PAN-AFRICAN UNIVERSITY
INSTITUTE OF WATER AND ENERGY SCIENCES
(Including climate change)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

ENERGY POLICY

Presented by

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Environmental and Economic Cost Analysis of a Solar PV, Diesel and hybrid PV-Diesel water Pumping Systems for Agricultural Irrigation in Rwanda: Case study of Bugesera district

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Academic Year: 2017-2018

DEDICATION

This Master thesis is highly dedicated to the Almighty God.

DECLARATION

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

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CERTIFICATION

This is to certify that the master's thesis entitled **"Environmental and Economic Cost Analysis of a Solar PV, Diesel and hybrid PV-Diesel water Pumping Systems for Agricultural Irrigation in Rwanda, Bugesera district"** is a record of the original bona fide work done by Jean Baptiste RUTIBABARA *in partial fulfillment of the requirement for the award of Master of Science Degree in Energy Policy track at Pan African University Institute of Water and Energy Sciences(Including climate science)- PAUWES during the Academic Year 2017-2018.*

Signature:  **Date: 15/09/2018**

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ABSTRACT

Rwanda agriculture sector has a significant impact on country's economy whereby 80% of population depend on agriculture. Poor performance of agriculture sector affects economic development in different angles as 91% of food consumption and 34% GDP are from national agriculture. One of the critical problems currently being faced by Rwandan government is to ensuring sustainable food production. Many irrigation projects were started with the principal objective of enhancing agricultural production while avoiding dependence on rain-fed agriculture, but the problem of power to pump water is still a major barrier. Therefore, that's why several economic analyses have been conducted in this thesis to establish the most cost effective solution for irrigation and to evaluate the project profitability toward the country's vision 2020.

This study intends to analyze environmentally and economically the cost of a solar PV, Diesel and hybrid PV-Diesel water pumping systems for agricultural irrigation in Rwanda.The HOMER optimization software was used to evaluate both the environmental and economic viability of the proposed pumping systems by taking into account the variations of both the solar radiation and diesel price. Although this master thesis has used Bugesera (Rwanda) as case study, PVWP technology can be applied for agricultural irrigation purposes all over the world especially in rural areas applications leading to higher incomes and better living conditions for farmers. Results show that using PVWP systems for agricultural irrigation is the most profitable when compared to the rest two alternatives. It was found that the costs of producing one unit of energy by PV system are lower than the rest two systems. The HOMER results show that COE for solar PV, Diesel and hybrid PV-Diesel systems are 0.192, 0.367 and 0.289 $/kWh respectively.

Finally the research found that by replacement of DWP with PVWP systems results to reduction of CO_2 emissions by 14.48 tonnes over DWP and 1.25 tonnes over hybrid PV-Diesel systems yearly. Although, PVWP has more advantages of reducing CO_2, there are also some disadvantages such as soil, farmland and grassland degradation and wildlife disturbance. However, Solar PV water pumping systems can contribute significantly positive to Rwanda economic development if all the identified barriers are well removed.

Keywords: Photovoltaic system; pumping system; economic analysis; CO_2 emissions; irrigation; Rwanda.

RÉSUMÉ

Le secteur agricole rwandais a un impact significatif sur l'économie du pays, 80% de la population dépendant de l'agriculture. La mauvaise performance du secteur agricole affecte le développement économique sous différents angles puisque 91% de la consommation alimentaire et 34% du PIB proviennent de l'agriculture nationale. L'un des problèmes critiques auxquels le gouvernement rwandais est actuellement confronté consiste à assurer une production alimentaire durable. De nombreux projets d'irrigation ont été lancés dans le but principal d'améliorer la production agricole tout en évitant la dépendance vis-à-vis de l'agriculture pluviale, mais le problème du pouvoir de pomper l'eau demeure un obstacle majeur. C'est pourquoi plusieurs analyses économiques ont été effectuées dans cette thèse pour établir la solution la plus rentable pour l'irrigation et évaluer la rentabilité du projet par rapport à la vision du pays pour 2020. Cette étude vise à analyser de manière écologique et économique le coût d'un système de pompage solaire PV, diesel et hybride PV-Diesel pour l'irrigation agricole au Rwanda. Le logiciel d'optimisation HOMER a permis d'évaluer la viabilité environnementale et économique des en tenant compte des variations du rayonnement solaire et du prix du diesel. Bien que ce mémoire ait utilisé le cas de Bugesera (Rwanda) comme étude de cas, la technologie PVWP peut être utilisée à des fins d'irrigation agricole dans le monde entier, en particulier dans les zones rurales. Les résultats montrent que l'utilisation des systèmes de PVWP pour l'irrigation agricole est la plus rentable par rapport aux deux autres alternatives. Il a été constaté que les coûts de production d'une unité d'énergie par système PV sont inférieurs à ceux des deux autres systèmes. Les résultats de HOMER montrent que les COE pour les systèmes solaires photovoltaïques, diesel et hybrides PV-Diesel sont respectivement de 0,192, 0,367 et 0,289 $ / kWh. Enfin, les recherches ont montré que le remplacement du DWP par des systèmes PVWP entraîne une réduction des émissions de CO2 de 14,48 tonnes par rapport au DWP et de 1,25 tonne par rapport aux systèmes PV-Diesel hybrides chaque année. Bien que la PVWP présente plus d'avantages à réduire le CO2, il existe également des inconvénients tels que la dégradation des sols, des terres agricoles et des prairies et la perturbation de la faune. Cependant, les systèmes de pompage d'eau PV solaire peuvent contribuer de manière significative au développement économique du Rwanda si toutes les barrières identifiées sont bien éliminées.

