DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research

University of Tlemcen

PAN AFRICAN UNIVERSITY

Institute for Water and Energy Sciences (Incl. Climate Change)

Sizing of a hybrid solar PV-wind-fuel cell power system for isolated location

Case study: Groupe scolaire Mukondo

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Date: 30 August, 2016

*Master in **Energy Engineering track***

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Declaration

I, Devotha NSHIMIYIMANA declares that this master thesis project is my work to serve as part of the fulfillment of the requirements for award of a master's degree in Energy Engineering.

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Date: 30 /8/2016

Dedication

Firstly, I dedicate this work to the Almighty God for his blessing and protection along this journey. I deeply dedicate this work to my beloved mother who inspired me to be strong to face all challenges in this life. I dedicated this work to my brothers and sisters for their understanding and overwhelming moral support. I dedicated this to my extended family and friends for their assistance and encouragement contribution to carry this work, my internal gratitude.

Acknowledgement

I would like to thank PAUWES (Pan African University Institute of Water and Energy including climate change) for giving me the opportunity to further my studies. I would like to deeply thank the director Prof. Dr Zerga Abdellatif and PAUWES staff for their encouragement and for all facilities that they provided for the completion of this work. I sincerely appreciate their inspiration and motivation along this journey.

I would like to take this opportunity to thank my project supervisor, Dr Abdellah Khellaf for his patience, guidance, motivation, support and time along the work of this thesis. Dr. Khellaf is splendidly a good supervisor who has an attitude of a genius in regard to research. I am grateful to him for his experience and invaluable guidance, without his persistent help this research would not have been successfully completed.

I would like to thank the Rwanda Meteorology Agency staff for providing me with the needed data for this research. This research would have not been meaningful without a trustable data source, which they have been. I would also like to thank Mr Dusabimana Emmanuel the director of Groupe scolaire Mukondo for giving all the needed information without hesitation.

Last but not least, I would like to show my since gratitude to everyone who, directly or indirectly contributed to the successfully completion of this work.

Abstract

At 23%, Rwanda electrification rate is still very low. Most of remote and rural areas are not connected to the grid network due to the insufficient power production and high capital cost for grid network extension. A large number of the population living in rural areas uses diesel generators to provide energy for different services, whereas an even greater number are still living without electricity. This strongly affects the provision of fundamental services such as education, social services and economic services. Many of these areas continue to experience low rates of development and livelihood improvement. In order, to change this trend, renewable off-grid power systems are a suitable option for the provision of a solution to institutions located in these regions with a sustainable, affordable and environment benefits.

This research was focused on the sizing of the fully-renewable hybrid power system (solar PV-wind and fuel cell) for a high school, (Groupe scolaire Mukondo) located in Rubavu district in the western province. The system sizing was based on climatic data of Rubavu district given by the Rwanda Meteorology Agency. The goal was to meet the electricity demand load of the school, while taking into consideration the environmental effects. The system sizing of the school was divided into two cases. The first case considered the present situation for which the school is not boarding and has no laboratory facilities. For this case, the primary load demand of 21kWh/day with a peak load of 91kW is considered. The second considered case, proposed the future of the school with laboratories, and where the primary load was calculated at 102kWh/day with a peak load of 15kW. Solar and wind resources were considered to power the demand with a share of 60% and 30% respectively. The fuel cell was used as a backup system for excess energy production to be used later when the demand goes high or when there no power production by the primary source. HOMER software was used to size the system.

After the data simulation, a system of 8kW PV system, 4 wind turbines and 1kW of fuel cell was proposed for the first case, and for the second case, a 12kW PV system, 9 wind turbines and 1kW system was proposed.

Key words: HOMER, wind speed, global solar radiation, Hydrogen, Fuel cell, off-grid hybrid power system.

Résume

Le Rwanda regorge d'un grand potentiel énergétique d'origine renouvelable telle que le solaire et l'éolien qui peuvent être exploités pour la production d'électricité. En dépit de ce potentiel, le pays enregistre un taux d'accès à l'électricité très faible de 23% et l'hydroélectricité représente la majeure partie de la production électrique d'origine renouvelable. Il est donc nécessaire que le pays s'inscrive dans l'exploitation des autres sources d'énergies renouvelables afin d'améliorer le taux d'électrification à travers le pays.

La présente étude consiste au dimensionnement d'un system hybride autonome (solaire - éolien - pile à combustible) pour subvenir aux besoins énergétiques d'une école secondaire (Groupe scolaire de Mukondo) situe dans le district de Rubavu dans la province de l'Ouest du Rwanda. Se basant sur les donnes météorologiques de la région, le dimensionnement de ce système s'est fait en utilisant le logiciel HOMER pour simuler et optimiser le système. Le dimensionnement s'est fait suivant deux différents scenarios : - Le premier, basé sur la présente situation de l'école, comme une école externe sans laboratoires avec une demande électrique estimée à 21kWh/jour avec une demande en puissance de pointe de 9.1kW ; - Le deuxième scenario envisage un futur développement de l'école comme une école moderne. La demande électrique a été estimée à 102kWh/jour avec une demande en puissance de pointe de 15kW. Les ressources solaire et éolienne ont été considérées avec des contributions respectives de 60% et 30%. Quant à la pile à combustible, elle est utilisée comme source de secours. La pile à combustible va être utilisée comme une source de secours.

Après la simulation, le système hybride retenu est compose d'un système solaire PV de 8kW, 4 aérogénérateurs et 1 kW du Pile à combustible ce qui concerne le premier scenarios et 12kW du système solaire PV, 9 aérogénérateurs et 1kW pour le deuxième scenario.

Le dimensionnement du système s'est appuyé sur les données climatiques du district de Rubavu fournies par Rwanda Meteorology Agency (RMA).

Mots clés: HOMER : la vitesse du vent, irradiation solaire, hydrogène, Pile à combustible, system hybride autonome.

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List of abbreviation

PV: Photovoltaic

BOS: Balance Of System

Hd: Daily global solar radiation [kWh/m2]

Hm: monthly value of the daily global radiation [kWh/m2/day]

Ni: Number of days

Hy: Yearly mean value of the daily global radiation [kWh/m2]

WEC: Wind Energy Conversion System

V: wind speed [m/s]

ρ: air density [kg/m^3]

Pt: Total power [W/m^2]

E-33: Enercon-33

K: shapeless parameter

C: scale parameter [m/s]

Pextr: extracted power [W/m^2]

E: Energy [kWh]

H: Height [m]

HAWT: Horizontal Axis Wind Turbine

VAWT: Vertical Axis Wind Turbine

H2: Hydrogen

CH4: Methane gas

FC: Fuel cell

NOC: Nominal Operating Condition

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

REB: Rwanda Education Board

MINENFRA: Ministry of infrastructure

Chapter 1 GENERAL OVERVIEW

Outline

Chapter 1. GENERAL OVERVIEW

1.1 Country profile

Rwanda is a small, landlocked country located in East Africa, bordered by the Democratic Republic of Congo (DRC) to the West, Uganda to the North, Tanzania to the East and Burundi to the South. The country is known as the land of a thousand hills with a total area of 26,338 km^2. Rwanda has an altitude that ranges from 900 meters to 4,507 meters above sea level. The average annual temperature ranges between 16°C and 26°C. Rainfall is abundant, with an annual average level of 1,200 mm with seasonal variations (UNEP, 2014). As shown in Figure 1.1, the country is divided into four provinces with each one of them divided into districts.

Figure 0.1: Administrative division of Rwanda (UNEP, 2014)

Rwanda's population is growing fast. The population in 2014 was estimated at 11,341,544 with a population density of 430capita/km^2, making it one of the most densely populated in Africa. Rwandan population is predominately young and a large number of the population is living in rural areas. Even though the proportion of the rural population still dominates, it is gradually reducing because of rural exodus. As shown in Figure 1.2, the urban population has more than doubled.

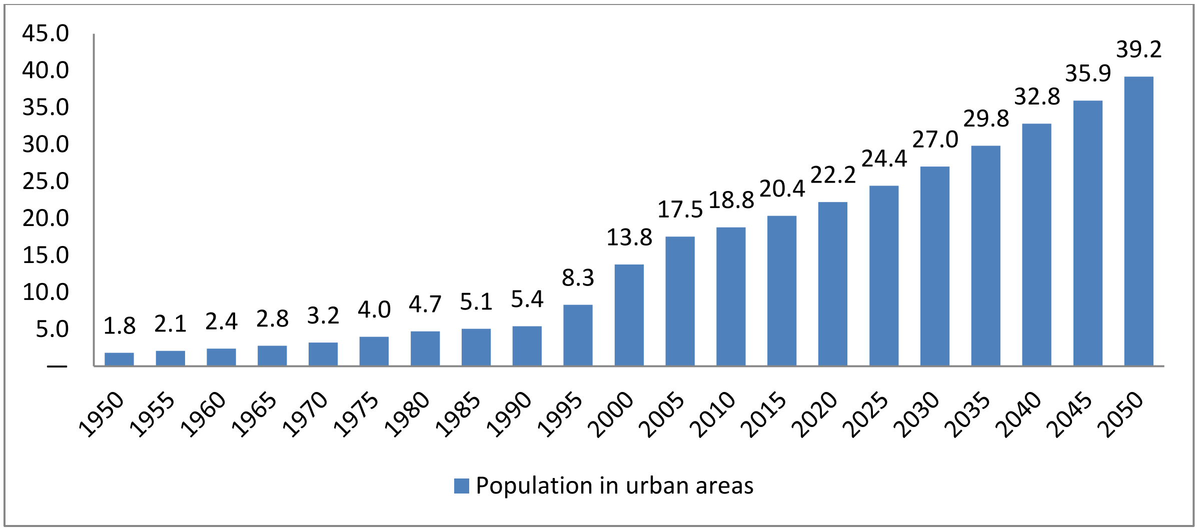

Figure 0.2: Percentage of the population in urban areas

In 2014, the rural population was estimated to account for 72 % of the total population. However, this value is undoubtedly going to down unless measures are taken to improve the livelihood of the rural population.

Rwanda is blessed with renewable energy resource potential. The country possesses a very rich hydro power potential, a large amount of methane gas reserve in Lake Kivu estimated at 55 billion m^3 to be extracted, global solar radiation intensity which varies between 4.3 to 5.2 kWh/m^2/day, peat reserves estimated at 155 million tons of dry peat which is equivalent to 1, 200 MW, a good potential for geothermal energy estimated to be between 170 and 340 MW and a considerable wind power potential (UWAMAHORO, 2012).

1.2 Problem statement

Several reports indicate that the energy supply in Rwanda is insufficient to meet the demand. It is reported that the main source of energy use is biomass as it contributes 86 % of the total energy consumption. Biomass is mainly used in its traditional form which causes a massive deforestation across the country and this has a great effect on the environmental and climate change.

Despite the fact that there exists abundant renewable energy resource within the country, the installed electricity generation is very low at 160 MW from all categories with only twenty-three per cent (23%) of the population having access to electricity. This power generation is not sufficient to fulfill the energy demands. Rural areas, especially the isolated ones, are the most affected by the lack of electricity supply, due to the high investment cost of the grid network extension, and this strongly affects the population living in those areas in different ways such as; the competitiveness in education remain at a low level, lack of modern activities, causing their development to lag behind.

1.3 Motivation

Renewable energy resources are clean. This means that the energy produced from these resources leads to the reduction in the impacts of climate change, by reducing the measure of greenhouse gases in the atmosphere.

It is known that energy plays an important role in the country's economic development. Thus the use of renewable energy provides huge benefits to the economic sector, as it relieves the importation of fuel energy which is expensive. The importance of energy is not only in the economic sector, but also appears in the development of social life by allowing the population to easily access the fundamental services such as water supply, communication, transportation, health care and education.

The country's electricity generation is still dominated by the hydropower, thus to increase the electrification rate, the power generation must be expanded through the exploitation of other renewable resources in order to satisfy the demands. As the electricity demand is increasing, the use of hybrid renewable off grid power system is one way that could be implemented to fulfill the electricity demands in isolated locations and contribute to their development through education and business creation. Hybrid renewable energy system offers a reliable, affordable and sustainable energy system which is crucial for the sustainable development of the country.

Generally, the country has a low electrification rate and the rural areas take the top position for the most non-electrified regions. However, the sustainable development of a country is tightly hinged to access to electricity, with which comes access to fundamental services, that could yield results such as eradication of poverty. The implementation of hybrid energy systems has the capacity to go a long way in enhancing the electrification state of the country.

1.4 Objectives

1.4.1 General objective

The main objective of this work is to size a hybrid PV-wind-fuel cell power system for Groupe scolaire Mukondo. The system will be composed of solar panels and wind turbine for the electricity production. An electrolyzer- hydrogen tank - fuel cell (FC) system is used first for hydrogen production and storage then electricity production when there is no enough solar energy or wind energy. This system is included to overcome the intermittent of the renewable energy.

1.4.2 Specific objectives

- To evaluate, through atlases, the solar potential and the wind potential of Rwanda.
- To describe solar and wind resource potential of Rubavu district (where Groupe scolaire Mukondo is located).
- To calculate the load demand for Groupe scolaire Mukondo. This Groupe is located in Rubavu. It has been providing education services. However, it lacks the basic electricity infrastructure to operate outside the lightday time.
- To size a PV system to meet the demand
- To size a wind system to meet the demand
- To analyze the result

1.5 Scope and Limitation of the Research

The research will be carried out on solar PV and wind turbine technologies in order to size a hybrid solar PV-wind and FC system. The study is limited to the sizing of a hybrid PV, wind turbine and fuel cell system for Groupe scolaire Mukondo.

1.6 Significance of the Research

The study of a hybrid solar PV-wind-FC power system will be based on Rwanda climate. The sizing of the system is then designed to be implemented in the future. It treats a real case where the basic energy infrastructures are lacking.

1.7 Research Methodology

A good research should be carried out due to different methods and variety of research techniques for the collection and analysis of the data. The present research project has been carried out at Groupe scolaire Mukondo located in Rubavu district. For the proper sizing of the system components, solar and wind data of year 2014 collected at Sebeya station were used as well as the demand capacity of Groupe scolaire Mukondo.

1.7.1 Data collection and procedures

The sizing of a hybrid system using renewable energy resource is completely dependent on the availability of energy resources potential. Therefore, the first stage was to identify a reliable source that may provide the reliable data. For this research Rwanda Meteorological Agency was contacted for global solar radiation and wind speed data. The wind speed data and global solar radiation received was collected at an interval of 10 minutes Sebeya station in Rubavu district.

The second method was the use of Meteonorm software, in which the meteonorm 7 wind speed and global solar radiation data of 1991 to 2010 were used to draw solar and wind map.

Then, for the writing of this research, more information based on the related research project of published papers of journals, online publication and books have been consulted and analyzed to reach out the meaningful and helpful information.

1.7.2 Data analysis

The ten minutes' interval collected data for global solar radiation and wind speed of the region was analyzed to determine the monthly values. Starting with the analysis of global solar radiation, Excel has been used to sort out the daily and monthly data.

For wind speed potential, the monthly average wind speed, shape parameter and the scale parameter were calculated using MATLAB. The Weibull function distribution was used to make the extrapolation of wind speed and calculate the wind power of the region at different height.

In general, it was found out that the region had solar and wind potential which can complement each other for practical application of a hybrid solar PV-wind power system.

1.7.3 Software

In this research project, different softwares have been used for data analysis such as MATLAB for wind speed data analysis and HOMER for the simulation of the system results.

1.7.3.1 MATLAB

MATLAB (MATrix LABoratory) is a high performance language for technical computing written to provide an easy access to matrix software developed by LINPACK and ELSPACK projects. In general, MATLAB deals with the computation, visualization and programming environment.

In the computation process, MATLAB performs a very wide variety of calculations such as basic arithmetic operators, number and formats, variables, and arrays, to mention but a few.

In the visualization, MATLAB provides easy access to the use of graphics to look clearly represent the computed results (Houcque, 2015).

In this research project, MATLAB was used to analyze wind data for getting the monthly average wind speed, shape parameter and scale parameter of the studied region.

1.7.3.2 HOMER

Introduction

HOMER (Hybrid Optimization Model for Electric Renewable) is a micro-power optimization model developed by the U.S National Renewable Energy Laboratory (NREL). The model is generally developed to assist and facilitate in the hybrid (off-grid or grid connected) system design as well as to facilitate in the power generation technologies comparisons.

In this research, HOMER was used to size a hybrid solar PV-wind and fuel system using the analyzed data.

1.8 Manuscript outline

The manuscript is divided into six chapters:

Chapter one is an introductory chapter that presents the background of the project, problem statement, objective of the research, the scope of the project and the research methodology used to collect data.

Chapter two deals with the actual energy situation in Rwanda, First a review of the studies carried out on the energy sector in Rwanda is presented. Then the overall energy situation of

Rwanda is analyzed and discussed. Its energy potential, particularly renewable potential, is evaluated.

Chapter three is the analysis of solar and wind potential.

Chapter four gives the overview on the storage system including the hydrogen production and fuel cell system.

Chapter five describes the sizing and simulation, in which there is a detail sizing of the demands side (case study) as well as the system components sizing, then the simulation of the system to find out the applicable system.

Chapter six includes the results and discussion.

Chapter seven is the conclusion and recommendation.

Chapter 2 LITERATURE REVIEW

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Chapter 2. LITERATURE REVIEW

2.1 Review of related works

According to Medhi Vafaei, a research on optimally-sized design of a wind-diesel-fuel cell hybrid system in Ontario (Canada) was conducted. The research was mainly based on the development of a micro-grid that combines wind energy resource and a hydrogen based energy storage system for a remote community. During this study, three scenarios were developed. The first scenario was the use of diesel only. The advantage of this scenario as mentioned out was the low capital cost, low maintenance and simple power management. Dependence on fuel and very high greenhouses gas emission were some of the big disadvantages. The second scenario was the operation of a fully renewable system. In this scenario, wind energy resource was considered to meet the demand side, then the diesel generator to be used as the backup system. The advantages of this scenario were the low operating cost, low emission and independent on fuel price variation. The disadvantages were assumed to be the high capital cost and the fluctuation of wind energy. The third scenario was the parallel system, in which the diesel generator and renewable resource shared the responsibility of feeding the load. This scenario was assumed to have a higher reliability, lower capital cost, and more efficient operation of diesel unit. The disadvantage was the dependence on fuel price and the environment effect issues.

Through the economical modeling, it has been found out that the capital cost for fully-renewable system is very high. As the study was conducted on the use of a hybrid system, the use of renewable resources combined with diesel units was proved to be a good choice for economical and environment benefits (Vafaei, 2011).

Another research carried out by Sandeep kumar and Vijay Garg described a hybrid solar PV-wind and fuel cell system in India. The research was carried out using MATLAB program. The paper is based on the comparison of a hybrid model solar-wind and fuel cell to the one that uses battery as the storage system. The research started through the description of a hybrid system. The study explained the use of solar energy as one of the free and non-polluting source of energy and how highly solar power depends on the insolation data and the area of a single PV panel. The IV and P-V characteristics of the used PV module at different solar illumination intensity showed that the generated current and power was high at higher illumination intensity.

Through modeling, PV voltage generated and power performance was evaluated. On wind energy system, the paper described how the power is directly proportional to speed as the power increases with the increase of wind speed. In wind power modeling, the coefficient of performance of 0.59 as the maximum theoretical coefficient of performance was used to evaluate the wind power generated. The voltage generated and power performance of a fuel cell as an electrochemical device that continuously converts the chemical energy fuel and oxidant into electrical energy had been also evaluated. Then a comparison has been made between a power based on solar PV-wind-fuel cell and solar PV-wind with battery and found out that hybrid system using fuel cell as the storage system is more efficiency, cheaper and has a long life (Sandeep Kumar, 2013).

2.2 Rwanda energy overview

Energy is a critical factor for economic growth of a country. A country's economy strongly depends on a reliable and affordable energy supply as it open doors for business set up by the government and by private sectors. It is recognized that the inadequate and expensive energy supply constitutes a limiting factor to the sustainable development.

