **No** (specify your relationship with the head of the household) ………………………

7. How many people are in the household? Fill in the table below

Years	Person
0 -6	
7 – 17	
18 – 60	
61 and over	
Total	

8. Source of reliable production

a) Agriculture
b) Non-agriculture (specify)

9. Do you have any of these domestic animals? If yes specify number

a) Cow

b) Sheep

c) Goat

10. What type of fuel do you use for cooking?

a) Wood and or straw

b) Charcoal

11. What do you use for lighting?

a) Candle

B) Dry Cell Battery

12. Do you need electricity? If yes specify the need for that electricity

a) No

b) Yes -lighting

-cooking

13. Now suppose you have electricity at home, which one of that electrical equipment do you need to have at your home?

a) Fridge

b) TV

c) Radio

d) Phone

e) Computer

Appendix B: Daily average solar radiation (KWh/m^2/day) of 2016 at Rulindo station in Northern Province

Daily average solar radiation(KWh/m^2/day)												
Days	January	February	March	April	May	June	July	Aug	Sept	October	November	December
day1	4.81	4.03	4.15	1.85	2.44	3.77	6.5	5.83	5.3	4.39	4.09	3.38
day2	4.71	4.38	4.45	3.84	4.52	4.22	6.26	5.96	6.83	1.23	5.39	5.83
day3	5.63	3.78	2.83	3.69	4	5.52	5.78	5.42	6.1	2.93	2.58	2.94
day4	4.38	5.54	3.65	3.45	3.59	4.15	5.23	5.13	4.22	2.65	5.19	4.29
day5	4.22	6.33	5.31	3.8	5.13	4.68	5.69	4.92	5.68	3.99	4.09	5.34
day6	5.35	6.23	6.18	6.93	4.18	3.52	5.75	4.3	5.68	5.97	4.23	6.62
day7	5.19	3.23	5.62	2.78	4.31	5.58	5.01	3.9	4.3	3.56	4.25	6.47
day8	5.93	3.94	1.25	4.12	2.62	6.47	4.54	3.21	4.14	5.52	1.54	5.72
day9	2.92	2.92	3.79	5.57	3.37	5.68	4.81	3.34	3.74	4.61	3.41	5.9
day10	2.45	2.11	4.97	3.76	5.25	5.41	5.82	4.6	5.54	3.91	4.66	1.87
day11	3.37	4.53	4.6	3.62	5.42	5.37	4.98	5.71	5.7	4.98	3.73	4.93
day12	3.42	3.38	5.66	3.51	4.24	5.39	3.72	5.13	5.16	7.05	4.23	4.99
day13	3.84	3.93	6.42	5	4.95	4.16	5.24	4.36	6.03	6.92	4.75	3.72
day14	3.7	4.26	6.22	3.58	4.54	5.04	4.92	3.71	6.82	6.43	4.63	3.61
day 15	3.79	6.24	6.54	4.08	3.27	4.17	4.47	4.31	4.05	5.68	4	6.21
day16	5.55	6.21	4.26	2.9	5.65	5.57	5.01	3.98	4.77	6.18	3.12	5.13
day17	3.48	5.87	3.77	4.21	5.68	3.95	5.33	5.54	5.53	5.29	3.29	5.19
day18	2.53	6.51	6.25	4.49	2.1	2.14	4.89	7.13	2.75	4.72	4.21	5.46
day19	2.47	3.44	6.57	2.32	3.15	4.23	5.81	6.48	5.7	5.77	3.54	4.59
day20	3.1	3.58	5.86	5.32	3.23	5.11	4.99	6.58	4.37	4.82	5.59	6.93
day 21	3.61	3.09	4.61	4.55	5.82	1.81	4.35	6.07	7.18	6.4	4.48	6.33
day22	3.77	6.22	4.49	4.92	5.14	3.19	4.76	5.6	4.61	6.22	3.39	5.52
day23	2.72	3.06	4.99	5.21	4.25	3.04	4.32	5.86	5.26	5.97	4.31	6.34
day24	3.86	5.57	3.34	4.86	5.42	3.55	4.88	5.73	4.61	6.41	4.77	6.94
day25	3.98	3.01	5.28	2.49	4.63	4.4	2.93	6.26	4.06	4.87	4.31	6.01
day26	3.65	5.21	6.12	2.88	5.6	3.94	4.17	3.79	3.34	2.62	5.08	5.25
day27	2.83	2.5	4.54	2.89	4.76	4.11	5.22	6.89	2.24	3.73	4.03	4.05
day28	2.67	5.89	5.41	2.5	5.2	6.45	4.87	7.08	2.76	5.37	5.21	3.93
day29	5.6	3.95	5.41	4.39	3.75	6.44	5.51	7.32	2.13	4.47	5.57	3.84
day 30	5.41		6.18	3.47	3.64	6.4	5.01	7.06	3.41	2.49	3.31	3.17
day31	5.49		4.03		4		5.63	6.74		4.83		4.28

Appendix C: detailed load profile of the village

Time	Households Load							Commercial load		Community load		Total Load
	lighting	TV	Computer	Radio	Fridge	Phone charger	Iron	Electric shaver	lighting	Shop lighting	nursery school lighting	(kW)
	(20W)	(100W)	(100W)	(2W)	(400W)	(7W)	(1000W)	(20W)	(32W)	(32W)	(20W)	
00:00-01:00					4000							4
01:00-02:00					4000							4
02:00-03:00					4000							4
03:00-04:00					4000							4
04:00-05:00					4000							4
05:00-06:00	10400			200	4000	1820						16.42
06:00-07:00	10400			200	4000	1820						16.42
07:00-08:00					4000							4
08:00-09:00			357.14		4000			60	32	320	28.57	5.00
09:00-10:00			357.14		4000		714.29	60	32	320	28.57	5.71
10:00-11:00				200	4000			60	32			4.29
11:00-12:00					4000			60	32			4.09
12:00-13:00				200	4000							4.2
13:00-14:00			357.14	200	4000							4.56
14:00-15:00			357.14	200	4000			60	32			4.65
15:00-16:00					4000			60	32			4.09

16:00-17:00					4000			60	32			4.09
17:00-18:00					4000			60	32	320		4.41
18:00-19:00	15600	8000			4000					320		27.92
19:00-20:00	15600	8000			4000					480		28.08
20:00-21:00	15600	8000			4000							27.6
21:00-22:00	15600	8000			4000							27.6
22:00-23:00	15600	8000			4000							27.6
23:00-00:00					4000							4
total daily use	98800	40000	1428.57	1200	96000	3640	714.29	480	256	1760	57.14	244.73