DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research

University of Tlemcen

جامعة أبو بكر بلقايد
UNIVERSITÉ DE TLEMCEN

Pan African University
Institute of Water
and Energy Sciences

PAN AFRICAN UNIVERSITY

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

THESIS PROPOSAL

(DEVELOPMENT OF RENEWABLE ENERGY SYSTEM PLANNING FOR RURAL ELECTRIFICATION)

CASE STUDY RWANDA

Student name: Clementine Ushizimpumu

Date: 24/08/2016

*Master in **Energy Engineering track***

Members of Jury:

President

Supervisor: Prof. Bhandari Ramchandra

Co-Supervisor: Sofiane Amara

Examiner 1:

Academic Year: 2015-2016

Abstract

Rwanda is currently experiencing daily load energy crisis. The Rwandan utility supply is not ever handling the increase of energy demand. Bugesera district is one of the district which are facing energy issue to improve the development. This master thesis is basically to choose a suitable electrification energy system planning for rural area in order to improve their welfare. Off grid Solar photovoltaic (PV) system is considered as an effective option to increase the energy yield production for rural areas community. It presents mainly the available energy resources, system requirements and investments of all major components of sustainable implementation of the solar PV power system as well as benefits. A suitable energy system capable of supplying energy of 65.18 MWh/year was designed and components sizing was carried out. Major system components such as the photovoltaic modules, the inverter are specified assuming insolation levels of four minimum sun hours per day. The use of solar PV off grid system is very beneficial and competitive with utility grid, as it decreases both operating costs and pollutant emissions. In addition, some further suggestions are discussed to improve the system.

Key words: Rural electrification, Energy system planning, Solar PV off grid system, Rural area community, Suitable energy system.

Contents

List of figures

List of tables

List of abbreviations and acronyms

SPV: Solar Photovoltaic
GWh: Gihawatt-hour
SPVWPs: Solar Photovoltaic Water Pumping system
kWh/m²/year: Kilowatt- hour per meter squared per year
GDP: Gross Domestic Product
EDPRS II: Economic Development and Poverty Reduction strategy II
MW: Megawatt
$: Dollars
C/KWh: Cent per Kilowatt – hour
VAT: Value Added Tax
UNDP: United Nation Development programmes
CO_2: Carbon Dioxide
g Co_2/KWh/year: Gram of CO_2 per Kilowatt hour per year
GHG: Greenhouse Gaze
TV: Television
IEA: International Energy agency
SHS: Solar Home system
Wp: Watt Peak
MWp: Mega Watt Peak
FAO: Food
DC: Direct Current
BOS: Balance of System
I: Current
V: Voltage
AC: alternative Current
SDGs: Sustainable Development goals
CWR: Crop water Requirement
ETc: Evapotranspiration of the crop
NASA: National Air and Space Agency
IRENA: International Renewable Energy Agency
DSM: Demand-Side Management
EE: Energy Efficiency
EAC: Est African Community
REG; Rwanda Energy Group
EARP: Electricity Access Roll-out Program
°C: Degree celicius
IRR: Internal rate of Return
NPV: Net Present Value
LCOE: Levelised Cost of Energy
TPWC: Total Present Worth Cost
TPWB: Total Present Worth Benefits
DPBP: Discounted Payback Period
Kc: Crop Factor
ETo: reference crop evapotranspiration, (mm/day)
IRn: Net Irrigation Requirement (mm)
Re: Effective rainfall (mm)
TDH: Total Dynamic Head

ρ: Density of water
G: Gravitational acceleration
V (m^3/day): Volume of water required per day
EH: Hydraulic energy
PSH: Peak Sun Hours
Ppump: Pump power
Pump eff: Pump Efficiency
Vdc: Volt Direct Current
E_L: Estimated average daily load energy consumption
PSI: Peak solar Intensity at the earth surface (1kW/m2)
$\eta_{b.o}$: Efficiency of balance of system
K_{Loss}: Loss Factor
f_{man}: Manufacturer's tolerance
f_{temp}: Temperature de-rating factor
f_{dirt}: Dirty factor
γ: Power temperature co-efficient
$T_{a.day}$: Day time average ambient temperature in °C
N_{ms}: Number of modules in series
V_{System}: System voltage
V_{module}: Nominal module voltage
N_{mp}: Modules in parallel
$\boldsymbol{P_{PV\ array}}$: Output power
C_x: Required battery capacity
N_c: Number of days of autonomy
DOD_{max}: Maximum depth of discharge
η_{out}: Battery loss
N_{breq}: Number of batteries required
N_{bs}: Number of batteries in series
N_{bp}: Number of batteries in parallel
$\boldsymbol{P_{total}}$: Inverter power rating
$\boldsymbol{P_{RS}}$: Power of appliances running simultaneously
$\boldsymbol{P_{LSC}}$: Power of large surge current appliances
$\boldsymbol{I_{rated}}$: Rated current of the regulator
$\boldsymbol{I_{sc}}$: Short circuit current
$\boldsymbol{N_{reg}}$: Number of regulator required
$\boldsymbol{I_{selected}}$: Selected charge controller
$\boldsymbol{f_{safety}}$: Safety factor
m^3/h: Meter Cube per hour
RWF: Rwandan Franc

1. INTRODUCTION

In this chapter, entitled Introduction, the general introduction is taking into consideration where it covers the overview of the thesis. In addition, the overview of the country is discussed and its energy situation as well. Furthermore, problem statement, objectives of the study are discussed and the methods used to tackle the issue as well as the limitation of the study.

1.1 General Introduction

How can renewable energy electrify villages in Rwanda? Photovoltaics, and other renewable energy technologies, can significantly contribute to economic and social development. Currently, about 1.5 billion people in the world, many of whom live in isolated areas, still do not have access to electricity and to clean water, primary health care, education and other basic service such food security, potable water, transportation and communication (Grégoire, 2013). The availability and affordability of certain basic services must be there in order to improve the lifestyle of a community and even to increase the prosperity. Access to electricity is both an active driving force of the basic services achievement and an active agent that can be used in promoting further development (SET, UNDP, & GEF, 2005)

Access to electrical power improves welfare, through better health (for example, in health care delivery, in indoor pollution reduction, and provide access to clean water), through better education (more effective education and training facilities and improved lighting to facilitate evening study at home), and through reduced manual labour and time spent by women in unproductive tasks (SET, UNDP, & GEF, 2005). Power is also a tool that can be harnessed to increase economic productivity and create new income generation opportunities. The important of access to electricity, particularly in remote areas, is to enable the use of modern communication systems, allowing otherwise isolated rural communities to take part in affairs beyond the limits of their own village. These information links enable very important connections between rural communities and their markets and local and national, which is very helpful for the community (SET, UNDP, & GEF, 2005).

In addition, food insecurity has become a major challenge for African countries and other countries with high rate of population growth. Agriculture is one of the sectors that needs to be developed in addressing food insecurity challenges and to enhance economic development to a higher level. In 2003, 850 million people in the world were food insecure, 60% of them living in South Asia and Sub-Saharan Africa, and 70% of the poor live in rural areas. In Sub-Saharan Africa the number of food-insecure people rose from 125 million in 1980 to 200 million in 2000 (FAO, 2015).

Water and energy are the main drivers that can be considered to tackle this issue. Out of the total percentage of water and energy consumption worldwide, water and energy used for agricultural purposes takes about 70% and 30% respectively (U.S.Department of Energy & Basalike, 2014). Nevertheless, those shares of water and energy in the agricultural sector will keep increasing directly proportional with population growth. Irrigating farmlands contributes positively in increasing crops productivity up to five times more than yields harvested without using irrigation (Maimbo & Basalike , 2010). In the area where rainfall water is not inadequate to meet the irrigation demand and also in the regions with underground or surface water resource which is not easily accessible, a pumping machine powered by diesel generator, electricity from the grid, windmills and as well as Solar Photovoltaic (SPV) system could be of help.

Regarding the environment, the agricultural sector is among the contributor sectors to global warming due to the use of electrical machines in agricultural purposes. Energy consumption all over the world in the agricultural sector is on average of 7.7×10^{6} GWh per year with renewable energies wind, hydro, biomass and solar contributing to the total energy use with a share of 29.6% (Basalike, 2015). SPV system cannot compete with the fossil fuels energy resources (coal, oil, natural gas and nonconventional hydro) for large scale and commercial industrial. Nevertheless, solar photovoltaic water pumping system (SPVWPs) is a suitable way to get water to the small scale remote applications where 24hrs electrical service is not essential, the community is dispersed and where maintenance is an issue. In rural areas, SPV system of pumping water could be of much help to the communities.

Solar system is green energy and is found all over the world from a free source. It can provide more than conventional fuels in case it is exploited in an optimum way. In addition, 74% of the African continent receives more than1900 kWh/m²/year of solar energy, which is a huge potential for solar energy production (Azoumah, 2014). Power cost trend from photovoltaic (PV) technology is declining due to rapid improvement of technologies, as well as the reduction of PV modules price, thanks to Chinese industries. Environmentally friendly, cost reduction of PV power technology and potential of solar irradiation in Africa are three factors that play a key role in conducting this study of developing solar energy system planning for an isolated remote area in Rwanda in order to improve welfare of rural population.

This thesis consists of three components. Chapter one describes energy overview of the country including its benefits. In addition, this chapter also explains the reasons of the research and it also covers such issues as the research method and the problem description. Literature review on what have been done is discussed in the second chapter. The third chapter talks about methodology in which energy demand and resource assessment is discussed. Related and socio economic data collection is being discussed in chapter three, as well as the description of the case study. It also includes the survey results discussions.

In the fourth chapter, theoretical system sizing is discussed for three different scenarios, in order to select the suitable system for the studied area. The results obtained and discussions from the sizing of the proposed off-grid PV systems are well found in chapter five. Chapter six includes conclusion based on the results discussed in the previous chapter. The final chapter gives the reflection of the further work on this thesis. In addition to that, executive summary, reference and appendices also are included at the end of this report.

1.2 Overview of the country

Rwanda is a small land - locked country situated in East Africa with a surface area of 26338 square km and population around 11.61million in 2015 (Economics, 2016) and it is in the most African countries with the highest density population. Rwanda has five provinces such as Eastern, Western, Northern, Southern and Kigali city as well.

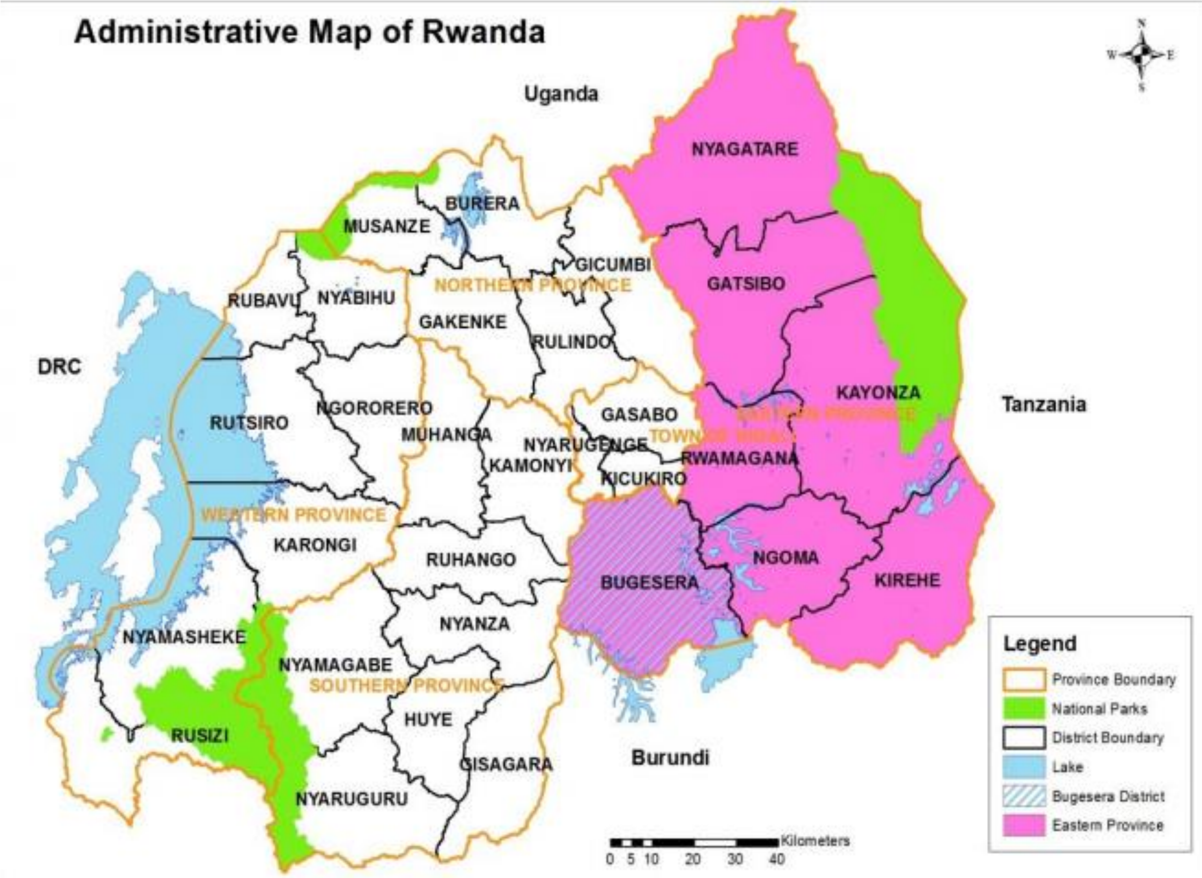


Figure 1.1: Administrative map including district and provinces boundaries (Bugesera District, 2013)

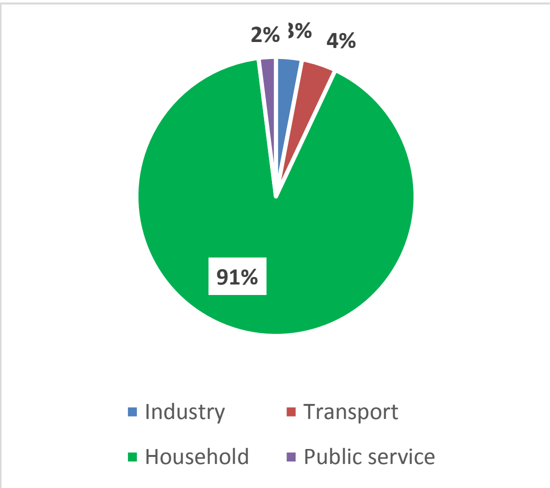
The GDP of the country in 2010, was 548 USD/capita. Rwanda's economy has been growing at an annual average rate of 8.3% and government is targeting to achieve an annual average growth rate of 11.5% over the period (2017/2018) (Ministry of Infrastructure, 2015) due to the Economic Development and Poverty Reduction strategy II (EDPRS II). Electrification rate from world Bank by 2015 was 18% and for rural electrification was just 9 % (World Bank, 2016), which is still a small number.

1.3 Rwanda Energy Situation

Rwanda has limited natural resources. The main exploited sources of energy are hydro, methane gas, peat, solar and biomass. Traditional biomass (charcoal and wood) is the most used form of energy at a share of 94%, followed by petroleum consumed at 11% and electricity form consumed at a rate of 4% (Ministry of Infrastructure, 2015).

Depending on its limited natural resources, Rwanda has been trying to improve the energy sector as shown in figure 1 below. However, those efforts have mainly been disrupted by lack of sufficient financial funds to improve efficiently the existing power plants.

Rwanda energy supply and demand is dominated by household sector with 91% of householder consumers, followed by transport sector, industry and public service in terms of energy consumption. Regarding to electricity consumption, residential sector is the dominant with 51% which is primary used for lighting, followed by industry due to its motor-drivers and lighting and finally public service consumes 6% just for street lighting, public building and water pumping as well (Ministry of Infrastructure, 2014).



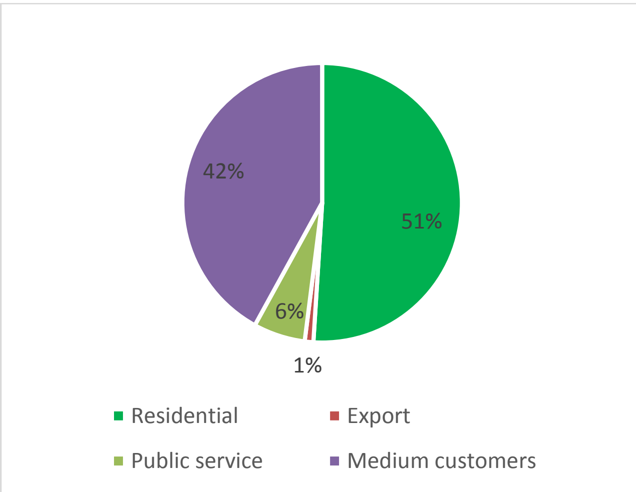


Figure 1.2: Energy Consumption by Sector (2009) Figure 1.3: Electricity Consumption by Sector (2012) (Ministry of Infrastructure, 2015).

Regarding to household cooking energy source, biomass is the dominant source with 97% where 86% is from firewood and 11% from charcoal. Crop waste is also used as an energy source on average of 2% and 1% from other fuels. In urban areas, electric stoves and microwaves are used but with a limited number of household.

1.3.1 On-grid Electricity

Currently, Rwanda is one of world the countries with the lowest electricity consumption rates per capita, at 42kWh per year compared to an average of 478 kWh for sub-Saharan Africa and 1,200 kWh for developing countries as a whole. Nowadays, around 20% of Rwanda's households are connected to the grid (Ministry of Infrastructure, 2015). This partially reflects a situation of "suppressed demand," in the country which can be partly attributed to the fact that the tariff of $0.24/kWh is relatively high for the region, and the topography and dispersed settlement patterns in the country render the infrastructure costs of grid extension projects expensive.

Some measures could be considered in order to address power generation and supply in Rwanda in order to increase the percentage of rural electrification as well as for urban areas. Firstly, as the produced energy cannot be stored for a large scale, therefore carefully planning and network operation are required to facilitate the instantaneous transmission power from the source of generation to the end consumers. Even though, the energy produced is not all reaching to the end users because in transmission lines there is significant amount of energy losses in the form of heat around 23% of losses; therefore, proper network planning and operation is essential to minimise these losses. Secondary, the generation output is not continuously available to the end users and this aggravate the situation. The production which is not constant throughout the day will render the blackout. However, to increase the productivity, different technologies such as renewable energies can fulfil different role. As the electricity production is quite expensive a decision to invest or inter into agreement with different private investors could make sense in order to sustain the whole asset and provide good service (Ministry of Infrastructure, 2015).

1.3.2 Off-grid Electricity

Most of rural areas are lighting their hommes by kerosene energy source and candles. The use of other sources such as solar, biogas and LPG is limited. Currently, on grid electricity tariff is quite expensive ($ 0.24C/KWh) and therefore, most of rural consumers cannot afford to pay for grid electricity and for appliances. Most of rural consumers would like to charge just their phones, radio and sometimes for lighting for few hours a day, which is not much energy demand. This means that as the load for these rural areas is still low, with dispersed settlement and the cost for grid electricity cannot be afforded easily, therefore, off grid system should be an alternative supply from grid electricity. For example, micro hydropower system, diesel stand-alone system, wind power system, solar power system, hybrid system incorporating multiple technologies (SET, UNDP, & GEF, 2005).

1.3.3 Electricity tariffs and generation cost

Taking into consideration the low standard of living of Rwandans, the price of electricity unit is not affordable to everyone. In addition, the price has increased day by day as shown in table below, that raised from the high dependency on imported fossil fuel used in diesel power generators.

Table 1.1: Rwanda electricity tariff excluding VAT (JICA, 2014)

	Previous tariff (RWF/KWh)	Tariff from August 2012 (RWF/KWh)
Average Tariff	110 (17.2 US cent)	132 (20.6 US cent)
Domestic	112 (17.5 US cent)	134 (20.9 US cent)
Industry (time of use)		
Low (23:00 – 7:00)	80 (12.5 US cent)	96 (15.0 US cent)
Mid (7:00 – 17:00)	105 (16.4 US cent)	126 (19.7 US cent)
High	140 (21.9 US cent)	168 (26.3 US cent)

At the end of 2014, the household electricity tariff raises to around 20 – 24 US cents (Ministry of Infrastructure, 2014).

1.3.4 Current status of rural electrification in Rwanda

Access to modern energy improves wellbeing, reduces hunger through food conservation and pumping system for irrigation and provides access to safe drinking water as well. It fosters education by providing light and communication tools, it improves gender equality by relieving women of fuel and water collecting tasks, it reduces child and maternal mortality as well as the incidences of disease by enabling refrigeration of medication and access to modern equipment. In addition, if access to energy is implemented with environmentally technologies, it directly contributes to global environmental sustainability.

Rural electrification rate is still low in most of African countries. Rural people are very important. Therefore, without growing any number of people having sustainable energy access, there will still low development progress (Rolland, 2011).

According to National Institute of statistic of Rwanda report, in 2010 -11 to 2013-14 the electrification rate of households for lighting have almost doubled at the national level from 11% to 20%. In addition to that, the access to electricity is predominantly very high in the households living in Kigali city where it has risen from 56% to 73 % while for other provinces it is on average of ranges between 9% and 15%. Urban electrification is on average of 58.2 to 71.8 from 2010 -11 to 2013-14 respectively and rural electrification is about 2.5% to 9% in 2010 -11 to 2013-14 respectively as well. Thus, the access to electricity for rural areas is still low compared to urban areas (Ministry of Infrastructure, 2015).

The figure below, shows the main source of lighting for rural areas in Rwanda. In most of the household, Batteries are the main used source. In addition, this kind of used batteries are those of dry cell battery and are used in the small torch.

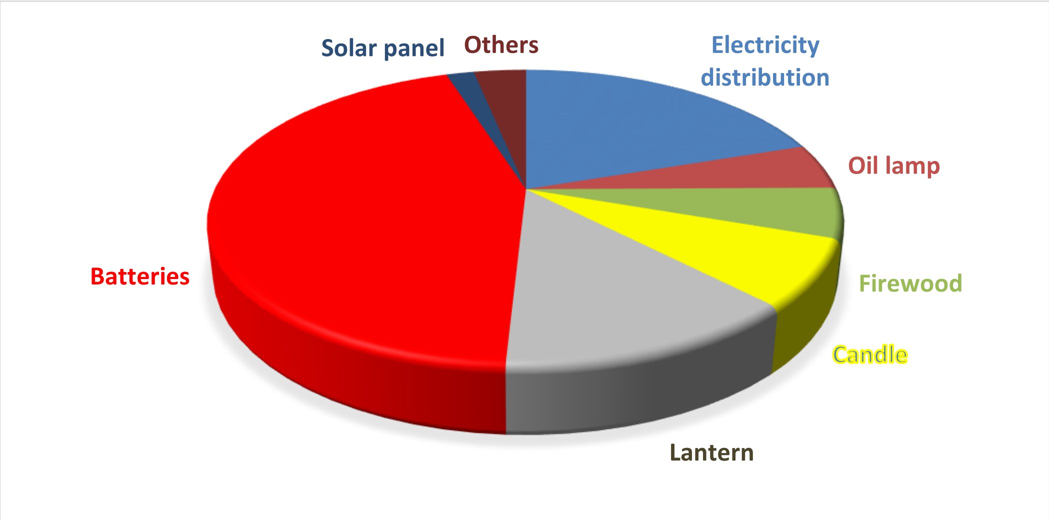


Figure 1.4: Main source of lighting in Rwanda (Ministry of Infrastructure, 2014).

For cooking, the main sources of energy are charcoal and firewood. Charcoal for cooking is mostly used by the majority from urban area with 67% of households while in rural area, firewood remains the most used type of cooking fuels with a percentage of 94. Furthermore, the main source for lighting in rural areas is candles and kerosene and these type of sources have negative impact on health. (National Institute of Statistics of Rwanda, 2016).

1.3.5 Trend in energy demand in Rwanda

Since 2008, power production has increased by 10% to a total of 502,053 MWh. In July 2014, the utility had about 450,775 household customers and 170 customers in the industrial category (Ministry of Infrastructure, 2015). From the figure below, the total energy consumption has been growing on an annual basis. However, a decrease in 2004 is remarkable due to the fact that, there have been an energy production crisis due to the regional drought leading to a rapid draw down of the reservoirs.

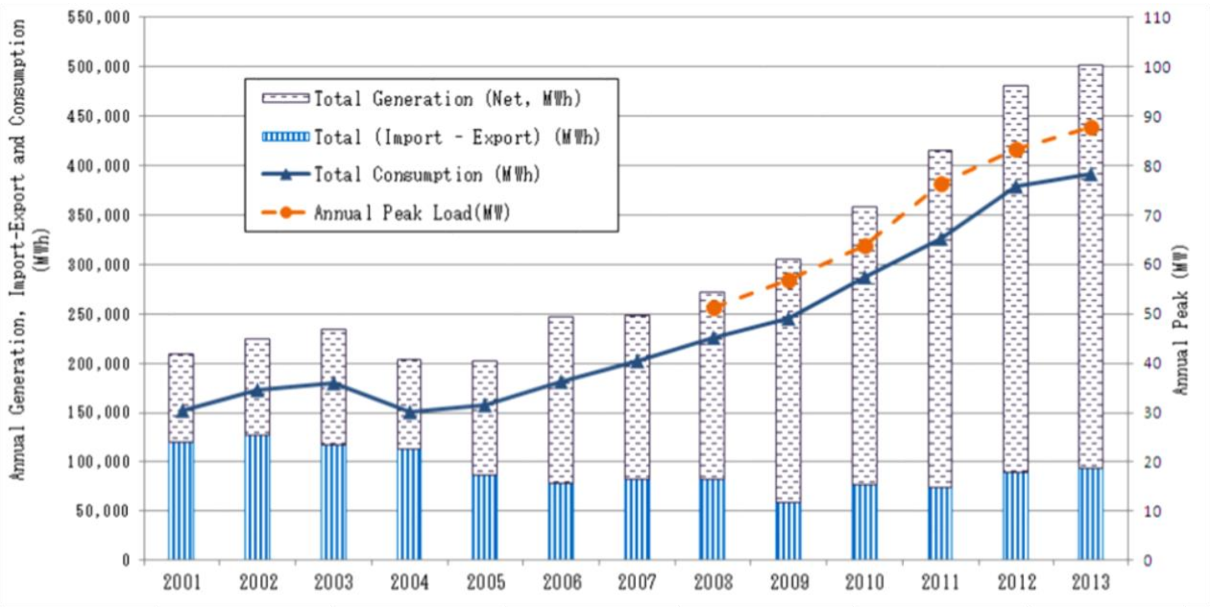


Figure 1.5: Energy Demand and Supply Situation (2001-2013) (Ministry of Infrastructure, 2015)

From 2008 up to 2013, Rwanda had a serious peak demand with on average of 87 MW in 2013 (Ministry of Infrastructure, 2015) This means that energy produced was not enough to meet the demand. In addition, this drought has also affected Kenya, Tanzania and Uganda, leaving Rwanda with no possibility of sourcing electricity from its neighbours (Ministry of Infrastructure, 2015).