Mots-clés: Système photovoltaïque; système de pompage; analyse économique; Emissions de CO2; irrigation; Rwanda.

ACKNOWLEDGEMENTS

First of all, I would like to give thanks to the Almighty God who has walked with me throughout this journey and before. Without the constant guidance and protection of the Lord, this master thesis would be a dream.

Secondly, my special thanks are addressed to African Union Commission and GIZ for giving the opportunity and providing me all the requirements in terms of financial support to accomplish my master's studies. I thank them so much.

Thirdly, I would like to express my sincere appreciation to my supervisor Dr. Wojciech M. Budzianowski for review of this thesis in detail and his important feedback. This Professor has patiently encouraged and guided me to do the best work throughout each stage.

Finally, I send many thanks to my family for their invaluable care, encouragement and support throughout my study. Because this work would not have been possible without the love and support of my parents, brothers and sisters, immediate family and friends who have always encouraged and believed in me, in all my endeavors. In fact, I received great inspiration from their love and friendship, even from thousands of miles away.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternate current
COE	Cost of energy ($/kWh)
DC	Direct current
DWP	Diesel water pumping
EAC	East African Community
EDPRS	Economic Development and Poverty Reduction Strategy
EICV	Enquête Intégrale sur les Conditions de Vie des Ménages
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
g	Acceleration due to gravity (9.8 m/s2)
G	Daily irradiance on the PV surface (kWh/m2/day)
GDP	Gross domestic product
GHG	Greenhouse gasses
GIS	Geographic Information System
Ha	Hectare
HDPE	High Density Polyethylene
HOMER	Hybrid Optimization Model for Electric Renewables
ICC	Initial capital cost ($)
IEA	International Energy Agency
IMP	Irrigation Master Plan
IRENA	International Renewable Energy Agency
IWR	Irrigation water requirement (mm or m^3/ha /day)
kWh	Kilowatt-hour (Unity of energy)
LCOE	Levelezed Cost of Energy (($/kWh)
MINAGRI	Ministry of Agriculture and Animal Resources
MININFRA	Ministry of Infrastructure
MPPT	Maximum power point tracker
N	Project lifetime (year)
NGOs	Non-Governmental Organizations

NISR	National Institute of Statistics of Rwanda
NPC	Net present cost ($)
NREL	National Renewable Energy Laboratory
O&MO	Operating and maintenance ($)
OC	Operation cost ($/year)
PAUWES	Pan African University Institute of Water and Energy Sciences
PBP	Payback period (year)
PV	Photovoltaic
PVWP	Photovoltaic water pumping
RAB	Rwanda Agriculture Board
RDB	Rwanda Development Boar
RWF	Rwandan Francs
SPTAR	Strategic Plan for the Transformation of Agriculture in Rwanda
SSIT	Small-Scale Irrigation Technology
TBA	To Be Announced
TDH	Total dynamic head (m)
V	Volume of water (m^3)
VAT	Value Added Tax
ρ	water density (1000 kg/m^3)

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CHAPTER ONE: INTRODUCTION

1.0. Thesis overview and outlines

The rapid increases of population and climate change will continue to raise the issue of food security. Agricultural productivity is very much affected due to variability of rainfall and drought (Bhattarai, M. et al., 2002).Von, B. J. et al. declared that farmers in rural areas have suffered from chronic poverty and severe food insecurity being vulnerable to climatic changes and dependent on variable rainfall. This is mainly attributed to a low level of agricultural productivity characterized by persistent rural poverty, and increasing population pressure has often resulted in a vicious circle of poverty and environmental degradation (Von, B. J. et al., 2008).

In order to solve those issues, agriculture is one of the sectors which need to be improved. As many of the low productivity areas have untapped water resources, irrigation development is being suggested as a key strategy to enhance agricultural productivity and to stimulate economic development (Bhattarai, M. et al., 2002). The irrigation system is promoted to increase crops productivity up to 5 times more than the crops harvested without application of irrigation (Maimbo, M.M.et al., 2010; MINAGRI, 2016). (Hussain, I. et al., 2001; Smith, L., 2004) confirmed that irrigated farming is recognized as central in increasing land productivity, enhancing food security, earning higher and more stable incomes and increasing prospects for multiple cropping and crop diversification. After floods and cyclones that occur in the rainy season, the introduction of irrigation in the subsequent dry season will allow farmers to grow an additional crop and facilitate an early recovery (FAO, 2014).