Rwanda's access to electricity is quite low. The primary energy source is dominated by biomass, which contribute 86 per cent of energy demand. The biomass is mostly used for cooking in its traditional form. The country does not have crude oil reserve. The fossil fuel energy used is imported in which petroleum products account for 11 per cent (11%). Rwanda is blessed with a significant renewable energy resource potential but through all those various sources of energy that the country is endowed with, hydropower is the most exploited resource as it contributes fifty-nine per cent (59%) of the total energy generated followed by one per cent (1%) which comes from methane gas. In order to increase the energy production, the country import oil-fueled thermal energy which contributes 40 per cent (40%) of the energy production (UNEP, 2014). The focus on the exploitation of only one energy resource potential which is hydro has proven to be of low effect on the accessibility to energy as Rwanda present only 42 kWh/year/inhabitant of electricity consumption per capita (Africa energy Forum, 2015).

Rwanda is endowed with renewable energy resources like hydro, solar, biomass, wind, geothermal and peat. In order to increase the access to electricity, it is very vital for the country to adopt the use of modern technology by exploiting different possible resources, and simultaneously keeping focus on the energy efficiency use. Currently, Rwanda is moving towards a good position as the government has set different targets through the Economic Development and Poverty Reduction Strategy (EDPRS) in order to increase the electrification rate. Some of these targets include; the reduction in wood energy consumption from 94 per cent up to 50 per cent and ensure an energy consumption growth rate of nearly 10 per cent per year, a rural electrification rate of 30 per cent in other to achieve 2020 vision, and the achievements of the Millennium Development Goals (UNEP, 2014). As it was reported by MINENFRA through EDPRS2 for 2013-2018, the electricity generation is expected to increase from 110 MW of 2012 to 563 MW by 2018 and the access to electricity has to reach seventy per cent (70%) for both urban and rural households by 2018 (UNEP, 2014).

2.3 Rwanda Energy situation

2.3.1 **Operational and proposed power generation**

The current installed electric power capacity is at 160MW coming from thermal power generation and renewable energy resources. This installed power capacity is mostly dominated by hydropower as it contributes as much as fifty-nine per cent (59%) of the total installed capacity (MINENFRA, 2015). Table 2.1, 2.2 and 2.3 illustrates the operational and proposed power generation from hydro, thermal and solar (Encyclopedia, n.d).

Table 0.1: Operational and proposed Hydro power station

	Hydroelectric station	Location	Type	Capacity [MW]	Year completed
Operational	Ntaruka power station	Ntaruka	Run of river	11.5	1959
	Mukungwa power station	Mukungwa	Run of river	12	1982
	MukungwaII Power Station	Mukungwa	Run of river	2.5	2010
	Nyabarongo Power Station	Nyabarongo	Run of river	28	2014
	Rukarara Hydroelectric Power station	Rukarara	Run of river	9.5	2010
	Rusuzi I HydroelectricPower Station	Rusizi	Run of river	30	1958
	Rusizi II Hydroelectric Power station	Rusizi	Run of river	44	1989
Proposed	Rusumo Power Station	Rusumo	Run of river	80	2018
	Nyabarongo II Power station	Nyabarongo	Run of river	120	2020
	Rusizi III Power station	Rusizi	Run of river	147	2020
	Rusizi IV Power station	Rusizi	Run of river	200	2025

Table 0.2: Operational and proposed Hydro power station

	Thermal Power Station	**Location**	**Fuel type**	**Capacity [MW]**	**Year completed**	**Notes**
Operational	Kivu Watt Power Station	Kibuye, Karongi District	Methane	25	2015	The remaining 75 MW include it in proposed it's not yet constructed
	Kibuye Power1 (KP1)	Gisenyi, Rubavu district	Methane	3.5	2012	_
Proposed	Gisagara Thermal Power Station	Gisagara District, Southern Rwanda	Peat	80	2020 (expected)	_
	Gishoma Thermal Power Station	Rusizi District, Western Rwanda	Peat	15	2016 (expected)	May be expanded to 55 MW
	Symbion Thermal Power Station	Nyamyumba, Gisenyi, Rubavu District	Methane	50	2018 (expected)	Can be expanded to 100Mw

Table 2.3: Operational and proposed solar power plant

	Solar Power Station	**Location**	**Fuel type**	**Capacity [MW]**	**Year completed**	**Notes**
Operational	Ngoma Solar Power Station	Kibungo, Ngoma District	Solar	2.4	2011	Operational
	Rwamagana Solar Power Station	Agahozo, Rwamagana District	Solar	8.5	2015	online
Proposed	Kayonza Power Station	Rwinkwavu, Kayonza District	solar	10	2020	Under development

2.3.2 Energy consumption

Rwanda's population relies on biomass for their daily energy needs which give the biomass energy consumption to be the most dominate as it contributes 86% of the total energy consumption. Wood fuel is the most commonly used type of biomass with 80.4% of the total energy consumption used by 17.7% of the population for lighting and 98.7% for cooking. Even though the country is relying on the use of biomass in its traditional form, this is believed to have a strong environmental impact as today; the country is facing the desertification issues caused by the cutting of trees that are used for energy production.

The Electricity consumption had a very low share in Rwanda energy consumption, as reported by MINENFRA by the end of 2012, electricity represented only four per cent (4%) of the primary energy consumed (MINENFRA, 2015). Today the power consumption from modern energy is dominated by hydro with 137.5MW followed by 28.5MW of thermal and 10.9MW coming from solar. Thus, the exploitation of renewable resources potential and the use of modern technology are highly recommended for the country's sustainable development.

Figure 2.1 presents Rwanda energy consumption coming from different sectors from 2000 to 2012

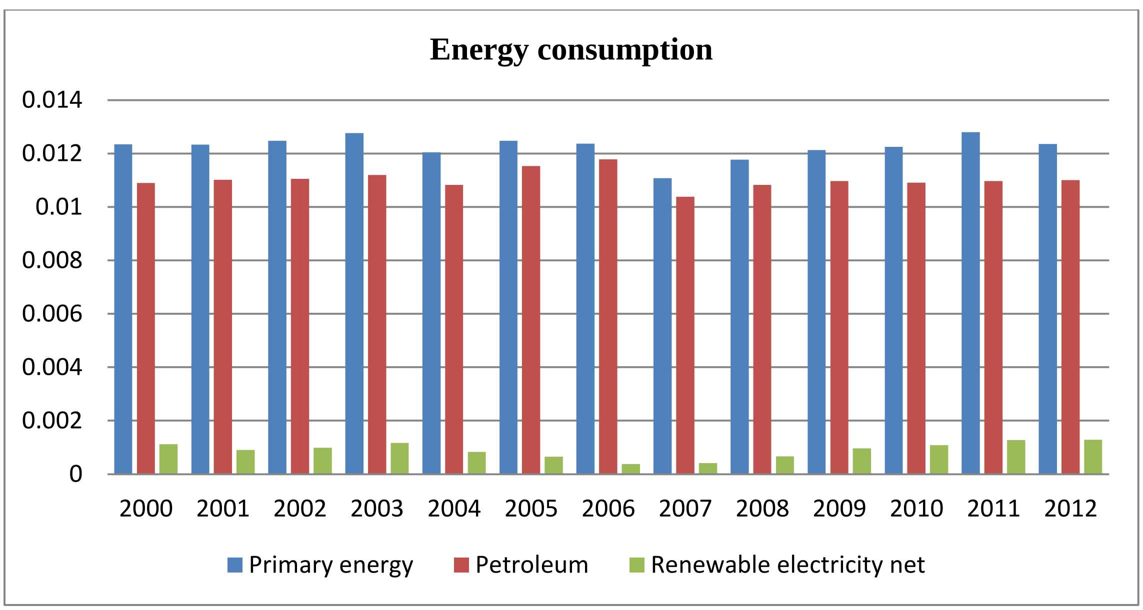

Figure 0.1: Energy consumption (IEA)

It was observed that the renewable electricity net consumption was very low compared to petroleum despite the fact that the country does not have fossil fuel reserves. The importation of petroleum strongly affects the country's economy.

2.3.3 **Energy mix**

Rwanda's energy mix was dominated by biomass that accounts for about 85% of primary energy use while petroleum accounted for 11% and electricity for the remaining 4%. The biomass was mainly used in the traditional form of energy for cooking as mainly as firewood in rural areas and as charcoal in urban areas (AfDB, 2013). The generation mix was characterized by 49% of hydro, 24% of thermal, 25% of methane, 5% of solar, 1% of off grid hydro and 9% of off grid thermal. The imported energy generation contributed a share of 10% (MINENFRA, 2015).

In order to improve and emphasize the sustainable use of biomass through modern technologies, as well as to mitigate the risks of deforestation so as to secure people's life, some strategies have been set out by MINENFRA such as:

- Promotion of improved technologies for charcoal production and improved cook stoves
- Promotion of biogas digesters to rural families where animal waste and human waste can be transformed into biogas.
- Encourage the production of methane or other forms of energy from solid waste landfills or through gasification processes (AfDB, 2013)

2.3.4 **Energy needs**

Energy demand and supply

For any energy supply plan, the demand side is a crucial part that has to be assessed in other to satisfy the needs. In Rwanda, households are considered as dominant consumers of electricity at a rate of 51% in which the majority demand is primarily used for lighting. The industrial and public sectors are considered to consume electricity at a rate of 42% and 6% (MINISTRY OF INFRASTRUCTURE, 2015).

Rwanda population is growing rapidly and therefore leading to an increase in the electricity demand. In order to increase the population with access to electricity, plans and target have been set out. As households are considered to be the dominant electricity demand side, through government plan it was estimated that, the number of household connected to the grid will increase from 350,000 in 2012 to 1,200,000 in 2017 and 2, 400, 00 in 2025. It is also envisaged that the electricity supply will provide 100 per cent electrification for the basics institutions including schools, health facilities and public sector offices either through grid connection network or through reliable off-grid systems by 2017 (AfDB, 2013)**.**

Based on the research carried out by MINENFRA, it was indicated that by 2018 the energy demand will be up to 473MW. In order to satisfy the demand, the government through its power sector strategy aims to expand the generation capacity to 563MW by 2018 (MINENFRA, 2015).

2.4 Energy resources potential

Energy resources are essential for any society. Energy is considered as the main factor in the country's sustainable development. There are fossil fuel sources of energy such as coal or petroleum and renewable energy sources such as solar, wind, geothermal, hydropower, and biomass. Rwanda has considerable opportunities for energy development from its own possessing renewable resources. In this part we will discuss on renewable energy resource as the country's vision for electricity generation.

2.4.1 Renewable energy resource potential

Renewable energies are known as clean energy. They are derived from natural processes that are replenished constantly. Rwanda has abundant renewable energy resources potential, including solar, wind, geothermal, biomass and hydro. These resources are spread across the country and could provide affordable and secure energy supply if they are well harnessed. Thus, the government of Rwanda through MINENFRA in its EDPRSII strategic plan; have renewable energy resources potential considered as an option for electricity generation for the future in order to ensure the energy sustainability, environmental protection and socio-economic benefits.

2.4.1.1 Biomass

Biomass is the most highly use source of energy in Rwanda. It is estimated that 20% of the total land areas are covered by forests. Biomass is mainly used in firewood form, charcoal and agricultural residues for the cooking purposes in Rwandan households, and also in some industries. It was estimated that a large number of the population are living in rural areas where an average of 99.5% of households used fuel wood as the main source of energy for cooking.

The biomass consumption is estimated to be at a rate of 86% in which wood contributes 57% followed by charcoal with an estimation of 23%, crop residues and peat contributes 6%.

Biomass consumption differed significantly from rural to urban households, as reported by MINENFRA the survey that had undertaken by the Africa Energy Service Group in 2012 showed that the biomass consumption by a rural household was on a yearly average of 1,885kg of fuel wood and 565kg of charcoal while the urban household consumed 1,891kg for fuel wood and 771kg of charcoal. The total biomass consumption was estimated to be 4,775million tons (MINENFRA, 2015).

2.4.1.2 Hydropower

Rwanda has significant hydropower potential resources and it has been the dominant source of power production since 1960. It is estimated that the overall hydropower potential is around 400MW for which only 98.5MW of power capacity was installed (MINENFRA, 2015).

Hydropower resources can be used in various ways depending on the size of the resources. Large scale and small scale hydropower systems are the most commonly used. Large-scale hydro resources are often more than 10 MW and used in combination with a storage dam and suitable for grid electricity production while the small hydropower plants that range from 1MW to 10MW may or may not incorporate dams. Others such as mini-hydro that ranges from 100 kW to 1MW, micro-hydro that ranges from 5 to 100 kW and Pico-hydro that are less than 5 kW are mainly used in off-grid power system and suited to run-of-river for electricity generation in remote areas (IRENA, 2015).

Hydropower dependent on a reliable supply of water, and the change in seasonal affect the quantity of energy generated that why when planning for hydropower plant, the seasonality and annual variability of hydro resources must be taken into consideration

2.4.1.3 Methane gas

Lake Kivu is the only water body with methane gas and Kivu-watt was the first project envisaged in the extraction of methane gas for electricity generation purposes. It was estimated that there is 300 billion m^3 of CO_2 and 60 billion m^3 of CH4 and that 120 to 250 million $m^3$of CH4 is generated annually in the bottom of Lake Kivu. According to the MINENFRA report, it was assumed that the potential to be extracted was almost 55 billion $m^3$of dissolved methane gas which was believed to be equivalent to 40 million tons of oil. The pilot projects have demonstrated that there is a commercial and technical viability of extracting methane from Lake Kivu within a potential of 350MW (UNEP, 2014). Thus methane gas is considered as a potential resource for the future grid electricity demands. It should be noted that currently, a 28.5 MW power plant executed by Kivu Watt power station and Kibuye power plant is in operation.

2.4.1.4 Solar

Solar energy is the most abundant permanent renewable energy resource on earth. Solar energy may be used in a direct or indirect form.

Rwanda is characterized by a savannah climate. Its geographical location endows it with considerable solar potential. The academic assessment undertaken in partnership with MINENFRA department of Meteorology in 2007 roughly showed that the solar radiation varies between 4.3 and 5.2 kWh per m^2 per day over all regions of Rwanda (MINENFRA, 2015). The government target is to increase access to electricity focusing on the use of renewable resources. It is in that case that solar has not lagged behind as the target was to increase the solar power plant up to 50KW by 2017 (MINENFRA, 2015).

Figure 2.2, drawn using the meteonorm 7 data presents the distribution of solar resource potential for the whole country.

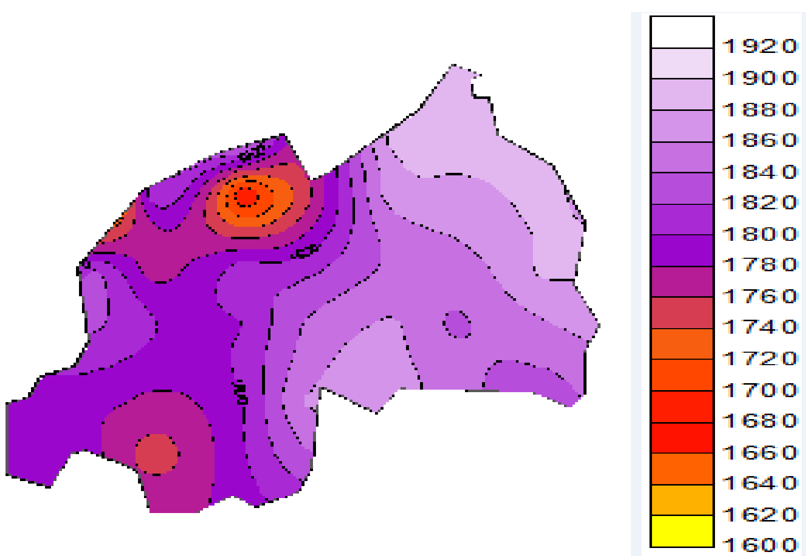

Figure 0.2: Rwanda solar distribution

It is observed that the Eastern province receives a greater intensity than the other regions even though there is a significance amount of solar radiation all over the country. This potential can be exploited for electricity generation by the use of solar technologies.

2.4.1.4.1 Photo Voltaic (PV) cell

A photovoltaic cell is a device that converts light energy directly into electricity. PV cells are mainly manufactured from a semiconductor material called crystalline silicon, which is available abundantly in the earth’s crust. They are free of moving parts and environmental friendly. They are strongly built, simple in design and require very little maintenance.

The first solar cells were made from single crystal silicon wafers and had efficiency of six per cent. From the start mainly the solar cell was used in space application. The energy crisis in the 20th century accelerated the research in new energy sources for diverse applications. This research resulted in a growing interest in solar PV energy. Beside that the major obstacle of using the solar cell for electricity generation has been a much higher price compared to the price of the electricity from the price generated from the traditional source of energy. In that case the important issue was to lower the electricity price from solar energy and increase the efficiency of the single crystalline silicon solar cell. The single crystalline solar cell has been improved and today it is the dominant solar cell technology. Crystalline silicon solar cell technology represents today not only single crystal silicon wafer-based solar cells, but also multi-crystalline silicon solar cells as the first generation solar cells. This technology is matured but the cost is still increasingly dominated by material costs such as silicon wafer and glass cover sheet. In order to decrease the material cost, the research has been conducted for the second generation solar cells for electricity generation by developing a thin-film solar cell which is highly dominated by copper indium gallium diselenide (CuInGaSe2=CIGS), cadmium telluride (CdTe), hydrogenated amorphous silicon (a-Si:H) and thin-film polycrystalline silicon (f-Si). Today solar cell efficiency is estimated to be at 16-17 per cent and research still continues in this field for the third generation solar cell.

The electricity generated by solar cells is increasing worldwide and very beneficial as it is estimated that the PV cells may transform 1/6 of solar radiation into electric energy (Bahta, 2013) and their life time may go up to 25 years. Cell efficiency and size of a solar panel are considered among the main criteria that describe the amount of electricity that could be produced by a solar panel.

PV cell classification

There are many materials used to make PV cells but silicon dominates as the main material used in the fabrication of PV cells because of its availability in the earth's crust and its properties. The electricity generation from solar depends on the size of the PV cell, the conversion efficiency, and sunlight intensity of the local area.

PV cells are classified as mono-crystalline, polycrystalline, and amorphous (Thin film PV cell).

a. Mono-crystalline PV cell

Mono-crystalline PV Cell is the first generation of all PV cells. It is made from uncontaminated silicon single crystals, cut-off from ingots. It has a dark color and it is with high heat resistant ability. The mono-crystalline PV cell is made of one crystal which makes it more efficient. It functions better in areas where low energy sources are required. One of the disadvantages of this technology is that it takes long time to be manufactured and is expensive. The mono-crystalline PV cell has the ability of converting 1000W/m^2 solar radiation to around 140W of electricity in PV cell surface area of 1m^2 (Bahta, 2013).

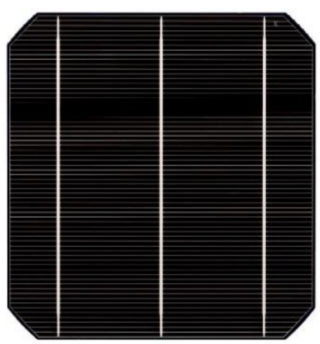

Figure 0.3: Mono-crystalline solar cell

b. Polycrystalline PV Cells

The polycrystalline PV cell is made from combination of smaller quantities of silicon crystal blocks. The polycrystalline PV cells are inefficient compared to mono-crystalline cells as they are not grown from single crystals but from a combination of many crystals. Polycrystalline PV cells perform better than mono-crystalline in slightly shaded conditions. It is estimated that this technology is the most widely used nowadays. Polycrystalline PV cell has the ability to convert 1000W/m^2 solar radiation to around 130W of electricity in PV cell surface area of 1m^2 (Bahta, 2013).