1.3.6 Rural electrification program

Government has an initiative to provide rural electricity and some measures has been put in place. For instance, some schools, health centre and household settlement have benefited from this program. With the donors that are involved in the program, 150 remote rural schools are connected with 1.7Kw by solar energy solution and 300 schools, 46 health centres are in progress of being connected. 15 rural settlements have been able to get solar lantern kits of 5W and 400 solar kits of 300W have been distributed to 4 rural settlements as well (Ministry of Infrastructure, 2015).

Due to the fact that the country is facing a biomass deficit of over 4 million m^3 per year, government through EDPRS II, willing to reduce the percentage of using traditional biomass fuel from 94% to 50% by 2018. Most petroleum fuels are imported from outside the county and are costing significantly on the power plant. For example, the diesel fuel and heavy fuel oil imported represent a share of a national burden and also is a factor driving the high cost of electricity and currency depreciation as well highly polluting. However, this fuel cost can be reduced by energy transition. In addition, government is assuring that by 2018, the electrification rate should increase from 19% to 70% through the energy mix and off grid solution (Ministry of Infrastructure, 2014).

With the help of the government and development partners, electricity from the grid is subsidised in order to make the grid connection fee affordable, even though it is still expensive compared to other countries in the region. The household tariff electricity fee is around USCent20 -24/KWh. However, this fee is considering only the unit of cost generation excluding transmission and distribution (Ministry of Infrastructure, 2014).

1.3.7 Problem and strategies

Kigali city is the prioritized city in electricity supply with a share of 62% of the entire produced electricity. This is due to many social, economic and administrative activities necessitating electricity (JICA, 2014). The below map shows the share of electricity distribution across the country.

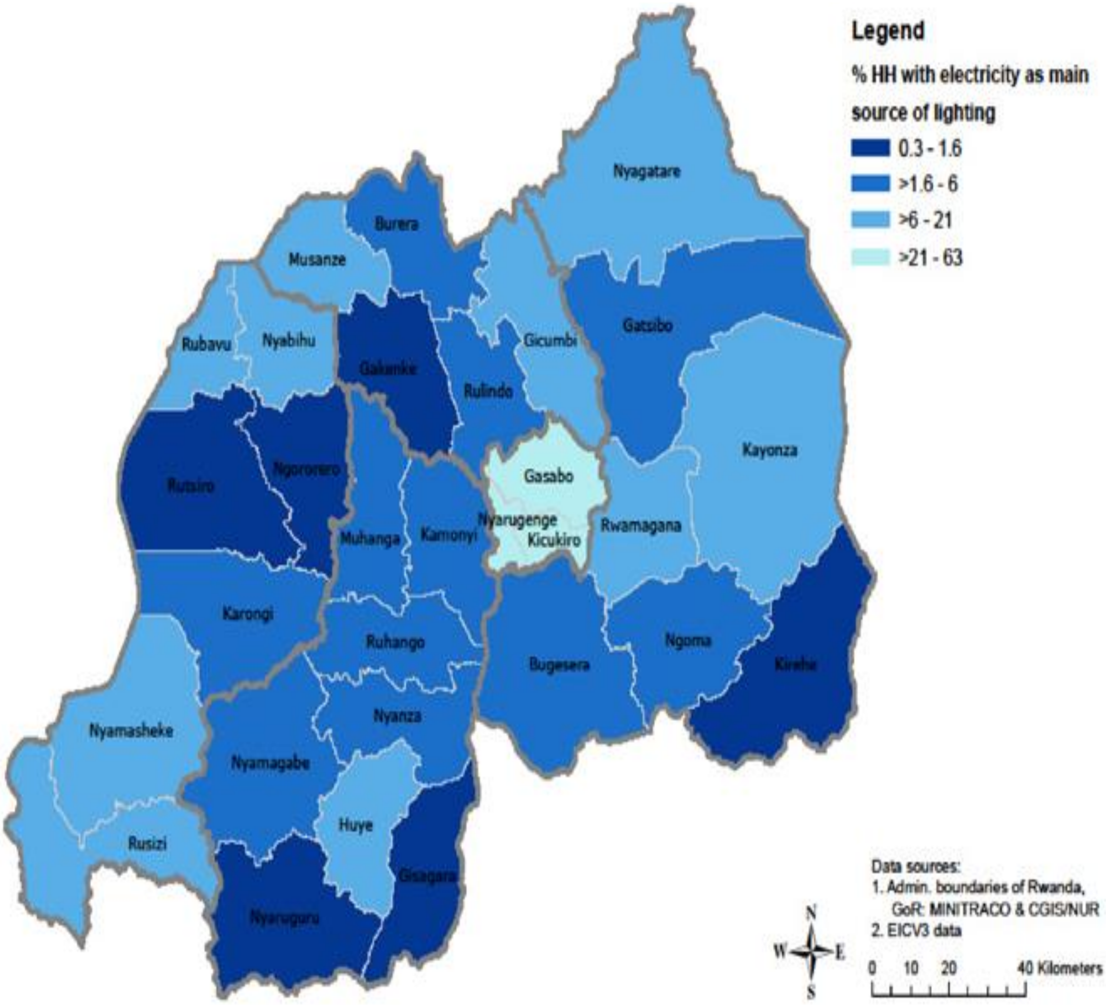


Figure 1.6: Households' Share using electricity as the main source of lighting by district (RNIS, 2011)

However, this prevents other cities and rural areas from being supplied reliably, thus frequent power shortages. Strategies and scenarios, as shown in table 1.2, have been put in place in order to meet the energy demand and reduce diesel generators electricity production costs. Note that those strategies are pretended to allow the raise of the electrification rate to 70% by 2017 via the exploitation of biogas digester, small off-grid hydro installations and more specifically solar energy utilization for electricity generation (JICA, 2014).

Table 1.3: Power development plan and plants construction scenarios (JICA, 2014)

Year	Installed capacity (MW)						
	Heavy/ Diesel oil	**Methane**	**Peat**	**Geothermal**	**Solar**	**Hydro**	**Total**
2013	47.2	5.1	-	-	0.25	55.5	108.05
2014	40	25	-	-	8.5	28	209.55
2015	20	-	15	-	10	-	214.55
2016	-	75	20	-	-	-	309.55
2017	-	-	80	-	-	18	407.55
2018	-	50	50	-	-	-	507.55
2019	-	-	-	-	-	26	533.55
2020	-	-	-	-	-	45	578.55
Total	67.2	155.1	165	0	18.75	172.5	578.55

1.3.8 CO2 intensity from electricity generation in Rwanda

Rwanda electricity production is delivered from 4 relevant systems. Grid electricity production is comprised of: Hydro power plant, solar power plant, methane powered plant and diesel powered plant. Regarding to CO2 emission from grid electricity production, the electricity sector has estimated a trend of carbon intensity emission per KWh of energy produced from 2005 to 2016.

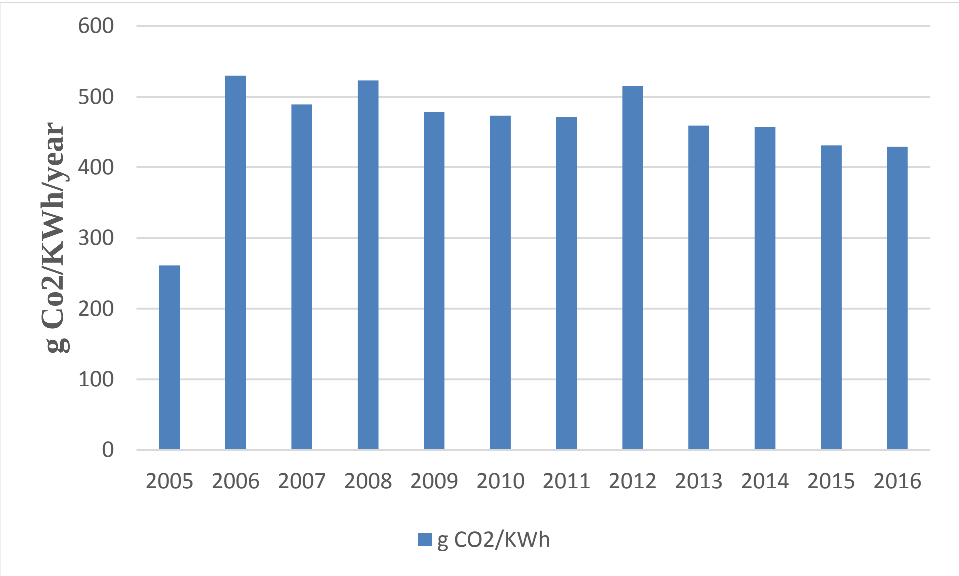


Figure 1.7: CO2 emission per KWh per year (Department for International Development, 2009)

Annual average of grams of CO_2 emission per KWh is estimated to be 459.7 (Department for International Development, 2009). It is important for each country to have an equivalent amount of CO_2 emission of its energy production in order to address global warming issue.

1.3.9 Benefits of Increasing Access to Modern Energy Services

Having access to energy increasing the development to rural communities in different sectors. Energy access has significant impact on three sustainable pillars which are social, economic and environment. For social, it improves the daily living activities, while for economic, it increases the productivity and for environment it reduces the GHG emission which is harmful for the environment. Some impacts are illustrated in the table below.

Table 1.4: Access to modern energy benefits (SET, UNDP, & GEF, 2005)

Social impact	**Economic impact**	**Environment impact**
Improve security by street lighting	Increase production through crop irrigation and animal drinking water	Reduce the CO_2 emission and global worming
Social evening activities by home lighting (entertainment)	Extend hour of working (increases daily income)	Improve air quality
School lighting & power by extending schooling hours	Increase the production through powered processing	Reduce the fossil fuels consumption (preservation of resources)
TV & Radio by informal education	Conservation of product	Prevent the deforestation
Refrigeration (Healthcare vaccinations)	Improving working condition Job creation	Reduce water pollution
Home appliances (time saving)	Attracts customers and tourists	Reduce rain acidity

1.4 Problem statement

Currently, the main barrier of national development in Rwanda is inadequate supply of electricity. In fact, power generation cannot run all of the time, mostly, due to the shortage of power. This lack of energy is mostly affecting rural development. Besides that, agriculture is mostly affected by that lack of energy and as a result, irrigation becomes very expensive. The price of diesel mainly used in power generation becomes expensive due to the import of petroleum from outside the country. Burera is one of the sectors in Bugesera district in the Eastern province of Rwanda. It is located in an isolated rural area not connected to the national electricity grid. Here, economic activities are mainly based on agriculture. However, lower agricultural output and having only one agriculture season instead of having two season or more is the major challenges that the community is facing due to the inadequacy of water for irrigation, and for livestock caused by scarcity of rainfall in the region. In addition, people from the area need to improve their life standards through the energy accessibility.

1.5 Objective of the study

The objective of this study is to develop a renewable energy project plan for energy supply of Mareba sector in Rwanda to improve standards of living of Mareba population in Bugesera district. Social, economic and environment are the major factors to take into consideration. This, is achieved by the following methods.

1.6 Methods

- Energy demand and resources assessment
- Energy related and socio economic data collection (site survey)
- Supply alternatives analysis, theoretical system sizing, techno-economic and environmental analysis of the project.

1.7 Scope

This project entitled "Development of Renewable Energy System Planning for Rural Electrification" is providing a reliable renewable energy system that contributes to only two different applications. Households use of electricity and agriculture productivity of Mareba village.

2 LITERATURE REVIEW

Literature review is taken into consideration in order to cover what other authors have done in the same field as this study. Rural electrification is discussed in general. The use of solar photovoltaic energy for rural development is discussed where it covers four applications such as irrigation, livestock watering, PV for the community and PV for rural household as well. The system of the Solar Photovoltaic is discussed in this chapter also. In addition, the literature on agriculture sector in Rwanda is taken into consideration in order to know the situation in the country. Finally, crop water and irrigation requirements is part of this chapter.

2.1 Rural electrification

Rural electrification is defined as the process of providing electricity to the households located in the remote areas or in the villages in order to improve the status of the standards of living in the country such as education, health, welfare and technology (Wijesinghe, 2014). The investment in rural electrification is necessary in many activities.

In general, rural electrification is divided into two main methods:

- Grid based electrification
- Off-grid based electrification

The two categories have different advantages and characteristics, however, there is even some common characteristics. For example, the grid connection compared to off grid gives advantages like the easier maintenance, billing and tariff collection. On the other hand, off grid systems inherit characteristics like small scale management enables project more economically feasible and possibility to reach scattered population. (Javadi, et al., 2013)

2.1.1 Global Scenario of Rural Electrification

From statistics all over the world, the access to electricity was around 22% of the population by 2008 and the world population was 1.5 billion. Around 85% of population without having access to electricity is located in rural areas, which is a quite big number. According to IEA, if there are not new measures taken to reduce this percentages, or the poverty alleviation, this percentage of the whole world without access to electricity will be increasing (Javadi, et al., 2013).

Some countries in Asia like Thailand and Singapore have already have 100% in electrification for household sector, whereas Bangladesh has only 32.5% of electrification rate in 2009. In addition, it has been realised that, in 2011 up to now, Sub Sahara African countries present the lowest electrification rate of 14.2%. The recorded in 2011, Africa becomes the world's lowest electrification area with 585 million of population without having access to electricity. Therefore, the lack of electricity and energy poverty are the main challenges that make developing countries to stay in poverty (Wijesinghe, 2014).

2.1.2 Barriers of Rural Electrification

As defined earlier that rural areas are the area which are far away from the national grid which is difficult to bring electricity to the nearby, there is unique barriers for providing electricity for rural area compared to urban area.

According to (Wijesinghe, 2014), by comparing urban electrification program and rural electrification program, there are many challenges that rural areas facing such as electricity demand level, the end users are pretty much scattered, the population density is low, low loading factors, high levels of power loss, and low paying capacity of consumers, etc.. Nevertheless, these challenges are overcoming due to the largest benefits in rural electrification areas.

According to the case study that has been done in Kenya, Nepal and Peru, it has been found that, grid extension possibility depends on distance from grid, topography and service quality of the existing grid (Wijesinghe, 2014).

In addition, those barriers of rural electrification, related to the grid extension are categorized in the table below with the corresponding examples.

Table 2.1: Rural electrification barriers (Wijesinghe, 2014)

Barriers	Examples
Weak institutions and organizations	Lack of capacity and low quality of organizations, incompatible donor policies and lack of investments
Economy and finance	Low productive use, low industrialization, tariff system and connection fees, subsidies
Social dimensions	Poverty, attitudes
Technical system and local management	High losses, weak maintenance, lack of skilled people
Technology diffusion and adaptation	Cultural mindset, lack of entrepreneurship
Rural infrastructure	Scattered population, nature reserves, national parks, limited road facilities, traditional houses

2.1.3 Drivers of Rural Electrification

Regardless the barriers of rural electrification, there are many different factors which encourage the establishment of rural electrification programs in developing countries. Policy strategies, political campaign, local initiative (for example, local entrepreneurs, industries that produce power system) and local demand (Wijesinghe, 2014) are ones on major factors to drive rural electrification.

2.1.4 Rural energy and rural development

Energy plays an important role in many basic human needs and in agricultural and economic development in rural areas. In most of developing countries, the majority of rural population is the most important in economic development. However, these rural areas often suffer from the access to energy due to marginalization. Rural electrification rate in most of the sub Saharan countries is still low. Some activities that require energy input in rural areas are distributed in different sectors such as agriculture, household sector, rural industry and commercial sector, community and social services. Irrigation is one of the applications in agriculture that can be supplied by energy for food security while lighting, cooking food processing are some application for household sector. In addition, in rural industry and commercial sector, lighting and food processing can be applications requiring energy. Finally, water pumping, refrigeration for health centres, lighting of communal buildings are also application of community and social services (Campen, Best, & Best, 2000). Solar Photovoltaic system has been proven as the solution for rural electrification since previous centuries.

The dynamics of the PV rural electrification starts by a PV demonstration project in the 1970s where PV pumping and community use were the system for uses, to Solar Home System (SHS) as pre-commercial pilot projects in the 1980s to finally a large scale project in the 1990s. From the lesson learnt since 1970s the use of solar PV system increases rapidly. For instance, SHS has been disseminated for a large scale, whereby solar PV rural electrification has been contributed significantly for PV application for communal use. For example, in small rural clinic for vaccines refrigeration.

The portable solar lanterns have also been introduced during 1990s just for poor people. This system has experienced a significant large market. However, the main challenge of it, is the battery storage.

Another interesting solar PV application that has been introduced in the market since 1990s also is the Solar battery charging stations (BCS), where it helps people who cannot afford SHS and even on the credits. Some countries that this technology is being applied including Colombia, Mali, Morocco, the Philippines, Thailand, Senegal and Vietnam. Finally, mini grid and other large PV system have been introduced in the market but not yet well developed in most of the countries.

Table 2.2:Overview of potential and limitations of PV systems (Campen, Best, & Best, 2000)

Type	Potential	Limitation	Results
Equipment and investment	Flexibility: Possible scaling ranges (from a few Wp upward)	High investment cost per Wp	Need for high financing mechanisms due to the low competence energy and low affordable capital in rural areas
Operation and maintenance	Reliability: low maintenance	Need for back-up or storage for use in days of low insolation	PV system often competitive on life cycle cost basis
Environmental aspect	Environmentally friendly; low emissions of CO2 and other emissions compared to fossil fuel technology	Throwing away of battery is a major environmental issue	Possible due to financing from climate change funds

2.2 Use of solar photovoltaic energy for rural development

In order to increase food production, energy plays a key role in agriculture sector. Energy consumption in agriculture sector results in promoting the use of modern technology and increasing yield production from a system. Energy in agriculture sector is used in both means. The first one is direct use, during irrigation and the second way is indirect used for equipment production, and for service required on the farm. The share of water pumping for irrigation system in crop production all over the world is at 15% whereas India and US are the leader in this regards with the share of 43% and 23% respectively.

Energy required in irrigation system depends on the type of irrigation. For gravity irrigation, the cost is low compared to the pressure irrigation. This is due to the fact that to lift water from a certain height and to achieve the level of pressure required to operate the system requires much energy. Nowadays, the energy powering the irrigation is from fossil fuels such as diesel oil and electricity from the grid. However, grid electricity is significantly high cost and is even not enough in order to be supplied in agriculture sector. In addition to that, fossil fuels present also some disadvantages like rising the price day to day; their resources are not replenished for the future planning and brings the hazardous on environment.

From different literatures, solar energy has been chosen as one of the alternative source to replace the conventional sources for rural electrification plan due to its environmental friendly, low maintenance cost and due to its variety scales (both small and large scale).

Rwanda has a huge amount of solar radiation with annual radiation of 5.2KWh/m^2/day (Blunk, 2013) However, electricity produced from is still less, only 1MWp (Brian Harding, 2009.). Solar water pumping for irrigation in Rwanda is not mostly used method although, pumps are mainly common used and pumped by diesel fuel or electricity when is available (Basalike, 2015). Different applications can be powered by solar energy system to improve standard of living.

2.2.1 PV for irrigation in agriculture sector

Based on the survey that has been conducted by FAO 2000, PV system is very important in promoting sustainable agriculture in rural areas. From the results, PV for irrigation is the most used in agriculture to provide water in the arid and semi - arid remote areas, followed by pumping drinking water for cattle.

Since most of the time, irrigation takes place only a part of the year, the availability of water is more variable with the peak of a particular period. However, this peak load requires to oversize the system in order to meet the peak demand which is not economically viable. This drawback of PV system for seasonal irrigation could be addressed by integrating new communal service for the PV power surplus in order to reduce the energy losses throughout.

Apart from seasonal irrigation problem, many advantages and barriers of PV system in general are the same as of PV pumping for irrigation. The good thing of PV pumping for irrigation, it does not require a battery back – up but it requires water storage which reduce the investment and maintenance cost and insures system reliability.

2.2.2 PV for livestock watering (pumping water for livestock drinking)

Apart from PV pumping for irrigation, PV pumping for cattle watering is also a system which is important in off grid areas. For instance, From the survey conducted by FAO, PV system of pumping water for cattle found that there is a significance positive impacts such as to increase both milk and meat cattle production. In addition, it contributes to the improvement of natural resource management. As long as drinking water is supplied to the place of livestock, trampling of vegetation and overgrazing near watering area could not happen. In addition, this could save time for those who taking care of cattle.

2.2.3 PV for rural households

According to survey done by FAO, SHS is one of the solar PV applications which is dominating in rural areas of developing countries. The access to energy in rural areas offers many benefits in different sectors such as economics income, welfare impact and gender aspects impact. Regarding economics, it contributes to household economic activities for the end users. In addition, due to the introduction solar PV applications in rural areas, there is income generation activities such as sewing, weaving, basket and other small artisanal activities. Furthermore, there is a surplus time due to the extended hours of light which offers also an income generation.

As most of rural areas usually use kerosene, candles which are not good for health, regarding welfare being, lighting service can improve lifestyle of the household level. In addition, it improves education level and reduce accidental fire. Furthermore, solar PV system can provide electricity in order to have access of information and entertainment and it has been realized that, solar PV system could be of help in slowing down the rate of rural urban migration.

Household electrification has a positive impact on women and children. According to FAO research, it has been realised that there is a high positive impact than men. For instance, having electricity helps enough to women to do the work at home more efficiently and helps children to study in the night. In addition to that, in most of developing countries, women are the most one who carry out at home some activities such as handcrafts, sewing, etc., and that access to electricity contributes significantly to the production due to means of extending working time, high quality light, and good time schedule management. Furthermore, access to electricity has positive impact on time saving. For example, water pumping could be used to bring water to the place of use or close to the households and this saves the time of going at a long distance for fetching water.

2.2.4 PV for communal services

PV system is used to communal service through improvement of health facilities, education and community services. Some activities that could benefit through access to electricity are quite a lot. For example, education, veterinary activities, public lighting, community centres, community religions, telecommunication, training centres, water pumping, desalination and purification as well. These social activities contribute to better quality in training and courses, better opening hour shops, restaurant, hair salon, higher health improvement as well as to the environmental improvement.

2.3 Solar Photovoltaic system

PV system is electrical power system that generates energy and is composed by PV panels. PV panel is a solar panel mounted with groups of photovoltaic cells that convert sunlight directly into electricity using semiconductors, in a manner similar to electronic transistors. The produced energy can be supplied on large scale and at variety applications. For example, it can be designed for a small load demand or large and can be used at any voltage of a service.

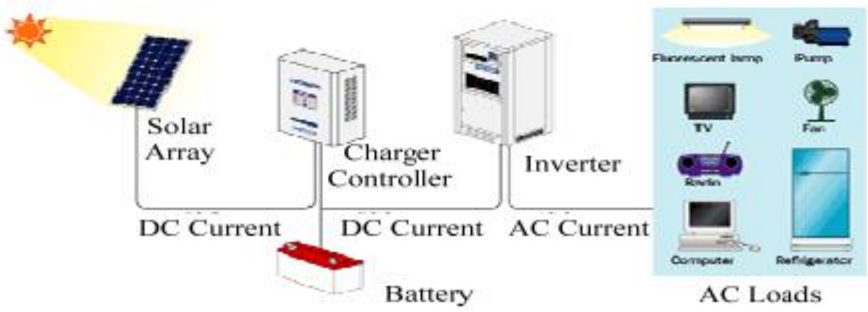


Figure 2.1:Solar Photovoltaic system (Nang Saw Yuzana Kyaing, 2011)

A major component of PV system is PV array module that convert solar energy to DC electrical energy. There is also power conditioning equipment, energy storage devices mainly batteries. Power conditioning equipment include inverters, chargers, charge and load controllers, and finally maximum power point tracker.

PV system can operate as hybrid system with other energy sources such as wind turbine, electrical generator, fuel cells and even it can be connected to the utility grid.

There is also a balance of system which includes all mechanical and hardware equipment used to assembly the major solar PV components together in order to supply electricity to the end users. Some of BOS equipments include conductor or wiring methods, junction and combiner box, Raceway or conduit, fuse and circuit breaker, grounding equipment, array mounting, etc (Jim Dunlop Solar, 2012)

2.3.1 Solar radiation, irradiance and insolation

Solar radiation is defined as the energy received from the sun that reaches the Earth. It expressed in KW/m^2. Normally, the Earth receives 1.36KW/ m^2 of solar radiation at its outer atmosphere, however, by the time it reaches to the earth surface, amount of solar radiation reduces to approximately 1KW/ m^2. The intensity of solar radiation depends on geographic location and climate season. For example, in the north of the mountain the solar intensity is different than in its south slop. In addition, when the sun passes through atmosphere, solar intensity is greatest at noon and least during early in the morning and late in afternoon hours. The most production solar radiation in the most area starts from 9am to 3pm during the day. Outside this range solar power could be produced but at very low level (United State Development of agriculture & Natural Resource Conservation Service, 2010).

Solar irradiance is defined as the amount of solar energy received by or projected onto a specific surface of the material. It is expressed in KW/m^2 and it is measured at the surface of material. For example, solar panel is considered as the surface of PV system (United State Development of agriculture & Natural Resource Conservation Service, 2010).

Solar insolation is the amount of irradiance measured over a given period of time. It is quantified in peak sun hours. In other words, it is the equivalent number of hours per day when the solar irradiance average $1KW/m^2$. Solar insolation depends on the altitude and the proposed tilt angle of the PV array (United State Development of agriculture & Natural Resource Conservation Service, 2010).

2.3.2 The Electric Characteristics of PV Modules: The Current Voltage (I-V) Curve

Photovoltaic module performance electrical characteristics is characterised by its current and voltage curve. Sometimes it may even be characterised by its voltage power curve which gives the same information as I-V curve. The I-V curve shows how the power output is affected by the operating voltage and it shows also where the peak power output occurs (Brooks & Dunlop, 2013). These characteristics help to know how well the PV cell is for the system.

In additon, by changing the solar irradiance the performance of PV module could change whereby increasing the solar irradiance increases the current. Regarding on voltage, there is a little increase (Brooks & Dunlop, 2013). Furthermore, the maximum power increases with increasing irradiance while maximum power voltage increases litlle with irradiance.

The variation of temperature also is one of the parameters that affects the performance of PV module. As the temperature increases, the current increases due to the rapid movement of molecules in the cell, while the voltage decreases. Therefore, by increasing the temperature of the PV module reduces the power. (Brooks & Dunlop, 2013)

2.4 Agricultural sector for Rwanda

Literature review has been taken into consideration in order to know the current situation and knowledge gaps about Solar Water Pumping for Irrigation. Reduction of poverty level in order to eradicate hunger is one of the Sustainable Development Goals (SDGs) to be achieved through the government of Rwanda. During pre - colonial time, the main crops cultivated in Rwanda were sorghum, finger millet, taro, peas, cowpeas and bananas. Currently, there is an improvement in the agricultural sector due to the measures taken by government to increase national food. Among the policies, there is an effort to increase the income of the country and raise the standard of living as well, include crop diversification, intensification and irrigation development. During irrigation, some crops consume huge amount of water requirement and others just a small amount. In addition, Rwanda has three agriculture seasons namely, season A which starts in September of one year and ends February of the following year, season

B starts in March and ends in July of the same year and season C starts in August and ends in September of the same year (Ministry of Agriculture and Animal Resources Repub, 2009). Table below shows the types of staple food grown with its corresponding agriculture season.

Table 2.3:Agriculture seasons and crops grown (Basalike, 2015)

Season	**Crop**	**Percentage (%)**
Season A: starts in September of one year and ends February of the following year	Beans	27
	Bananas	19.7
	Cassava	12.6s
	Maize	11.9
Season B: starts in March and ends in July of the same year	Bananas	17.9
	Beans	17.4
	Cassava	15.9
	Sorghum	14.6
Season C: starts in August and ends in September of the same year	Irish potatoes	71
	Beans	14
	Vegetables	12

2.4.1 Rwanda irrigation system

Irrigation system is a way of conveying water from the source to the point of use in a controlled manner. Depending on elevation of water and availability, Rwanda has three form of irrigation. flood plain irrigation; sprinkler irrigation where water is transported to the crop area either by pumping or channels/ canals and hillside irrigation. The gravity method used for water surface situated at higher slope has a share at 57.7%. Secondly, pumping method or pressure method is used for underground water even for surface water which is at a low slope that could be taken to the place of use and its proportion is at 26.9% (Basalike, 2015). Despite, there are still challenges in agricultural water management. One of the main issues of agriculture water management is the level of efficiency in agriculture water use. For instance, both rain fed and irrigation water evaporate very fast and this brings unimproved soil water conservation. Drip irrigation known as localized irrigation which conveys directly water to the soil at low flow rate through tubes with small diameter; is recommended for water management and energy efficiency. However, the upland irrigation or modern irrigation is unknown or not yet developed in the country.

2.4.1.1 Sprinkler irrigation system

It is a system that applies irrigation water which is similar to natural rainfall. It consists of pipe lines through which water flows under pressure and delivered to the crops through sprinkler nozzles. Sprinkler system is applied and suitable for most of the crops except for those whose leaves are not compatible with prolonged water supply and those who are requiring to be prolonged in the ponding water supply for their particular stage of life (start, development, medium or end stage) (Sawa, Andreas.P, & Franken, 2002).

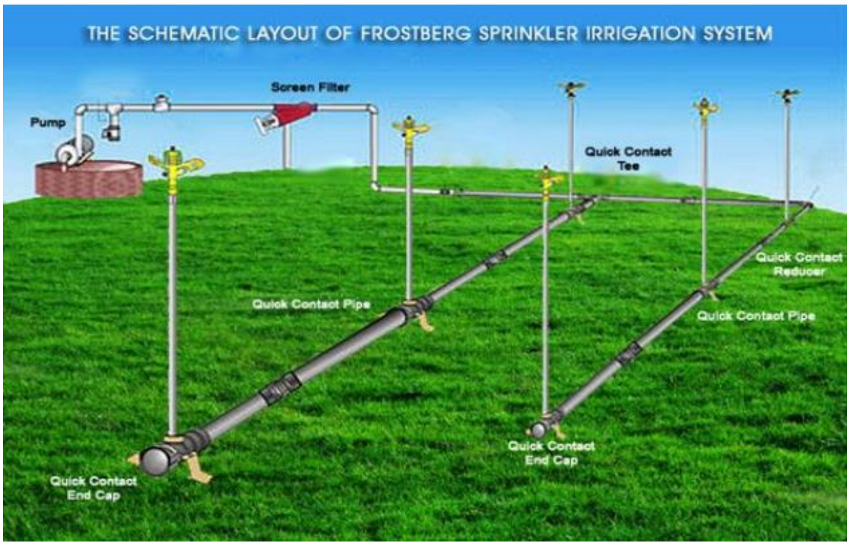


Figure 2.2: Sprinkler irrigation system (Sawa, Andreas.P, & Franken, 2002).

Comparing sprinkler to surface irrigation which is done by gravity system where water surface is situated on higher slop, sprinkler irrigation system, requires mush less work. However, it is fairly highly energy demand to lift water from the source to the point of use and requires water quality in terms of sodium and chloride. In addition, due to its design, this system is highly risky to the wind conditions (Sawa, Andreas.P, & Franken, 2002).

2.4.1.2 Drip irrigation system

Drip irrigation is one of the main categories of localized irrigation system. It is a system which uses emitters to supply water gradually to the plants or to the soil surface. Basic components of drip irrigation system basically start from the pump which filters and supplies water to the main pipe (a head of the system). Main pipe is connected to the sub main pipe whereas sub main line is directly connected to the lateral lines supplying water through attached emitters, called dripper emitters. Emitters are used to discharge water through the soil in order to regulate the determined flow rate that can be conveyed to the crop (Basalike, 2015).

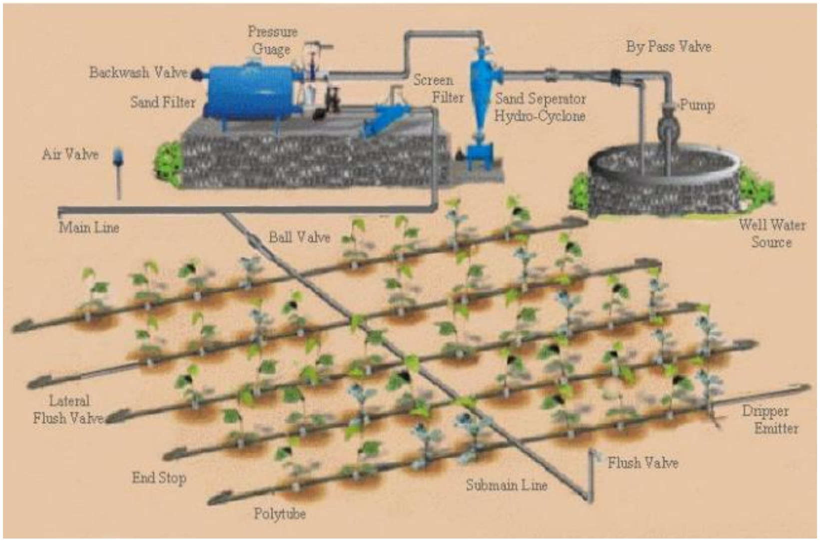


Figure 2.3: Drip irrigation system (Basalike, 2015).

Localized irrigation system is normally an efficient method compared to surface and sprinkler system. it reduces water requirement for irrigation, increases crop yields and crop quality as well. Project efficiency which is defined as the product of field conveyance efficiency, field canal efficiency and field application efficiency is high compared to other irrigation methods. Project efficiency for localized irrigation varies according to climate season. By considering no losses in the distribution system, localized irrigation method has 85%, 0.90% and 95% for hot dry, moderate, and humid climate consecutively. Its overall efficiency is on average of 90%. The installation of this system is easy, not expensive, easy to design but with skilled labours and can diminish the disease issues of crops related to the high level moisture compared to others (Sawa, Andreas.P, & Franken, 2002).

The method is suitable for shallow soil and shallow root crops as well but does not take into consideration the slop. In addition, the row crops like maize can be designed with drip irrigation because it is suitable to them. In contrast, drip irrigation requires high investment cost, their pipes can be easily blocked (clogged) and also can easily accumulate localized salinity especially in the low rainfall areas. The reason why high management maintenance is highly recommended (Sawa, Andreas.P, & Franken, 2002).

2.4.2 Irrigation efficiencies

As there is an increase in use of water source for different applications like industrials, agriculture, domestic application or environmental purposes, the use of water resources in efficient means is significantly important in order to avoid the conflict between those sectors (Sawa, Andreas.P, & Franken, 2002). From literatures, irrigation efficiency applied on a finite water source could result on a larger area with lesser leaching of nutrient and damage to the soil and this makes the system to be more environmental friendly (Sawa, Andreas.P, & Franken, 2002). The saved water from irrigation efficiency can be used in other purposes mentioned before.

2.4.3 Parameters affecting the selection of an irrigation system

The choice of irrigation system is affected by several factors, such as; water, soil and topography, climate and crop, energy, capital and labours, social aspect and policies, socio economic aspects, health aspect and environmental aspect.

Water factor takes into consideration the source of water either surface or underground, it takes into consideration also water quality, its salinity and sediment loads. For example, for drip irrigation method, water quality factor is highly significant because it can make the pipe to be easily clogged. In addition, water quantity is another factor that has to be considered based on the discharge availability and the seasonality of water supply.

Soil texture, soil depth and soil salinity affect the choice of irrigation system. For instance, there are types of soil that has high intake rate and low soil moisture storage capacity, for example coarse textured soils, can easily accumulate water but the capacity of storing the water is very low. In contrast, some others could have low intake rate with high soil moisture resistance. In addition, soil depth influences water storage capacity while soil salinity causes the leaching of water from the roots of the plant. Therefore, the choice of irrigation has to be well chosen to avoid water stress on the crops. Furthermore, topography of the site selection should be also considered as the land slop affects the irrigation choice. For a high slop land more than 5%, surface irrigation could not be considered because levelling the land is significantly costly and fertile topsoil will be removed (Basalike, 2015).

Crops type is very important factor that should also influence the choice of irrigation method. Some crops are sensitive to the means water is applied to them. For instance, there are those whose leaves can be easily fade when water is applied on them, fruits spotting, and crown rot as well through sprinkler irrigation. There are others which cannot resist in a ponding of water caused by surface irrigation. Therefore, the type of crops could influence the choice of irrigation.

Energy requirement is another important factor that has to be taken into account in choosing the irrigation method. Studies that have been done in Washington States showed that, surface, drip and sprinkler irrigation energy requirement increases respectively. This study has taken into consideration the energy requirement including manufacturing, transport and installation of irrigation systems. However, as surface irrigation requires huge amount of water due to its lower irrigation efficiency, implies that more energy has to be supplied if pumping water is the case. Hence, minimum energy is preferable for a suitable design on both economic and environment point of view.

2.5 Crop water and irrigation requirements

Crop water requirements (CWR) is defined as the amount of water required to compensate the water loss through evapotranspiration of the crop (ETc) for cell construction and transpiration. The values of CWR and ETc are identical because what the crop losses is what it requires to consume. Irrigation requirement (IR) refers to the amount of water supplied to the crop through irrigation to ensure that the crops receive full amount of water in order to grown up. Sometimes, the crop can be either supplied only by irrigation source or can receive some of water from other sources such as rainfall, water stored in the ground, etc. This means that, for the first case, irrigation will always be greater than or at least equal to crop water requirement. While for the second case, irrigation water could be less than water requirement for the crops. The Net Irrigation Requirement (NIR) is obtained without considering water losses when applying water on the crop. When it constitutes the losses it is called Gross Irrigation Requirement (GIR).

Crop water and irrigation water requirements are calculated using CROPWATT software. This tool enables to calculate CWR and IR of different crops considering the planting date, crop coefficient factor at different growing stages, crop rooting depth at different stages, the acceptable level of soil moisture and the yield response factor. The calculation done with this tool gives water requirement in decades (ten days for each decade) and each month assumed to have thirty days.

3 ENERGY DEMAND AND RESOURCE ASSESSMENT

Both energy demand and resource assessment are the most important in the energy planning system and are covered in this chapter.

3.1 Hydropower resource

Rwanda is a mountainous country with the altitude ranging betwee 900 meters and 1707meters, and annual rainfall of 1250m (MIDIMAR, 2015). Five percent of the national territory(equivalent of 1352.6 square kilometer) is occupied by rivers and lakes (Zhou, Habiyakare, & Nianqing, 2015). Hydropower is the most exploited resource for electricity generation (EWSA, 2014).

Hydropower has generated the bulk of electricity in Rwanda since 1960s. Due to the suitable topography of Rwanda, hydro is considered to be exploited for medium to high-head, pico and micro-hydro run-of-river systems. Overall technically, hydropower potential has been estimated to be on average of 400MW and this varies at different studies made at different times. The study that has been conducted by Rwandan Hydropower Atlas found that the majority of potentially feasible sites would be rated between 50KW and 1MW in capacity. The assessment that has been conducted by the African Development Bank in 2013 found Rwanda's hydro power domestic at 313 MW, broken down into 130 MW of domestic and 183 MW of regional hydro resources. Furthermore, 193 sites have been identified for pico hydro with capacity which is below than 50KW. The installed hydro power capacity by 2014 was 73.69MW according to the International Renewable Energy agency.

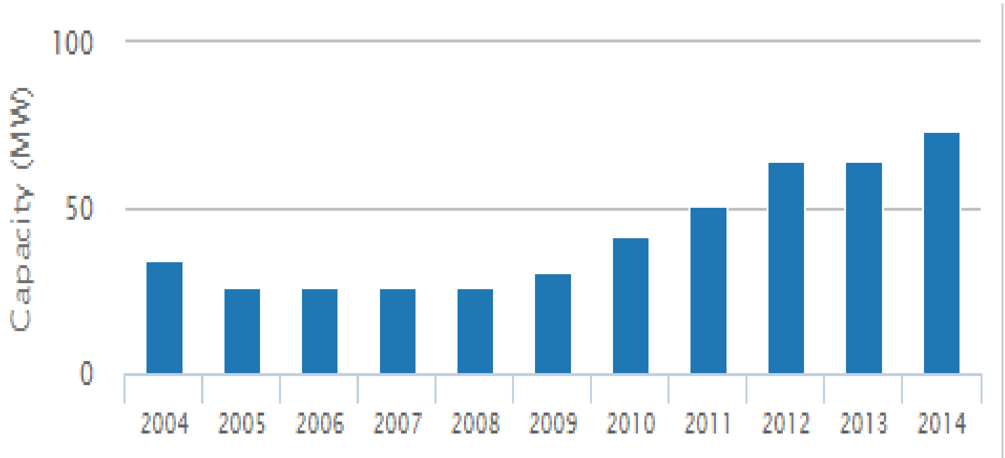
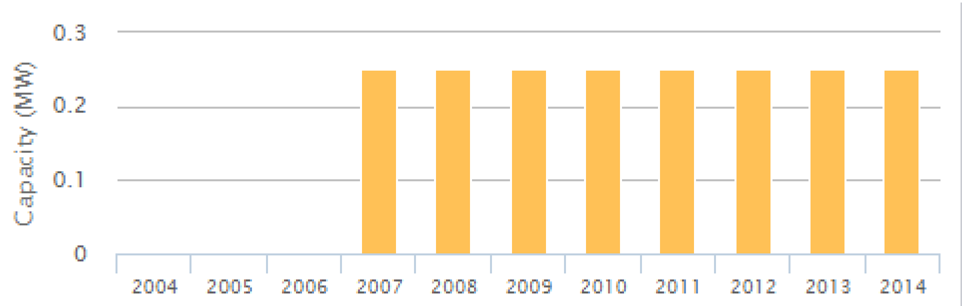


Figure 3.1:Installed hydropower capacity (International Renewable Energy agency, 2016)

3.2 Solar energy

Rwanda has significant solar radiation and solar resources potential which can be harnessed for energy production. This potential has been assessed by U.S. National Air and Space Agency (NASA) as well as the University of Rwanda. In addition, with the partnership with MININFRA under Meteorology agency in 2007, monthly averaged global solar radiation has been estimated between 4.3 and 5.2 kWh per m^2 per day across the country. Therefore, due to its potential, solar technology could be used to electrify remote rural areas in Rwanda for stand – alone scale or even for micro grid scale as well.



c

Figure 3.2: Installed solar power capacity (International Renewable Energy agency, 2016).

The data obtained from IRENA shows that installed solar power capacity in Rwanda is still low, and the potential remains constant over a period of years. Currently, there is high interest from private sector on grid solar power development. Rwanda has the first utility solar PV system scale (called 8.5MW solar power plant), located in the Eastern province, and is a grid connected and is also the first commercial solar field in East Africa. The installed power capacity is around 8.5MW, it contributes to the national electricity production by 6%. However, due to its intermittent, the harmonization of solar power to the grid is limited by the technical capacity of the grid.

3.3 Bioenergy resource

Biomass is the one of energy resources with high potential in Rwanda where is used in form of charcoal and wood fuel for cooking in households and for some industries. The use of this technology produces emissions to the environment and harmful for the health. The government is putting more effort to reduce the percentage of household which are using traditional method. In addition, the use of biomass also causes the deforestation. Furthermore, the production of biogas, which is produced from biomass resources, from agricultural, human, and municipal waste is still low. However, due to government subsidy (50%), 3700 digesters have been disseminated to institutions (schools, households and prisons) through local credit in order to improve people's health. In Addition, the government is willing by 2018 to install 12000 biogas digesters (Ministry of Infrastructure, 2014).

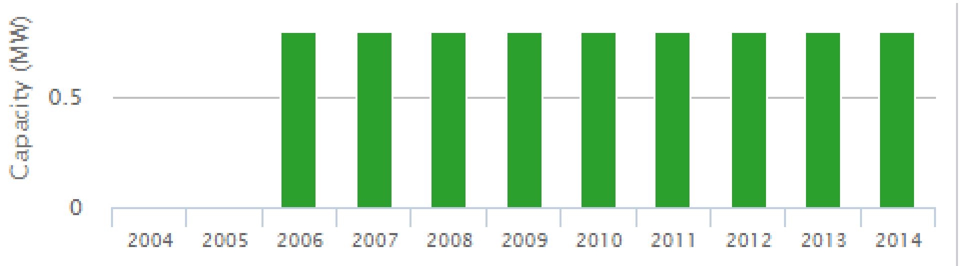


Figure 3.3: Installed bioenergy capacity (International Renewable Energy agency, 2016)

3.4 Wind resource

Resource potential for wind energy production in Rwanda is low due to its geographical coordinates. Based on the data recorded of wind speed and climate data, most of the country has not sufficient wind speed for energy production. However, based on the modelling analysis of Gisenyi meteorological site, wind recorded measurement located in western province could produce electricity. Therefore, feasibility assessment on wind has to be done for more viable wind potential in Rwanda.

3.5 Supply alternatives analysis

The term alternative energy encompasses a variety of power generation sources. Generally, it refers to electrical power derived from renewable sources and fuel fossil sources. The most common forms of alternative energy available today are solar power, diesel power and on grid electricity power.

The use of renewable energy sources is considerable as they have many benefits towards the users. From the environmental point of view, renewable resources are low-carbon emitting unlike fossil fuel which releases a lot of carbon dioxide to the environment.

For the user, consuming renewable sources in electricity generation may reduce the frequent power cuts as the power generated from renewable sources can be stored in battery bank to provide backup power if utility power fails.

Today, since people can sell the energy generated to the national grid, going for renewable energy results in lower monthly electric bills, and also it can generate income for the owner with a large renewable energy system.

Countries with no fossil fuel always suffer from the unexpected changes in oil prices. This has a negative impact on the country's economy as the energy sector is the most affected by all of those changes. There are many criteria to be considered while choosing which energy source is reliable and beneficial in order to reach a sustainable development.

Table 3.1: Comparison criteria

Criteria	**Diesel Generator**	**Solar PV**	On grid
System type	- Portable	- Portable	- No portable
Capital cost	- Low initial cost,	- High initial cost,	Very high initial cost
O&M cost	- Periodic maintenance	- Virtually free for lifetime.	
Optimal use	- Larger loads - Produce constant energy regardless of load consumption.	- Small loads - Store extra energy and supply it when required.	Large loads
Emission	- Harmful for to the environment	- Environmental friendly.	-
Cost per KWh	- Fluctuates with fuel prices	- Free after a given period of time.	-
Reliability	- Lifetime is shortened by the environment	- Is always ava-ilable during day time and has unlimited potential.	-
Set up time	- Refuelled before being used	- Starts generating when the sun is shinning	It cannot work when there is no resource
Off time	- Lies idle when not being used	- Continue to charge as long as exposed to sunlight.	Lies idle when not being used
Life time	8-10 years	Up to 25 years	

Table 3.2:Criteria weighting

Criteria	PV	Diesel	On grid
Capital cost	High	Low	Very high
O&M	Low	High	High
Optimal use	Low	High	High
Emission	Low	High	High
Cost per KWh	Medium – after a given period of time	High	Fair
Return on Investment	High		
Reliability	High	Low	Low
Life time	High	Low	High

Regarding through all the criteria weights, PV will be a good and reliable choice to go through for the coming years due to the fact that it will help in savings and in environmental protection.

3.6 Energy usage trend scenario across different demand end users

From the strategic framework for Rwanda's energy sector, 70% is the target willing by the government by 2017/2018 in order to improve the economic development and standards of living. Whilst, 100% of having access to electricity is targeted by 2020 vision.

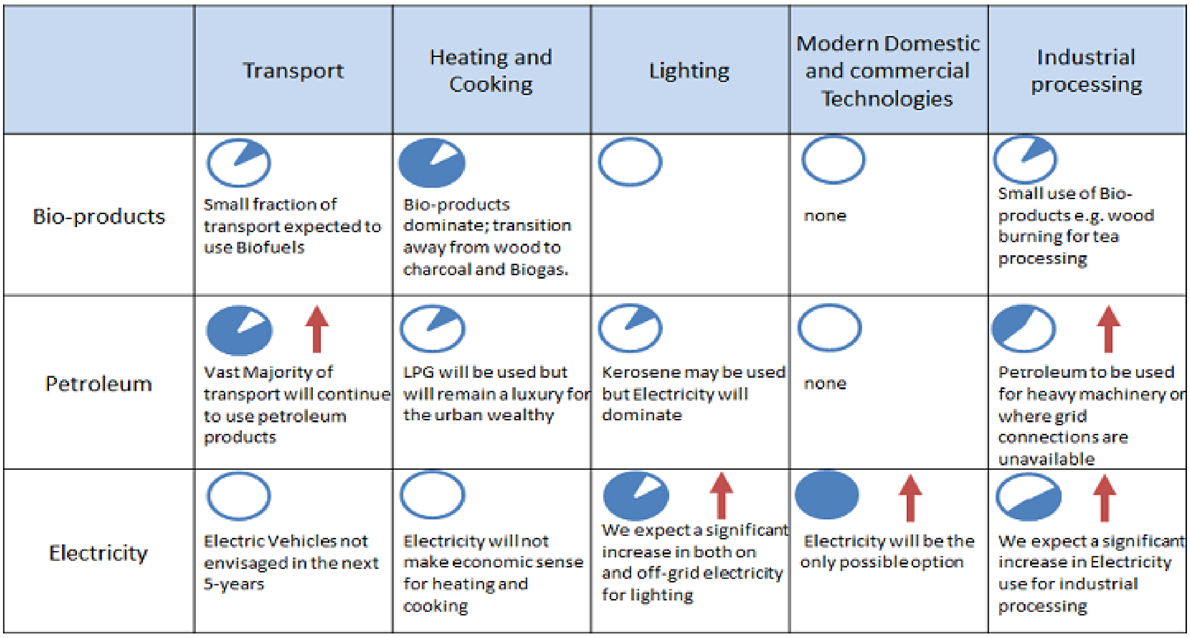


Figure 3.4:Illustrative view of energy use patterns and transitions from different sources by 2018 (Ministry of Infrastructure, 2015)

Note: A red arrow shows just a significant rise of a specific type of energy source for a given activity

3.7 Energy Efficiency and Demand-Side Management

To achieve the target of energy usage transition (increase in electricity usage for example), Energy efficiency (EE), energy conservation, and demand-side management (DSM) activities, are of strong importance in the country because of limitation of resources. Promoting the demand side management is the key factor of contributing indirectly to reduce the supply requirement in order to decrease the long run cost of power (Ministry of Infrastructure, 2015).

These key driving factors are reached by implementing some measures such as adopting new low, regulations and codes through agencies to insure energy efficiency usage in public institutions, households, and commercial businesses. This is done for example by improving smart building and building materials. To change the electricity tariff methodology in order to improve efficiency; establish a demand-side management program within the utility (REG), encourage energy audits among commercial and industrial end-users; promote and remove barriers to implementing priority efficient lighting initiatives; develop and adopt an East African Community (EAC) wide energy standards and labelling scheme for common household appliances; institutionalize "green" public procurement guidelines and strategies focused on equipment with a high energy footprint as well. In addition, an increase in energy efficiency through demand side management is expected to rise by 10% and an addition of 8% from the reduction of grid energy losses by 2018 (Ministry of Infrastructure, 2015).

3.8 Primary objectives of the Rural Electrification Strategy

The primary objective of rural electrification strategy in Rwanda is to ensure the access to electricity at 70% of population by 2018 and 100% of Rwandans by 2020 vision. This will be done by implementing new systems from a range of standalone solar systems, mini off - grids and increasing the availability of grid connection across the country (Ministry of Infrastructure, 2014).

Each household will be encouraged to have access to the affordable form of electricity system based on their income level. Therefore, to promote the use of diversities technologies.

Over the last seven years, both extension of national distribution system and providing to consumers the access to grid electricity have been prioritized across the country. The trend of historical connection rate is shown in the figure below.