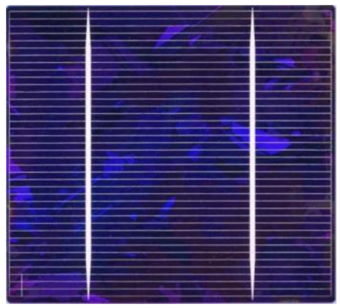

Figure 0.4: Polycrystalline solar cell

c. Thin Film PV Cells

Thin film PV cells are not made from real crystals preferably the silicon is deposited on stainless steel, plastics or glass to form the solar module. These types of PV cells are much less efficient than mono and polycrystalline PV cells. Currently companies are pursuing lower-cost, non-vacuum approaches for manufacturing the thin-film. Most thin films are direct band gap semiconductors; they are able to absorb the energy contained in sunlight with a much thinner layer than indirect band gap semiconductors such as traditional c-Si PV. The most common thin-film semiconductor materials are cadmium telluride (CdTe), amorphous silicon (a-Si), and alloys of copper indium gallium diselenide (CIGS). The thin film PV cells have a low efficiency as their efficiency vary from 5% to 13% and their lifespan is about 15-20 years (Bahta, 2013).

PV efficiency

PV efficiency describes the ability of panel to convert sunlight into usable energy. The efficiency of a PV cell, η, is calculated as the ratio between the generated maximum power, P_m, by a solar cell to the incident power, P_{in}. The incident power is equal to the irradiance of AM1.5 spectrum, normalized to 1000 W/m^2. The η is calculated as:

$$\eta = \frac{Pm}{Pin} = \frac{Vm*Im}{Pin} = \frac{Isc*V0c*FF}{Pin}$$

Factors that affect the PV efficiency

There is no technology that is one hundred per cent perfect. The study done on PV working principle reveals that there are different factors that affect the efficiency of solar panel. Some of those factors are entitled to increase or decrease the solar power production. Some of those factors are solar irradiance (sun intensity), temperature, dust, tilt and orientation.

i. Solar irradiance

Irradiance is defined as the power per unit area received from the sun in the form of electromagnetic radiation in the wavelength range whereas irradiation is the measure of energy density of sunlight. Solar irradiance and irradiation are two terms strongly related to solar components. Solar is a fluctuating natural energy resource due to the environmental condition as consequence the solar irradiance change depending on the weather condition. The increase of solar irradiance enhances the increase of open circuit voltage and short circuit current thus the increase of the power (Subhash Kumar, 2014).

ii. Temperature

Temperature is a major factor that affects the solar cell working principle thus playing an important role in the determination of its efficiency. As the fabrication of solar cells depend on semiconductor materials, the working principle of the semiconductor material shows that the increase in temperature reduces its band gap which increases the rate of photon generation, thereby resulting in the increase of the reverse saturation current. The solar cell saturation current is directly proportional to the reverse saturation current, thus the increase in the reverse saturation current increases the diode current and reduce the cell current.

Temperature is considered to be a negative factor of the solar cell performance as the research proved that the cell voltage is reduced by 2.2Mv per degree rise of temperature. Therefore, the reduction in voltage results in the reduction of the theoretical maximum power.

The best performance of a solar cell is calculated when the solar cell is exposed at a reference temperature, which is considered to be $25^{o}C$. It has been proven by different studies that solar cells perform better cold rather than hot (Furkan Dinçer, 2010).

iii. Dust

A dust layer that often settles on solar cells affects PV module performance as it blocks the transmission of sunlight. Dust layer plays a role of an obstacle of the solar radiation that is towards the solar cell. When light intensity falls on dirty PV module, some of the radiation becomes absorbed and other refracted by the dirty resulting in heating of the glass cover which increases the temperature of the PV module and reduces its output power. It is estimated that for every degree rise in temperature, the output power efficiency is reduced by 0.5%.

The other effect of the dust on PV module is the reduction of the irradiated areas which also result in the reduction of the generated output power. Dust does not only affect the PV module by the temperature increase but also has other effects on the PV module like erosion of the glass cover depending on the type of dust that the module is exposed to. The erosion of the PV module results in the reduction of the radiated areas thus reducing the output power as the roughness and the reflective index of the glass cover has been reduced (Subhash Kumar, 2014).

iv. Orientation and tilt angle

Orientation and tilt angle are two parameters that greatly affect the PV performance. The amount of solar radiation received by the surface of a PV module in a particular region is determined by how the PV model is orientated and tilted to face the sun. The solar panel captures the maximum radiation when the sun light hits perpendicularly the panel surface that why the region located in the northern hemisphere the panel should be installed facing south or the equator and for the region in southern hemisphere the panel should be installed facing the northern hemisphere and at an angle approximately equal to the site latitude (Subhash Kumar, 2014).

v. Shading

Shading is an important factor that affects the performance of a PV module. Shading may be considered as trees and large buildings surrounding the PV array. Trees and large buildings may cause partial or full shading. Shading is considered as an obstacle for the solar radiation to reach the PV module resulting in the reduction of the output power or absence of the generated power. The effect of shading is also related to the fact that it makes the maximum power point tracking system difficult thus reducing the output power of the system (Subhash Kumar, 2014).

2.4.1.5 Geothermal

Geothermal energy is a clean and reliable source of energy, which is not affected by weather fluctuations. It is stated that the exploitable geothermal systems occur in a geological environments that are largely bound to areas of young volcanism, seismic and magmatic activity known as the ring of fire.

Rwanda has been estimated to possess geothermal resources as it lies along the Western branch of the East Africa Rift Valley which is a ring of fire. The investigations on Rwanda geothermal resources started in 1983 with a view of diversifying energy resources for electricity generation. Studies on geothermal resources that have been done by different national and international companies indicate that there are two zones within geothermal energy potential resources as shown in the figure 2.5. The first zone which is associated with volcanoes was located in the North–Western region precisely in Gisenyi, Kalisimbi and Kinigi areas. The second zone which is associated with the East Africa rift valley was located in southern region precisely in Bugarama area.

It was investigated that that the north-western area had a high temperature geothermal system while the south area presented a low to moderate temperature geothermal system (Rutagarama, 2013).

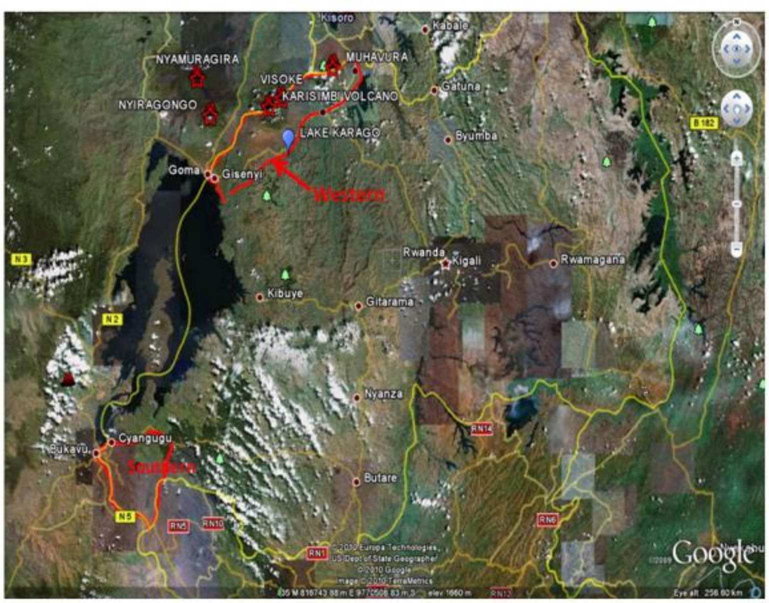

Figure 0.5: Location of geothermal prospective zones (Rutagarama, 2015)

In 2006, the study carried out by Chevron in Bugarama and Gisenyi areas estimated that there was a geothermal reservoir of temperature which was more than 150^0C. Thus the Government of Rwanda has been looking forward to invest in the assessment of geothermal resources. In 2008 the study carried out in Gisenyi, Karisimbi and Kinigi areas on geothermal potential conclude that there was a geothermal system with temperature greater than 200^0C on the southern part of Karisimbi volcano and a medium temperature of 150^0 to 200^0C of geothermal resource around Lake Karago.

Based on the assessment done before, the exploration drilling in the Karisimbi prospect area carried out from June 2013 to March 2014 showed that there was no geothermal system existence (Rutagarama, 2015).

The studies are still being conducted in geothermal energy sector and there is a chance in the existence of the potential as MINENFRA in its energy strategic plan of March 2015 reported that the geothermal power potential was estimated to be around 350 MW and the target for geothermal development was set at 300 MW by 2017 (MINENFRA, 2015).

2.4.1.6 Wind

Wind energy is among the fastest globally growing renewable energy. It is estimated that there is wind potential in Rwanda even though there is insufficient information about its potential. Few studies that have been conducted on wind energy resource shows that for some areas there is wind potential that may offer possible solutions to electricity generation, water pumping and windmill.

The study done in 2007 on two stations located in western province (Gisenyi and Kamembe) using the recorded data at height of 10m above ground showed that the mean wind speed ranges from 0.3m/s to 3.45m/s from 6am to 6pm. The highest diurnal wind speed was found at Kamembe station with a range of 1.22m/s to 3.45m/s (Otieno Fredrick Onyango, 2014).

In this research, using the data from meteonorm 7 from 1991 to 2010, it was found out that Rwanda wind speed varies between 2.5 to 3.5m/s with an annual average value of 2.92m/s as illustrates in table 2.3.

Table 0.3: Monthly and annual wind speed from Meteonorm 7 data

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Wind speed (m/s)	3.25	3.46	3.31	2.70	2.52	2.53	2.59	2.64	2.87	3.02	2.99	3.2	2.92

Figure 2.6 drawn using the meteonorm 7 data from 1991 to 2010 describes the country wind speed variation in which it was observed that the Western province has a higher wind potential than the other provinces.

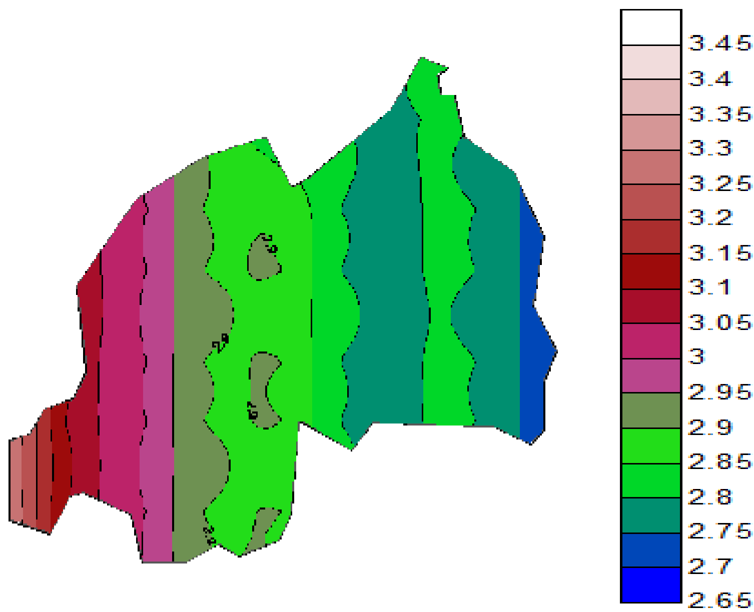

Figure 0.6: Map of wind speed variation

It is reported that in Rwanda, wind energy has been used in only two sites, one at the Mount Karisimbi's summit for the FM transceiver antenna of the National Radio and Television that was destroyed during the 1994 Genocide and the other which is a wind turbine for pumping water installed at Gabiro district, in the Northern Province (UWAMAHORO, 2012).

There is a great chance that the existing wind potential may be extracted to generate electricity but a comprehensible assessment is needed to determine the Rwanda wind potential.

2.4.1.6.1 Wind turbine classification

a. According to the size

Wind turbine is implemented depending on the demand side. The turbine may be of small size (up to 2KW) mainly for remote application or places requiring low power. The turbine may also come into a medium size (2-100 kW) to supply several residency or local use requiring power which is under 100KW or in a large scale size (100 kW and up) for power generation and distribution in central power grids.

b. According to the orientation

There are two main classes for wind turbine depending on their orientation. The horizontal axis wind turbine and vertical wind turbine. For horizontal axis wind turbine (HAWT), the axis of rotation is parallel to the direction of the wind. HAWT may be designed depending on the number of blades as single-bladed, double-bladed, and three-bladed or depending on the orientation of the blades with respect to wind direction where up-wind and down-wind type may be found. The use of a variable blade pitches in an HAWT gives the turbine blades the optimum angle of attack which gives a greater control through the adjustment of the angle of attack providing the maximum collection of wind energy. Also the height of tower allows access to stronger wind in sites with wind shear as it is estimated that at every ten meters up, the wind speed can increase by 20% and the power output by 34%.

Figure 0.7: Horizontal axis wind turbine (Y. Amirat, 2007)

In Vertical Axis Wind Turbine (VAWT) the axis of rotation is perpendicular to the direction of wind. The main advantage of VAWT over HAWT is their omni-directional, which means that the VAWT accept wind from any direction which simplifies their design (Óskarsdóttir, 2014).

Figure 0.8: Vertical axis wind turbine

2.4.2 **HOMER Software**

Working principal

HOMER model works through three principal tasks in which it calculates the energy for a particular configuration system that is needed to be calculated. The model works trough: simulation, optimization and the sensitivity analysis.

During the simulation, HOMER deals with the configuration of a particular micro-power system and determines the technical feasibility and life cycle cost of the system.

In the optimization, HOMER performs many configuration systems so that the user may choose the one that may satisfy the technical constraints at low life cycle cost. During the optimization of the system, the optimal system indicates the size and number of components that can be used to satisfy the energy demands.

In the sensitivity analysis, HOMER deals with multiple optimizations under different inputs assumptions. As for one side, the optimization gives the optimal value for the variables that can be controlled by the system such as the size and number of components to be used by the system, the sensitivity analysis on the other side comes out to assess the uncertainty or changes in variable that cannot be controlled by the system such as renewable resource data, interest rate or future price of fuel (Tom Lambert, 2005).

2.5 Summary

This chapter presents a literature review on the Rwanda energy overview and renewable energy resource potential.

First of all, the chapter starts with a review on the research done on sizing of a hybrid wind/diesel/fuel cell power system in Canada and solar PV/wind and fuel cell power system in India. Then, continues with a review on energy situation in Rwanda and renewable energy resource potential. It is found out that the country is blessed with renewable energy resource but the energy sector strongly depends on the hydropower energy resource as it represents fifty-one per cent (51%) of energy production. Finally, the chapter gave a description on solar cell and wind turbine.

Chapter 3 HBRID RENEWABLE ENERGY SYSTEM AT GROPE SCOLAIRE MUKONDO

Outline

Chapter 3. HYBRID RENEWABLE ENERGY SYSTEM AT GROUPE SCOLAIRE MUKONDO

Groupe scholaire Mukondo is a twelve-year basic education center located in Rubavu district, Western province. The school has no electricity. The aim of this paper is to size a hybrid off-grid system for the electrification of Groupe scolaire Mukondo.

In general Rwanda climate is characterized by four seasons, a short wet season from October to November, a short dry season from December to February, a long wet season from March to May and a long dry season from June to September. Rwanda's average annual temperature is estimated around 15-17℃ in high altitude areas and goes up to 30℃ in lowlands in the east and southwest (n.d, 2015).

For the case study, the global solar radiation and wind speed sources data was given by the Rwanda Meteorology Agency (RMA). The used data was collected from Sebeya station located in Rubavu district. The wind data was measured at 10m above ground surface within 10 minute intervals. The global solar radiation also was measured at 10 minute intervals.

3.1 Solar Photovoltaic system (PV system)

3.1.1 Introduction

Photovoltaic (PV) power generation is a promising technology for generating energy from solar irradiation. PV system is the most known system that converts directly the sunlight into electricity using semiconductors cells.

A PV system is made of three main parts which comprised of solar panels for the electricity generation, the balance of the system (BOS) for the equilibration of the system and the load. Solar panels are made of the combination of PV cells connected together to provide a significant amount of electricity output, the BOS is mainly composed of inverter and controller to connect and control the solar power inputs before it will be supplied to the electrical grid and other electrical components and battery for the storage of the excess produced power. Then there is a load which is made with the demand side appliances such as lighting, radio and TV set (zeman).

PV system for electricity generation is described as one of the safe, reliable, maintenance free and environmentally friendly source of power generation system with a life time expectance of over 20 years.

3.1.2 PV system components and their description

A PV system is the combination of different design components put together to assure the electric power supply from sun radiation as the power source. PV system is composed of photovoltaic cells, charge controller, storage and inverters as shown in figure 3.1.

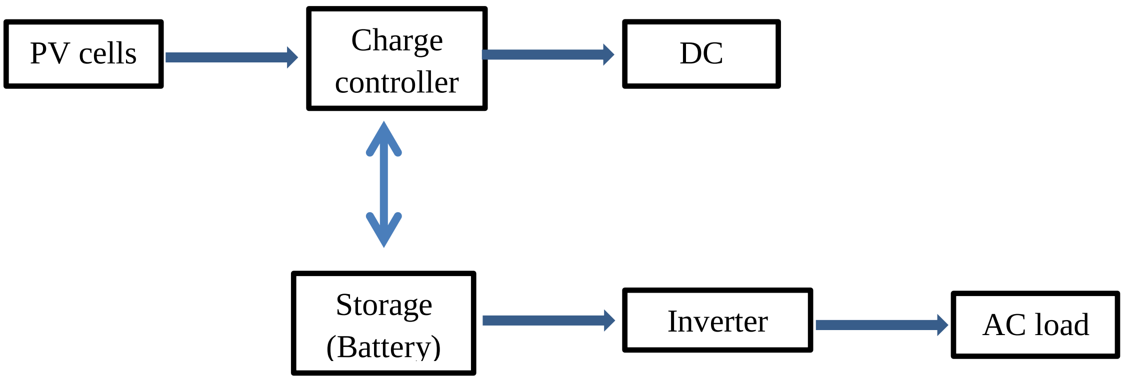

Figure 0.1: PV system components

3.1.2.1 PV cell

A PV cell device converts the sun light directly into electricity by the photovoltaic effect. This device is a building block of the PV module. The PV cell device is characterized with different electrical characteristics in which parameters such as current, voltage or resistance, vary depending on the received amount of sun intensity. Through different research, it was proven that one solar cell is not enough to produce the amount of electricity needed, and that is why individual solar cells are interconnected together to get the module in order to generate sufficient energy.

3.1.2.2 PV module/array/panel

PV module consists of multiple solar cells connected together, nearly in series in order to increase power and voltage. The PV module voltage is usually chosen to be compatible with a 12V battery. It is estimated that the cell voltage lies between 0.5 and 0.6V under the Normal Operating Condition (NOC) at 25^0C, AM 1.5 and 1000W/m^2 of illumination. The PV modules are usually formed by 36 cells connected in series. PV modules are combined together to get solar panel and then multiple panels combined together gave an array (Bahta, 2013).

3.1.2.3 Charge controller

These are device used for regulating the working mode of charging and discharging of the battery, solar panel and other equipment. A charge controller is usually used to control the voltage and flow of electricity. It prevents system damage by ensuring that the battery does not get overcharge by the solar module, or does not over-discharge by having the loads. It also provides protection from the current running backwards to the solar panels by providing useful information about the battery's state of charge (Bahta, 2013).

3.1.2.4 Inverters

An inverter is a device which converts direct current (DC) into alternative current (AC). Inverters are used indifferent applications including consumer power electronics, electric vehicles and energy storage interconnections to power distribution systems. Inverters may be stand-alone (off-grid) to supply generated power solely to connected loads, or they may be tied into the grid and allow generated power to be supplied to a utility's distribution network (Bahta, 2013).

3.1.2.5 Storage system

Solar is a fluctuating source of energy which means that it can experience fluctuations in energy in a very short time (uneven irradiation that could change hourly and on a daily basis). The storage system is very useful for such kind of fluctuating sources of energy as it is mainly used to store excess energy and release the stored energy when load demand goes high compared to the production. Storage is mainly needed in off-grid system to improve the system reliability, efficiency and flexibility throughout the frequency regulation (Bahta, 2013)

A storage system contains different primary components like battery, monitoring and control systems, and a power conversion system.

3.1.3 **PV working principal**

A PV cell is generally made of semiconductor materials such as silicon which have intrinsic optoelectronic properties. These present an absorbent character in a solar spectrum range and have the capability of transferring energy between two levels with a lowest possible electrical resistance in order to ensure the collection of electrons-holes generated.