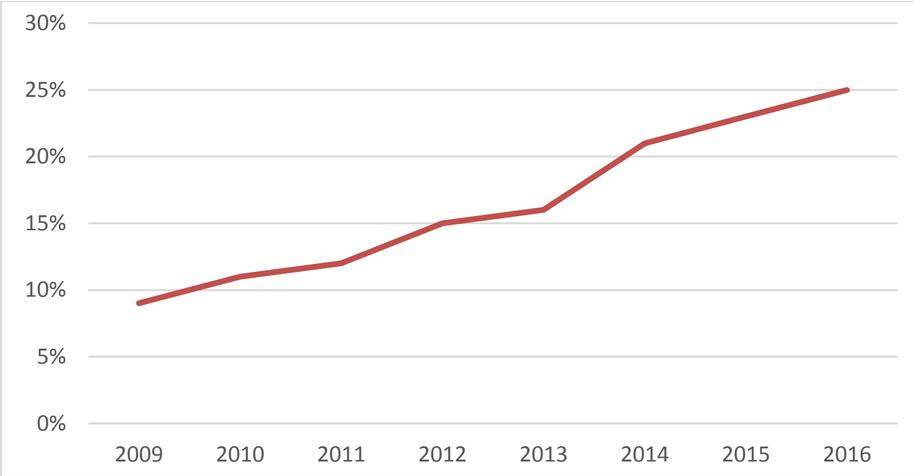


Figure 3.5: Percentage of the population with grid access (Ministry of Infrastructure, 2014).

From 2012 to 2016 the households access to electricity has increased by 24%. In other words, electricity access increased from 364,000 households in June 2012 to 590,000 households by June 2016 (Ministry of Infrastructure, 2014).

Based on the percentages of consumers connected under EARP by consumption levels, most a half of consumers are currently using less than 20KWh per month.

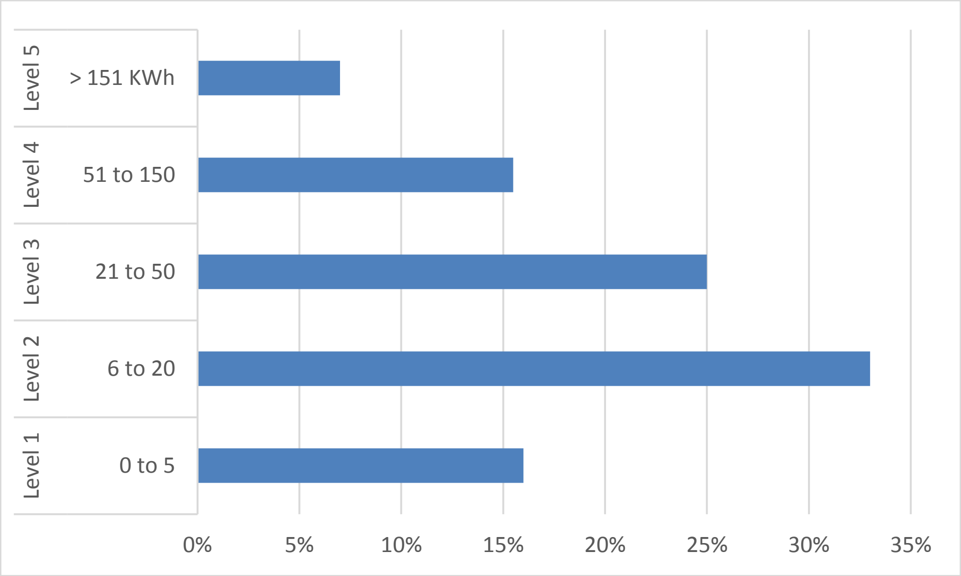


Figure 3.6: Levels of household energy consumption from solar system (Ministry of Infrastructure, 2014).

From figure above, it can be seen that the use of electricity in the whole country is still low and therefore, to meet the consumer needs, a more strategy approach is required and rural electrification approach could be of help. The significance meaning of levels from 1 to 5 is the level of energy usage depending on the loads. For example, for the level 1, the energy usage is just for household lighting, radio and phone charging whine for the level 2 is level 1 including basic appliances (TV, fan). The level 3 is the combination of level 2 and medium appliances such as refrigeration. Level 4 covers level 3 plus high power appliances like pumping. Finally, level 5 takes into consideration high power for commercial and industrial energy uses. (Ministry of Infrastructure, 2014).

3.9 The Key Challenges Faced by the Stand-Alone Solar Market

Some key challenges that affect the implementation of stand - alone solar system are affordability of the systems for consumers. Lack of awareness of the technology to consumers and into finance are also one of the factors that stand alone solar system is facing (Ministry of Infrastructure, 2014).

4 ENERGY RELATED AND SOCIO ECONOMIC DATA COLLECTION

To be able to provide a suitable and feasible system planning, energy related is discussed. In this section, the required parameter for the system are covered such as climate data, the availability of water resources for irrigation. In addition, social economic data are discussed where it takes into consideration the percentage of food insecure for different regions to be able to select the case study.

4.1 Province Selection

4.1.1 Climate data

In selecting a suitable area, climate condition is taken into consideration. Climate data are taken from reliable source which Rwanda meteorological for irrigation water requirements and climate condition for a solar PV system as well. To assess water requirement for irrigation, temperature, precipitation and evapotranspiration is necessary and is analysed in this chapter. In addition, the potential of solar energy has been used to select the site also whereby the site with high potential has been taken into consideration.

4.1.1.1 Solar potential

Rwanda is located in East central Africa in the south of the equator, approximately two degrees. Its high altitude helps to keep the moderate temperature throughout the year with an agreeable tropical climate that's not too hot or too cold (Dixon, n.d.).

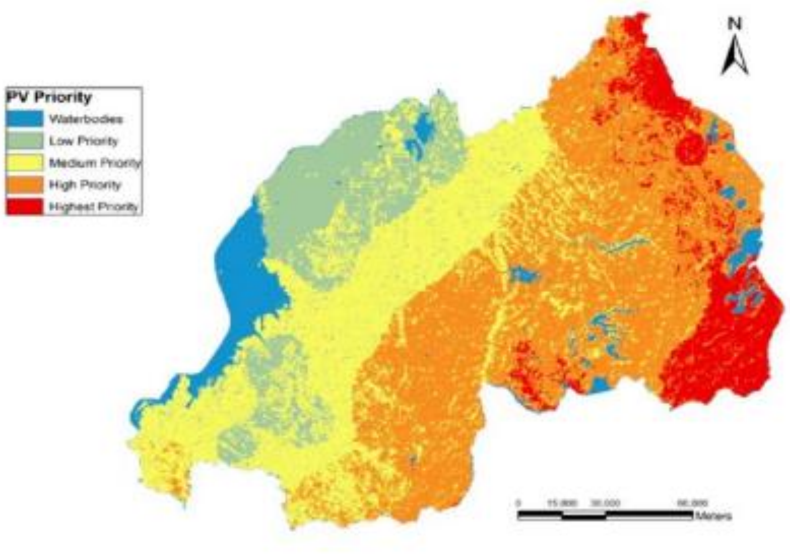


Figure 4.1:Distribution of solar potential (Ministry of Infrastructure, 2014).

It has enough solar irradiation intensity around 5KWh/m^2 per day with a peak sun of 5 hours. It can be seen from the figure above that the potential across the country is localised in the eastern province. Based on the solar availability and its potential, this region can be used for PV system to produce electricity.

4.1.1.2 Temperature

Due to the high altitude 1463m of Rwanda, the temperature and precipitation are more moderate compared to another humid and hot countries located in the same equatorial region. However, their season variation is the same throughout the year.

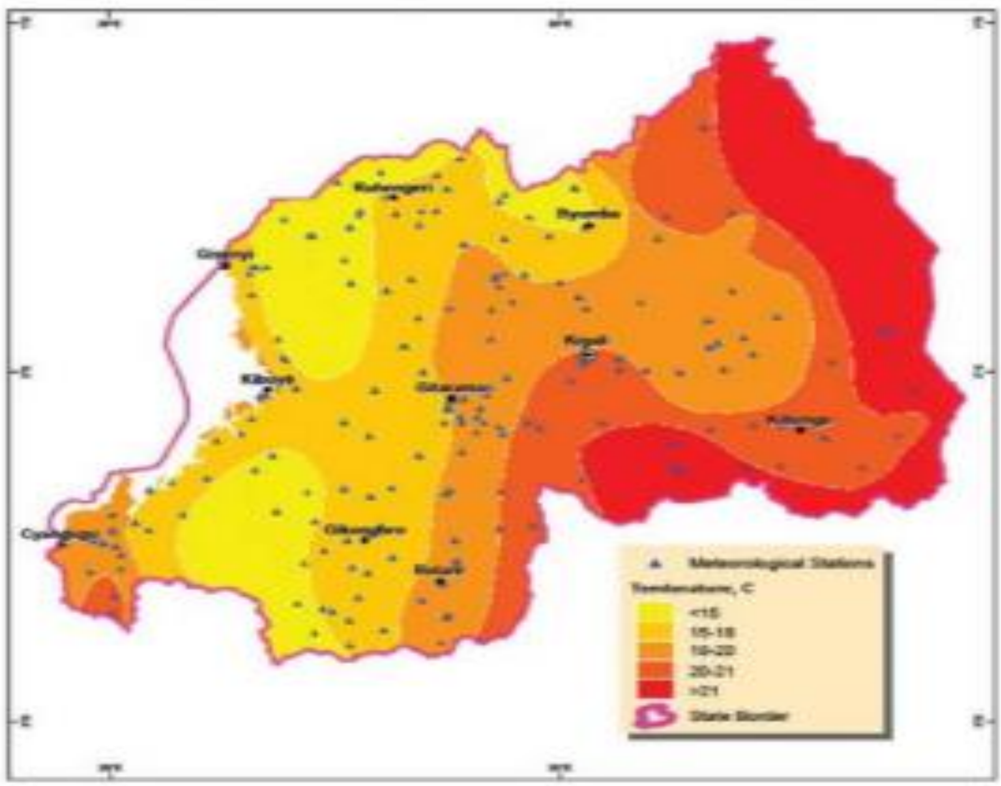


Figure 4.2: Annual average temperature (Betalla & Andreu, 2015).

The lowest temperature in the country is in the highland region with temperature ranging between 15°C and 17°C whereas in the low height regions (Eastern province) the temperature is higher and can be even reach over 30°C.

4.1.1.3 Precipitation

Rainfall is a parameter that considered as the main source of the agriculture. It has significance important in Rwandan economy and food security as well. For instance, 90% of population is based on agriculture and normally, Rwanda's agriculture is rain fed. The country receives average annual precipitation of 1200m. Rainfall distribution ranges as low as from 600m in Eastern province to 2000m in high altitude such as Northern and Western regions. The table below shows in numbers climate data of different altitude zones.

Table 4.1: Climate data of different altitude zones (UNEP, 2009)

Parameters	High altitude zone (1800 -3000)	Medium altitude (central plateau) zone (1500 – 1800m)	Low Altitude (Eastern plateau) (1250 -1400m)
Rainfall (mm)	1300-2000	1200-1400	600-1400
Temperature (°C)	16-17	18-21	20-24
Evapotranspiration (mm)	1000-1300	1300-1400	1400-1700
Relative humidity (%)	80-90	70-80	50-70

The fact that, the precipitation is unequally distributed in time and space, there is influence of utilisation and availability in different regions- and season as well. For example, the month of April has huge amount of precipitation compared to the month of August. Or, the amount of rainfall in the West is completely different to the amount of East region. Table below shows the precipitation distribution in the country by seasons.

Table 4.2: Precipitation distribution in the country (Bugesera District, 2013)

Seasons	period
Long dry season	June to mid-September
Long rainy season	March to May
Short dry season	December to February
Short rainy season	October to November

Due to the climate change, rainfall is changing intermittent and unpredictable. This implies that agriculture can no longer rely on the precipitation alone. Therefore, irrigation could be an important alternative measure. Effective precipitation is the amount of rainfall that can be added and stored in the soil and to be used by the crop. In contrast, the deep percolated and run off water cannot be used by the plant. In other words, it is not part of the effective precipitation and is not even used for growing crops (Betalla & Andreu, 2015).

Water resources

Water is a natural resource that can contribute to any country's development in terms of economy, social and culture. As 90% Rwandan population is dependent on agriculture, this water resource has a significance importance on the agriculture. Rwanda is a country that has dense hydrological network encompasses of a huge number of small rivers, stream and wetland that flows into lakes and other reservoirs (Kamanza, 2011).

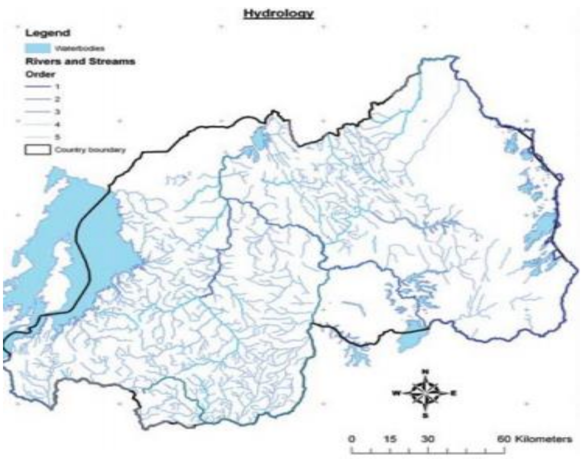


Figure 4.3: Hydrography (lakes and rivers) (The goverment of Rwanda & Ministry of Agriculture and Animal Resourcess, 2013).

Even though, water resource is abundant in the country, the distribution of water is not the same in the whole regions. For instance, western region presents a big number of water resource compared to the Eastern area because the topography of West is the hillside and allow rainfall water to quickly flow to the valleys bottom, marshlands, rivers or lakes whereas East is lowland as it can be seen in the figure above. Hence, Western region can support agriculture even during dry season but for Eastern region, irrigation is necessary. Table below shows how water resources is distributed across the country.

Table 4.3: Water distribution in Rwanda (The goverment of Rwanda & Ministry of Agriculture and Animal Resourcess, 2013)

Water Resources	Area (ha)	Share of total
Runoff for small reservoir	125.627	21.0%
Runoff for dams	31.204	5.2%
Direct river and flood water	80.974	13.6%
Lakes water resources	100.153	16.8%
Groundwater resources	36.434	6.1%
Marshlands	222.418	37.3%

Slop of the land is another important factor to be considered by choosing the area of the site for the case study. As the selected crops do not require large slops for their growing and being well comfortable for the flat land, the non - slop land or small tilt land area is preferable.

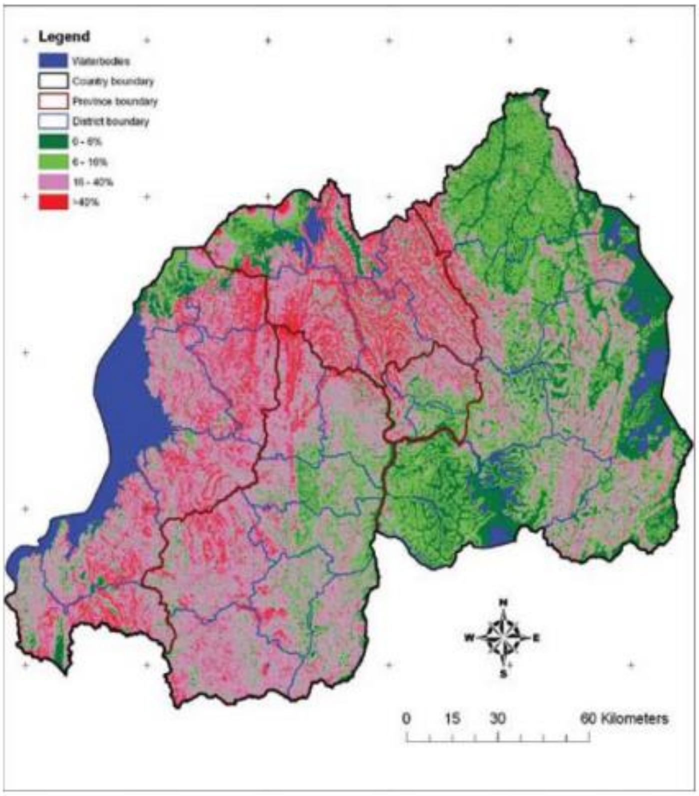


Figure 4.4: Rwanda slop percentage (The goverment of Rwanda & Ministry of Agriculture and Animal Resourcess, 2013).

The suitable slop land can be found in most of the regions of Eastern province of the country as it can be seen from figure above. From North to the South of Eastern province, the slop is appropriate for crop growing.

4.2 District Selection

The design of Photovoltaic system requires the collection and analysis of different data in order to select a suitable area to be able to maximize Photovoltaic yield of electrifying remote rural area. Once the appropriate province has been chosen, which is Eastern province, it is necessary to select the suitable site in the Eastern province which is composed by seven districts: Nyagatare, Bugesera, Kayonza, Rwamagana, Gatsibo, Kirehe and Ngoma.

Within the country, the number of meteorological weather station is still low. There are some stations across the country without enough measurement data due to the lack of equipment. For instance, in this study, Kigali station is used because it is near to the Eastern region and has the data for many years.

4.2.1 Precipitation

Bugesera district is one of the dry area which has not enough precipitation due to its geographical topography. From the figure below, it is obvious that the area has a high frequency of rainfall deficit. Therefore, evapotranspiration in the region is very high.

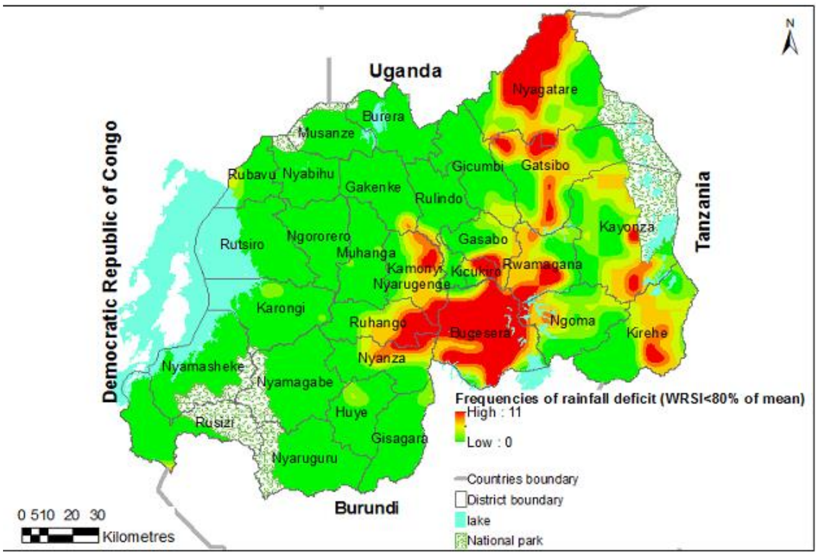


Figure 4.5: Frequencies of rainfall deficit in Rwandan regions (The goverment of Rwanda & Ministry of Agriculture and Animal Resourcess, 2013)

4.2.2 Evapotranspiration

To be able to select the district for the study, Evapotranspiration parameter has been taken into consideration as well. The chosen area should have the highest value in ETo so that the irrigation effective can be significant. The data provided from CROPWAT. 8 tool has been used in the analysis.

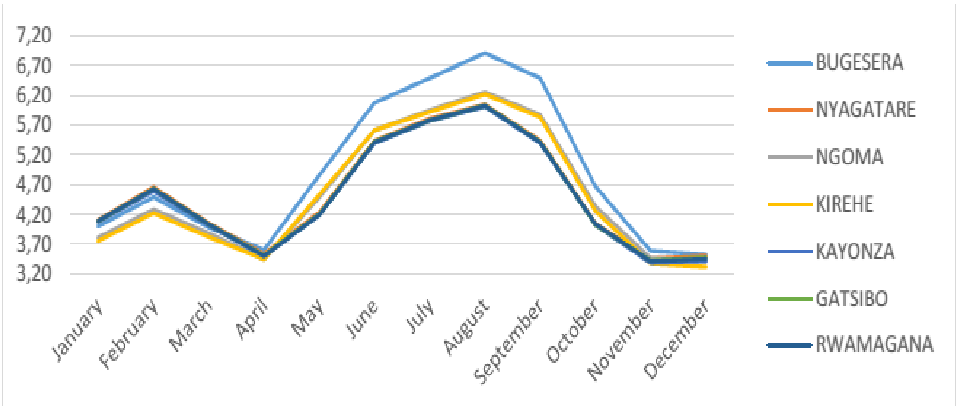


Figure 4.6: Evapotranspiration ETo (mm/day) (Betalla & Andreu, 2015).

Comparing reference evapotranspiration (ETo) of Eastern districts, the trend of ETo is quite similar however, Bugesera is recognised as the one with the highest from April to the end of the year as it can be seen from the figure above. In addition, the district is facing a problem of low agriculture productivity and the irrigation of hillside is still low.

4.2.3 Percentage of food insecure

Poverty is an indicator taken into consideration also in selecting the studied area. The main factor driving food insecurity and water scarcity in Bugesera is the drought caused by the climate change.

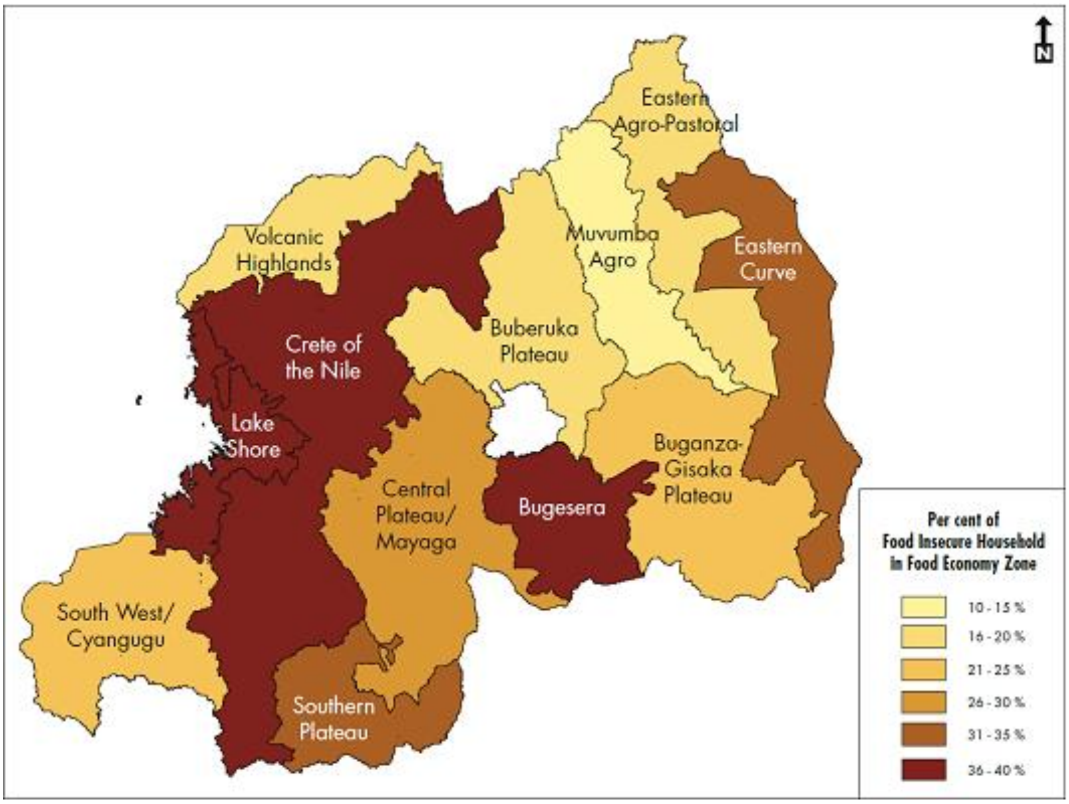


Figure 4.7: Per cent of food insecure household in food economy zone (Betalla & Andreu, 2015).

In particular, from 1999 to 2002 There was a long and continuous drought which resulted in even death of humans and livestock, as vegetation was washed-out, and from that time, the entire region depended on external food handouts. Therefore, food scarcity effected by the droughts were felt beyond the region.

To accelerate the process of socio economic and cultural development, EARP has targeted mostly in rural electrification areas. This method of accelerating rural electrification areas aims to provide electricity but also to reduce disparities between urban and rural population. This is done by generating off farms new jobs, female empowerment, income earning opportunities, and increasing productivity in agriculture.

4.2.4 Energy access and availability in Bugesera district

The energy sector is one of the most influential sectors that shape the development of Bugesera. The total Rwanda's energy consumption is 502,053 MWh. The share for Bugesera is being accessed by only 4.3% of total electricity household, whereas the rest consumes different energy shown in table 7.

Table 4.4: Main source of lighting and percentage of consumers (National Institute of Statistics of Rwanda, EICV3 District Profile, 2011)

Electricity distributors	Oil lamp	Firewood	Candle	Lantern	Battery	Solar panel	Others	Total	Total number of households
4.3%	13.8%	5.8%	7.4%	31.9%	31.9%	0.3%	4.6%	100%	80,000

Bugesera district has been taken as the studies area due to the fact that, energy cost is high and Bugesera people has a low financial accessibility, thus still a limited access to socio economic infrastructure. Moreover, there are still facing even low investment of private sectors. In that area, most of the significant rural centres are far from the electricity grid and due to the fact that the financial income is still low, it will be difficult to provide for them the requirement energy to meet the demand. In addition to that, it is even still costly for the investors and private sectors. This challenge of inadequate of access to energy, has negative impact to rural population. Therefore, having access to energy could stimulate basic activities such as the creation of small jobs like saloons, cottage factories, welding, telephone repair and charging, as well as carpentry workshops in order to improve the lifestyle.

5 STUDY AREA DESCRIPTION

In this section, site survey has been covered where it takes into consideration the household and agriculture energy usage. In addition, the results from the survey is discussed as well.

5.1 Site Survey

The survey has been conducted in Mareba sector, Bugesera district located in the Eastern Province of Rwanda. The sector covers 58.3Km2 and its population is at 22,377 living in 5344 households. The population density is on average of 400/km^2. Mareba sector is composed of 5 cells and 52 cluster rural settlement (imidugudu). The main activity for Mareba population is agriculture and its economic activities are still low compared to other sectors like Mwogo sector due to the aforementioned factors.

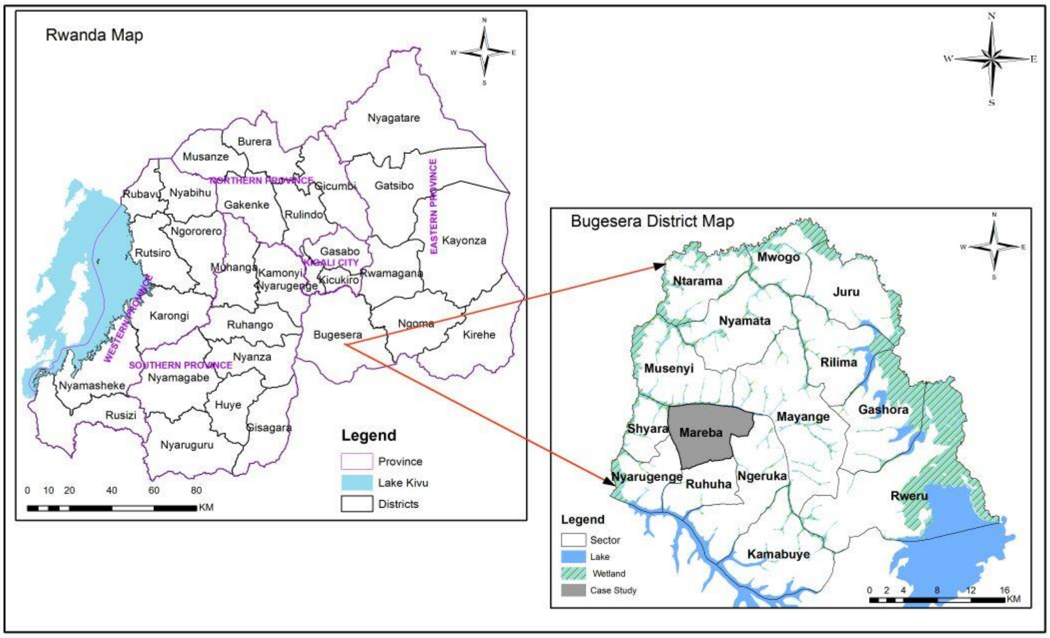


Figure 5.1: Map of the study area

To be able to meet the demand of Mareba sector, a survey has been conducted in different activity sectors. Activities to be considered including agriculture sector which will be conducted in more than one cooperatives, collection of rural households' electrical appliances and their usage hours in a day, and the communal services such as small shops, saloon. For instance, the questionnaires have been distributed in order to have significant image on the site. The raised questions have been addressed to the cooperatives and households.

The interviews with the households and cooperatives were based on the survey that can be found in appendix A and B in details: Survey form for Households and for cooperative agriculture energy use. The questions were asked directly to the consumers. The answers were registered by the interviewer. A total of significance number of consumers answered the survey. The questions are meant to give a picture of what lies behind the consumption of electricity in each household. The questionnaire also tried to cover like background information, the quality of the electrical distribution, and the consumption of other energy sources. The accuracy of the answers varies depending on who answered the questions and how well informed the person was about the situation of the household. Head of household, wife of head of households, workers, children and cooperative members were sometimes the persons who answered.

5.2 Survey Results and Observations

5.2.1 Household energy usage

Generally, the survey was based on three different groups: residential, commercial and agricultural cooperatives. From the survey, Mareba sector is facing a problem of access to electricity. Most of the population does not light their homes even though the population is staying in a cluster rural settlements (imidugudu).

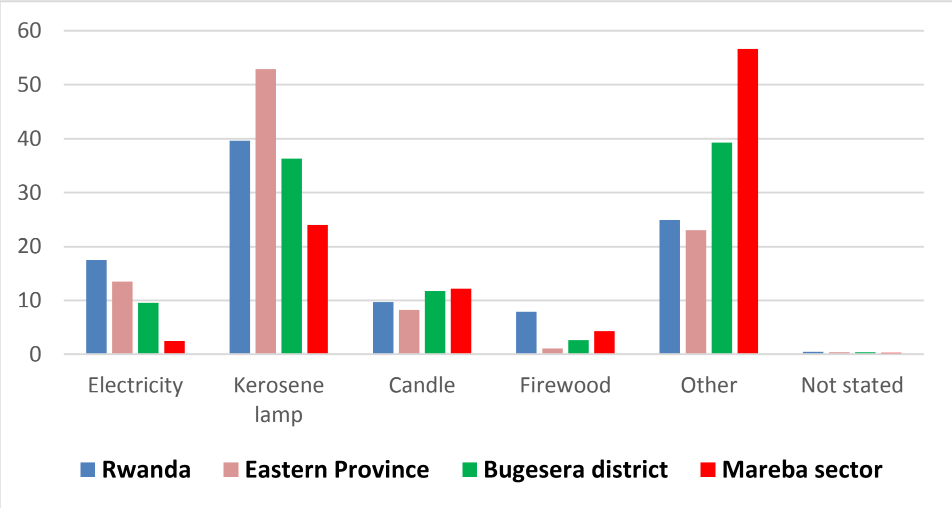


Figure 5.2: Main source of energy for lighting (Ministry of Finance and Economic Planning & National Institute of Statistics of Rwanda, 2015)

Previously, most of the population used kerosene from lighting their houses, but as it is not health and it is even very expensive comparing to their economy, there is a shift from kerosene to others sources as it can be seen in the figure above.

Apart from lighting, energy for cooking has been investigated and the results is given in the following figure.

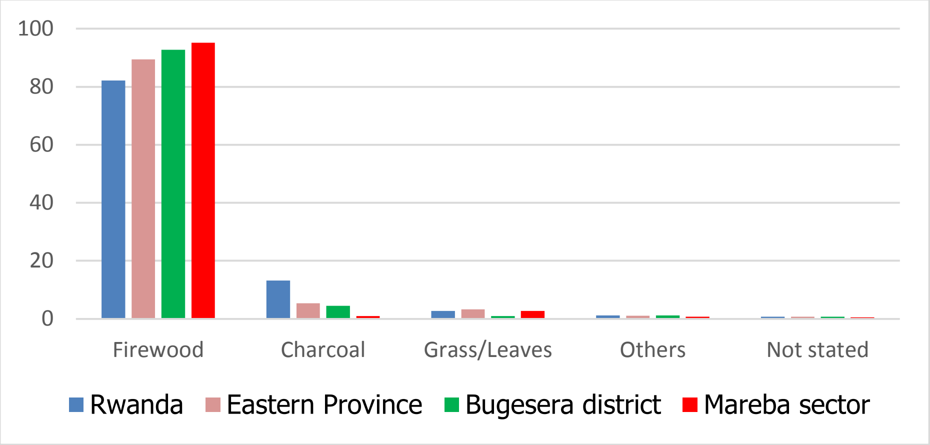


Figure 5.3: Main source of energy for cooking (Ministry of Finance and Economic Planning & National Institute of Statistics of Rwanda, 2015)

As in the whole country, the main source used for cooking is wood, in Mareba sector also is the same case. Using electricity is not used in cooking in Mareba village. The reason is because that the electricity is not yet connected there and even is quite expensive for those who have it. In addition, firewood is the most used, however, it is not easily found and even affordable.

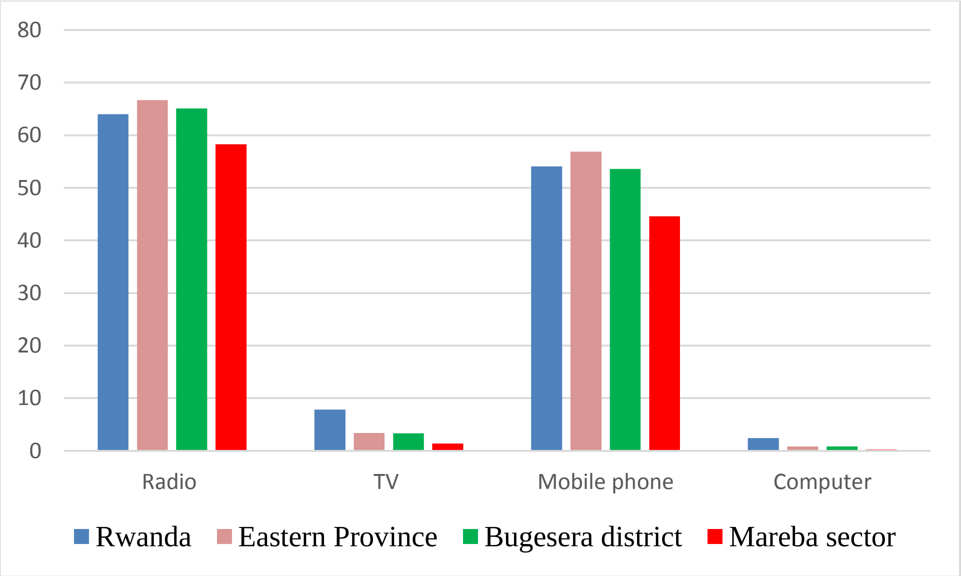


Figure 5.4: Electrical equipment assets (Ministry of Finance and Economic Planning & National Institute of Statistics of Rwanda, 2015)

Most of appliances used in communication, in Mareba villages are radio and mobile phones. This is because of the lack of electricity. For radio, it is just small dry batteries used. Phones are charged by money to those who have electricity. However, people from Mareba sector are willing to buy different equipment once the electricity is available. For example, radio, fridge, television, milling machine, iron, computer, electric scissors, etc.

5.2.2 Agricultural usage of energy

Mareba is a predominantly rural area, and the main occupation of the population is subsistence agriculture. Nevertheless, the production is not sufficient due to the climate change. Previously, some crops were abundant in the region like suit potatoes which were used to be cheap to everyone even to the poor people. However, this crop is only affordable by the rich people were there are no longer grown in the region because of the increased soil water stress and have become locally unaffordable since they are 'imported' from outside Bugesera district.

Agriculture in the region is mostly rain fed and the farming activities follow the rainfall pattern. One of the cooperative in the site called IZMGMA, has a serious problem of having only one planting season due to the lack of rainfall in the second season. Their types of crops are only maize, beans, and rice and sometimes soybeans. Rice is the most crop cultivated by that cooperative. Even though this cooperative has a marshland field, unfortunately, it is facing water scarcity for their crops. The person interviewed even said that, it is not as such marshland because there is not enough water, there is a need for irrigation. In addition, most of the cooperative members are aware that there is a positive impact on agriculture and livestock productivity.

The area of crop field is quite big, where it measures around 25ha. Regarding on the source of water that can be used in irrigation, it has been found that the distance from the source to the place of use is in between of 350m to 400m. This cooperative is only for agriculture not for livestock.

Majority of the farmers in the site are in the cooperatives for their daily subsistence and also to contribute to the government income.

One of the farmers apart from cooperatives has an advanced agriculture compared to the existing cooperatives. The main crops for that private farmer are onions, tomatoes, green peppers, eggplants and sometimes maize because of government program.

The surface area for the crops is on almost five hectares (4.5ha). both eggplants and green peppers are irrigated three times a week and other crops are for twice a week (both onions and tomatoes). For this farmer the source of water is close to the field, in 200m to the place of use. However, it is not sufficient because the water is sharing with other farmers.

To increase the productivity or to have more than one planting season, the cooperative requires irrigation in the dry season. However, there is no possibility to afford for the technology. The cooperative does not use electricity in their crop production, but, it is using it in the offices for their logistic computer. The number of livestock in this region is not significant for big production comparing to the place of Umutara district where even one farmer could have more than hundred cows.

Apart from IZMGMA cooperative which has only one planting season because there is no possibility of affording irrigation system, this second interviewed farmer has adopted the system for irrigation and all the crops are planted two seasons. For tomatoes, green peppers and eggplants are both for season A and C. On the other hand, onions are only one crop for one season which is season C because of maize plantation. In addition, all these crops are planted in a permutation pattern.

The farmer was using previously manual irrigation, but currently, it is pressure irrigation which marks big difference. However, even if, it is pressure irrigation, there still much work to do. The distribution of water onto the crops is done by man power instead of drip or sprinkler irrigation. This means that, there are two diesel pumps, one for pumping water from the source to be stored in the ground tank and the other one for pushing water to the field to be distributed by the man power onto the crops.

By using irrigation, there are significant positive impacts on the system said by the owner of the farmer. For instance, there is higher productivity (higher yields), more land to cropped, multi crops per year, new and more marketable products. In addition, there are also better quality production as well as better natural resource management.

In conclusion, having the amount of water requirement for irrigation on the selected crops and knowing the electrical appliances used by the population, different design scenarios are presented in the following chapter.

6 SYSTEM DESIGN AND ANALYSIS

In order to choose suitable energy system plan for Mareba sector, different scenarios are analysed. Firstly, system scenario for providing electricity to pump water in order to improve food production is analysed. For instance, it considers crops water requirement for irrigation and total dynamic head of water source. Secondary, a scenario system based on water requirement for irrigation with drinking water for cattle is designed. Finally, a scenario considering irrigation, drinking water for livestock and community appliances as well (shops, salons, households, health centres, nine years' school) is taken into consideration. Note that, to be able to select the feasible system, NPV, IRR and LCOE indicators are used of each system.

6.1 Scenario 1: Solar Photovoltaic Water Pumping System (SPVWPs) for Irrigation

6.1.1 Crops and water requirement

To know the energy required by the pump, water needed for crops is estimated using CROPWATT 8. Software. Rwanda 's agriculture is the backbone of its economy, and the majority of households are mainly involved in agriculture of some crops and livestock for their subsistence and production activities. Agriculture sector contributes at 35% to the GDP and provide the employment at 80% to the labour force. Among the staple food as mentioned early are banana, maize, cassava, beans, sweet potatoes.

As Rwanda is among with the highest density in Sub-Saharan Africa at 230 inhabitants per square kilometre, the increase in agriculture production for a such growing population was not an easy process. However, due to the several ambitious program that the Government of Rwanda has been implemented, there is an improvement in agriculture productivity. The main objective is to modernise agriculture and livestock in order to increase food security and good nutrition. The expansion of several crops for example maize coffee and tea as well, contribute significantly to the increase of the productivity. For instance, coffee and tea are the main high quality crops for exportation while other crops are for local consumption.

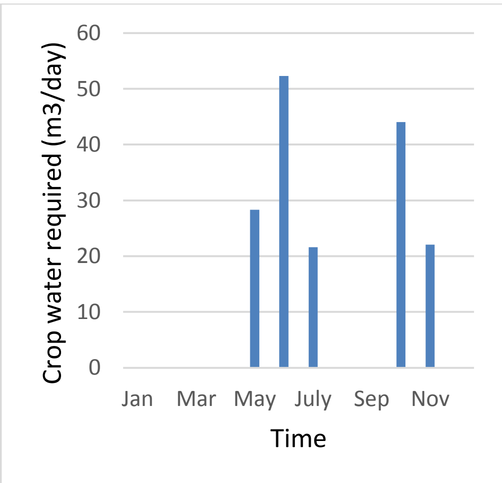
Once the selected crop types are chosen, the first step in designing SPVWPs is to calculate daily crop water requirement. Parameters involved in designing Irrigation Water Requirement (IWR) are effective precipitation, evapotranspiration, solar irradiance and type of crops as well. These parameters were calculated using CROPWATT 8. Software.

A cropping programme showing the seasonal cropping patterns and the occupying area for each crop is made. Table below, shows the planting dates, the length of the growing season and the harvesting time and land preparation of the next season. It includes also the type of crops that have been considered. It must be noted that, the time for harvesting and land preparation should not be included when calculating crop water requirement.

Crops	Area (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize	25	End 3		Start 1				End 3		start 1			
Beans	25			Start 1			End 18			start 1			End 19
soybeans	25			Start 1		End 24				start 1		End 24	
Tomatoes	25	End 23		Start 1				End 23		start 1			

Figure 6.1: Planting period

A three hectares' smallholder irrigation scheme of a group of farmers is proposed on a site in Mareba sector. As mentioned before, that the number of site weather climate stations in Rwanda is still low, the climate station of Kigali is proposed as it is the one can be located near to the site with full data.



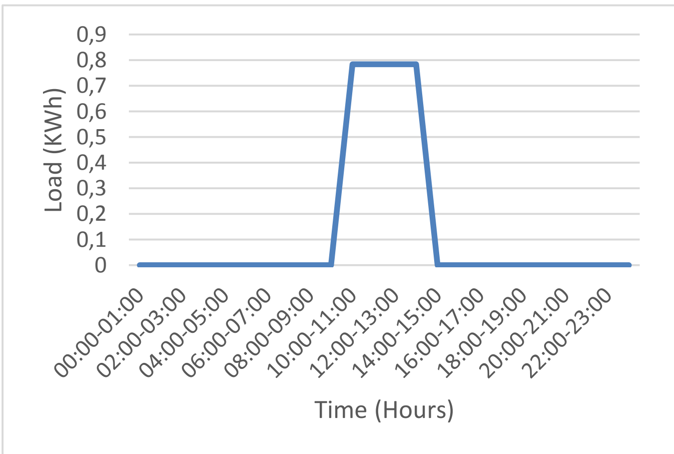


Figure 6.2: Crop water requirement for irrigation, Figure 6.3: Daily load energy profile

The amount of Net Irrigation Requirement is used to calculate the energy needed to meet the demand. For instance, the energy required to meet the demand is designed based on the peak water requirement per day in a particular month. This means that, if in some month, irrigation is not necessary because effective rain is enough for the crop or in harvesting period, at that time the system will produce energy but it will be considered as the losses due to the fact that the pump will not be working. That is why, different scenarios in this thesis should be designed in order to analyse which is profitable or feasible in rural area. The picture of daily energy required and daily energy produced per each month is given in the figure below.

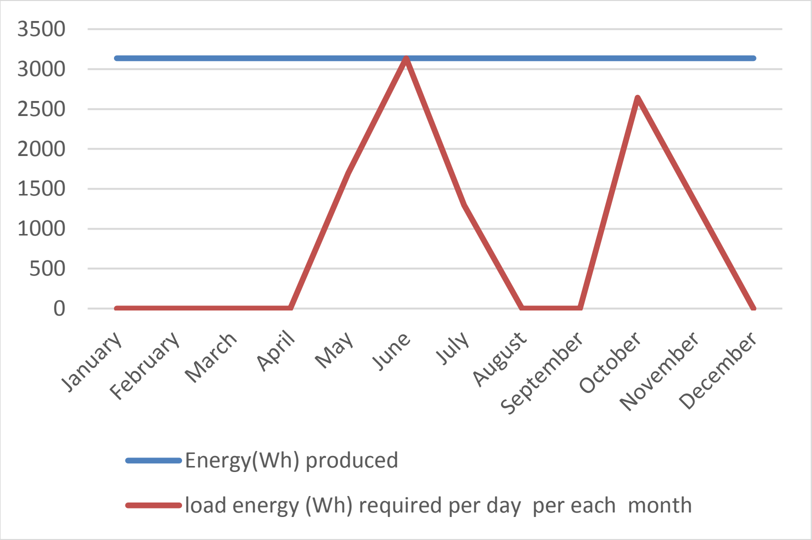


Figure 6.4: Energy produced and energy required

6.1.2 Design process of solar PV Water Pumping system

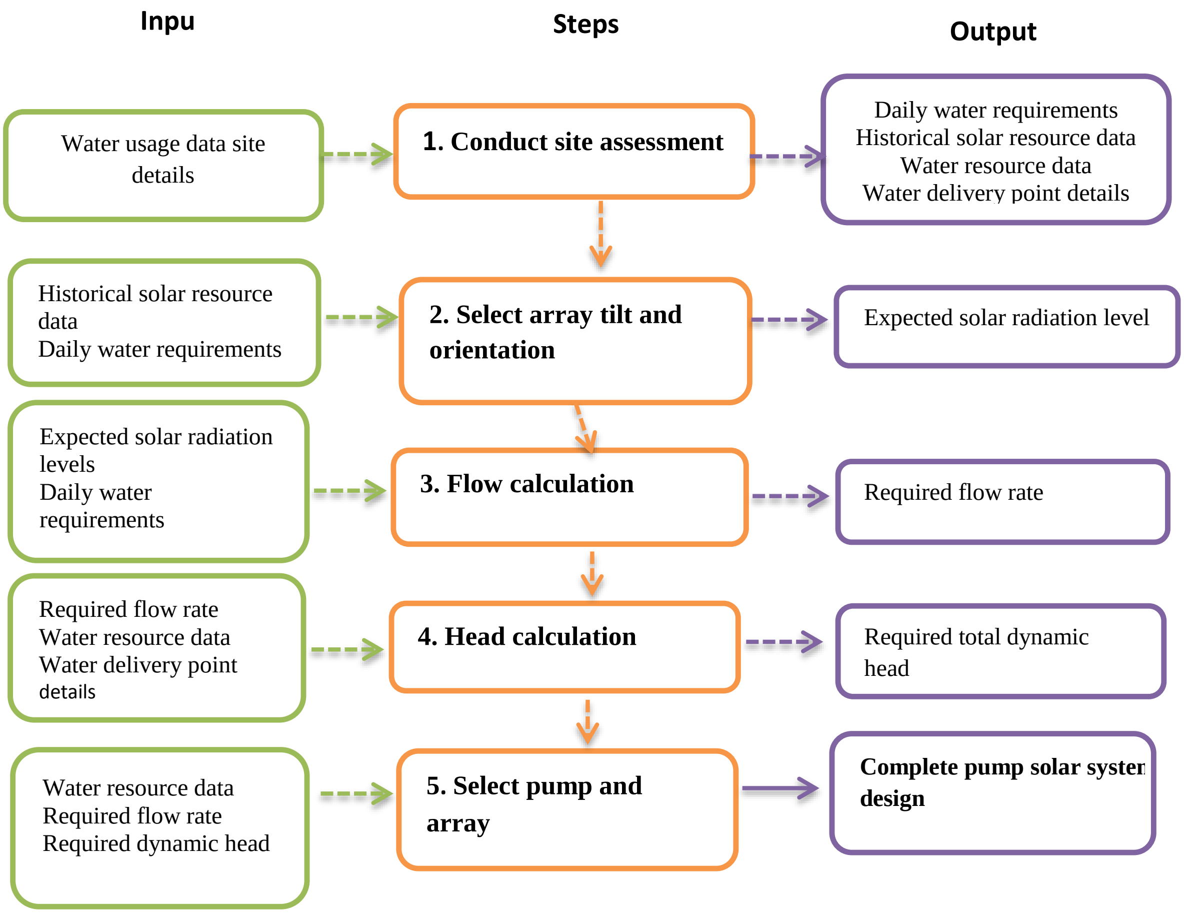


Figure 6.5: The main steps required in designing solar PV water pumping **(nsw Farmer, 2014)**.

Daily water requirements assessment is the centre of design solar water powered system, involves to evaluate overall daily water usage for the operation. From this study, typical water use requirement is for irrigation on a given acre crop land. Amount of water required depends on the growth of plants, the season, the irrigation type as well the surface area to be irrigated. In addition, the type of soil and climate parameters are other factors that need to be taken into consideration. It is very important to irrigate optimally during the stage of flowering to maturity. An approximate water usage is millimetre per day. Regarding irrigation, the water should be supplied either in seasonal or monthly period depending on how much of effective rainfall on the crop. If effective rainfall in the soil is more or equal to the crop water requirement, then, at that time irrigation is not significant. By using Penman Monteith model from CROPWATT 8., the following equation is used to estimate crop evapotranspiration (Narale, Rathore, & Kothari, 2013).

$$\boldsymbol{CWR = ETc = ETo \times K_c} \qquad \textbf{Equation 1}$$

$$\mathbf{IR_n = ETc - Re} \qquad \textbf{Equation 2}$$

$$\mathbf{IRg} = \frac{\boldsymbol{IR_n}}{\boldsymbol{Drip\ irrigation\ efficiency}} \qquad \textbf{Equation 3}$$

CWR	Crop water requirement, (mm) has the same value as ETc
K_c	Crop factor
ET_o	reference crop evapotranspiration, (mm/day)
IR_n	Net Irrigation Requirement (mm)
ETc	Crop Evapotranspiration (mm/day)
Re	Effective rainfall (mm)

Historical solar resource data helps to determine amount of energy produced by solar PV array in the provided site and amount of time per day for which the system will be able to operate. Proposed location of the solar power system (geographical coordinates), PV panel location and shading around PV array vicinity should be investigated. An appropriate and enough solar data should be used to determine the amount of solar insolation (peak sun hours) at the site of use. In order to maximize the energy production, the PV array should be facing in the north, the significance of shading of trees from surrounding area and also the potential effect of future growth of the trees should be considered as well. However, when determining the amount of available solar energy, the shading appears early morning and late evening, should not be considered or not be a problem because it will not affect the system.

The configuration of water source will be determined mainly by the type of water source used (a bore, dam, river or lake), the recovery rate of the proposed water source (recovery rate must be higher than the rate of the proposed pump otherwise the water source will be dry), the depth of the water source, and also by the distance from the top of this water source to the ground (nsw Farmer, 2014). The water source considered is surface or underground. Underground water system is preferable than surface water source due to its quality and steadiness even though is expensive in terms of drilling. In addition, the availability of water surface source is not consistent and has low quality. If the available water source is subsurface, the following parameter should be determined: static water level, seasonal depth variation, recovery rate and water quality as well. Otherwise, seasonal variations (water availability and water level); and water quality, including presence of sediment, organic debris should be determined. In addition, for surface water, the screening is important in order to ensure that the debris should not be pumped into the system.

The delivery point is necessary in order to determine the location to which water will be pumped to (directly to irrigation, or into the storage tank). The higher or far away the delivery point is from the pump, the greater pumping power the system will require to pump water to delivery point. Most of panel arrays are usually located in the remote area far away from the roads and public access in order to avoid the shadow on the PV panels. However, the potential of vandalism is quite significant. Therefore, when locating PV panel, it is very important to ensure that the system is well secured. Secure fence should be used to avoid the risk of vandalism or thefts as well as the damage caused by animals.

System layout will be designed once solar resource, water source and delivery point of use has been calculated. It is the determination of the layout of entire system including the location and the elevation of water source, pump, PV panel, storage tank, point of use and pipeline routes. It is important to minimize the distance between all these components to minimize the losses and also to provide the efficient solar PV water pumping system even the system cost.