Mainly PV cell effect is based on three main principals whose action generated the conversion of solar energy into electric energy. Those actions are:

- Photon absorption
- Energy conversion of the absorbed energy into free electrical charges
- Collection of particles in an external electrical circuit.

The semiconductors materials are made of at least two layers of different charges. There is a P-type (Positive) layer and N- type (Negative) layer which are separated from each other by a junction. When the sunlight hits the solar cells, some of the photons are absorbed by the semiconductor atoms generating the electron-hole pairs which are separated by an electric field in other to avoid the recombination. During the separation of the generated electron-hole, free electrons from the cell are moved towards the negative layer and holes towards the positive layer. This flow of electrons produces electric current (Tom Markvart, 2012).

The energy conversion depends on different physical parameter such as the energy gap of the semiconductor, the type and level of doping, the mean free path of carrier's photo-generated electric charges that determines the lifespan, the absorption coefficient, the surface reflection coefficient, the nature and the impurity density of the materials which are related to the type of radiation and the intrinsic properties of the receiving material.

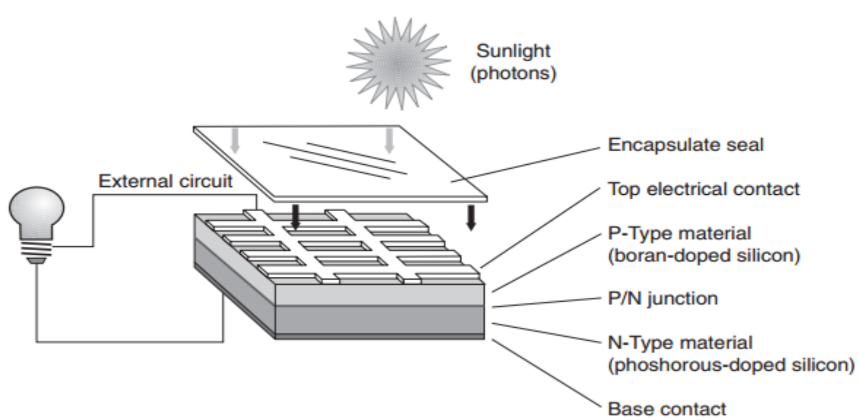

Figure 0.2: Solar cell construction (Tom Markvart, 2012)

3.1.4 **Site solar energy potential (Solar PV)**

Solar radiation is the radiant energy emitted by the sun, particularly electromagnetic energy. In fact, solar energy is highly required for the convenient working of the system as PV cells transform solar energy into electric energy.

The global solar radiation data used was collected at 10 minutes apart for each day and was expressed in W/m^2 as attached in the appendix, thus the daily and monthly data collection was calculated using the following formula:

Daily global solar radiation

$$\mathbf{Hd} = \frac{\boldsymbol{\Sigma}\ \dot{\mathrm{H}}\dot{\mathrm{m}}}{\mathbf{6000}} \quad \textbf{[kWh/m2]} \qquad \textbf{\textit{Equation 1}}$$

Monthly global solar radiation

$$\mathbf{Hm} = \frac{\boldsymbol{\Sigma Hd}}{\boldsymbol{N}\mathrm{i}} \quad \textbf{[kWh/m2/day]} \qquad \textbf{\textit{Equation 2}}$$

Yearly solar global radiation

$$\mathbf{Hy} = \frac{\boldsymbol{\Sigma(Hm\ X\ Ni)}}{\mathbf{365}} \quad \textbf{[kWh/m2]} \qquad \textbf{\textit{Equation 3}}$$

Where: Hd: Daily global solar radiation

$\dot{H}\dot{m}$: Global solar radiation at each 10 min

Hm: monthly value of the daily global radiation

Ni: Number of days in each month

Hy: Yearly mean value of the daily global radiation

Figure 3.3 presents the monthly average global radiation of Rubavu district based on the calculated data.

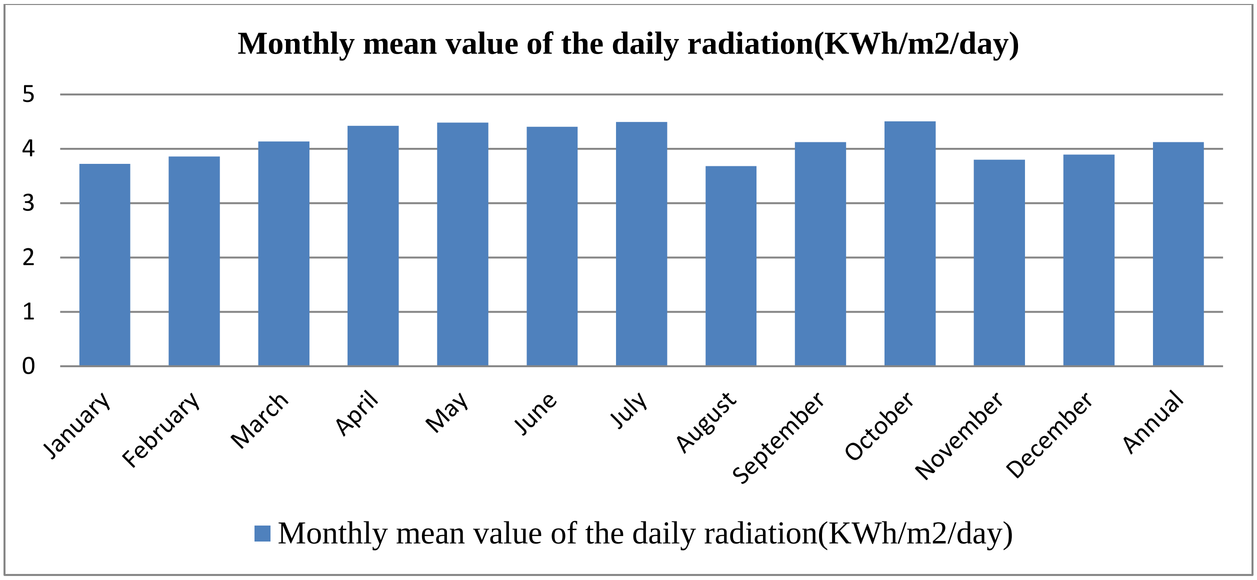

Figure 0.3: Monthly average value of solar radiation of Rubavu district

As it is observed in Figure 3.3 May, July and October were the sunniest months as the solar radiation went up to 4.5kWh/m^2/day and the solar radiation was little down in August with 3.68kWh/m^2/day. This gave an impression that the region has remarkable solar source potential that should be exploited.

The daily global solar radiation throughout the year presented in figure 3.4 shows that there exists very little variation from day to day. It was observed that the minimum daily radiation was recorded at 0.5kWh/day in January and the maximum radiation was recorded at 7.5kWh/day in September. It is also observed that there is a significant amount of solar radiation even during the wet season.

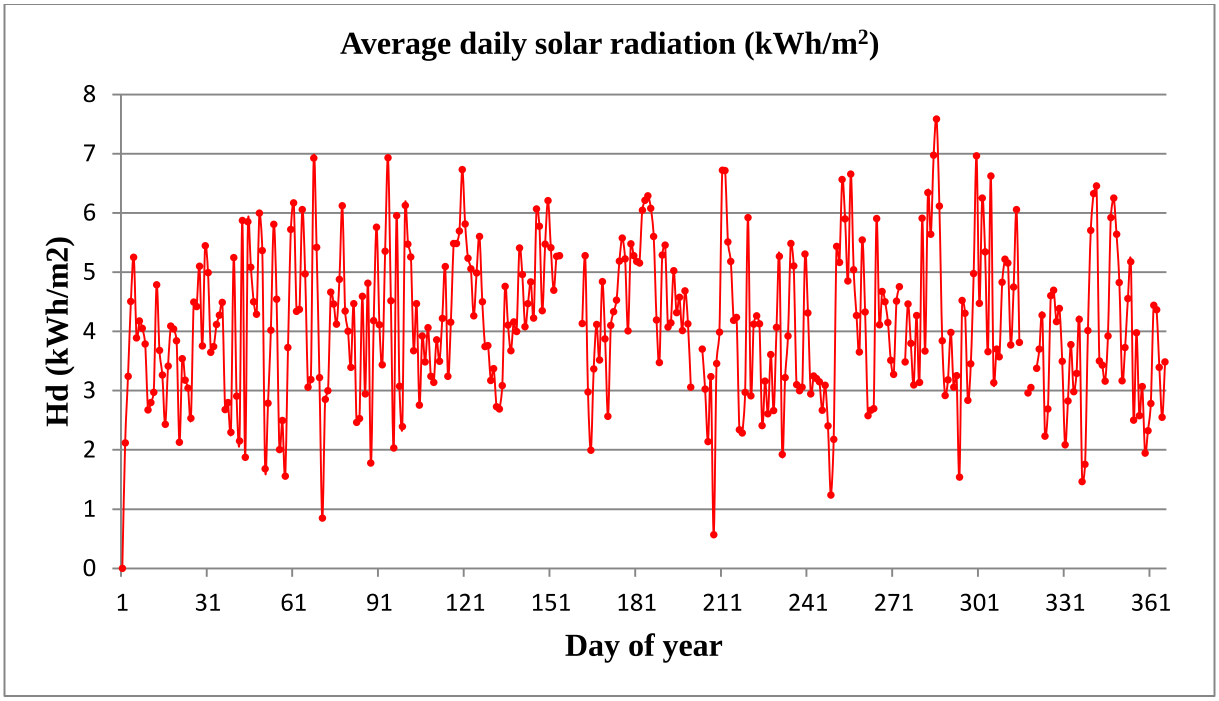

Figure 0.4: Average daily global solar radiation for Rubavu district

The study of solar energy potential of the site shows that the installation of PV system at the site would provide a significant amount of electricity for the needed demand.

3.2 Wind energy conversion system (WECS)

A wind energy conversion system is a set-up of different components for converting the kinetic energy available in the wind to mechanical energy that can be used to power machinery or to operate an electrical generator. A typical wind energy conversion system is constructed with a wind turbine, generator, interconnection apparatus and control system as the major component.

A wind turbine is a rotary engine that extracts energy from the flow of wind. Wind turbines can be classified into two types depending on their axis, vertical axis and horizontal axis as stated in chapter 2. Nowadays, most modern WECS use a horizontal axis configuration with two or three blades, operating either down-wind or up-wind. Wind turbines are designed based on the speed where a wind turbine can be designed for a constant speed or variable speed operation. It is estimated that the wind turbine with a variable speed operation can produce 8% to 15% more energy output as compared to their constant speed counterparts, however, they necessitate power electronic converters to provide a fixed frequency and fixed voltage power to their loads (Asis Sarkar, 2012).

The generator as one of the main component of WECS is driven by the force of the wind on blades or rotor, and converts mechanical energy into electrical energy. The generator is fixed on the tower and directly connected to the wind turbine. It is estimated that in a direct drive configuration, where a generator is coupled to the rotor of a wind turbine directly, offers high reliability, low maintenance, and possibly low cost for certain turbines. Interconnection apparatuses components are devices used to achieve power control, soft start and interconnection function. The mainly interconnection apparatuses uses are the power electronic converters devices. The control system or yaw system is a component responsible for the orientation of the wind turbine rotor towards the wind (Asis Sarkar, 2012).

The wind energy conversion system main components are shown in the figure 3.5 in horizontal and vertical axis type.

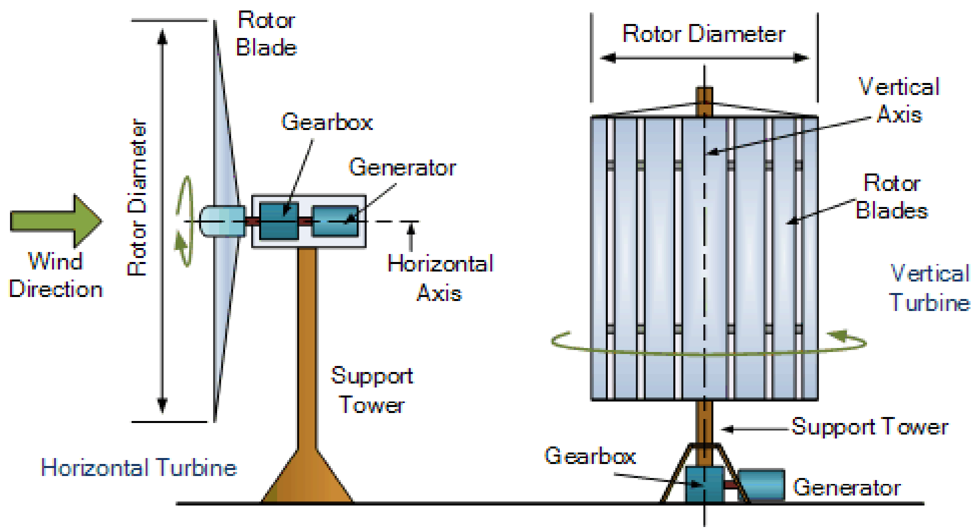

Figure 0.5: Wind Energy Conversion System (Y. Amirat, 2007)

The wind power production is mainly the function of wind speed. It is roughly proven that wind turbines start to generate power when the wind speed flow passes the minimum wind speed (cut-in speed). The wind turbine power increases with the wind speed until it reaches the rated speed where it produces maximum power (Asis Sarkar, 2012).

The power production from a wind turbine is a function of wind speed. Wind power production is unique to each turbine model and to site specific settings. Wind resource fluctuation results in turbine operating at continually changing power levels. The electricity generated from wind depends on wind speed, as the power available from the wind is a function of the cube of the wind speed. This indicates that the electricity increases with the increase of the wind speed (Asis Sarkar, 2012). Figure 3.6 shows the wind turbine components

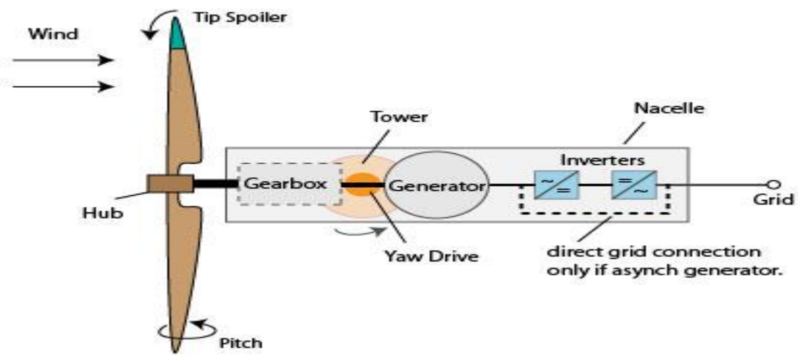

Figure 0.6: Wind turbine components (Y. Amirat, 2007)

The power production from a wind turbine is given by the following formula:

$P = \frac{1}{2}\pi\rho C_p R^2 v^3$ ***Equation 3.2.1***

Where: ρ: air density

R: radius

ν: wind speed

$C_{p:}$ turbine power coefficient (Y. Amirat, 2007).

3.2.1 **Wind statistics**

Wind is roughly originated from the heating of the atmosphere by the sun, variations in the earth's surface, and rotation of the earth. The wind power system is generally characterized by two important components which are the turbine and the generator. The amount of energy that can be harnessed from a wind turbine depends on three main factors which are the speed of air, amount and density of air and the swept area.

i. Wind power equation

The kinetic energy from wind is calculated as:

$KE = \frac{1}{2}*m*V^2$ ***Equation 3.2.2***

The available wind power for any site by unit of time and by unit of area is given by ***Equation 3.2.3***:

$Pt = \frac{1}{2}*\rho*A*V^3$ ***Equation 3.2.3***

Where ρ: air density [kg/m^3]

A: Rotor swept area, $A = \pi*r^2$

V: wind Speed [m/s]

m: mass of the air [Kg]

Pt: Total power [Watt]

The average wind speed is calculated as:

$V^3 = \int_0^\infty V^3 f(V)dV$

Which gives: $V^3 = c^3\Gamma\,(1+\frac{3}{K})$ ***Equation 3.2.4***

ɼ represents the gamma function.

- **The extracted wind power:** This is the power extracted by the turbine, as the available wind power potential at any site is not fully extracted. The extracted wind power is calculated using the Betz limit and power coefficient. The power coefficient, **Cp**, is defined as the ratio of the power extracted by the turbine to the total power of the wind resource.

$Cp = \frac{Pextr}{Pt}$ ***Equation 3.2.5***

Where: Pextr represents the power extracted by the turbine and Pt, the total wind power.

Through different studies it was estimated that, the possible maximum power coefficient (Cp) is equal to 16/27 (**$C_p = \frac{16}{27}$**). So that the extracted power by the turbine is given by the ***Equation 3.2.6.***

$$P_{extr} = Cp*Pt \quad \text{or} \quad P_{extr} = \frac{16}{27} * Pt$$ ***Equation 3.2.6***

Replacing the air density = 1.225kg/m^2 in ***Equation 3.2.3,*** the total power becomes

Pt= 0.625* V^3

Substituting ***Equation 3.2.3*** in ***Equation 3.2.6***, and replacing the air density by its value (1.225kg/m^3), the average extracted wind power by unit of surface in function of average wind velocity is given as:

$$Pextr = 0.37*V^3$$ ***Equation 3.2.7***

The average annual energy extracted is given by:

$$E = Pextr *\Delta t = 0.37*24*366*V^3 \text{ [KWh/m}^2\text{]}$$ ***Equation 3.2.8*** *Invalid source specified.*

3.2.2 Weibull Distribution

Weibull distribution is a method used to describe the wind variation for getting the good variation of wind distribution for any typical site. The weibull distribution is mainly characterized by two parameters:

1. The shape parameter (dimensionless) symbolized by **K** and
2. The scale parameter (m/s) symbolized by **C**

The weibull distribution function is given by:

$$f(v) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{K-1} \exp[-\left(\frac{V}{C}\right)^{K}]$$ ***Equation 3.2.9***

There are different methods used to calculate **K** and **C** parameter. If the average wind velocity is known, the following equation may be used to calculate these parameters:

The average wind speed is expressed as

$V = C*\Gamma*\left(1+\frac{1}{K}\right)$ ***Equation 3.2.10***

The standard deviation is expressed as;

$\sigma^2 = C^2\,[\Gamma\,(1+\frac{2}{K}) - \Gamma^2 * \left(1+\frac{1}{K}\right)]$ ***Equation 3.2.11***

(BHATTACHARYA)

From the ***Equation III.2.11*** the acceptable approximation value of **K** is determined as

$K = \left(\frac{\sigma}{V}\right)^{-1.086}$ ***Equation 3.2.12***

And from ***Equation 3.2.10*** the value of **C** is determined as:

$C = \frac{V}{\Gamma\left(1+\frac{1}{K}\right)}$ ***Equation 3.2.13***

3.2.3 Extrapolation of wind speed data at different heights

Based on different evidence, the land surface influence on the wind is negligible for a great height over the ground surface. However, the ground surface friction speed affected the wind speed for the lowest atmospheric layers.

For any site location, it is strongly recognized that the wind speed and wind availability are determined based on the local topography and weather patterns. Generally, the wind speed increases with altitude, thus hills and mountains regions may come close to the high wind speed areas of the atmosphere.

In order to build-up a site, the wind speed initial measurements are generally taken at ten- meter heights but for some purposes, sometimes it is necessary to use speed at higher altitudes.

Hellmann exponential law that correlates the wind speed readings at two different heights is the most commonly used method to determine the wind speed at two different heights where the wind speed at V_1 and H_1 is determined using the wind speed at V_0 and H_0 using the following relation:

$\frac{V1}{V0} = \left(\frac{H1}{H0}\right)^n$ ***Equation 3.2.14***

Where ***V1*** is the speed to the height ***H1***, ***V0*** is the speed to the height ***H0*** (frequently referred as a 10 meter height) and ***n*** is the friction coefficient or Hellman exponent. This coefficient is a function of the topography at any specific site.

From different undertaken research in several locations, the findings have proven that the friction coefficient (***n***) varies with the height, hour of the day, time of the year, land features, wind speeds and temperature. Table 3.1 shows the friction coefficients of various land spots that are given in function of the land roughness (Francisco Bañuelos-Ruedas).

Table 0.1: Friction coefficient

Landscape type	Friction coefficient (n)
Lakes, ocean and smooth hard ground	0.10
Grasslands	0.15
Tall crops, hedges and shrubs	0.20
Heavily forested land	0.25
Small town with some trees and shrubs	0.30
City areas with high rise buildings	0.40

3.2.4 Site wind potential

Wind speed used was measured in 2014 at Sebeya station located in Rubavu district. The recorded data was over 24 hours with a 10 minute interval at 10 m above ground.

The wind speed of the area given in table 3.2 was calculated using MATLAB. The recorded data was at 10m above ground. After the analysis of the data, it was observed that the average yearly wind speed of the studied area was around 1.6349 m/s at 10m above ground.

i. Site characteristics: Table 3.3 presents the characteristics of different parameters such as weibull parameters, average wind speed, available power, and extracted wind power as well as the annual energy produced. The parameter has been calculated at the height of 10m using MATLAB. The used data are from RMA, year 2014, SEBEYA_AWS station, Rubavu district in the western province.

It was observed that at height of 10m above ground, the wind power is 4.6349 W/m^2.

ii. The annual wind speed distribution: the weibull function distribution of the studied area represented in figure 3.7 was calculated using the MATLAB and showed that the annual distribution of the wind speed is not stable. The annual average wind speed of the studied site was recorded at 1.6349m/s which is very low for electricity generation.

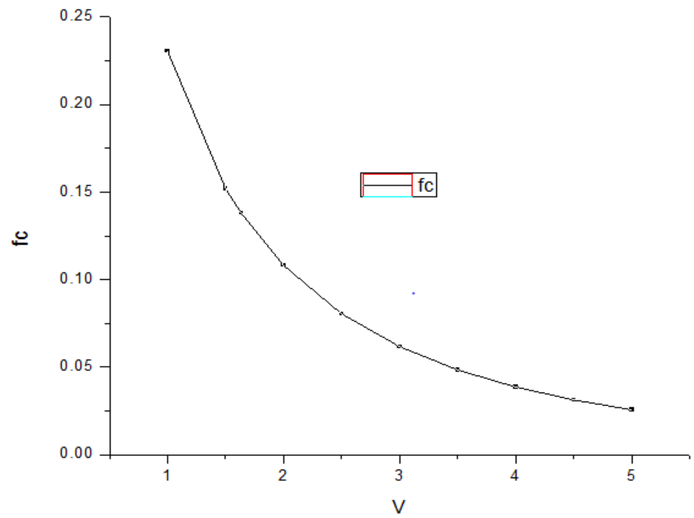

Figure 0.7: Weibull function distribution

Table 0.2: Site wind speed at 10m above ground

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Average
Wind speed (m/s)	0.7582	0.7313	0.7264	0.7686	0.9259	1.4433	1.8539	1.9219	1.9316	1.8795	1.8544	1.8418	1.6349

Table 0.3: Site parameters

Parameter	
K	0.6287
C (m/s)	1.1516
V (m/s)	1.6349
V^3 (m^3/s^3)	12.5143
P (W/m^2)	7.8214
Pextr (W/m^2)	4.6349
E (KWh/m^2)	39.2673

N.B. Energy has been calculated using 353 days as there were some missing data.

iii. Monthly extracted energy: Figure 3.8 presents the monthly extracted energy by unit of area at 10m above ground. The energy was calculated using *equation 3.2.8.*

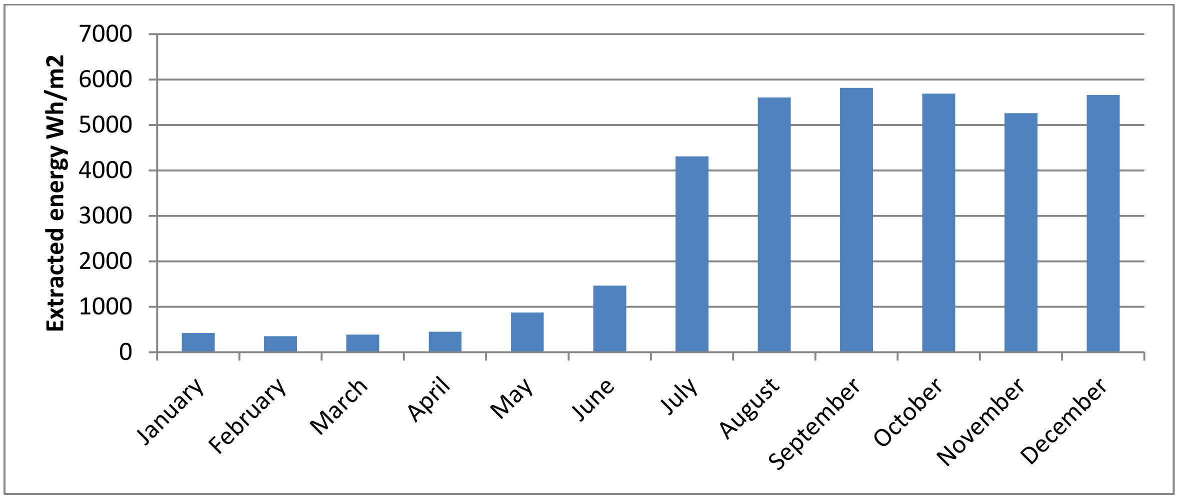

Figure 0.8: Monthly extracted energy at 10m above ground

Figure 3.7 clearly shows that the extracted energy varies from one month to another. It was observed that the higher amount of energy can be extracted from July to December, and the low amount of energy to be extracted varies from January to June.

iv. Site evolution: Table 3.4 specifies wind speed variation, the extracted power and the annual available energy calculated at different height.

Table 0.4: Sites characteristics at different height

Height in m	V in (m/s)	V^3 in m^3/s^3	Shape parameter K	Scale parameter C in m/s	Total available power in W/m^2	Extracted power in W/m^2	Annual energy in Kwh/m^2
10	1.6349	12.51467766	0.628675	1.151597	7.665240067	4.630430734	39.56240019
20	2.012798	19.45037169	0.787956	1.417782	11.91335266	7.196637526	61.48807102
30	2.273147	25.27049945	0.899233	1.601168	15.47818091	9.350084797	79.88712451
40	2.478045	30.4849234	0.987592	1.745494	18.67201558	11.27942166	96.37137865
50	2.649611	35.29936739	1.062064	1.866343	21.62086253	13.06076593	111.5911841
60	2.798573	39.82236616	1.127062	1.971269	24.39119927	14.73427548	125.8896497
70	2.931032	44.119838	1.185112	2.064571	27.02340077	16.32434006	139.4751615
80	3.050831	48.23552858	1.237807	2.148955	29.54426125	17.84714557	152.4860118
90	3.160559	52.20030684	1.28623	2.226246	31.97268794	19.31411353	165.019786
100	3.262054	56.03696215	1.331148	2.297738	34.32263931	20.73367599	177.1485277

Note: the friction coefficient used is 0.30

It was observed that within the change in height, the available annual energy by unit of surface changed from 39.3227kWh/m^2 at 10m up to 175.648kWh/m^2 at 100m. It was estimated that there is an increase of 12kWh/m^2 at each 10m of height and 1.5W/m^2 was being added to the extracted power at each 10m. This showed that the extracted power and available energy increase with the increase of height.

Figure 3.9 describes the effect of height on the shape parameter, the scale parameter and wind speed. It was observed that all of these parameters increase with the increase in height which proves that the turbine installation at high altitudes should provide more energy.

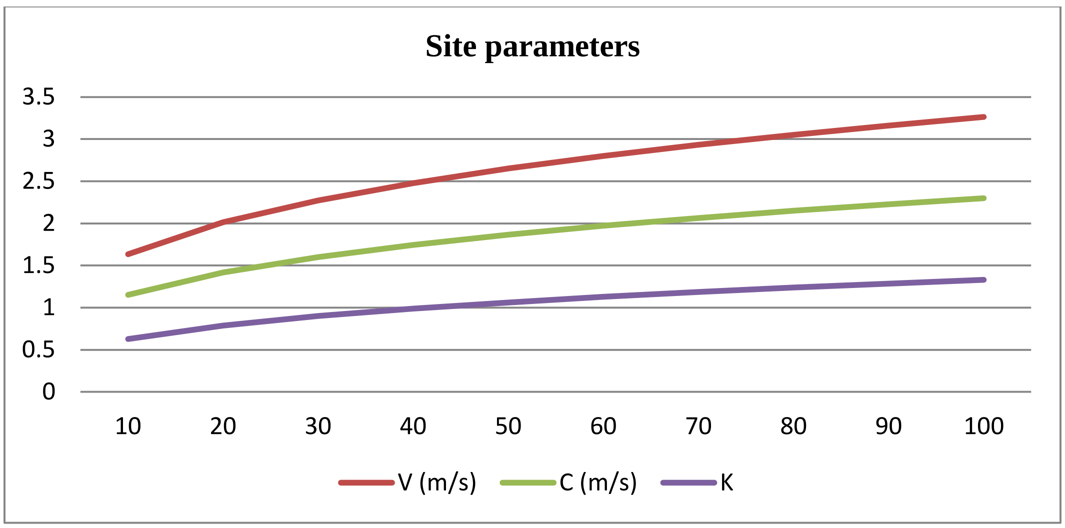

Figure 0.9: Site parameter variation due to height

For our case study, wind speed is observed to be low at 10 m above ground but increases at 100m to reach at 3.26m/s. Thus we calculated all parameter at 100 m as the preferable height for the wind turbine installation.

It was observed that at 100m above ground, the wind turbine could produce a high annual energy of 27.05kWh/m^2 in September and a minimum annual energy production of 2kWh/m^2 in March as illustrated in table 3.5.

Table 0.5: Monthly wind parameters and energy production at 100m

Month	**V in (m/s)**	**Shape parameter K**	**Scale parameter C in m/s**	**V^3 in m^3/s^3**	**Total available power in W/m^2**	**Extracted power in W/m^2**	**Annual energy in Kwh/m^2**
January	1.512807887	3.550936	1.693871	8.007644	4.904682	2.962828	2.204344
February	1.459135331	3.310613	1.623826	7.33395	4.492044	2.713561	2.01889
March	1.449358546	3.30466	1.612656	7.19108	4.404537	2.6607	1.979561
April	1.533558615	3.146329	1.696794	8.625226	5.282951	3.191333	2.374352
May	1.847413377	2.364994	1.924069	15.51475	9.502784	5.740457	4.2709
June	2.879762099	1.176587	1.718222	30.17954	18.48497	11.16643	8.307824
July	3.699016806	1.263425	2.440673	74.35581	45.54293	27.51165	20.46867
August	3.834694643	1.331755	2.702695	91.10963	55.80465	33.71056	25.08066
September	3.854048688	1.383124	2.836296	98.2523	60.17953	36.35335	27.04689
October	3.750095521	1.41162	2.821009	93.26774	57.12649	34.50907	25.67474
November	3.700014437	1.444045	2.84932	92.44505	56.62259	34.20467	25.44827
December	3.674874132	1.478531	2.896294	93.37549	57.19249	34.54893	25.7044

3.3 Summary

This chapter gave a look on the solar and wind potential of Rubavu district. It was observed that the region has a significant solar energy potential for the installation of a PV system. The wind speed of the region was found to be low at 10m above ground but the calculated wind speed at 100m showed that WEC can be used for the extraction of wind potential.

Chapter 4 HYDROGEN PRODUCTION AND FUEL CELL

Outline

4.1 Hydrogen

4.1.1 Hydrogen property

4.1.2 Hydrogen production method

4.1.2.1 Natural gas Reforming

4.1.2.2 Gasification

4.1.2.3 Electrolysis

4.1.3 Hydrogen storage

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4.1.4 Hydrogen application

4.1.4.1 Chemical application

4.1.4.2 Energy application

4.1.5 Advantages and disadvantages of hydrogen

4.2 Fuel cell

4.2.1 Fuel cell working principal

4.2.2 Types of fuel cells

4.2.3 Fuel cell advantages

4.3 Summary

Chapter 4. HYDROGEN PRODUCTION AND FUEL CELL

4.1 Hydrogen

Hydrogen is the most abundant element in the universe. It can be mostly found in combination with other elements such as oxygen in water and carbon in hydrocarbons.

Hydrogen is an energy carrier, not an energy source, meaning it can store and deliver energy in a usable form. Hydrogen is an environmental friendly element as it can be produced using different source of energy such as fossil fuels, renewable energy resources and nuclear energy and results in nearly zero greenhouse gas emissions. Hydrogen can be used in almost all sectors such as in transportation, industrial, and buildings (R.Boudries, 2010).

4.1.1 **Hydrogen property**

- Hydrogen is an odorless, tasteless, colorless and nontoxic gas
- Hydrogen (H2) is the lightest gas, being about 1/14 as dense as air
- Liquefied hydrogen has a very low boiling point (-252.88^{o}C)
- Hydrogen is a stable molecule with high bond energy (435.99KJ mol^{-1})
- Hydrogen easily reacts with oxygen at wide range to form water (Abe, n.d)

4.1.2 **Hydrogen production method**

Hydrogen is produced by the extraction and isolation of the hydrogen molecule from the feedstock (such as water). The extraction mainly takes place in the electrolyzr where the electric current is applied between two electrodes of an electrolyzer separated by an aqueous electrolyte. Hydrogen can be obtained based on the following equation:

At the anode:

$$H_2O \longrightarrow 2H^+ + 1/2O_2 + 2e^- \qquad E_{anode}(25^oC) = 1.23V$$

At the cathode:

$$2H{+}{+}2e{-} \longrightarrow H2 \qquad E_{cathode}(25^oC) = 0V$$

Net reaction:

H_2O+ Electric energy $\longrightarrow H_2 + 1/2O_2$ E_{cell} (25^oC) = 1.23V)

Hydrogen extraction can be processed through different methods. As shown in figure 4.1, three methods such as photolysis, electrolysis and thermochemical can be used for the hydrogen extraction depending on which feedstock it can be extracted from.

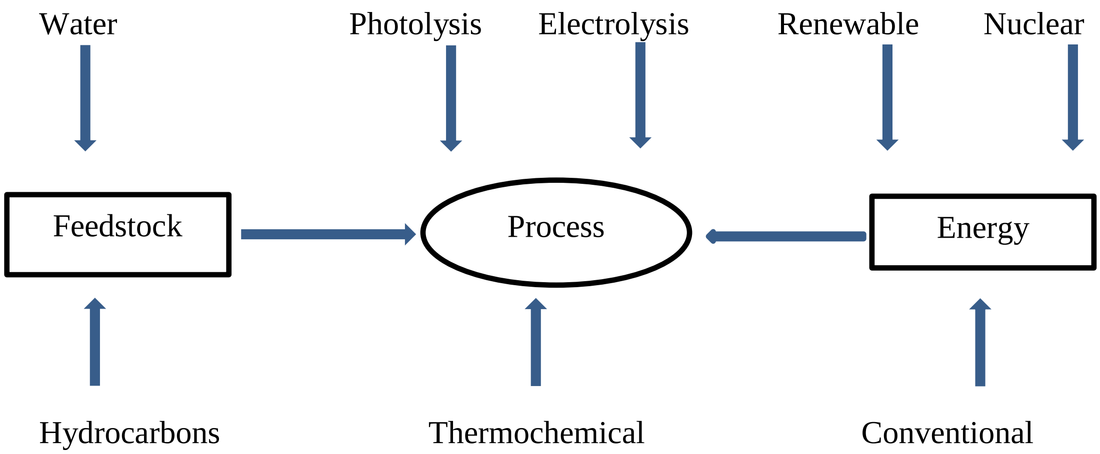

Figure 0.1: Hydrogen production method

As shown in Figure4.1 the feedstock could be water or hydrocarbons such as methane or any other hydrogen compound element. The process can be through photolysis, electrolysis or in thermochemical. For any process, conventional, nuclear or renewable energy source could be used in the extraction of hydrogen. However the sustainability of hydrogen production can be realized by the use of renewable sources of energy (R. Boudries, 2014) .

Based on the Faraday law, the quantity of hydrogen production in an electrolyzer cell is directly proportional to the current density of the electrons at the electrodes (Muzhong Shen, 2011). The quantity of hydrogen production is calculated as:

$$\eta_{H2} = \frac{jA}{2F} = \frac{\eta F * \eta C * ie}{2F}$$

With: η_{H2} in Kmol/sec, j: operating current density, i.e.: electrolyser current, ηc: number of cells in series, ηF = Faraday efficiency (96 500 000^{o}C/mol)

Generally, hydrogen can be produced in three different ways such as natural gas reforming, gasification and electrolysis.

4.1.2.1 Natural gas Reforming

Natural gas reforming is an advanced and mature method used for hydrogen production. In natural gas reforming method, the extraction of hydrogen and carbon monoxide contained in the methane is done by the use of thermal process. In natural gas reforming, there are two main processes such as steam-methane reformation and partial oxidation.

In steam-methane reformation, the process is done at the presence of a catalyst where methane reacts with steam under 3 to 25 bar pressure and produce hydrogen, carbon monoxide, and a small amount of carbon dioxide (Boudries, 2010) . Steam methane reforming generally present two reactions, water-gas shift reaction in which the carbon monoxide and steam reacted under a catalyst to produce carbon dioxide and hydrogen then a pressure –swing adsorption reaction in which the produced carbon dioxide and other impurities are removed leaving pure hydrogen (n.d).

The following equations state the hydrogen production by the natural gas reforming method.

- **Steam-methane reforming reaction**
  $CH_4 + H_2O$ (+ heat) $\rightarrow CO + 3H_2$
- **Water-gas shift reaction**
  $CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

4.1.2.2 Gasification

Gasification is a process that converts organic or fossil fuel based carbonaceous materials into carbon monoxide, hydrogen and carbon dioxide. The gasification method for hydrogen production is separated into two processes. The first process which occurs at low temperature (below $600^{O}C$) consists of the release of the volatile components of the fuel by the process of pyrolysis. At the end of this process there are some products of pyrolysis that has not been vaporized. These products mainly consist of fixed carbon and ash. There is then a second process which occurs at a high temperature at which the remaining carbon is combusted with pure oxygen in order to extract hydrogen. The gasification with pure oxygen results in a higher quality mixture of carbon monoxide and hydrogen (Klein, 2002).

4.1.2.3 Electrolysis

Electrolysis is the process of using electricity to split the water molecule into hydrogen and oxygen. This process takes place in a unit called electrolyzer which consist of two electrodes (anode and cathode) separated by an electrolyte as shown in figure 4.2

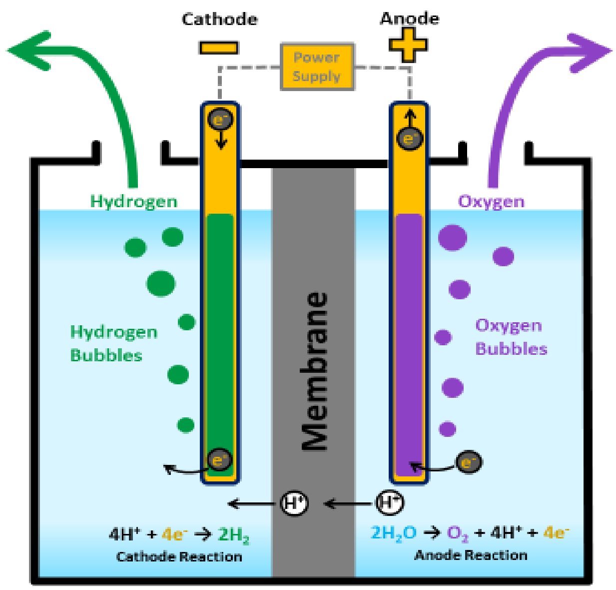

Figure 0.2: Electrolyzer (Klein, 2002)

There are different electrolyzers which vary from one to another due to the type of electrolyte materials that are involved. The most significant technologies in the process of water electrolysis are the alkaline electrolyzers, the polymer membrane electrolyzers and the oxide membrane ceramics electrolyzers.