6.1.3 Selecting the array tilt and orientation

Conducting the site assessment step is followed by selecting the array tilt and orientation of PV panel because both of them result in affecting the calculations of flow rate of water required for the system. Array tilt affects the amount of solar radiation received throughout the day while array orientation affects amount of solar radiation received throughout the year. PV array tilt angle can be fixed, single tracking or dual tracking system. Fixed PV array tilt is easy, simple and not expensive. However, tracking system maximise the energy production from solar radiation but it is costly high.

The period of water requirement such as monthly or seasonal is necessary in selecting the tilt angle and the orientation of the array. The default tilt angle is given by the same value of the altitude of the site and is considered as the best choice during the dry season than rainy season. By this default of tilted angle, the array will receive the greatest amount of solar radiation throughout the year with more solar radiation received in dry season than in the rainy season. A lower tilt angle will give greater solar radiation during the dry season while a steeper slop tilt angle will give higher solar radiation in the rainy season which is not interesting for the period of irrigation. Therefore, throughout the period of irrigation, lower tilted angle is quite interesting in order to maximize the required amount during the dry season.

6.1.4 Flow calculation for the pump

Flow rate for the pump is defined as the amount of water that can be pumped within a certain period of time. It can be per minute, per hour, or day unit. It is calculated by the ratio of the total required amount of water for the system and the peak sun hour defined for the site. Having flow rate of the pump and total dynamic head, manufacturer's pump curve can be easily used to select the pump required (United State Development of agriculture & Natural Resource Conservation Service, 2010).

$$\textbf{Flow rate } (\boldsymbol{m^3}/\textbf{ m/day}) = \frac{\boldsymbol{Total\ daily\ water\ required\ (m^3/day)}}{\boldsymbol{(Peak\ sun\ hr \times 60\ m)/hr}} \qquad \textbf{Equation 4}$$

There are two options of designing water flow rate. Firstly, it is possible to design flow rate considering the average daily solar radiation. By choosing this option, the performance of the system will be based on an average solar radiation, which means that on average solar radiation, the system will be able to deliver water. Sometimes the water requirement will be less than on average or much more than the average. Second option is about designing a flow rate taking into consideration less than average solar radiation. Regarding this option, the system requires a storage tank to store the excess water pumped once there will be sunny day. The second option is more relevant than the first, where the system requires to store water and to compensate the variability of the amount of water pumped.

Having calculated the flow rate values (hourly flow rate or flow rate per minute), only a single flow rate value has to be selected. There are some options to follow regarding the selection. First one is to choose the highest flow rate value which will be able to pump water even in the worst month solar radiation and also provide excess of water during the best month of solar radiation. Secondary, low value could be also chosen, but here during the worst month solar radiation, the pump will not be able to provide enough water to the point of use, but in the best months it will be able to provide water required. Finally, on average flow rate value may be used also, however, in the worst solar radiation, less water will be pumped and excess of water in the best solar radiation.

6.1.5 Total Dynamic Head calculation

Total dynamic head (TDH) is defined as the total resistance against water flow in the pump from the water source to the delivery point of use. The main two components supposed to be considered are presented as follow. There is static head which takes into consideration the height from water source to surface of the storage tank and is defined as the total difference in elevation between the pump and the water destination for subsurface pump, whereas for surface pump is defined as the vertical distance between the surface water (stream surface) and the delivery point. There is also dynamic head refers to the friction loss due to the flowing of water in the pipe from the source to destination. TDH is calculated as follow (United State Development of agriculture & Natural Resource Conservation Service, 2010).

$$\mathbf{TDH = Static\ head + dynamic\ head} \qquad \textbf{Equation 5}$$

Static head is calculated by considering only the vertical lift and is estimated in different means based on the source of water.

Static head (submersible) = drawdown level +static water level + lift from surface

Static head (surface pump) = suction lift + lift from surface

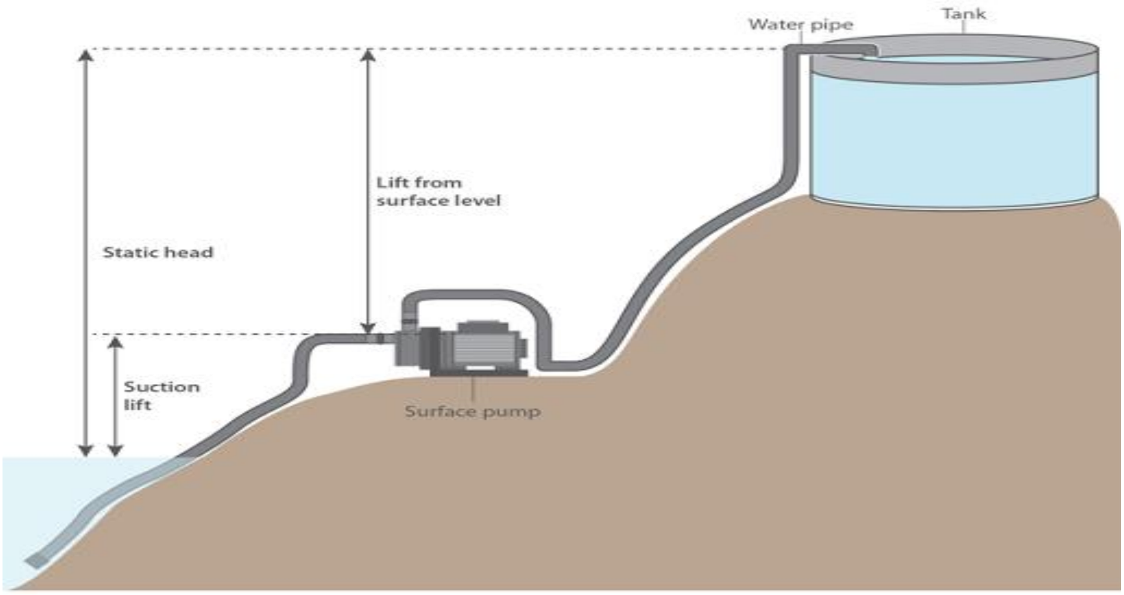


Figure 6.6. Total dynamic head (surface pump) (nsw Farmer, 2014)

Dynamic head is defined as the friction loss which is the pressure loss due to the water friction in the pipe. The friction loss in the pipe is determined by four factors: pipe size (inside diameter), the flow rate, the length of the pipe, and the pipe's roughness. Mostly, total dynamic head can be affected by pipe diameter and change in direction of water (Nshimyumuremyi, 2015). Having a system with a large diameter whereby the flow rate is high, the friction dynamic head can be reduced significantly, although, a large diameter and good quality will increase the cost of the system. However, using an appropriate pipe with high quality, there will be increase in system efficiency.

In addition, change in water direction or in pipe diameter, results in the change in friction loss. Therefore, the number of pipe fittings like elbow, valves, etc. should be minimized and used where are crucially required in order to minimize the losses. Furthermore, the length of the pipe does not significantly affect the head loss. However, the distance from the source to the storage tank should be located in close vicinity to one another in order to minimize the cost. Manufacture's pipe present different catalogues for the system layout (nsw Farmer, 2014).

6.1.6 Water storage

Due to the fact that water supplied depends on the flow rate and amount of solar radiation, water storage is very significant. Solar radiation is intermittent. This means that it can take less than three days or more without showing (during the cloudy days) and therefore, in the sizing, engineers should take into consideration the water surplus to cover the gap. In addition to that, a tank can be used to store enough water during the peak energy production to meet water need in the overcasting days. Furthermore, stored water in the container can be used during the maintenance issue with the power system (United State Development of agriculture & Natural Resource Conservation Service, 2010).

$$\boldsymbol{Water\ storage = Total\ daily\ water\ required\ \times overcasting\ days}$$ **Equation 6**

Once the water storage has been estimated, the storage tank must be sized, and therefore, it will be easy to find the size and the cost of the tank at the market. Three days is considered as the number of overcasting days in this thesis. This results will be used in the economic analysis.

It is recommended that; the tank should be installed on the foundation which can be a strong support of the required weight of the storage water.

6.1.7 Selecting pump and arrays

This is the last step for Solar Water PV Pumping (SWPVP) sizing. Solar pump design may be done in different means. There is a method of using pump performance curve, where the input parameters are total dynamic head and the flow rate that have been estimated in the previous steps. From the pump curve diagram, flow rate is on the vertical axis while total dynamic head is on curves and horizontal axis has peak power values. The intersection of a line crossing from the value of flow rate to the curve value of head gives the value of the appropriate peak pump power at the bottom of the diagram, and is expressed in watt unit.

On the other hand, the pump's power required is obtained by using hydraulic energy as the input and this method is the one which has been used in this thesis. Thus, mathematical equation of hydraulic energy is given as the equation7 (Nshimyumuremyi, 2015).

$$\boldsymbol{E_H\ (KWh) = \frac{\rho \times g \times TDH \times V}{3.6 \times 10^6} = 0.002725 \times TDH \times V}$$ **Equation 7**

Having the energy required to pump water, it is easy to get the power of the pump. Therefore, to get the pump power is just to divide this obtained hydraulic energy by the number of solar sun peak hours. Hence, the needed power pump for SPVWP system is given by the following equation (Nshimyumuremyi, 2015).

$$P_{pump}\,(KW) = \frac{\rho \times g \times TDH \times V}{3.6 \times 10^{6} \times PSH \times pump\ eff} = \frac{E_H\,(KWh)}{pump\ eff}$$ **Equation 8**

Table 6.1: Input parameter for hydraulic energy

ρ = 1000 kg/m^3	Density of water
G = 9.81 m/s^2	Gravitational acceleration
TDH (m)	Total dynamic head
V (m^3/day)	Volume of water required per day
E_H (KWh/day)	Hydraulic energy
3.6×10^{6}	Conversion value of hydraulic energy from Joule to KWh
PSH	Peak Sun Hours
P_{pump}	Pump power
Pump eff	Pump efficiency

It may be possible that the operating characteristics of given pumps offered by a pump manufacturer is the same but different voltage. Regarding the best pump in terms of efficiency, the one with high voltage can be considered due to the fact that a higher operating voltage tends to reduce the electric losses by decreasing the current flow.

Power = Volts × Amps

Power loss = $Current^2 \times Resistance$

General rule thumb stated that "*If the array consists of four or more panels and is located more than fifty feet away from the pump, Then the use of higher voltage pump should be considered*" (United State Development of agriculture & Natural Resource

Conservation Service, 2010). Therefore, the high voltage pump should be taken into consideration instead of increasing the current which can though increase the power losses as it can be seen in the power loss mathematical equation above.

Once the pump power is selected, PV modules can be sized. It is obtained by dividing total PV panels energy required by the Sun Peak Hours of the site location. For safety, to get PV panels energy required, the hydraulic energy is multiplied by the energy loss factor in the system, which is assumed at 1.3. Thus, the following equations.

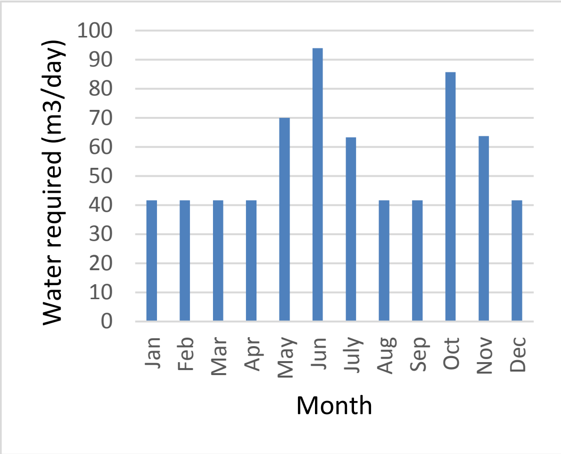
Total PV panels energy required = $E_H \times Energy\ loss\ factor$

PV panels capacity = $\frac{\text{Total PV panels energy required}}{SPH}$

To get the number of panels needed for the system, module characteristics under operating normal condition has to be selected. Once it has been chosen, the total number of panels required is obtained by dividing the total PV panels capacity for the system by the rating power of the selected panel. From there, wiring panels either in parallel or in series is also important in order to maximize the voltage of the system to reduce the power losses.

6.2 Scenario 2: Solar Photovoltaic Water Pumping System (SPVWPs) for Irrigation and Cattle Drinking Water

This design consists of irrigation and cattle drinking water. The design of this system is similar to the previous system, however, instead of pumping water for irrigation only, cattle drinking water also will be added. To do that, a survey of water requirement has been done in order to sum up together with amount needed for irrigation, to be able to come up with total water requirement per day. As it has been said early that most of the time irrigation is done seasonally or there are some months it is not necessary to irrigate due to the fact that effective rainfall is sufficient at that time energy produced will get lost. Therefore, to avoid losses, addition of cattle drinking water can be of help. The distribution of the load profile should look the same as the one considering only irrigation despite that the load has been scaling up. The analysis should be done to see whether this system is feasible or not.



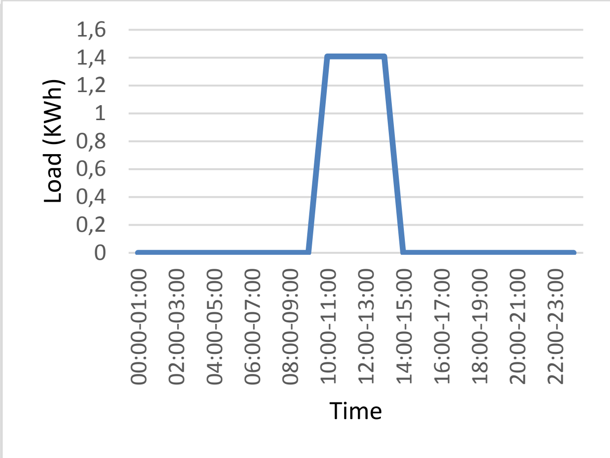


Figure 6.7: Water requirement (irrigation and cattle)   Figure 6.8: Daily load profile

Total water requirement for the system is given by the following formula. It is the sum of daily irrigation water requirement and daily cattle drinking water. AWR express Animal Water Requirement.

Total water required to be pumped = IRn + AWR   **Equation 9**

Design procedure PV Water Pumping system of this scenario is similar to the one for irrigation. Most of the input parameters are the same. For example, source of water, total dynamic head, solar radiation in the site as well as the array tilt and orientation. The changed parameter is only daily water requirement which affects the energy produced in terms of the amount as it is shown in the figure below.

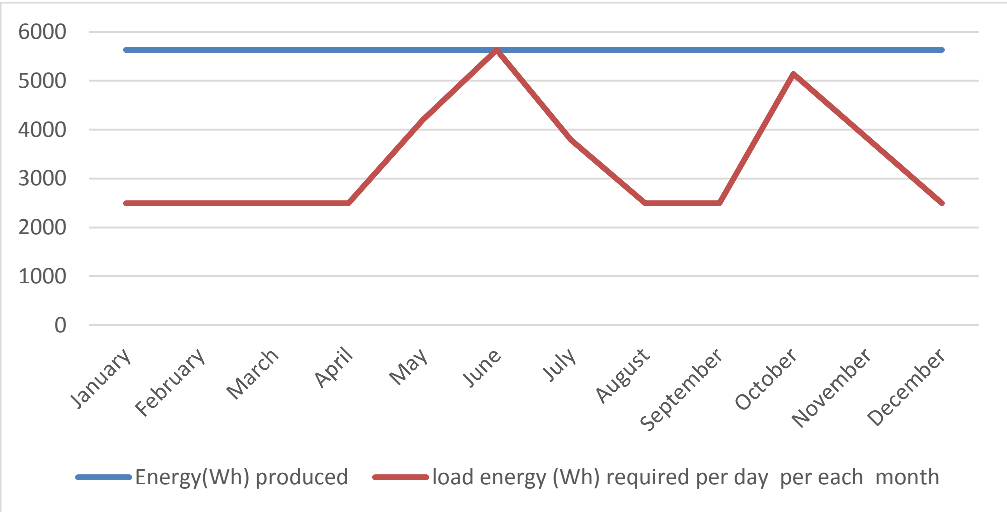


Figure 6.9: Energy required and energy produced (irrigation and cattle)

Not only water pumping system in this study has been done but also rural electrification is being analysed. An energy planning in a small community in the selected site has been taken into consideration and is discussed in scenario three.

6.3 Scenario 3: Community Solar Power System (SPS)

6.3.1 Introduction

Based on the purpose of this study which is to provide rural electrification renewable energy planning system, different scenarios are being conducted to be able to choose the suitable one, which is feasible and effective for rural population.

Firstly, a survey on rural activities should be done. Once activities in the area are known, energy load profile should be designed based on the basic appliances for the community. Once the load is already determined then solar PV system could be sized. Note that, some appliances are supposed to be used during the time when the sun is not shown. Therefore, for this system, battery storage is needed in order to meet the demand. This system has to be investigated careful to avoid oversizing.

It can be said that for water pumping system, the storage is just water in the tank instead of energy in the batteries. In contrast, for the third scenario, energy will be stored in the batteries. The load profile here is expressed in Watt and this helps to calculate amount of energy required per day by considering the time in hours each appliance is being used in a day.

System layout of this scenario should look like solar PV system discussed early in literature review of this study. In addition, as water pumping for irrigation and livestock will be included in the scenario, therefore, in the layout should be included as well.

6.4 First step: Load estimation

Daily load energy required depends on two type of appliances used by the community. It takes into consideration AC or DC loads. Nowadays, most of appliances used in the world are AC equipment due to the less cost compared to DC equipment and also their installation is easier than DC appliances. However, DC equipment are quite efficient than AC.

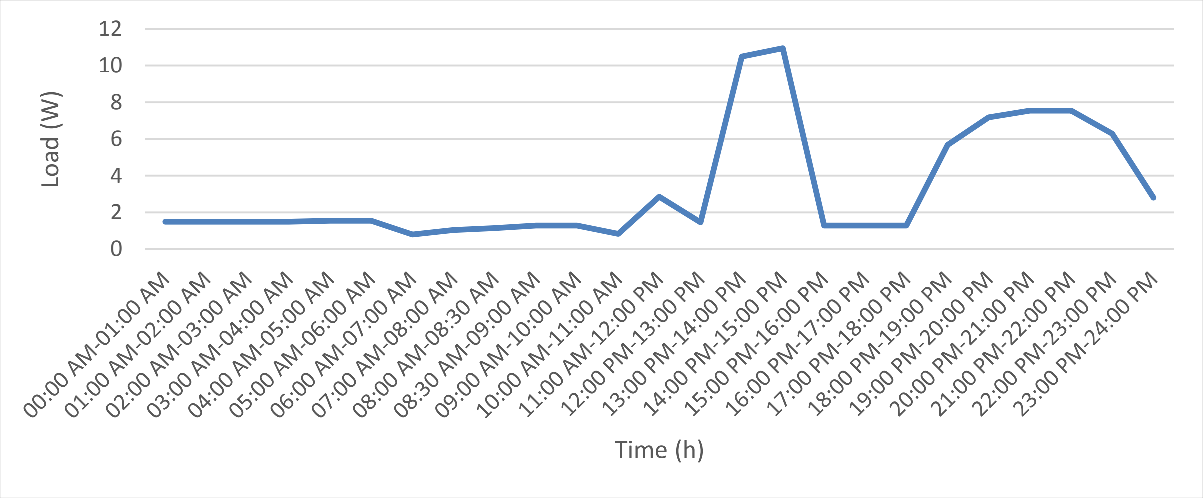


Figure 6.10: Load profile of Mareba sector

SPS are generally simple, built-up arrays of photovoltaic (PV) modules, which feed power through a charge controller to a battery bank, from where the system load is fed. Energy produced from PV module is in DC form and this should be converted to AC through inverter to be fed to AC appliances.

6.5 Selection of System Voltage

To choose the system voltage, overall system requirements have to be known. The voltage increases with an increase of daily load. Though, SPS for community, inverters play a key role also in selecting the voltage. When the loads require AC power, the voltage system is selected after choosing the inverter characteristics (Ishaq , 2013).

6.6 Selection of PV Module

PV module for PV system is selected based on the module performance warranty, efficiency and the locally replacement module in case of any problem. The selected module is PS250M-20/U for Phono Solar (Phonor Solar, 2015).

6.7 Determination of PV Array size

The PV array output power $\boldsymbol{P_{PV\ array}}$ can be estimated by the following equation (Ishaq , 2013).

$$\mathbf{P_{PV\ array}} = \frac{\mathbf{E_L}}{\mathbf{\eta_{b.o} \times K_{Loss} \times H_{tilt}}} \times \boldsymbol{PSI} \qquad \textbf{Equation 10}$$

E_L: Estimated average daily load energy consumption in KWh/day or Wh/day

H_{tilt}: Average solar radiation in peak sun hour's incident for specified tilt angle.

PSI: Peak solar intensity at the earth surface (1kW/m2)

$\eta_{b.o}$: Efficiency of balance of system

K_{Loss}: A factor determined by different losses such as module temperature, losses, dust, etc

$$\eta_{b.o} = \eta_{Inverter} \times \eta_{Wire\ losses}$$ **Equation 11**

In this study $\eta_{Inverter}$ and $\eta_{Wire\ losses}$ are taken as 85% and 90% respectively.

$$K_{Loss} = f_{man} \times f_{temp} \times f_{dirt}$$ **Equation 12**

f_{man}: manufacturer's tolerance

f_{temp}: Temperature de-rating factor

f_{dirt}: De-rating due to dirt if in doubt, an acceptable derating would be 5%

$$f_{temp} = 1 - [\gamma(T_{cell.eff} - T_{STC})]$$ **Equation 13**

γ : Power temperature co-efficient

$T_{cell.eff}$: Average daily temperature in °C and can be determined as follow

$$T_{cell.eff} = T_{a.day} + 25$$ **Equation 14**

$T_{a.day}$: day time average ambient temperature in °C

γ, $T_{cell.eff}$, T_{STC} and f_{man} for the selected specific module should be estimated.

Having all those figures, then f_{temp} from equation (13) could be also estimated. In addition to that, PV array size (equation 10) could be easily calculated as well.

6.7.1 Number of modules in series

The number of modules in series (N_{ms}) is determined by the ratio of the designed system voltage V_{System} and the nominal module voltage V_{module} given at the Standard Test Condition. Its formula is illustrated in Equation 15.

$$N_{ms} = \frac{V_{System}}{V_{module}}$$ **Equation 15**

6.7.2 Number of modules in parallel

The number of modules in parallel (N_{mp}) is determined by the ratio of the designed array output power $P_{PV\ array}$ and the selected module output power $P_{PV\ array}$ with the number of modules in series N_{ms}. The formula is shown in the following equation.

$$N_{mp} = \frac{P_{PV\ array}}{P_{module} \times N_{ms}}$$ **Equation 16**

The total number of module N_{mt} is obtained by multiplying number of modules in series and number of modules in parallel. Hence, the following equation.

$$N_{mt} = N_{ms} \times N_{mp}$$ **Equation 17**

6.8 Sizing of Battery bank capacity

Generally, Batteries used in solar systems sizing are expressed in ampere hours under standard test condition of 25°C. The maximum depth of discharge for a battery is provided by the manufacturers. The depth of the discharge is defined as an amount the total battery capacity has been consumed. In addition, to take into consideration the autonomy days or cloudy days, the minimum five days should be taken into consideration. These five days depend of the location by location. In this study, the minimum days of autonomy considered is 3 days as long as is for rural appliances. The storage battery capacity can be calculated using equation below (Ishaq , 2013).

$$C_x = \frac{N_c \times E_L}{DOD_{max} \times V_{system} \times \eta_{out}}$$ **Equation 18**

C_x: Required battery capacity

N_c: Number of days of autonomy

E_L: Estimated load energy in Wh

DOD_{max}: Maximum depth of discharge

η_{out}: Battery loss

6.8.1 Number of batteries required for the system

To be able to calculate the number of batteries required for the system, a specification of Battery type to be used has been chosen (296Ah of battery capacity and 12V of nominal voltage). The selected battery should have a specific nominal capacity and nominal voltage. These two values depend on the selected type of battery. The most used nominal battery voltage is 12V. Number of batteries required (N_{breq}) is obtained by dividing battery capacity of the system by nominal battery capacity and is given as follow (Ishaq , 2013).

$$\boldsymbol{N_{breq}} = \frac{C_x}{C_{selected}}$$ **Equation 19**

Having the number of batteries of the system, it is easy to get number of batteries in parallel and batteries in series. To estimate them, the following two provided equations could be used.

6.8.1.1 Number of batteries in series is given by equation

$$\boldsymbol{N_{bs}} = \frac{V_{System}}{V_{selected}}$$ **Equation 20**

6.8.1.2 Number of batteries in parallel is given by equation

$$\boldsymbol{N_{bp}} = \frac{N_{breq}}{N_{bs}}$$ **Equation 21**

6.8.2 Sizing the Inverter

Inverter sizing is done by taking into consideration first of all the actual power drawn from the appliances that will run at the same time. In addition, surge factor should be considered in order to take into consideration the big motor for their starting current. In this regards, surge factor is considered as zero as long as the load for appliances for Mareba sector in general in rural areas is low. To insure the safety of the system, safety factor is multiplied to the power required. The safety factor is gives as 1.25. Equation below illustrate total power for the system (Ishaq , 2013).

$$\boldsymbol{P_{total} = (P_{RS} + P_{LSC}) \times 1.25}$$ **Equation 22**

$\boldsymbol{P_{total}}$: Total power rating for inverter

$\boldsymbol{P_{RS}}$: Power of appliances running simultaneously

$\boldsymbol{P_{LSC}}$: Power of large surge current appliances

Therefore, the recommended inverter capacity should not be less than the Total power rating for inverter $\boldsymbol{P_{total}}$ (in KVA) and a nominal voltage of the system.

6.8.3 Sizing of charge controller

The voltage of charge controller is typically sized amperage and voltage capacities. The voltage charge controller is selected to match the voltage of PV array and batteries. A recommended charge controller should have enough capacity to handle the current from PV array. The equation below illustrates the rated current of the charge controller in general. The selected charge controller characteristics is at 60A load current and 12 nominal voltages (Ishaq , 2013).

$$\boldsymbol{I_{rated} = N_{mp} \times I_{sc} \times f_{safety}}$$ **Equation 23**

$\boldsymbol{I_{sc}}$: $Short\ circuit\ current$

$\boldsymbol{f_{safety}}$: Safety factor and is equal to 1.25

The number of regulator required for the system depends on the selected charge controller characteristics and therefore, is given by the following equation.

$$\boldsymbol{N_{reg} = \frac{I_{rated}}{I_{selected}}}$$ **Equation 24**

7 RESULTS OBTAINED AND DISCUSSIONS FROM THE SIZING OF THE PROPOSED OFF-GRID PV SYSTEMS

This chapter covers the results obtained of the three different scenarios. Cost and benefit analysis of the System selected system is discussed as well. Sensitivity analysis of the selected system is covered also, risk and environmental analysis are included as well.