A. Alkaline electrolyzers

Alkaline electrolyzer is the most developed electrolyzer technology used in the electrolysis process. In alkaline Electrolyzer, hydrogen is generated at the cathode and the oxygen at the anode. To assure that there is no interaction between the two generated gases, there is a membrane placed between the two electrodes. The alkaline electrolyzer uses 25 to 30% of alkaline aqueous (such as potassium hydroxide or sodium hydroxide) solution as an electrolyte which circulate through the electrolyzer to ensure the system cooling and preserving the ionic concentration. It is estimated that the alkaline electrolyzer operates at 80^{o}C and its efficiency is around 50 %. Some of the disadvantages associated to the alkaline electrolyzer are their high energy cost and lower efficiency (Boudries, 2010).

B. Polymer membrane electrolyzers (PEM)

The polymer membrane electrolyzer uses an acid polymer membrane made of Nafion as an electrolyte. During the process the molecule of water split into oxygen and hydroxonium ion (H_3O^+) at the anode. After this decomposition, the hydroxonium ion migrates through the acid membrane to the cathode where hydrogen and water are formed. It is estimated that the maximum temperature in PME is 100^{o}C, the operating current is usually higher than 1600 mA/cm^2 and the efficiency could be high up to 70% (R.Boudries, 2010).

C. Solid oxide electrolyzers cell (SOEC)

SOEC uses an oxygen ion (O^{2-}) as an electrolyte. This electrolyte conducts a ceramic membrane that acts as a gas separator. During the operation process, there is formation of hydrogen and oxygen ion at the cathode, then a migration of oxygen ion through the acid membrane to form oxygen at the anode. It is reported that the SOEC is used with high temperatures system such as concentrating solar power systems or high temperature nuclear reactors, thus the electrolysis takes place at high temperature and the water is in the vapor state. SOEC are more efficient with an efficiency which could go up to 95%. Despite having a high efficiency, SOEC Electrolyzer suffers over time from performance and durability degradation rerated to chemical stability of the Electrolyzer component material (R.Boudries, 2010).

4.1.3 **Hydrogen storage**

Hydrogen can be stored in different ways:

4.1.3.1 Conventional storage:

The conventional storage is the most used storage mode for hydrogen. In this method hydrogen can be stored under gaseous form or in a liquid form. In the gaseous form, hydrogen is compressed to a pressure varying between 200 and 300 bars with a density which is around 11kg/m^3. It is stated that, the main issue with this form of storage is the low volume density for different applications. In a liquid form, the hydrogen is first liquefied to 20K before its storage. The density of the liquefied hydrogen is estimated to be around 71 kg/m^3 which fulfill the requirement for the application in different sectors (R.Boudries, 2010). Hydrogen is preferably to be stored into a liquid form rather than a gaseous form.

4.1.3.2 Solid state hydrogen storage:

In solid state hydrogen storage, hydrogen is stored as a metal hydride or a hydrogen adsorption in metal organic frameworks. In this system, hydrogen is stored in the miso-porous materials by physisorption in which the hydrogen capacity of a material is proportional to its specific surface area. The storage by adsorption is very attractive as it tends to lower the overall system pressure for equivalent amount hydrogen within a safer operating condition (Rahul Krishna, 2012).

4.1.4 **Hydrogen application**

There is two different ways in which hydrogen serves in its application. Hydrogen can be used as a chemical product or as an energy vector.

4.1.4.1 Chemical application

In chemical application, hydrogen is used as a reactant in various chemical processes such as oil refining or ammonia. Hydrogen is used in the refining of fuel and oil product in order to obtain strict standard concerning the environment requirement. Also, hydrogen and nitrogen reaction under a high temperature results in the production of ammonia which is an essential element for the manufacturing of manure for agriculture (R.Boudries, 2010).

4.1.4.2 Energy application

Hydrogen can be used in thermal engines in the industry and transport sectors. Hydrogen can also be used as energy vector for electricity storage and transportation.

4.1.5 **Advantages and disadvantages of hydrogen**

Advantages

- Energy production per unit of mass of hydrogen is more compared to the one produced by conventional energies system.
- Hydrogen is the most versatile energy vector.
- Hydrogen can be converted into useful energy in various ways.
- Hydrogen is an environmental friendly element.

Disadvantages

- Costly to produce: One of the big problems of hydrogen fuel cell is that its production is very expensive.
- Flammable: Hydrogen is disposed to catching on fire which comes from itself.
- Difficult to store: Hydrogen is very hard to move around, thus its storage and transport is so expensive.
- It is dependent on fossil fuels**:** Even if hydrogen is a renewable energy, its production comes from the non-renewable sources such as coal, oil and natural gas.

4.2 Fuel cell

A fuel cell is an electrochemical device that directly converts the chemical energy in fuel into electrical energy with high efficiency and low environmental impact. Fuel cells use hydrogen as the basic fuel and oxygen as the oxidant. The hydrogen and oxygen reaction generates electricity and their combination forms water. The fuel cell is formed by two electrodes (anode and cathode) separated by an electrolyte.

Fuel cell is one type of energy storage. In its basic working principle, it behaves like a battery but differs from it due to the continuous replenishment of the reactant which enables a continuous operation. Generally, there are different varieties of fuels and oxidants to be processed by the fuel cell but the most used today is hydrogen as a reactant and ambient air as the oxidant (Eduardo I. Ortiz-Rivera).

4.2.1 Fuel cell working principal

Fuel cell is formed by an electrolyte, anode and cathode together referred to as the membrane electrolyte assembly (MEA). During its working process, fuel such as hydrogen is fed into the anode and an oxidant usually oxygen into the cathode, then a driving chemical force appear thus hydrogen and oxygen react to produce water. At the presence of a catalyst, the atom of hydrogen split into a proton and an electron. The proton directly passes through the electrolyte and the electron creates a separate current that can be used before it returns to the cathode to be reunited with the hydrogen and oxygen in a molecule of water (Eduardo I. Ortiz-Rivera). The figure 4.3 shows the typical fuel cell.

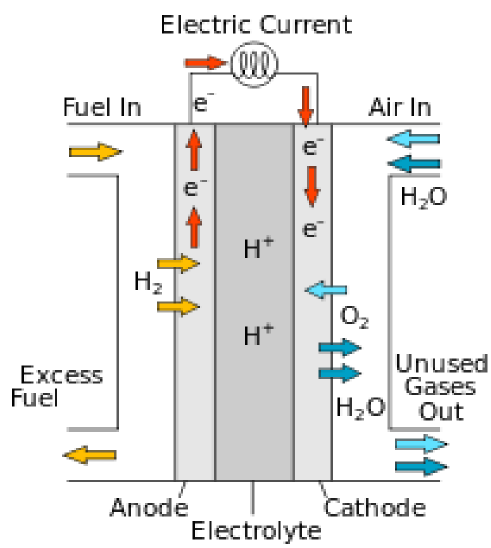

Figure 0.3: Fuel cell (MEZIANE, 2011)

4.2.2 Types of fuel cells

There are five types of fuel cells which are available as summarize in table 4.1 (R.Boudries, 2010).

Fuel cells are classified according to the nature of their electrolyte. Acid, basic solution or conducting polymer membrane of ion, the electrolyte determines the operating temperature of the fuel cell and the range of its applications. As summarized in table 4.1, fuel cell can be divided into two categories depending on their operating temperature. There are low-temperature fuel cells that operate in the range 50°C to 250°C (such as proton exchange membrane, alkaline, and phosphoric acid fuel cells), and high-temperature fuel cells that operate above 500°C (such as molten carbonate, and solid oxide fuel cells).

Table 0.1: Types of fuel cell

Fuel cell	**Temperature (^oC)**	**Fuel**	**Electrolyte**	**Mobile ion**
PEM (Proton exchange membrane)	70-110	H2, CH3OH	PEPM	$(H_2O)_n H^+$
AFC (Alkaline fuel cell)	100-250	H2	Solution of KOH	OH^-
PAFC (Phosphoric acid fuel cell)	150-250	H2	Phosphoric acid	H^+
MCFC (Molten carbonate fuel cell)	500-700	hydrocarbons, CO	Li, $2CO_3$ and KCO_3 in Li AlO_2	CO_3^{2-}
SOFC (Solid oxide fuel cell)	700-1000	hydrocarbons, CO	ZrO_2 and Y_2O_3	O^{2-}

4.2.3 Fuel cell advantages

- Fuel cells offer high efficiency
- They have an excellent load performance
- They have a lower emissions pollutant, and a wide size range
- They do not require recharging. Means that fuel cell produces energy as long as fuel is supplied.

4.3 Summary

This part describes hydrogen, its production, its storage, the application as well as its advantages and disadvantages. The chapter went on to discuss the working principle of the fuel cell, types of fuel cells and their advantages.

Chapter 5 SIZING AND SIMULATION

Outline

Chapter 5. SIZING AND SIMULATION

5.1 Sizing and optimization of the system components

The purpose of the optimization is to find out an optimum value for each component of the system. Thus for the optimization and simulation of our hybrid solar PV-wind- FC power system, HOMER has been used for different configurations.

5.1.1 Sizing of the technical components

The proposed hybrid system that will meet the demands of Groupe scolaire Mukondo was made of solar and wind energy as the source of energy. The hydrogen tank, electrolyzer and fuel cell were added to the system for storage purposes for the excess energy produced to be used later during the night or days when there is not enough energy production by the source.

1. **Wind turbine characteristics and cost**

The choice of a wind turbine depend mainly on the wind speed sources and the cut-in wind speed of the turbine as the turbine has to generate significant amount of energy to the system. In order to have a required amount of energy, one or a more wind turbines are used. The wind turbine chosen in this work is Enercon-33 (E-33). It is a three- bladed wind turbine with a cut-in wind speed of 2.5m/s (Müller, 2005). The difference characteristics of E-33 are described in table 5.1 and the power curve of this wind turbine is shown in figure 5.1.

Table 0.1: E-33 characteristics (Müller, 2005)

Characteristics	**Value**
Rated power	330KW
Cut in wind speed	2.5m/s
Cut out wind speed	28-34m/s
Life expectancy	20 years

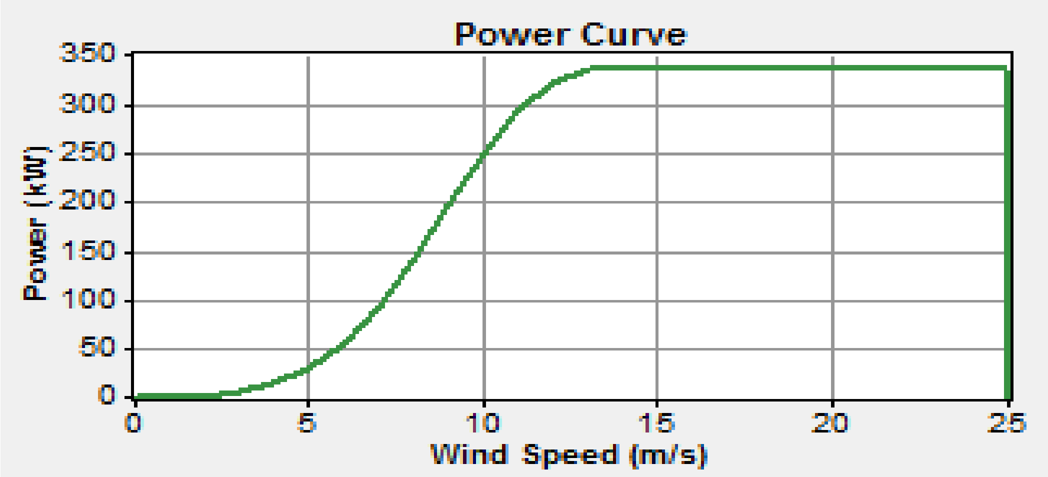

Figure 0.1: Enercon-33 power curve (Müller, 2005)

E-33 wind turbine was chosen as the most suitable choice to be used in this place as it produces around 5kW at a wind speed of 3m/s.

The investment cost of the wind energy conversion system was estimated at 1403$/kW (L. Fingersh, 2006). The O&M and replacement cost were calculated at 10% and 80% of the initial investment cost respectively. E-33 life time was of 20 years.

2. PV system characteristics and cost

In this research for PV system, no PV technology has been chosen as the model was based on the size of the system. The PV system investment cost was estimated at 2150$/kW based on the report of National Renewable Energy Laboratory on the U.S Photovoltaic prices and Cost Breakdowns (Donald Chung, 2015). The O&M and replacement cost were estimated at 1% and 80% of the investment cost respectively. PV life time was set at 25 years.

During the simulation, the PV system was modeled as a fixed tracking system. For sufficient amount of electricity generation other parameters such as the derating factor which was set at 80% and the ground reflection considered at 20% were considered.

3. Electrolyzer characteristics and cost

In the system, electrolyzer is used to transform the excess energy production into hydrogen. The electrolyzer was estimated to work within an efficiency of 75% at a DC mode function. The investment cost of the electrolyzer was estimated at $2000/kW. The

O&M and replacement were estimated at 1% and 80% of the investment cost respectively. The electrolyzer lifetime was estimated at 15 years.

4. Fuel cell characteristics and cost

Fuel cell is a device that produces a continuous electric current directly from the oxidation of a fuel such as hydrogen. Fuel cell must present sufficient power in order to satisfy the electric demands. Based on the report of Frank Bruijn, the fuel cell used in power generation operates in a range of 40.000 to 90.000 hours which is equivalent to 5-10 years and the system cost of 1kW varies from $1000 - $2000 (Bruijn, 2011).

For our system, the investment cost was calculated at $3000/kW. The O&M and replacement cost was calculated at 0.5% and 80% of the investment cost respectively. The operation lifetime of fuel cell normally depends on the fuel quality and operation condition which makes difficult to specify the operation lifetime. After the simulation, fuel cell operation lifetime was estimated at 3565 hours which is equivalent to the number of hours that the fuel cell will operate in 5 years.

5. Power converter characteristics and cost

The main purpose of a power converter is to process and control the electric energy flow by supplying the current in a suited form of energy that is needed for the user. Converters are used to convert the alternating current to direct current or vice versa. The chosen converter was estimated to operate with 90% efficiency. The investment cost was considered at $800/kW, the replacement and O&M cost was considered at 80% and 1% of the investment cost respectively. The converter life time was 15 years.

6. Hydrogen tank characteristics and cost

The hydrogen tank must be sufficient to store the excess produced energy converted into hydrogen by the electrolyzer. The hydrogen tank investment cost estimated at $1500/kg. The replacement cost was calculated at 80% of the investment cost and the O&M cost was calculated at 2% of the investment cost. The hydrogen reserved volume was set at 80% and the life expectancy was around 20 years.

5.1.2 Weather condition and energy resource potential

As discussed in chapter 3, wind speed, global solar radiation and temperature data were obtained from Rwanda Meteorological Agency. The data were collected at Sebeya station located at -1.7° latitude and 29.33° longitude. The monthly average wind speed, global solar radiation and temperature were calculated based on the data of year 2014. The monthly average wind and global solar radiation data of the region are shown in figure 5.2 and figure 5.3 respectively.

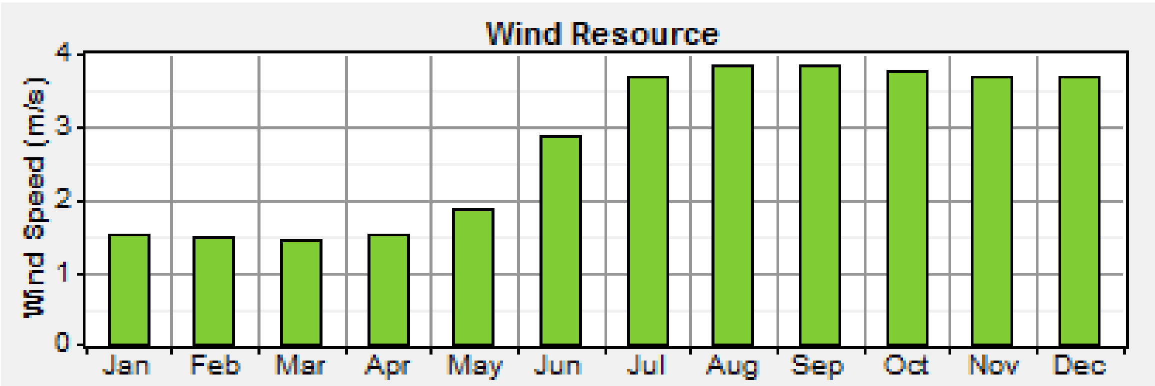

Figure 0.2 Monthly wind speed at 100m

The highest wind speed was found to be from July to December where the wind speed reaches at 3.5m/s. The low wind speed was found to be in January to June with wind speed which was less than 3m/s.

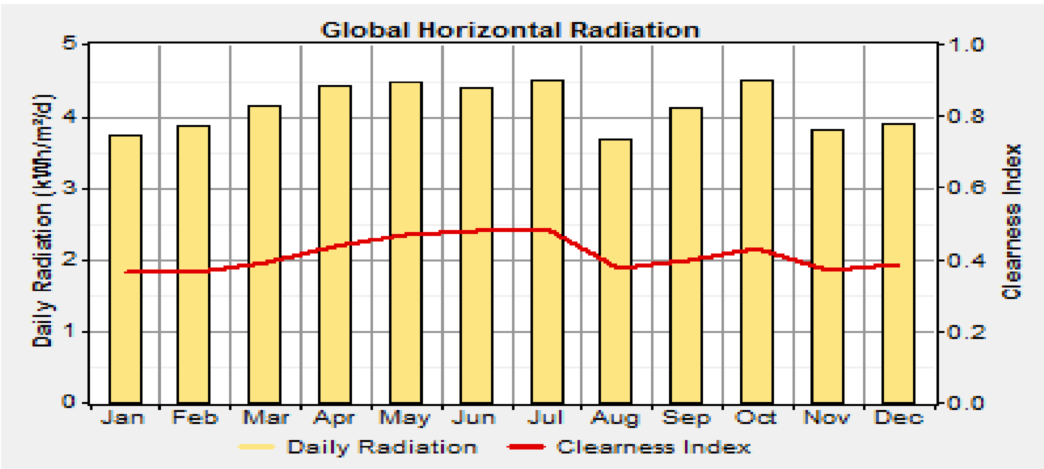

Figure 0.3: Monthly global horizontal radiation and index factor

Figure 5.3 presents the monthly global solar radiation recorded in 2014 for the studied region. It was observed that the solar radiation varies between 3.7kwh/m^2/day to 4.5kwh/m^2/day.

5.2 Case study

5.2.1 Introduction

Groupe scolaire Mukondo is a non-electrified secondary school located in a remote area in Mukondo cell, Rubavu district in Western province. The school had 414 students for ordinary and advanced level within 14 classrooms, 3 boarding staffs, 17 professors and 2 security guards. The school also has a house of 8 rooms and 2 sitting rooms to facilitate professors during rainy time.

Generally, the school's electricity consumption varies depending on the school calendar. In this research paper the electric load demand of Groupe scolaire Mukondo was divided into four categories based on the Rwanda Education Board (REB) school calendar of 2015 as illustrated in table 5.2. The first category considered the full months of studies (February, March, May, June, September and October); the second category considered the full months of holiday (January and December); the third category considered the short break of 2 weeks in April and the fourth considered the short break of one week in (July, August and November). A number of 450 persons were taken into consideration for the sizing of the system.

Table 0.2: Yearly school break calendar

	Start	**End**
First break	1st April	14th April
Second break	23rd July	7th August
Third break	20th November	1st February

5.2.2 Primary load

Primary load is the load that should be fulfilled by the energy provided by the system. The primary load of the sized system was divided into school and professor's house electric load demands which mainly included the lighting (classroom lighting, toilet lighting), electronics appliances (TV, Radio, computer, refrigerator, etc.) and water pumping. The appliances used for the system were selected based on the low wattage to ensure the system affordability. The daily consumption of the system was calculated by summing up the hourly consumption of each appliance in order to size the system that will meet the needs.

Daily consumption (KWh) = quantity of appliances x power rating of each appliance (KW) x hours of operation.

5.2.2.1 School load demand

The school electric load was majorly based on lighting and water pumping. The estimation of electricity load consumption was calculated based on the school calendar. The school load demand was calculated for 14 classrooms, 3 offices, 6 sanitations and water pumping for 450 persons. For water pumping, 4litre per person was estimated only for sanitation with a pump that has a discharge of 10l/min for 96 W. It was proposed that the lighting will be from 18:00 to 21:00 for evening studies as the school is not a boarding school. Table 5.3 illustrates the primary load appliances considered and their working time based on the full month of study.

Table 0.3: School electricity load consumption

Appliances	**Quantity**	**Capacity for each components (Watts)**	**Run time (Hour)**	**Peak load (Watt)**	**Daily Energy (KWh/day)**
Classroom lighting (T8)	28	32	3	896	2.688
Offices lighting (T8)	3	32	3	96	0.288
Toilet lighting (Compact fluorescent)	6	13	3	78	0.238
External lighting	4	100	11	400	4.4
Computer	3	150	9	450	4.05
Printer	1	50	1	50	0.05
Water pumping (10litre/min uses 96W)			3		0.29
Total					**12**

It was observed that the daily electricity usage for the school was around 12kWh/day

5.2.2.2 House load demand

For the bright future of the students, professors need to prepare their courses, thus the load consumption was calculated for the household of 8 rooms and 2 sitting rooms. For water pumping, 17 persons with an estimation of 11litres per person was taken into consideration and others different appliances as shown in table 5.4.

Table 0.4: House electricity load consumption

Appliances	**Quantity**	**Capacity for each components (Watts)**	**Run time**	**Peak load [Watt]**	**Daily energy (Kwh/day)**
Room lighting (Compact fluorescent)	8	13	5	104	0.52
Sitting room (T8)	2	32	5	64	0.32
TV	2	100	5	200	1
Radio	2	20	14	40	0.56
Refrigerator	1	350	24	350	8.4
Cooker	1	2500	2	2500	5
External lighting	2	100	5	200	1
Water pumping			3		0.03
Toilet (Compact fluorescent)	2	13	2	26	0.026
Bathroom (Compact fluorescent)	2	13	2	26	0.026
Total					**16.9**

It was observed that the energy needed by the house was around 17kWh/day.

For this research, two cases were proposed for the electrification of the school.

I. CASE 1

The first case was based on the real situation, as the school is not a boarding school; we propose that students living near the school may do their homework and evening studies at school from18:00 to 21:00.

Based on the school calendar as described in table 5.1, there was a two weeks break in April thus the power demands of April were considered to be half of the full month study power demands. For July, only one week break was considered and the demands were set at 3/4 of the full month of study. For January, the power demands were calculated for outside lighting for security purposes. The professor house demand was not included in the full month of holiday. Figure 5.4 and 5.5 shows respectively the PV-wind-FC power system and the seasonal load profile simulated by HOMER.

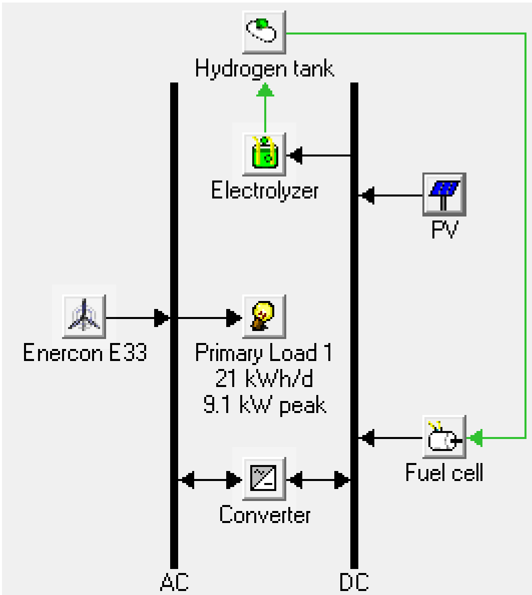

Figure 0.4: PV-wind-FC power system

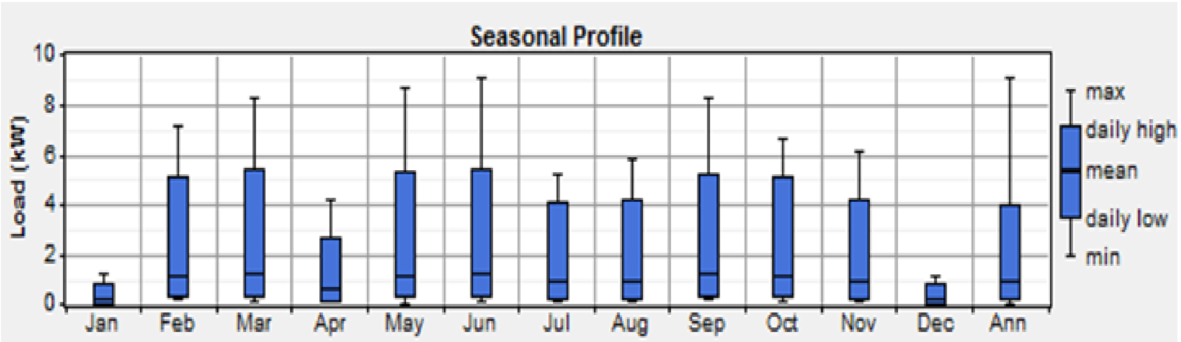

Figure 0.5: Site power demands

As shown in figure 5.5, the highest average load demands were recorded to be at 5.8 kW for the full studied months and went down up to 1kW in January and December. The annual average load demand was recorded at around 4kW.

5.2.3 **Simulation of the configuration**

The simulation of the system using HOMER gave a clear view of each uploaded data that has been used by the system.

After the simulation, HOMER displays a list of possible configuration listed from top with a low NPC system. The system configuration of our hybrid solar PV-wind and FC system is given in figure 5.6 below.

PV (kW)	E33	FC (kW)	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FC (hrs)
8	4	1	2	2	1	$ 32,912	11,878	$ 106,594	3.359	1.00	0.40	708
6	7	1	2	2	1	$ 32,821	12,008	$ 107,311	3.382	1.00	0.40	691
8	4	1	3	2	1	$ 33,712	11,897	$ 107,510	3.388	1.00	0.40	708
6	7	1	3	2	1	$ 33,621	12,027	$ 108,227	3.411	1.00	0.40	691
10	3	1	2	2	1	$ 35,809	12,072	$ 110,695	3.489	1.00	0.40	727
8	6	1	2	2	1	$ 35,718	12,124	$ 110,923	3.471	1.00	0.39	705
10	3	1	3	2	1	$ 36,609	12,091	$ 111,610	3.518	1.00	0.40	727
8	6	1	3	2	1	$ 36,518	12,142	$ 111,838	3.500	1.00	0.39	705
10	4	1	2	2	1	$ 37,212	12,046	$ 111,933	3.504	1.00	0.39	716
8	4	1	1	2	2	$ 33,612	12,697	$ 112,374	3.532	1.00	0.40	759
10	4	1	3	2	1	$ 38,012	12,064	$ 112,848	3.533	1.00	0.39	716
8	7	1	2	2	1	$ 37,121	12,238	$ 113,038	3.531	1.00	0.39	703
8	7	1	3	2	1	$ 37,921	12,257	$ 113,954	3.559	1.00	0.39	703
6	4	1	2	2	2	$ 30,112	13,537	$ 114,086	3.577	1.00	0.40	814
5	7	1	3	3	1	$ 33,471	13,042	$ 114,371	3.595	1.00	0.40	754
6	6	1	2	3	1	$ 33,418	13,071	$ 114,497	3.589	1.00	0.40	765
5	6	1	2	2	2	$ 30,768	13,510	$ 114,576	3.589	1.00	0.40	795
6	4	1	3	2	2	$ 30,912	13,556	$ 115,001	3.606	1.00	0.40	814
12	3	1	2	2	1	$ 40,109	12,114	$ 115,255	3.613	1.00	0.39	727
5	6	1	3	2	2	$ 31,568	13,529	$ 115,492	3.618	1.00	0.40	795
12	4	1	2	2	1	$ 41,512	11,993	$ 115,909	3.608	1.00	0.39	710
10	3	1	1	2	2	$ 36,509	12,813	$ 115,988	3.643	1.00	0.40	773
8	6	1	1	2	2	$ 36,418	12,833	$ 116,020	3.618	1.00	0.39	749
10	6	1	2	2	1	$ 40,018	12,260	$ 116,066	3.608	1.00	0.38	711
8	3	1	2	3	1	$ 33,509	13,317	$ 116,119	3.647	1.00	0.40	806
12	3	1	3	2	1	$ 40,909	12,133	$ 116,171	3.642	1.00	0.39	727
6	7	1	2	3	1	$ 34,821	13,123	$ 116,222	3.634	1.00	0.39	759

Figure 0.6: Possible system configuration for solar PV- wind –fuel cell power system

The optimal system chosen for our case study is made of 8kW of solar PV stem, 4 wind turbines, one1kW fuel cell, and 2kW of converters, 2kW of electrolyzers and 1kg of hydrogen tank.

II. CASE 2

5.2.4 Load profile

The load demand was estimated taking into consideration the possibility of future expansion and load growth of the school as the advanced level has a science combination, the need of laboratories, computer lab and libraries are crucial for the competitive education of the students.

The sizing of the system that will meet the load demand was estimated based on the report of Luisa Dias Pereira on energy consumption in school. According to this report, it was estimated that the secondary school annual electrical energy consumption in Europe varies in the range of 16-22kWh/m^2 in Northern Ireland; 29-33 kWh/m^2 in Portugal and 25-33kWh/m^2 in United

Kingdom (Luísa Dias Pereira, 2014). Thus, for our case study the estimation of 16kWh/m^2 was taken to full fill the energy need of the school.

Rwanda climate is almost the same for the whole year, no winter time thus no need of heating like in European countries, for that reason the electricity consumption was estimated to be the half of the chosen one thus 8kWh/m^2 per year was taken into consideration.

Groupe scolaire Mukondo has 6160 m^2 of areas, thus the annual energy needed is of 49280kWh, the monthly energy consumption was calculated to be at 4106.67kWh. Based on the school calendar presented in table 5.1, the energy consumption for the full months of studies (February, March, May, June, September and October) was estimated to be around 4106.67kWh, the energy consumption for April was estimated at 2053.3kWh, for July, August and November the energy consumption was estimated at 3080kWh and for January and December, the consumption was estimated at1026.7 kWh (Half of April).

Figure 5.7 and 5.8 present a hybrid solar PV-wind and FC and the seasonal profile of the load demands respectively.

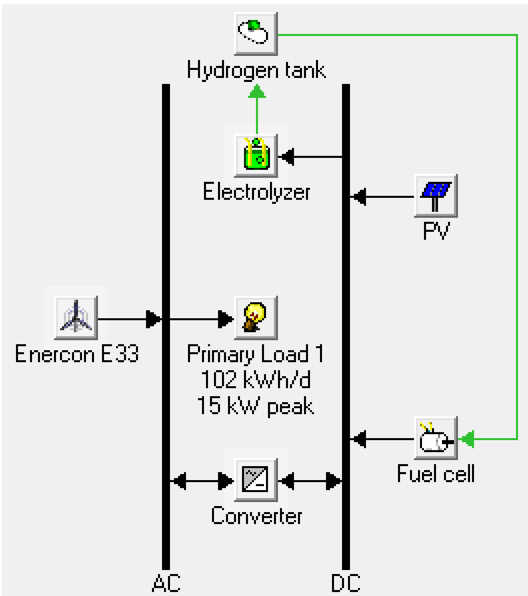

Figure 0.7: Solar PV- wind and FCsimulated system

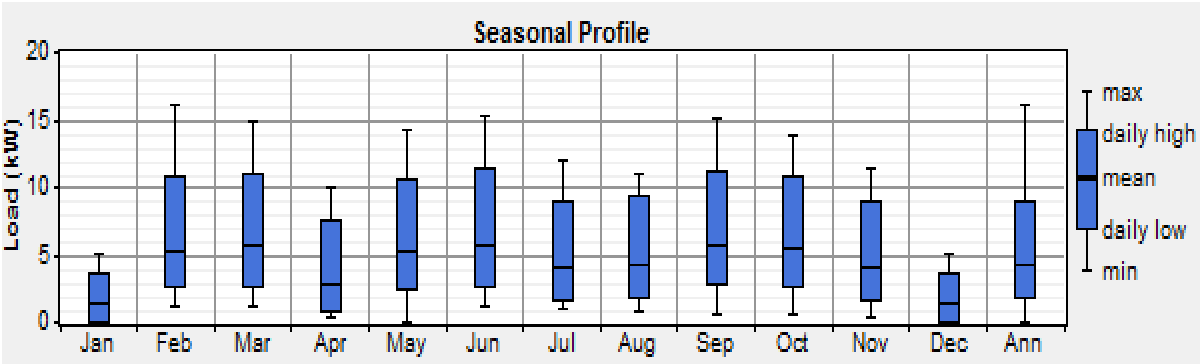

Figure 0.8: Seasonal load profile

It is observed that the highly load demands goes up to 12 kW, the low load demand is down in January and December with approximately 5kW and the annual demand is up to 9 kW.

5.2.5 Simulation of the configuration

Figure 5.9 presents differents configuration of the estimated load profile

PV (kW)	E33	FC (kW)	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FC (hrs)
12	9	1	7	3	1	$ 54,527	22,106	$ 191,656	1.343	1.00	0.50	663
12	9	1	6	3	1	$ 53,727	22,241	$ 191,694	1.345	1.00	0.50	668
12	9	1	8	3	1	$ 55,327	22,064	$ 192,191	1.346	1.00	0.50	661
12	10	1	7	3	1	$ 55,930	22,038	$ 192,633	1.346	1.00	0.50	656
12	10	1	6	3	1	$ 55,130	22,203	$ 192,860	1.350	1.00	0.50	662
12	9	1	9	3	1	$ 56,127	22,082	$ 193,107	1.352	1.00	0.50	661
12	10	1	8	3	1	$ 56,730	21,995	$ 193,167	1.350	1.00	0.50	654
12	10	1	9	3	1	$ 57,530	22,013	$ 194,083	1.356	1.00	0.50	654
12	10	2	6	2	1	$ 56,130	22,640	$ 196,573	1.381	1.00	0.50	341
12	10	2	7	2	1	$ 56,930	22,598	$ 197,108	1.383	1.00	0.50	340
12	10	2	8	2	1	$ 57,730	22,494	$ 197,264	1.383	1.00	0.50	338
12	10	2	9	2	1	$ 58,530	22,513	$ 198,179	1.390	1.00	0.50	338
15	7	2	7	2	1	$ 59,171	23,509	$ 205,004	1.425	1.00	0.50	361
12	9	1	7	4	1	$ 56,527	23,937	$ 205,013	1.434	1.00	0.50	721
15	7	2	8	2	1	$ 59,971	23,406	$ 205,160	1.424	1.00	0.50	359
15	8	2	8	2	1	$ 61,374	23,184	$ 205,188	1.419	1.00	0.50	353
12	9	1	6	4	1	$ 55,727	24,103	$ 205,242	1.437	1.00	0.50	727
15	8	2	9	2	1	$ 62,174	23,080	$ 205,344	1.419	1.00	0.50	351
15	8	2	7	2	1	$ 60,574	23,349	$ 205,413	1.423	1.00	0.50	356
12	10	1	7	4	1	$ 57,930	23,776	$ 205,416	1.433	1.00	0.50	711
12	9	1	8	4	1	$ 57,327	23,894	$ 205,548	1.437	1.00	0.50	719
15	7	2	6	2	1	$ 58,371	23,736	$ 205,609	1.433	1.00	0.50	365
15	8	2	6	2	1	$ 59,774	23,514	$ 205,638	1.428	1.00	0.50	359
12	10	1	6	4	1	$ 57,130	23,942	$ 205,645	1.437	1.00	0.50	717
15	7	2	9	2	1	$ 60,771	23,363	$ 205,695	1.427	1.00	0.50	358
12	10	1	8	4	1	$ 58,730	23,733	$ 205,950	1.436	1.00	0.50	709

Figure 0.9: Possible system configuration for solar PV- wind –FC power system

The optimal system chosen for our case study was made of 12kW of solar PV sytem, 9 wind turbines, 1kW of fuel cell, 7kW of converters, and 3kW of electrolyzers and 1kW of hydrogen tank.

5.3 Economic characteristics of the system

For the optimization of the installed power, despite the investments cost, replacement and O&M cost, HOMER provide also the economic inputs window parameter including project lifetime, annual real interest rate, capacity shortage penalty, fixed capital cost, system fixed O&M cost and real interest rate. In this research the project life time was estimated at 25 years, the annual real interest rate was set at 15.7% as the Rwanda annual real interest rate of 2015. The fixed capital cost, system fixed O&M cost as well as the capacity shortage penalty was set at 0. Table 5.5 illustrates different cost of the hybrid system for both cases.

Table 0.5: Economic characteristics of the hybrid system components

Components	Investment cost [$]		Replacement cost [$]		O&M cost [$]		Total cost [$]	
	Case1	**Case 2**	**Case1**	**Case2**	**Case1**	**Case2**	**Case1**	**Case2**
PV	17,200	25,800	0	0	1,042	1,563	18,2424	27,363
E-33	5,612	12,627	243	546	3,474	7,816	9,241	20,792
Fuel cell	3,000	3,000	2,115	2,113	66,343	123,385	71,458	128,493
Converter	1,600	5,600	144	503	66,343	347	1,832	6,411
Electrolyzer	4,000	6,000	359	539	99	372	4,579	6,869
H2 tank	1,500	1,500	65	65	248	186	1,728	1,728
System	**32,912**	**54,527**	**2,926**	**3,765**	**71,392**	**133,666**	**107,080**	**191,656**

5.4 Summary

This chapter gives the description on the characteristics and cost of the system components. It goes ahead to describe the case study, as well as the load demands for the present and future projection. Finally, the results of the simulation for a hybrid solar PV- wind- FC power system are presented.

Chapter 6 RESULTS AND DISCUSSION

Outline

Chapter 6. RESULTS AND DISCUSSION

This chapter gives the detail on the optimization results for the selected hybrid power system for Groupe scolaire Mukondo. The system was designed using Homer software. Based on the inputs, the following outputs were a result including; monthly electrical energy production, monthly electricity consumption , monthly PV output, monthly wind output, monthly fuel cell output and the monthly hydrogen production of the configuration system for the two studied case.

6.1 Systems configuration

As stated in chapter 5, for the first case with a peak load demands of 9.1kW, the optimized system will be made of 8kW PV system, 4 wind turbines, 2kW of converters, 2kW of electrolyzers, and 1kW of fuel cell and 1kg of hydrogen tank.

For the second case with a peak load demand of 15kW, the optimized system will be made of 12kW PV system, 9 wind turbines, 7kW of converters, 3kW of electrolyzers, and 1kW of fuel cell and 1kg of hydrogen tank.

6.1.1 Total Energy production

The electric energy production is shown in figure 6.1 for the first case and figure 6.2 for the second.