7.1 System Design Obtained

7.1.1 Scenario I

The system sizing results are summarised in the following table. Remember, scenario I considering only irrigation system located in Mareba district. It is done only four hours in a day, three times in a week and five months in a year.

Table 7.1: Results obtained from the sizing of the system scenario I

Component	Description of Component	Result
Load Estimation	Total Estimated Load	16.99KWh/day
PV Array	Capacity of PV array	5.75KW
	Number of modules in series	2
	Number of modules in parallels	12
	Total number of modules	24
Area	PV module covered surface	$36.8m^2$
Pump motor	Capacity of pump motor	4.23KW
	Number of pump motor	4
Storage tank	Water stored for three days	$156.92m^3$
Voltage charge controller	Capacity of voltage regulator	21.15A
	Number of voltage regulators required	1

The system is designed based on the energy peak load which is in June. The total dynamic head is estimated to be 71.5m and the volume to be pumped is $52.3m^3$. The pump flow rate is $12.07m^3/h$. The pump selected characteristics power is around 1118.5W. Water stored is calculated by considering the storage of three cloudy days or for the repairing the system. Due to the fact that, the system of this scenario is seasonal only 5 months for irrigation in a year, the following figure shows well when irrigation is required and how much needed.

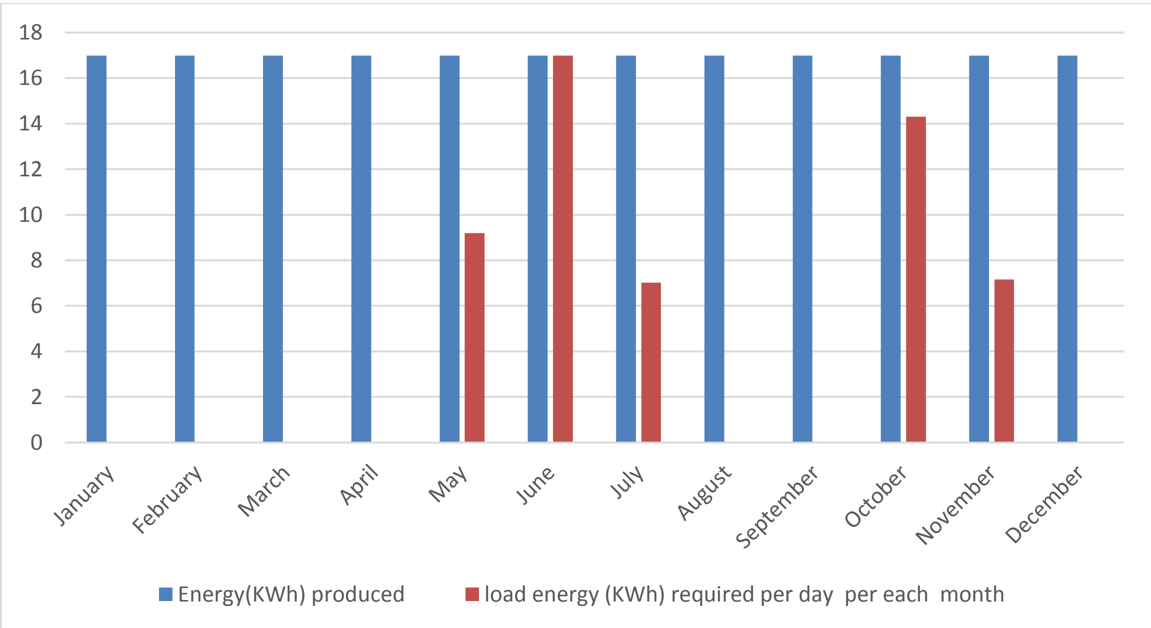


Figure 7.1: Energy produced and energy used (scenario I)

It can be seen that, most of the months in the figure above, there is no need of energy for irrigation because the effective rain in some months of planting is sufficient and other months there was no planting period. Therefore, there is a lot of lost energy with this system while considering irrigation plan using solar PV system. In addition, solar PV system always generates energy as long as it is implemented. That fact should also be taken into consideration in choosing the suitable renewable system plan for the rural population.

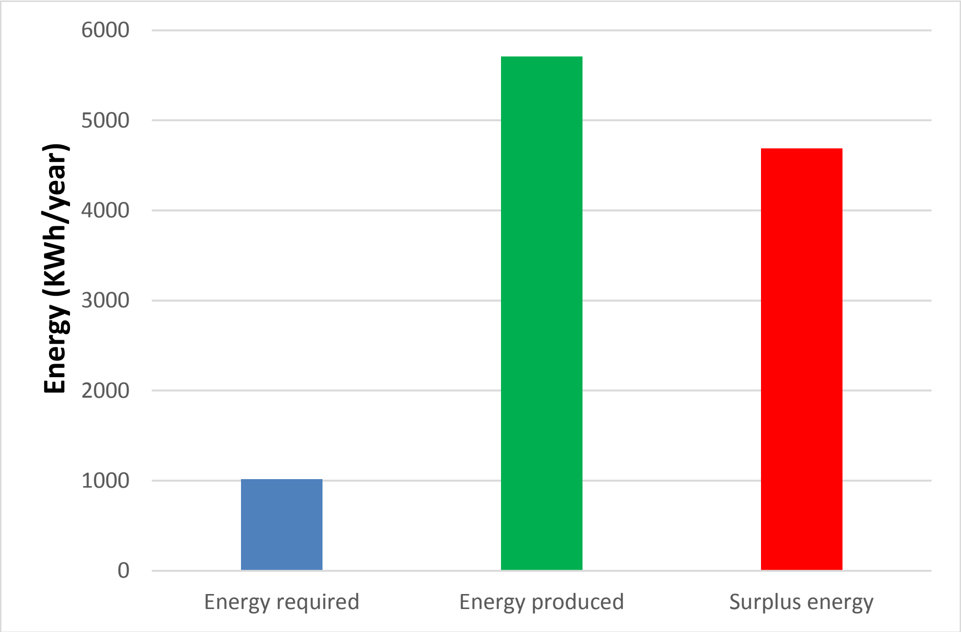


Figure 7.2: Energy surplus scenario I

The amount of energy produced is on average of 5707.01KWh per year where 4687.90KWh per year is an extra energy. This surplus energy, which is not needed for irrigation could be used for other applications.

7.1.2 Scenario II

Scenario II takes into consideration water pumping for both irrigation and drinking water for cattle applications. It considers the crops used in scenario I and the planting date, which means irrigation water requirement is the same as in scenario I. however, it takes into consideration also drinking water for cattle. The number of animals considered is around 850 (Milk producing cows, Calves and dry dairy/bulls). Each animal is supposed to take 22 litters per day for milk producing cows, 8 litter for calves and 15 Litter for dry bulls. By adding the amount of water both for irrigation and for cattle, the maximum volume water required per day is estimated to be 93.9m^3. Total dynamic head (TDH) is the same as the one in the previous scenario.

Table 7.2: Results obtained from the sizing of the system scenario II

Component	Description of Component	Result
Load Estimation	Total Estimated Load	30.51KWh/day
PV Array	Capacity of PV array	10KW
	Number of modules in series	20
	Number of modules in parallels	2
	Total number of modules	40
Area	PV module covered surface	64m^2
Pump motor	Capacity of pump motor	7.627KW
Storage tank	Number of pump motor	7
	Water stored for three days	281.852m^3
Voltage charge controller	Capacity of voltage regulator	21.15A
	Number of voltage regulators required	1

The energy designed is scaled up in each month compared to the scenario I, because, drinking water is daily required and scaled up the total water requirement for each month. Thus, the flow rate of this system is estimated to be on average of 23.4m^3/h. The system is designed for the whole year where it takes into consideration twelve months. However, as irrigation application is seasonal, therefore, surplus energy is also recognised. Thus, the following picture of the energy produced and energy used.

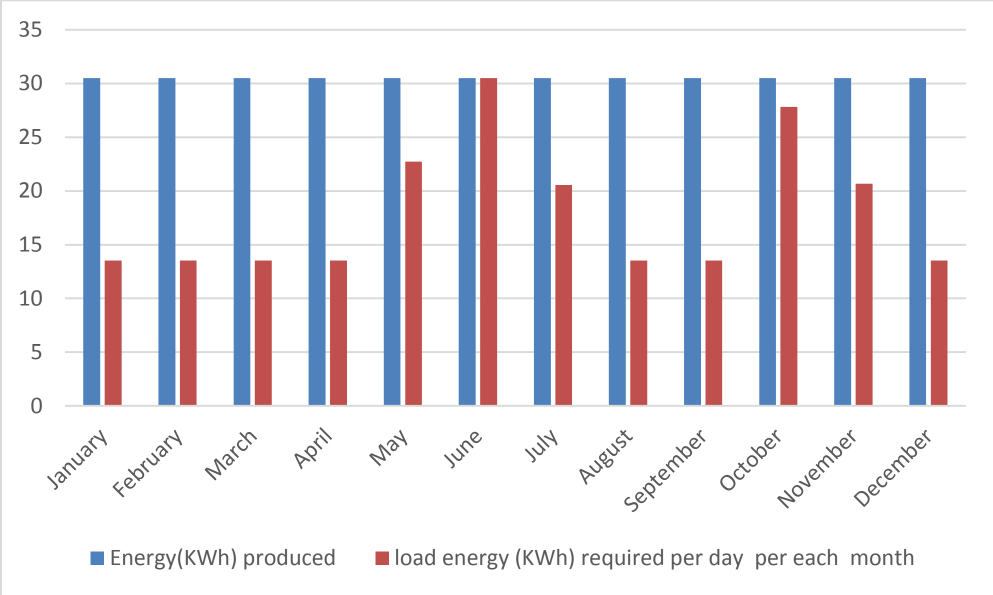


Figure 7.3: Energy produced and energy used (scenario II)

The yearly total energy require is 5562.82KWh and the yearly energy produced is given 10250.72KWh while the Surplus energy is around 4687.9KWh.

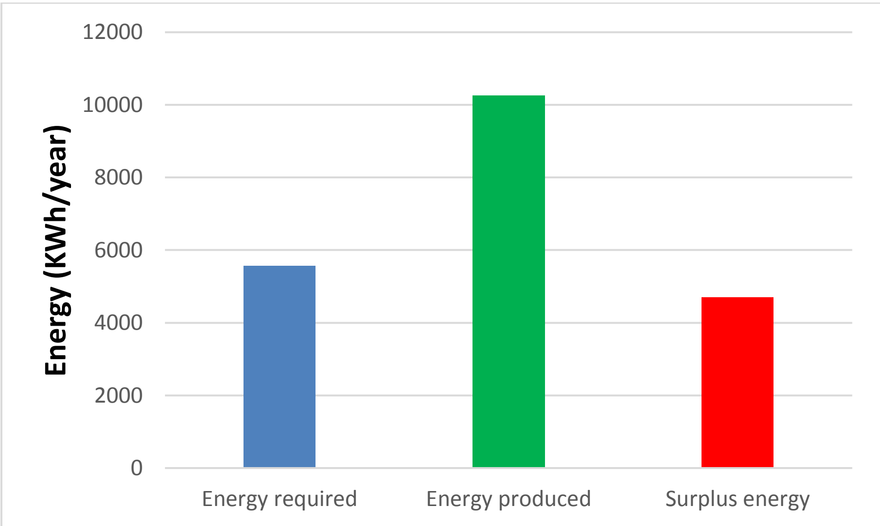


Figure 7.4: Energy surplus scenario II

The amount of energy produced is much higher than the amount of energy required in the system scenario I, however, both systems have the same surplus energy due to the fact that, the additional amount of energy is constant throughout the year.

7.1.3 Scenario III

This system, takes into consideration electrical appliances for hundred households and refrigerator for a small hospital and one nine years' school equipment such as laptops including lighting. In addition, it encompasses also pumping system for scenario II.

Table 7.3: Results obtained from the sizing of the system scenario III

Component	Description of Component	Result
Load Estimation	Total Estimated Load	193.98KWh/day
PV Array	Capacity of PV array	61.60KW
	Number of modules in series	2
	Number of modules in parallels	124
	Total number of modules	248
Area	PV module covered surface	396.8 m^2
Battery Bank	Battery bank capacity	17829.78Ah
	Number of batteries in series	4
	Number of batteries in parallel	16
	Total number of batteries required	61
Voltage Regulator	Capacity of voltage regulator	1373.3A
	Number of voltage regulators required	23
Inverter	Capacity of the inverter	42.4KVA

The last system plan takes into consideration the whole community needs based on the survey that has been done at the site. From the load profile, in figure.6.10, It can be seen that the peak load is only one hour during the day, from 2pm to 3pm. Energy storage is necessary because there are some needs during the night and therefore, solar PV system cannot produce enough energy. In rural area, most of the energy needs during the night is just for lighting. Despite, a refrigerator used at the small hospital works twenty-four hours. Thus, a significance energy needs during the night. The summary of this system can be seen in table 7.3.

7.2 Cost and Benefit Analysis of the System

The cost estimate of each system is summarised in the following tables. By using given formulas in the appendix. I, economic indicators of each scenario could be of help in selecting a suitable solar PV system for rural area in Mareba district. The results of each scenario is summarized in the corresponding column.

Table 7.4: Energy system economic indicators

Indicator	Scenario I	scenario II	Scenario III
Energy load (KWh/Year)	1019.11	5562.8	65180.0
LCOE ($/KWh)	2.81	1.28	0.16
TPWC ($)	39466.9	70369.0	103769.9
TPWB ($)	3232.0	12601.5	147652.7
NPV ($)	-37158.29478	-57767.5	43882.8
DPBP (Year)	> 25	> 25	9
IRR (%)	-39%	-9%	15%

7.3 Systems Analysis

Having different economic indicators, various system analysis is discussed in order to be able to select a suitable system plan for the selected site. LCOE with load energy, Economic indicators (NPV, TPWC, TPWB) with load energy and NPV with IRR are analysed for different scenarios.

From the figure below, it can be seen that the load energy of the system scenario I is very low while its LCOE is very high compared to scenario III. Thus, by comparing a system with huge amount and small amount of load energy production, while considering long lifespan of both system, the significant LCOE is the one with the big producing.

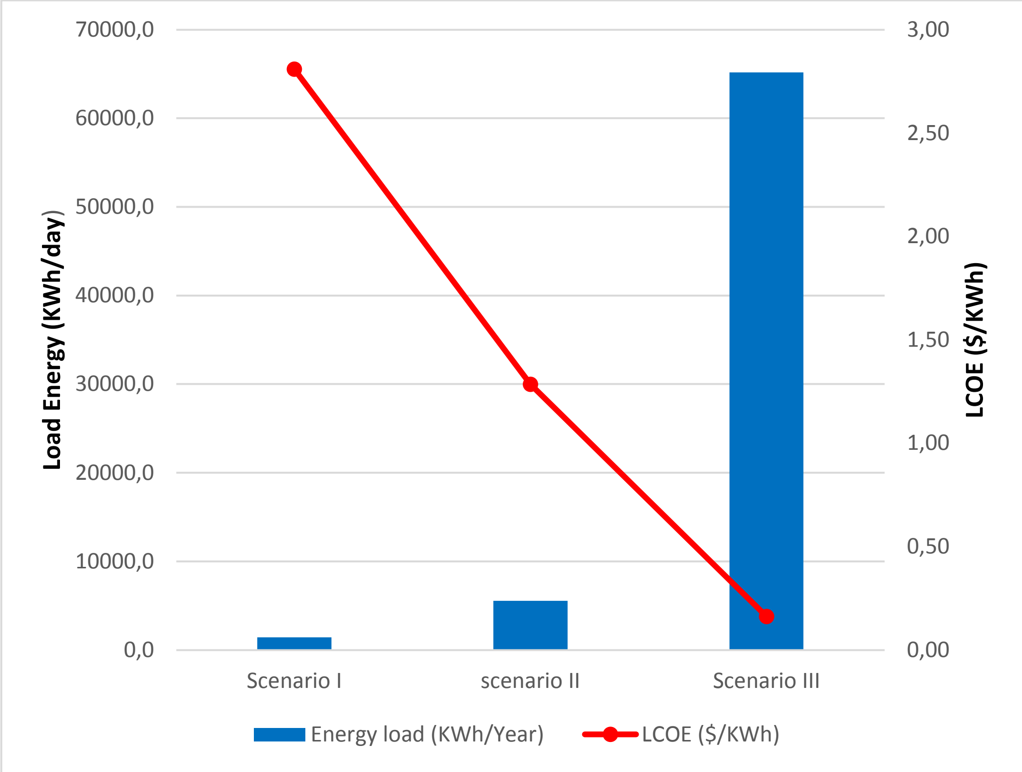


Figure 7.5: Load energy and LCOE analysis

Thus, LCOE of scenario III is effective compared to other scenarios. Furthermore, it is even significant value by comparing it with the electricity tariff of the utility 0.23 USD.

In terms of load energy of each scenario and their corresponding NPV, TPWC and TPWB comparison; scenario III is significantly effective. Even though, TPWC is high, at the end of the day it brings significant benefit and also the NPV of the system is positive which makes the system to be feasible and save money as well.

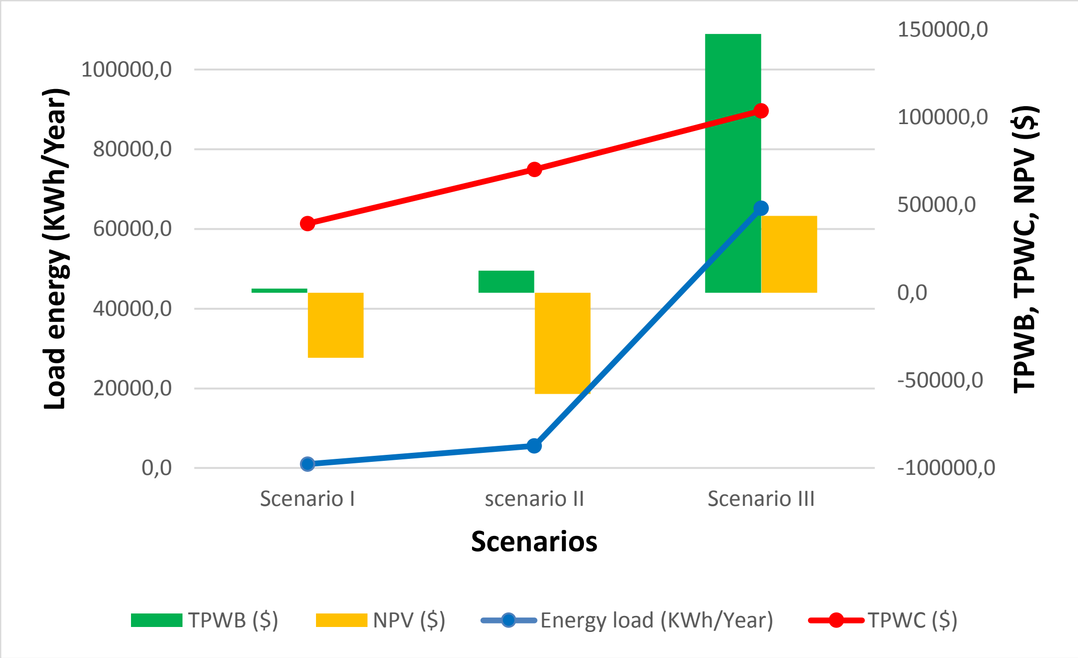


Figure 7.6:NPV, TPWC, TPWB and load energy analysis

Figure above, shows the variation of NPV by increasing the energy production within a long period of lifespan of the system, as well as the increase of NPV while increasing the cost of the system.

In the figure.7.7, it can be seen that, both system scenarios I and II, present negative NPV with less load energy and less Internal Rate of Return of the system.

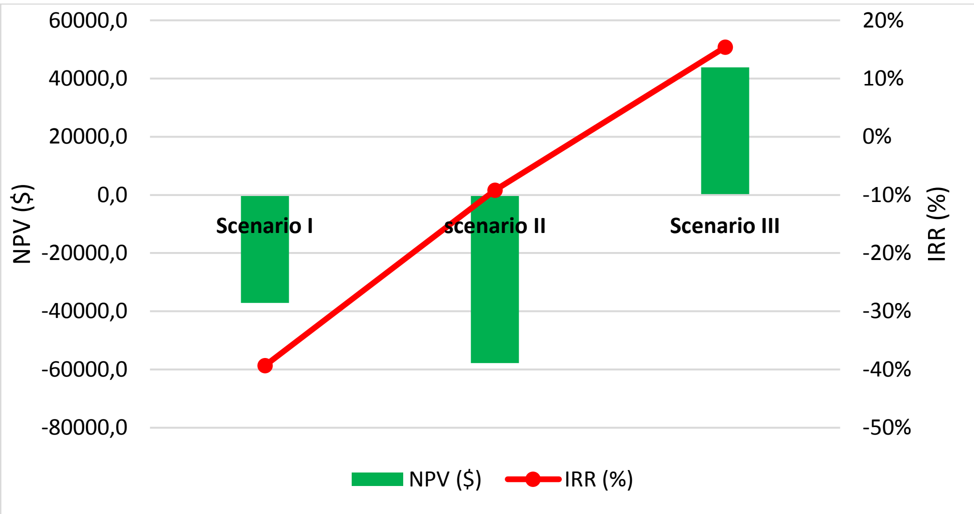


Figure 7.7: NPV and IRR analysis

The Rate of Return of the system scenario III is greater than the borrowing rate of 8%, and this makes the system to be profitable than the remaining scenarios. Both IRR of scenario I and II do not break even because are less than the selected rate of borrowing money, in fact, their values are negative.

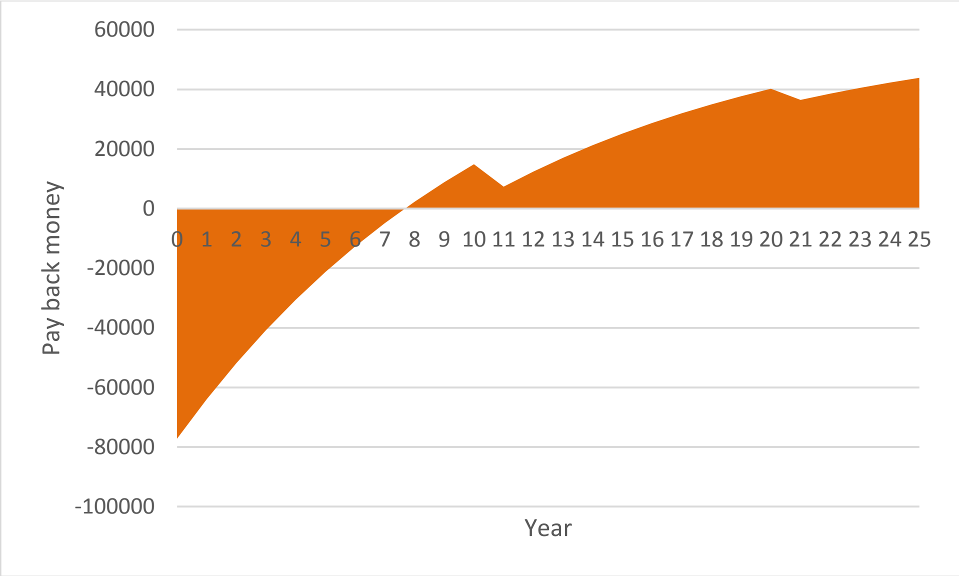


Figure 7.8: Payback period

The cost estimate of the system ‘s components takes into consideration the cost of modules, batteries, inverter, charge controller, balance of system as well as the maintenance cost. Taking into consideration of all those parameters, both two scenarios, scenario I and II show also long period of payment of the system. From the results shown in table.7.4, the period of payment is more than the lifespan of the system. For scenario III, the payback period (PBP) is quite good and is almost 9 years as it can be seen in the figure above of payback period.

From the analysis of three scenarios, LCOE, NPV and IRR have been used in making decision of which one is feasible and reliable. Scenario III has a small LCOE compared to those of scenario I and II. In addition, its IRR is higher than the borrowed rate and NPV is positive as well. Thus, scenario III is chosen as the profitable system planning for the studied area.

7.4 Sensitive Analysis of the Selected System

The sensitivity analysis has been done by evaluating the change of NPV with different values of interest rate. It is obvious that the interest rate is inversely proportional to the NPV. This means that by increasing the interest rate, NPV will decrease.

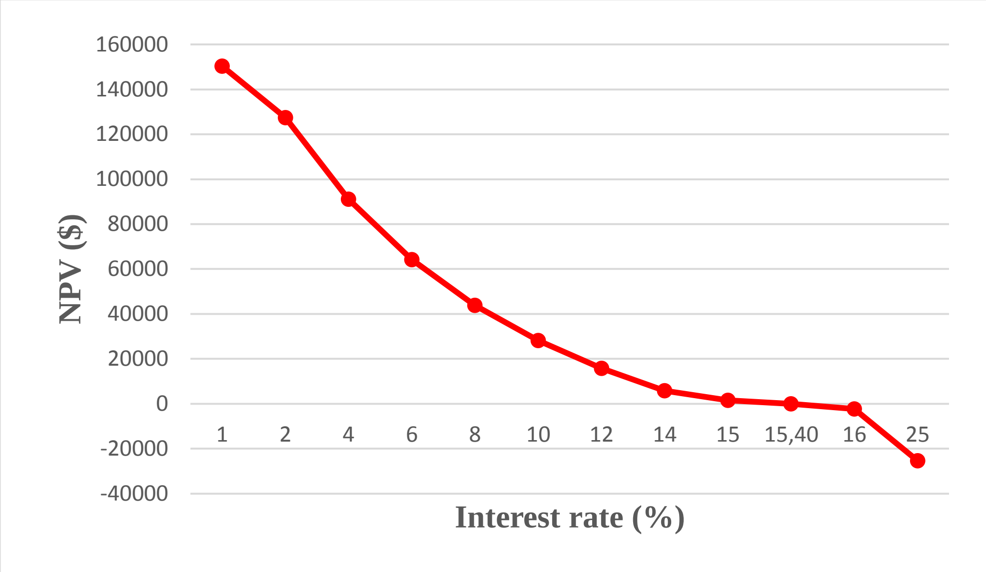


Figure 7.9: NPV vs Interest rate.