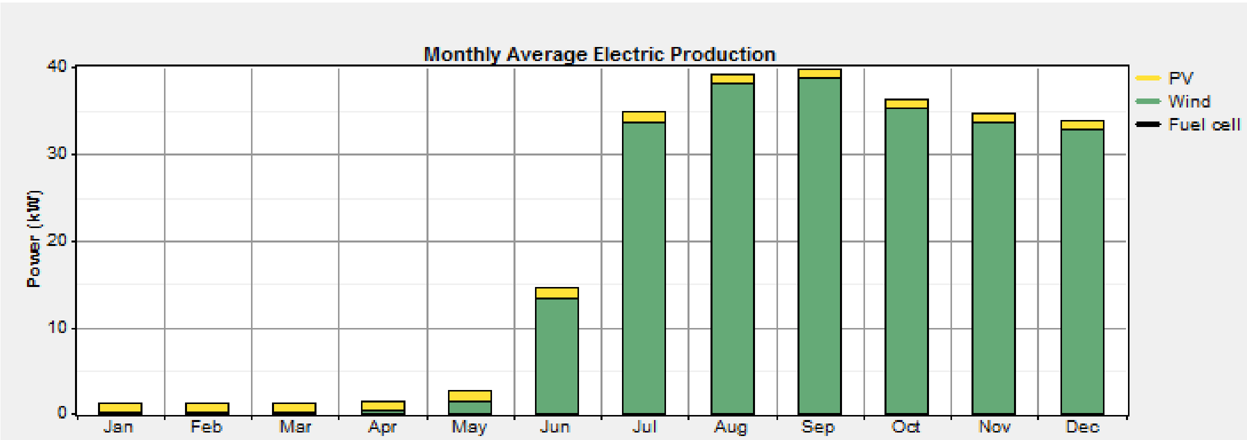

Figure 0.1: Monthly electric production for case 1

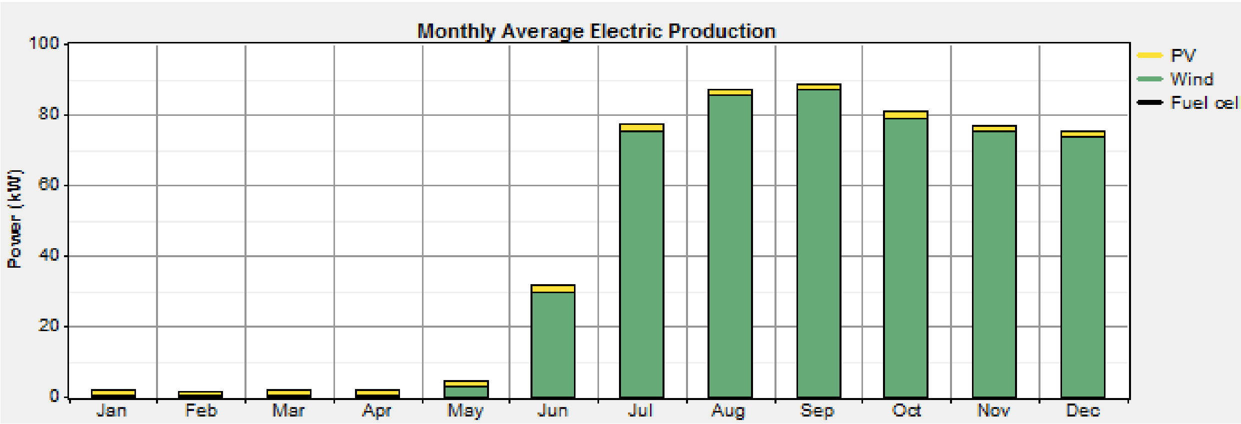

Figure 0.2: Monthly electric production for case 2

It was observed that solar PV system remains producing the electricity throughout the year whereas wind conversion system electric power production dominated from June to December with a minimum production in May and no appearance of wind power production from January to April due to low wind speeds.

Fuel cell contribution was observed to be negligible which indicates that the demand can be satisfied by the produced power from wind and solar without the intervention of fuel cell. In this case, the storage system (for the excess energy production) will be used for the future increase energy demands.

- For case 1, the total power production of the system is 176,759kwh/year whereas the electric energy consumption is 12,509kWh/year within 41% consumption by the load and 59% by the electrolyzer.
- For case 2, the total power production of the system is 389,343kwh/year whereas the electric energy consumption is 31,366kWh/year within 73% consumption by the load and 27% by the electrolyzer.

6.1.2 **Monthly solar energy production**

- For case 1, the solar power generation varies between 0.8 and 8kW. Solar PV mean output energy production was obtained at 25.3kWh/day.
- For case 2, the solar power generation varies between 1 and 10kW. Solar PV mean output energy production was obtained at 35.1kWh/day.

Table 6.1 illustrates different results of PV system simulation for both cases.

Table 0.1: PV system simulation results

	Value	
Quantity	**Case 1**	**Case 2**
Rated capacity (kW)	8.00	12
Maximum output power (kW)	7.35	9.37
Mean output energy (kWh/day)	25.6	35.1
Hours of operation (Hour/year)	4,380	4,380
Levelized cost of energy ($/kWh)	0.319	0.345

6.1.3 **Monthly wind energy production**

For both cases, it was observed that the wind power production was high from July to December and there are traces of wind power production in June. From January to May, no wind power production existed because of the wind speed which is very low.

- For case 1, the maximum output wind power was recorded to be around 329kW with a mean output of 19kW. The levelized cost was found to be at 0.00891$/kW.

- For case 2, the maximum output wind power was recorded to be around 740kW with a mean output of 43kW. The levelized cost was found to be at 0.00891$/kW.

Table 6.2 illustrates different results of wind power system simulation for both cases.

Table 0.2: Wind power system simulation results

	Value	
Quantity	**Case 1**	**Case 2**
Total rated capacity (kW)	1,320	2,970
Maximum output (kW)	329	740
Mean output (kW)	19	43
Hours of operation (Hour/year)	4,635	4,635
Total production (kWh/year)	167,127	376,035

6.1.4 Monthly hydrogen production

Figure 6.3 and figure 6.4 present the monthly hydrogen production for case1 and case2 respectively.

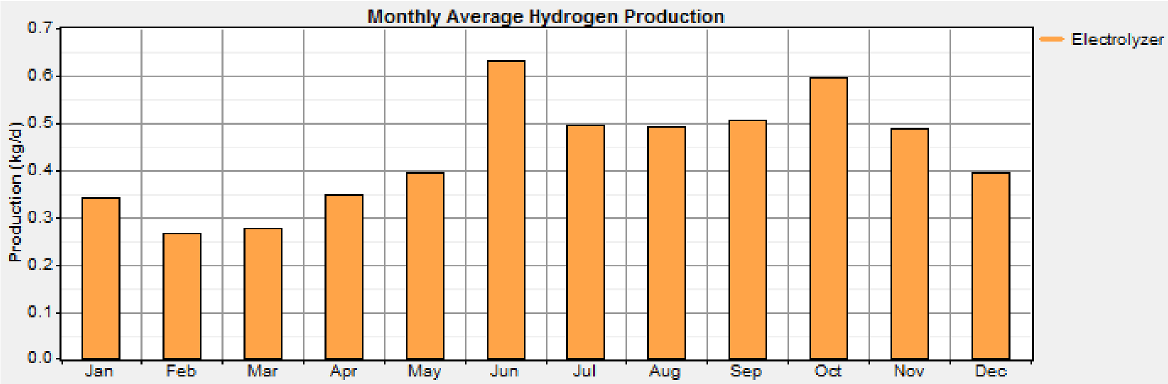

Figure 0.3: monthly hydrogen production for case 1

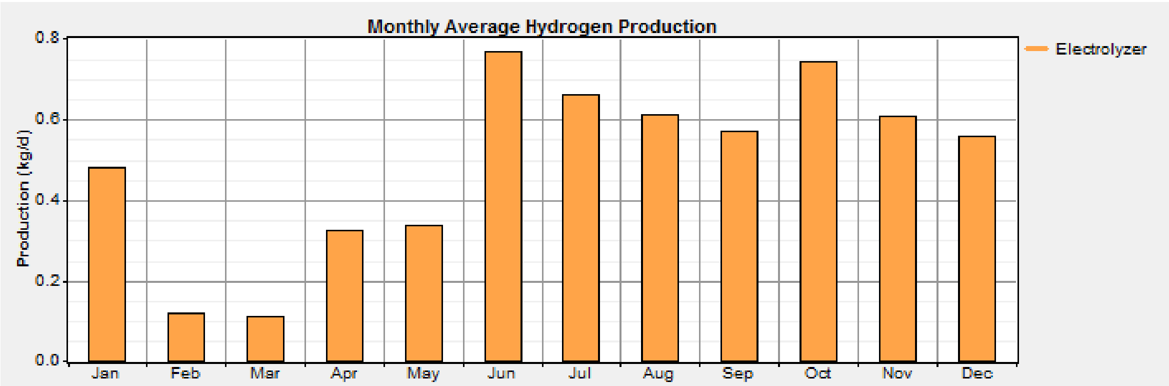

Figure 0.4: Monthly hydrogen production for case 2

The monthly average hydrogen production represents the excess energy produced by the system which is converted by the electrolyzer into hydrogen and stored into the hydrogen tank for later use.

- For case 1, it was observed that the hydrogen production is highest in June with 0.63kg/day and the minimum production is in February with 0.28kg/day. The total hydrogen production was obtained to be at 159kg/year and the hydrogen. The levelized cost of hydrogen was around106$/kg.
- For case 2, it was observed that the hydrogen production is highest in June with 0.63kg/day and the minimum production is in March with 0.3kg/day. The total hydrogen production was obtained to be at 180kg/year and the hydrogen. The levelized cost of hydrogen was 172$/kg.

6.1.5 **Monthly fuel cell output**

The fuel cell system is meant to start producing energy when the demand goes high and cannot be covered by the production of both wind and solar system. As shown in table 6.3 fuel cell maximum electrical production by the proposed systems was 1KW.

Table 0.3: Fuel cell power system simulation results

	Value	
Quantity	**Case 1**	**Case 2**
Electrical production (kWh/year)	409	507
Mean electrical output (kW)	0.574	0.765
Min. electrical output (kW)	0.300	0.300
Max. electrical output (kW)	1	1
Hydrogen consumption (kg/year)	159	180

6.1.6 **Emission**

Table 6.4 presents the amount of greenhouse gases emitted by the propose systems.

Table 0.4: Emission

	Pollutant	CO2	CO	SO2	NO
Case 1	Emission [Kg/year]	-1.63	1.04	0	9.24
Case 2	Emission [Kg/year]	-1.84	1.17	0	10.4

It was observed that the quantity of greenhouses gases emitted by the system was negligible. This is due to the fact that the system is a fully renewable system.

6.2 Summary

This chapter summarizes the electrical output for the whole system as well as the electric output for each component and the amount of gases that will be emitted/ prevented during the operation of the system. The electrical output was calculated based on the energy demand of the studied cases. It was observed that for both cases studied, the proposed systems will provide the electrical energy that will cover the demands and the systems were found to be environmental friendly.

Chapter 7 CONCLUSION AND RECOMMANDATION

Outline

7.1 General conclusion

7.2 Recommendation

Chapter 7 CONCLUSION AND RECOMMENDATION

7.1 General conclusion

The presented work has been conducted on the sizing of a hybrid solar PV-wind-FC power system for Groupe scolaire Mukondo located in Rubavu district. The used wind speed and global solar radiation data were obtained from Rwanda Meteorological Agency (RMA). The collected data was for the year 2014 for the Sebeya station located in Rubavu district. Wind speed data was measured at 10m above ground at 10 minute intervals. The monthly average wind speed data were analyzed using MATLAB. At 10m above ground, the wind speed was found to be very low thus extrapolation and calculated the wind speed at 100m. Global solar radiation data were collected at 10min apart. The monthly average of daily global solar radiation was analyzed using excel. The annual average wind speed and global solar radiation of the region was found at 2.77m/s and 4.126kWh/m^2/day respectively.

The sizing and optimization of the proposed off-grid hybrid system was done by HOMER. The system was sized based on different factors such as the load demands, climatic data and cost of the components. Two cases were studied during this research; the first case that was based on the present situation and the second case was based on the future load projection for the school. For the first case, with a peak load demand of 9.1 kW, the favorable system found out was made of 8kW of solar PV system, 4 wind turbines, 1kW of FC, 2kW of converter, 2kW of electrolyzer and 1kg of hydrogen tank. For the second case with a peak load demands of 15kW, the favorable system was found to be made of 12kW of solar PV system, 9 wind turbines, 1kW of fuel cell, 7kW of converter, 3kW of electrolyzer and 1kg of hydrogen tank. For both cases, the results show that the implementation of the system will be successful to meet the demands.

The economic study of the system shows that the PV system is expensive as it had a share of 52.3% and 47.3 % of the total system cost for the first and second cases respectively. The levelized cost of electricity was found to be at 3.37$/kWh for the first case and 1.34 $/kWh for the second case. The levelized cost of electricity for both systems is high compared to the actual levelized cost of electricity in Rwanda. This is due to the fact that the system is fully renewable, thus the system components are expensive. The high real annual interest rate in Rwanda, which is at 15.7%, is an additional factor. It is found out that a big system is more beneficial compared to the small system.

For the environmental effect, it was found out that the implementation of the system will result in the reduction of the amount of carbon dioxide and other greenhouses gases which make the renewable system a good choice to implement in the future. It is proposed that these systems be implemented by the non-electrified schools of regions with similar weather conditions as Rubavu region.

7.2 Recommendation

The electrification of schools located in rural areas is an important move towards improving access to better education for the future generation living in rural areas. As the country is blessed with renewable resources, the promotion and awareness on the exploitation of other renewable resources such as solar and wind should be enforced in order to electrify the rural areas. Due to the sustainability and affordability of the system, off-grid hybrid renewable energy power system would be a good way to electrify the region.

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Appendix

Table 1 illustrates the daily average of global solar radiation of 2014 collected at SEBEYA- station in Rubavu district.

Daily global solar radiation [kWh/m^2]

Date	January	February	March	April	May	June	July	August	September	October	November	December
1st	2.12	3.75	6.17	6.17	5.24	5.26	6.05	5.18	3.15	3.49	3.13	4.21
2nd	3.24	4.12	4.34	4.34	5.06	5.28	6.21	4.19	2.67	4.46	3.70	1.47
3rd	4.50	4.27	4.37	4.37	4.26	4.13	6.29	4.23	3.09	3.80	3.57	1.76
4th	5.25	4.49	6.06	6.06	4.99	5.28	6.08	2.34	2.41	3.10	4.83	4.02
5th	3.89	2.68	4.97	4.97	5.60	2.98	5.60	2.29	1.24	4.27	5.22	5.70
6th	4.17	2.80	3.06	3.06	4.50	1.99	4.19	2.97	2.18	3.14	5.15	6.32
7th	4.05	2.30	3.19	3.19	3.74	3.37	3.48	5.92	5.43	5.91	3.77	6.45
8th	3.79	5.25	6.93	6.93	3.76	4.12	5.29	2.91	5.17	3.67	4.75	3.50
9th	2.67	2.90	5.42	5.42	3.17	3.52	5.45	4.12	6.56	6.34	6.05	3.43
10th	2.80	2.15	3.22	3.22	3.37	4.84	4.07	4.26	5.90	5.64	3.81	3.16
11th	2.97	5.87	0.85	0.85	2.73	3.88	4.14	4.13	4.85	6.98	2.96	3.93
12th	4.79	1.88	2.85	2.85	2.69	2.57	5.03	2.41	6.66	7.59	3.05	5.92
13th	3.68	5.85	3.00	3.00	3.08	4.10	4.32	3.16	5.04	6.11	3.38	6.25
14th	3.26	5.08	4.66	4.66	4.76	4.33	4.57	2.61	4.27	3.84	3.70	5.64
15th	2.43	4.50	4.46	4.46	4.11	4.53	4.02	3.61	3.65	2.92	4.27	4.83
16th	3.41	4.29	4.12	4.12	3.67	5.19	4.68	2.66	5.54	3.18	2.23	3.16
17th	4.09	6.00	4.88	4.88	4.16	5.58	4.13	4.07	4.33	3.98	2.69	3.73
18th	4.04	5.36	6.12	6.12	4.00	5.22	3.06	5.27	2.58	3.06	4.60	4.56
19th	3.84	1.68	4.34	4.34	5.41	4.01	3.70	1.93	2.67	3.25	4.69	5.17
20th	2.13	2.79	4.00	4.00	4.96	5.48	3.03	3.22	2.70	1.54	4.17	2.50
21st	3.54	4.02	3.39	3.39	4.08	5.28	2.14	3.92	5.90	4.52	4.39	3.98

22nd	3.18	5.81	4.47	4.47	4.47	5.18	3.24	5.48	4.11	4.31	3.50	2.58
23rd	3.04	4.54	2.46	2.46	4.84	5.15	0.57	5.11	4.67	2.84	2.09	3.07
24th	2.53	2.01	2.53	2.53	4.23		3.46	3.10	4.50	3.45	2.82	1.95
25th	4.49	2.50	4.59	4.59	6.07		3.99	3.00	4.15	4.97	3.78	2.32
26th	4.42	1.56	2.95	2.95	5.77		6.72	3.06	3.51	6.96	2.98	2.78
27th	5.10	3.73	4.82	4.82	4.35		6.71	5.30	3.27	4.47	3.29	4.44
28th	3.76	5.72	1.78	1.78	5.47		5.51	4.31	4.51	6.25		4.36
29th	5.45		4.18	4.18	6.21			2.94	4.75	5.34		3.39
30th	4.99		5.76	5.76	5.41			3.25		3.66		2.55
31st	3.65		4.11	4.11	4.70			3.20		6.62		3.49

Figure 2 illustrates the average wind speed recorded at SEBEYA-station at 10m above in 2014

Wind speed [m/s]

Date	January	February	March	April	May	June	July	August	September	October	November	December
1st	0.5	0.9	0.8	0.8	1.3	2.3	6.4	4.4	1.8	2.1	1.7	1.7
2nd	0.7	0.8	0.9	0.9	1.5	2.2	4.9	3.5	1.4	1.2	1.8	0.8
3rd	0.9	0.9	0.9	1.0	1.2	2.8	7.1	2.8	1.5	1.1	1.7	0.7
4th	1.1	0.8	1.0	0.8	1.8	0.0	6.0	4.3	1.5	0.9	2.5	1.7
5th	0.7	0.4	0.8	0.6	1.3	0.0	4.9	4.4	0.9	1.2	2.6	1.8
6th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7th	0.8	0.6	0.8	0.5	1.3	0.0	3.8	4.1	2.2	2.3	1.8	2.1
8th	0.5	0.8	1.0	0.5	1.0	0.0	4.4	3.7	2.8	1.9	1.8	1.3
9th	0.6	0.6	0.8	1.0	0.9	3.4	4.1	4.4	2.4	1.7	1.9	1.2
10th	0.8	0.5	0.7	0.9	0.8	6.5	4.6	3.1	1.8	1.8	2.3	1.5
11th	1.0	0.8	0.6	1.2	0.8	4.9	5.6	3.8	2.1	2.3	2.1	1.4
12th	1.0	0.5	0.8	0.7	0.9	4.9	4.2	1.6	3.3	2.4	1.6	1.7
13th	0.7	1.0	0.7	0.7	1.5	3.6	3.8	1.0	2.2	1.8	1.5	1.6
14th	0.7	0.8	0.5	1.0	1.5	1.8	4.8	1.0	2.5	1.2	1.3	1.6
15th	0.8	0.6	0.5	1.2	1.6	2.0	4.9	1.4	2.4	1.4	1.8	1.9
16th	0.9	0.8	0.6	0.9	1.3	3.8	3.9	1.6	2.5	1.0	1.9	1.8
17th	0.9	0.8	0.8	0.8	1.6	3.4	4.5	2.3	2.0	1.1	0.9	1.6
18th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19th	0.8	0.5	0.7	0.8	1.9	2.2	2.3	1.1	1.1	1.1	1.3	2.4
20th	0.4	0.7	0.7	0.9	1.7	3.8	0.0	1.2	2.3	1.0	1.0	1.5
21st	0.5	0.7	0.5	1.0	1.0	6.1	2.2	1.3	2.8	1.4	1.5	2.0
22nd	0.8	0.8	0.7	1.1	1.4	6.9	2.9	1.5	2.1	0.9	1.4	1.0
23rd	0.6	0.6	0.6	0.9	1.6	6.1	3.9	1.7	1.8	0.8	1.3	1.9

24th	0.6	0.4	0.6	0.9	2.3	8.0	4.1	1.1	2.3	0.8	1.3	1.5
25th	0.8	0.5	0.7	1.0	1.7	6.4	2.9	1.8	2.1	1.1	1.0	1.7
26th	0.8	0.7	0.6	0.8	2.0	6.1	2.7	1.8	2.0	1.6	0.8	2.5
27th	0.7	0.7	0.6	1.2	2.2	6.6	4.4	1.8	1.6	1.4	1.4	1.8
28th	0.5	0.9	0.5	1.1	1.9	7.5	3.1	2.6	1.8	1.5	1.5	3.3
29th	0.7	0.0	0.8	1.1	2.4	7.4	4.5	1.8	1.9	1.5	1.3	2.0
30th	0.9	0.0	0.8	1.2	2.3	4.6	4.9	1.3	1.5	1.1	1.3	1.3
31st	1.0	0.0	0.8	0.0	2.5	0.0	3.4	1.3	0.0	1.9	0.0	1.5