7.5 Risk Analysis

Table 7.5: Risk analysis table

Risks	**Explanation**
Political and Regulatory change	Law concerning land or feed-in-tariff may change and this may affect the project cost
Lack of loan	In case the bank does not give the loan or set high interest rate
Environmental	Harmful caused by solar cell in manufacturing
Construction	Errors may be made during the installation of the system.
Technological	Components may generate less electricity over time than expected
Solar intensity fluctuation	Unexpected reduction of solar irradiation during the day, which automatically affects the energy produced and reduces the reliability of the system
Vandalism	Solar panels may be stolen which reduces the expected power generation
Inefficient of irrigation	Inadequate of water resource should reduce the production

7.6 Environmental Analysis

To address global worming issue, it is very important to estimate CO2 emission from the designed system thereby quantify its reduction. The CO2 emitted when the designed electricity is produced from national grid is estimated taking into consideration the CO2 emission per KWh per year. As it has been said in the introduction chapter, the average of CO2 emitted from grid electricity production in Rwanda is estimated on average of 459.7 gCO2/KWh per year. Thus the saved energy from our system is at 29.9 tonnes of CO2 per year. The estimation of the annual CO2 released in Rwanda is 594000 tonnes per year (Basalike, 2015). Therefore, the amount of energy saved from SP system contributes to an annual reduction out 0.00005% of total Annual CO2 emitted. The percentage could be more high even when more users are familiar with the system.

8 CONCLUSION

The study was focussed on planning a renewable solar system energy for rural development considering different scenarios in order to come up with the viable one. The scenarios were arranged into various applications. PWPVs was designed firstly, to fulfil irrigation water requirements of maize; beans, soybeans, and tomatoes on a three hectares of crops for the rural population surviving. Secondary, pumping water for irrigation combined with cattle water drinking was also designed and solar photovoltaic system for a community including irrigation to improve rural population wellbeing. Having these three scenarios, it was possible to select the suitable system considering on some economic indicators.

Regarding the results of the first scenario, the only warries was about the surplus energy that was considered as energy lost due to the fact that, the irrigation was seasonal and more energy was getting lost compared to the energy required for irrigation. Thus to come up with the second scenario, in order to use the energy surplus from scenario one. However, there was no changing result because the second scenario which was to include water for cattle drinking was just to scale up the size compared to scenario one. However, it produces also significance surplus energy which can be used for other applications. Therefore, Solar PV system for a community including irrigation, the third scenario has been designed. The selected system, was designed for 100 households, a school of nine years, small hospital and pumping water as well, on 3 hectares.

Considering irrigation point of view, the method used to irrigate water was drip irrigation due to its higher efficiency both in terms of water saving and energy consumption. CROPWAT software has been used to design water requirement in order to design pump power required. MS Excel was mainly used for the design, analysis, evaluation of CO2 emission and reduction. Having the pump power required and households' energy required from the site survey, the energy produced was much higher compared to other scenarios. The system was equipped by batteries in order to be able to meet the demand.

Electricity surplus produced from all the alternatives stated above were determined and discussed. The electricity surplus of the first both alternatives (scenario one and scenario two) was estimated to be the same. In terms of economy, LCC, NPV, IRR and PBP were analysed comparing all three alternatives. In addition, the lifecycle cost of scenario three was much higher due to the fact that its energy production was quite big. However, scenario three has a significance benefits taking into consideration the analysis of LCOE, NPV, IRR and PBP for long lifespan system. These economic indicators were calculated considering the utility cost of electricity in order to know whether the system is feasible and viable. Furthermore, CO2 emissions from the selected system and its corresponding reduction when the same amount of electricity production from the utility is fully replaced by SPs were calculated and discussed. Fully replacement of grid by PVs results in CO2 emissions reduction of about 29.9 tonnes.

9 RECOMMENDATION OF FURTHER WORK

To have more accurate system, variation of meteorological data of the region under study should be carefully considered. Meteorological data are important input parameters and mostly affect the performance of the system in general. Thus, further work should consider the meteorological data on the studied site. In addition, due to a huge amount of electricity surplus from PVWPs, the excess of electricity should be integrated to the electrical grid nearby for further work. Furthermore, it is recommended also to analyse the system profitability (saving money) for both scenarios (scenario I and scenario II) in terms of yield production with and without pumping water.

10 EXECUTIVE SUMMARY

The aim of this study was to development a renewable energy project plan for energy supply of Mareba sector in Rwanda to improve standards of living of Mareba population in Bugesera district. Energy demand and resources assessment, energy related and socio economic data collection (questionnaire preparation), supply alternatives analysis, theoretical system sizing, techno economic and environmental analysis of the project were conducted. The results indicate that, the system which takes into consideration the necessary needs for the community (scenario three) was viable and feasible comparing to the one for seasonal irrigation as well as the one of irrigation combined with drinking water for the cattle. The report concludes that, solar PV off system could be of help to improve the wellbeing of Mareba community. It is recommended that, the surplus electricity in both scenarios (I and II) should be integrated to the national grid in order to avoid the losses and to consider the yield production with and without irrigation.

Le but de cette étude était d'élaboration d'un plan de projet d'énergie renouvelable pour l'approvisionnement en énergie du secteur Mareba au Rwanda pour améliorer le niveau de vie de la population Mareba dans le district de Bugesera. L'évaluation de la demande et les ressources d'énergie, l'analyse économique et environnementale liées à l'énergie et la collecte de données socio-économique (préparation du questionnaire), l'approvisionnement analyse des alternatives, théorique dimensionnement du système, techno du projet a été réalisée. Les résultats indiquent que, le système qui prend en considération les besoins nécessaires à la communauté (troisième scénario) était viable et réalisable comparant à celui pour l'irrigation saisonnière, ainsi que celui de l'irrigation combinée avec de l'eau potable pour le bétail. Le rapport conclut que, le système solaire pour PV pourrait être d'une aide pour améliorer le bien-être de la communauté de Mareba. Il est recommandé que, le surplus d'électricité dans les deux scénarios (I et II) devrait être intégrée au réseau national afin d'éviter les pertes et d'envisager la production de rendement avec et sans irrigation.

11 BIBLIOGRAPGY

Blunk, M. (2013). *Potential for Solar PV Water Pumping for Irrigation in Bihar: Opportunities in Biha, India.* GIZ, Indo Germany Energy Programm.

Nshimyumuremyi, E. (2015). *Solar Water Pumping System in Isolated Area to Electricity: The Case of Mibirizi Village (Rwanda).* Kigali: Scientific Research Publishing.

Azoumah, Y. (2014). Energy Resources in Africa. *Lecture.* Tlemcen: PAUWES.

Basalike, P. (2015). *Design, Optimization and Economic Analysis of Photovoltaic Pumping Water Technologies, Case Rwanda.*

Betalla, G. H., & Andreu, P. U. (2015). *Water Supply in Rwanda, Use of Photovoltaic Systems for Irrigation.* University of Agder.

Brian Harding. (2009.). *"Review of the Economic Impacts of Climate Change in Kenya.*

Brooks, W., & Dunlop, J. (2013). *PV installation Professional Resource Guide.*

Bugesera District. (2013). *District Development Plan (2013-2018).*

Campen, B. V., Best, G., & Best, G. (2000). *Solar Photovoltaic for Sustainable Agriculture in Rural Development.*

Department for International Development. (2009). *A Rapid Assessment of a National Energy and Low Carbon Path for Rwanda.*

Dixon, L. (n.d.). *Weather & Climate of Rwanda*. (USA TODAY) Retrieved 2016, from http://traveltips.usatoday.com/weather-climate-rwanda-15612.html

Economics, T. (2016). *Rwanda Population*. Retrieved from Trading Economics: http://www.tradingeconomics.com/rwanda/population

EWSA. (2014). *Expression of Interest for Scaling up Renewable Energy Program (SREP) Financing for Energy Projects in rwanda. P. 3.* Kigali: Republic of Rwanda.

FAO. (2015). *LAnd and Water Division*. (FAO Water Development and Managment Unit) Retrieved February 12, 2015, from http://www.fao.org/nr/water/topics_irrigation.html

Grégoire, L. (2013). *Rural Electrification with PV Hybrid Systems.* INTERNATIONAL ENERGY AGENCY.

International Renewable Energy agency. (2016, 03). *Inatalled renewable energy*. Retrieved from International Renewable Energy agency,: http://resourceirena.irena.org/gateway/countrySearch/?countryCode=RWA

Ishaq , M. (2013). *Design Of An Off Grid Photovoltaic System: A Case Study Of Government Technical College, Wudil, Kano State.* International journal of Scientific & Technology Research.

Javadi, F., Rismanchi, B., Sarraf, M., Afshar, O., Saidur, R., Ping, H., & Rahim, N. (2013). *"Global Policy of Rural Electrification.".* Renewable and Sustainable Energy Reviews.

JICA. (2014). *The Project for Preparation of Electricity Development Plan for Sustainable Geothermal Energy Development in Rwanda.* Kigali: Republic of Rwanda.

Jim Dunlop Solar. (2012). *Overview of Potential and Limitations of PV Systems Configurations.*

Kamanza, S. (2011). *Water Resources Managment Sub-sectors Strategic Plan.* Kigali: Ministry of Natural resources.

Maimbo, M. M., & Basalike , P. (2010). *Rwanda Irrigation Master Plan.* World Agroforestry Centre (ICRAF).

MIDIMAR. (2015). *The National Risk Atlas of Rwanda; P. 36.* Kigali: Government of Rwanda.

Ministry of Agriculture and Animal Resources Repub. (2009). *Strategic Plan for the Transformation of Agriculture in Rwanda – Phase II (PSTA II).*

Ministry of Finance and Economic Planning, & National Institute of Statistics of Rwanda. (2015). *Fourth Population and Housing Census, Rwanda, District Profile, Bugesera.*

Ministry of Infrastructure. (2014). *Sustainable Energy for All Rapid Assessment and Gap Analysis Rwanda.* Ministry of Infrastructure.

Ministry of Infrastructure. (2015). *Energy Sector Strategic Plan 2013/14 - 2017/18.*

Nang Saw Yuzana Kyaing. (2011). Design Considerations of PV Water Pumping and Rural Electricity System (2011) in Lower Myanmar. *International Journal of the Computer, the Internet and Management*, 68.2.

Narale, E., Rathore, D., & Kothari, D. (2013). *Study of Solar PV Water Pumping System for Irrigation of Horticulture Crops.*

National Institute of Statistics of Rwanda. (2011). *EICV3 District Profile.* Kigali: National Institute of Statistics of Rwanda.

National Institute of Statistics of Rwanda. (2016). *Rwanda Integrated Household Living Conditions Survey [EICV] 2013/2014.*

nsw Farmer. (2014). *Solar-Powered Pumping in Agriculture: A guide to System Selection and Design.*

Phonor Solar. (2015). *High Performance AC Solar Module 250W -270W.*

RNIS. (2011). *EICV3 District profile.* Kigali: National Institute of Statistics of Rwanda.

Rolland, S. (2011). *Rural Electrification with Renewable Energy Technologies, quality standards.* Alliance for Rural Electrification.

Sawa, Andreas.P, & Franken, K. (2002). *Development Monitoring and Evaluation of Irrigated Agriculture with Farmer Participation Planning.*

SET, UNDP, & GEF. (2005). *A practical Guidebook for a Development Renewable Energy System for Village Power Projects.*

The goverment of Rwanda, & Ministry of Agriculture and Animal Resourcess. (2013). *Rwanda Irrigation Master Plan.*

U.S.Department of Energy, & Basalike, P. (2014). *The Water Energy Nexus: Challenges and Opportunities.* US Department of Energy.

UNEP. (2009). *wnda: From Post -conflict to Environmentally Sustainable Development.*

United State Development of agriculture, & Natural Resource Conservation Service. (2010). *Design of Small Photovoltaic (PV) Solar-Powered Water Pump Systems.* PORTLAND, OREGON.

Wijesinghe, N. (2014). *Rural Electrification - Sri Lanka: A Case Study & Scenario Analysis.* KTH School of Industrial Engineering and Management.

World Bank. (2016). Retrieved from Access to electricity (% of population): http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=RW

Zhou, Habiyakare, T., & Nianqing. (2015). *Water Resources Conflict Management of Nyabarongo River and Kagera River Watershed in Africa.* Shangai & Kigali: Journal of Water Resource and Protection.

12 APPENDICES

APPENDIX I.

Indicators	**Formula**
Present Worth Cost, PWV	PWC = Total cost/$(1+i)^n$
Degradation Energy (kWh), DE	DE = E×$(1-e)^{(n-1)}$
Discounted Energy (KWh), Disc.E	disc.E = DE/$(1+i)^n$
LCOE	LCOE = Total PWC/ Total Disc.E
Benefits	Benefits= DE× utility cost
PWB (USD)	PWB = benefit/(1+i) ^n
NPV	NPV = Total PWB - Total PWC
Cash flow	Total benefit – Total cost

APPENDIX II: HOUSEHOLD SURVEY FOR RURAL ENERGY USE

Name of interviewer: Ms. Clementine Ushizimpumu

Date of interview:

I. Household Profile

Part 1 Address of Interviewee

Province:

District:

Village:

Household number:

Part 2 General Information about the Household

1. Name of Respondent:
2. Sex of Respondent:
3. Age of Respondent:
4. Education Level of Respondent:
    a) Never attended school
    b) Attended primary school
    c) Attended junior middle
    d) Attended senior middle school
    e) Vocational School
    f) College level or above

5. Occupation of Respondent:
    a) Worker
    b) Farmer
    c) Teacher
    d) Business
    e) Administrative Personnel
    f) Other (specify)

6. Respondent's Relationship to Head of the Household is:
    g) Head of the Household
    h) Wife or Husband of the Head
    i) Daughter of the Head

j) Son of the Head
k) Daughter-in-law of the Head
l) Son-in-law of the Head
m) Oher (specify)

7. How many people are in the household?
(Fill in according to age.)

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

8. Source of reliable production
   a) Agriculture
   b) Non agriculture

9. Area of the house: m^2

10. What types of fuels do you use for cooking?
    a) Coal and/or Charcoal
    b) Wood or straw
    c) Electricity
    d) Gas
    e) Other (specify)

11. What did you use for lighting, previously?

12. What do you use for lighting, currently?
    a) Electricity
    b) Kerosene
    c) Dry Cell Battery
    d) Candle

e) Other (specify)

II. Information on Household Electricity and Fuel Uses

Part 1: General Information

2.1. Do you use electricity (yes or no)?

2.2.What is your source of electricity?

a) Grid
b) Own generation

2.2.1. What kind of generator are you using, if your electricity is self-generated?

a) Diesel generator
b) PV
c) PV/diesel hybrid
d) Others (specify)

2.3. Do you have any possibilities of being connected to the grid in the near future (yes or no)?

2.4. How much money for you to connect to the grid? RWR

[If the household does not know, interviewer should find out this information]

2.5.How far is the household from the nearest grid? Km

[If the household does not know, interviewer should find out this information]

2.6. Monthly electricity and fuel consumption

Type	Amount per month	Total cost per month
Electricity	KWh	RWF
Firewood	Kg	RWF
Charcoal	Kg	RWF
Kerosene	Liter	RWF
Diesel	Liter	RWF
LPG/LNG	Kg	RWF
Straw	Kg	RWF
Others (fuel name:)	Unit ( )	RWF
Others (fuel name:)	Unit ( )	RWF

Part 2: Energy Consumption by Functional Equipment

2.7.Food Preparation Equipment

Type of equipment	Manufacturer	Power or size	Model year	Fuel Type	Operating hours/day
Stove 1					
Stove 2					
Heater 1					
Heater 2					
Electric kettle 1					
Electric kettle 2					
Rice cooker 1					
Rice cooker 2					
Oven 1					
Oven 2					
Others (name:)					
Others (name:)					

2.8. Lighting

Type of equipment	Manufacturer	Power or size	Model year	Fuel Type	Operating hours/day
Fluorescent Tube 1					
Fluorescent Tube 2					
Fluorescent Tube 3					
Fluorescent Tube 4					
Incandescent 2					
Incandescent 3					
Incandescent 4					
CFL 2					
CFL 3					
CFL 3					
CFL 4					
Kerosene 1					

2.9. Household appliances

Type of appliances	Manufacturer	¨Power or Size	Model Year	Fuel type	Operating hours/day
Radio 1					
Radio 2					
Tape recorder 1					
Tape recorder 2					
Black & white TV 1					
Black & white TV 2					
Color TV 1					
Color TV 2					
VCR 1					
VCR 2					
Computer 1					
Computer 2					
Iron 1					
Iron 2					
Water Pump 1					
Water Pump 2					
Hair drier 1					
Hair drier 2					
Electric scissors					
Others (name:)					
Others (name:)					

2.10. Other equipment

Type of appliances	Manufacturer	¨Power or Size	Model Year	Fuel type	Operating hours/day
Milling machine					
Health center (refrigeration)					
Food processing (Fan)					
Others (name:)					

Part 3: Future Energy Load Growth

2.11. Do you plan to buy new electric appliances in the near future (yes or no)?
[If yes, specify types and Sizes of required appliances]

Type of electric appliances	Size of electric appliances
	W
	W
	W
	W
	W

2.12. How much electricity do you need in each month in the next five years?

Year	Monthly amount
1	KWh
2	KWh
3	KWh
4	KWh
5	KWh

III. Information on Household Energy Systems

Part 1 Diesel generator

If the household is using a Diesel generator, please fill out the following items.

Engine size	W
Operating hours per day	Hrs/day
System capital cost	RWF
Generator lifetime	Years
Generator cost	RWF
Annual maintenance and repair cost	RWF
Fuel consumption	Kg/Hr
Fuel unit cost	RWF/Kg
Fuel transport cost	RWF/Kg
Do you have troubles using this system (yes or no)?	

Part 2 PV System

If the household is using a PV system or a PV/diesel hybrid, please fill out the following items.

PV module manufacturer	
Cell type	
Module rater power	Wp
Module area	m^2
Array angle	radians
Module efficiency	%
System capital cost	RWF
Module lifetime	Year
Module unit price	RWF/Wp
Salvage value of the module	RFW
Annual maintenance and repair cost	RWF/year
Do you have troubles using this system (yes or no?	

Part 4 Balance-of-System (BOS) Equipment

If your system is equipped with batteries, inverters or/and controllers, please fill out the following items.

Battery manufacturer	
Battery type	
Number of batteries	
Battery voltage	V
Battery capacity	Ampere - hours
Battery depth of discharge	%
Battery lifetime	year
Battery cost	RWF
Inverter size	KW
Inverter lifetime	Year
Inverter cost	RWF
Controller size	KW
Controller lifetime	Year
Controller cost	RWF
Do you have troubles using this equipment (yes or no)	

IV. Household Attitudes

Part 1. Your Views on Energy Options

4.1 Please give your view to the following energy types.
Using the numbers 1 through 4 to rank your choice. “1” indicates the best, and “4” the worst.

Type	Cost	Availability	Reliability	Convenience	Cleanliness	Safety	Overall view
Electricity from the grid							
Electricity from PV							
Coal							
Natural gas							
Kerosene or Diesel							
Fuel wood/Charcoal							
Straw							

4.2 Which of the following stand-alone systems do you have a desire to buy and why?
Using the numbers 1 through 4 to rank your choice. “1” indicates the best, and “4” the worst.

Type	Your desirability	Reliability	Price
Solar PV power			
Diesel generator			

4.3 Benefits of electricity

Category	Yes	No
Economic benefits:		
i. Agricultural/livestock productivity		
ii. Small business development		
Entertainment (Watching TV, etc)		
Information and education		
Household quality of life		
Safety		

4.4 Advantages of using electricity generated from renewable energy

Category	Yes	No
Reliability		
Lower cost		
Easier maintenance		
Flexibility (self - control)		
Cleanliness		
Safety and health improvement		

Part 2. Demand Side Management

4.5 Do you think your energy expense (fuel and/or electricity) is:

a) very expensive
b) expensive
c) fair
d) cheap
e) I do not pay for fuel

4.6 If your energy expense is high, what are the reasons?
Overconsumption of energy?
High fuel cost Type of fuel: Cost (RWF/Kg):
High electricity cost Cost (RWF/KWh):
Other reasons

4.7 How do you rate the quality of the electricity supply, if you have?

a) Very satisfied
b) Satisfied
c) Acceptable
d) Not satisfied due to frequent blackout and unstable electricity voltage
e) I do not care

4.8 If the electricity supply is of bad quality, do you experience:

a) economic losses from electricity blackout
b) appliance damage from unstable voltage
c) Both of above

4.9 Have you ever adopted energy saving measures (yes or no)?

4.10 Are you willing to take actions to reduce your electricity consumption,
If the actions are not difficult and are not too costly (yes or no)?

4.11 When you buy electric appliances, what features do you care most?

a) Brand
b) Price
c) Function
d) Low Electricity Consumption

e) Other (specify:)

Part 3. Affordability and Willingness to Pay for Renewable Energy Systems

4.12 Would you be willing to pay more for electricity if more reliable service will be provided (yes or no)?

4.13 Type of system you would like to buy in the near future:
a) <50W PV
b) 50W-100W PV
c) >100W PV
d) Large PV/diesel Hybrid (>100W PV and >100W diesel)
e) Diesel Generator

4.14 How much are you able to pay for a renewable energy system?
a) Less than 360,000 RWF
b) 360,001 – 600,000 RWF
c) 6000,001 – 1,200,000 RWF
d) 1,200,001 – 1,800,000 RWF
e) 1,800,001 – 2,400,000 RWR
f) More than 2,400,000 RWR

4.15 How much are you willing to pay for a renewable energy system?
a) Less than 360,000 RWF
b) 360,001 – 600,000 RWF
c) 6000,001 – 1,200,000 RWF
d) 1,200,001 – 1,800,000 RWF
e) 1,800,001 – 2,400,000 RWR
f) More than 2,400,000 RWR

4.16 How much are you willing to pay with a possible loan?
a) Less than 360,000 RWF
b) 360,001 – 600,000 RWF
c) 6000,001 – 1,200,000 RWF
d) 1,200,001 – 1,800,000 RWF
e) 1,800,001 – 2,400,000 RWR
f) More than 2,400,000 RWR

4.17 How would you like to pay for the renewable energy system?
a) Lm Sum
b) Two Payments
c) Three Payments
d) Leasing (Pay a Monthly Fee)

Part 4. Factors Concerning the Use of Renewables

4.18 Which factors do you care the most when purchasing a renewable energy system?
Capital Cost

Quality
Capacity

4.19 What are your biggest concerns of using a renewable energy system?

a) Maintenance
b) Parts
c) Repair and Services

4.20 What kind of equipment that you have experienced with major problems?

a) PV
b) Battery
c) Controller
d) Inverter
e) Gasoline or Diesel Generator
f) Lantern

APPENDIX III: COOPERATIVE AGRICULTURE SURVEY FOR RURAL ENERGY USE

Name of interviewer: Ms. Clementine Ushizimpumu
Date of interview:

I. Cooperative Member Profile

Part 1 Address of Interviewee

Province:
District:
Village:
Cooperative Name:

Part 2 General Information about the cooperative

13. Name of Respondent:
14. Sex of Respondent:
15. Age of Respondent:
16. Education Level of Respondent:
    g) Never attended school
    h) Attended primary school
    i) Attended junior middle
    j) Attended senior middle school
    k) Vocational School
    l) College level or above

17. Respondent's Relationship to Head of the Household is:
    Head of the cooperative
    Assistant
    Others

18. How many members are in the cooperative?

    Fill in according to age.)

Years	Person
16 – 60	
61 and over	
Total	

II. Agricultural & livestock productivity

19. What types of crops do you produce?

Crops	Yes	No
Maize		
Beans		

Banana		
Soybeans		
Tomato		
Vegetables		
Cassava		
Sorghum		
Coffee		
Irish		
Suit potatoes		
Others		

20. Area of the crop field (ha)

21. Is there any water source close to the field?

22. If yes, what is the distance between the field and the water source (please tick one)
    a) Less than 10m
    b) 11 – 50m
    c) 51 – 100m
    d) 101 – 150m
    e) More than 150m

23. How many cattle do you have?
    None
    Less than 50 cows
    51 – 100 cows
    101 – 150 cows
    151 – 200 cows
    More than 200 cows

1. How much water each requires per day
    a) Less than 10Litter per day
    b) 11 – 15 litter per day
    c) 16 – 20 Liter per day
    d) 21 – 25 Liter per day

24. How many planting seasons do you have in a year? (please tick one and justify)
    a) 1 Season
    b) 2 Seasons
    c) 3 Seasons
    d) More than 3 seasons

25. Which type of irrigation did you use, previously?

26. Which type of irrigation do you use, currently?
    a) Manual
    b) Drip irrigation
    c) Sprinkler
    d) Others

27. What is your source of irrigation system?
    a) Man power
    b) Diesel generator
    c) PV system
    d) Others

28. In your opinion does the electricity-systems lead to an impact on

	Yes, or No
Agricultural/livestock productivity	
Other (productive) activities *please specify/describe*	

29. Do you use electricity in your cooperative for increasing production (yes or no)?

30. If yes, what is the electricity is used for?
    Please tick more than one if appropriate

    Pumping (irrigation)
    Water pumping for cattle drinking
    Lighting of Poultry /Livestock
    Veterinary service (refrigeration, lighting, etc)
    Refrigeration (Agricultural products, dairy, fish, etc.)
    Office equipment (computers, etc.)

31. What beneficial impact(s) did the systems have?
    please check, more than one if necessary
    Higher productivity (higher yield)
    More land to be cropped
    Multiple crops per year
    New, more marketable product
    More animals can be raised
    Lower losses (death rate) or faster production
    Better quality product (higher prices/more sales)
    Access to more profitable markets (e.g. Through conservation of product for transport)
    Better natural resource management
    Others

32. Could you quantify these benefits?

If possible please describe quantitatively the impact indicated above, e.g. how much more income was earned or how much crops were produced/sold, etc

33. Were there other positive or negative impacts?

If yes, please, describe any impacts not yet covered or that need further explanation.