Water and energy are the main drivers and form an engine to the development of agriculture. In global, agriculture occupies a big portion of water and energy consumption where about 70% of freshwater withdrawals are utilized in that sector while energy used accounts 30% of energy consumption (U.S. Department of Energy, 2014). In fact those figures will keep increasing with expected population growth. According to (Gebrehiwot, N.T. et al., 2015; Thrupp, L.A., 1998), a doubling in global food demand projected for the next 50 years poses huge challenges for the sustainability both of food production and of terrestrial and aquatic ecosystems and the services they provide to society.

In regions where available rainfall is not able to meet the water requirements of irrigation or the water resource is mainly underground water, pumps are needed to take water to the point of use (Sawa, A.P. and Frenken, K., 2001). Water pumping worldwide is generally dependent on conventional electricity or diesel generated electricity (Foster, R. et al., 2014). From the environmental perspective, agriculture is among the sectors mostly causing global warming due to the use of fossil fuels to power generators which produce greenhouse gas emissions which are harmful to the environment and human life. In Worldwide, the total energy consumed by agriculture sector is estimated to $7.7*10^6$ GWh per year. Only 29.6% of renewable energy such wind, photovoltaic, hydroelectricity and biomass contribute to the total energy use for irrigation (Bardi, U. et al., 2013). Solar water pumping can be used to minimize the dependence on diesel, gas or coal based electricity. The uses of diesel water pumping systems require not only expensive fuels, but also create noise and air pollution. The overall upfront cost, operation and maintenance cost, and replacement of a diesel pump are 2 to 4 times higher than a solar photovoltaic (PV) pump (Foster, R. et al., 2014). However solar energy system is environment friendly; require low maintenance with no fuel cost and a source which can be found all over the world for free.

This thesis consists of the following chapters:

Chapter 1 Introduction

To introduce the background information, problem statement, objectives, Significance of the study and thesis outline.

Chapter 2 Literature review

To review the situation of agriculture sector in Rwanda, conceptual framework, methods and technologies of irrigation, and the work conducted regarding the development and application of PVWP system.

Chapter 3 Methodology and description of models

To describe the methodology and models adopted for simulations, optimization, and environmental and economic evaluation.

Chapter 4 Results and discussions

To present the main results achieved in this thesis and underline the main discussion points for findings.

Chapter 5 Conclusions and recommendations

To highlight the main findings of this master thesis and suggest some recommendations for government and future researchers.

1.1. Background

Rwanda is a small land-locked country of 26,338 km^2 in area with a population of 11,689,696 people (national census, 2012). It is a country located in central Africa and whose geographical coordinates are between $1^0$04' and $2^0$51' latitude South and between $28^0$45' and $31^0$15' longitude East (NISR, 2013). In 2014, GDP in Rwanda was 643 USD/capita (Ministry of infrastructure, 2015). Consequently its population density is among the highest in Africa with 407 persons/ sq. km, while the majority of its population living in rural areas and surviving on subsistence agriculture (Mbonigaba, M.J.J., 2013).

Agriculture sector has a significant impact on Rwanda's economy whereby 80% of population depend on agriculture (Mbonigaba, M.J.J, 2013). Poor performance of agriculture sector affects economic development in different angles as 91% of food consumption, 34% GDP and 70% of the revenue are from national agriculture (Bizimana, C. et al., 2012; Harding, B., 2009).The rainfall pattern of Rwanda is above 1500 mm in mountainous western regions of the country and below 700 mm in eastern regions. The average annual temperature in Rwanda is between 15-17℃ in high altitude areas and up to 30℃ in lowlands in the east and southwest (Netherlands Commission for Environment Assessment, 2015).

The popular irrigation methods used in Rwanda are watering can which provides a simple and accessible irrigation technique that is understandable and widely practiced by small-scale farmers for vegetable production but it is labour intensive and allows irrigation of only a small garden (50 to 100 m^2) and motorized which uses diesel fuel to pump water (FAO, 2014). In Rwanda, there are two (2) main rainy seasons in Rwanda. These are Season A which starts from September and ends in January of the following calendar year and Season B that starts from February and ends in July. There is also dry season C that begins in May and ends in September (MINAGRI, 2016). The main water resources used in Rwanda for irrigation are lake, river, runoff for small reservoirs, runoff for dams, flood water, marshlands and groundwater resources (IPAR Rwanda, 2009).

Figure1. 1 Administrative map of Rwanda

Source: www.minaloc.gov.rw

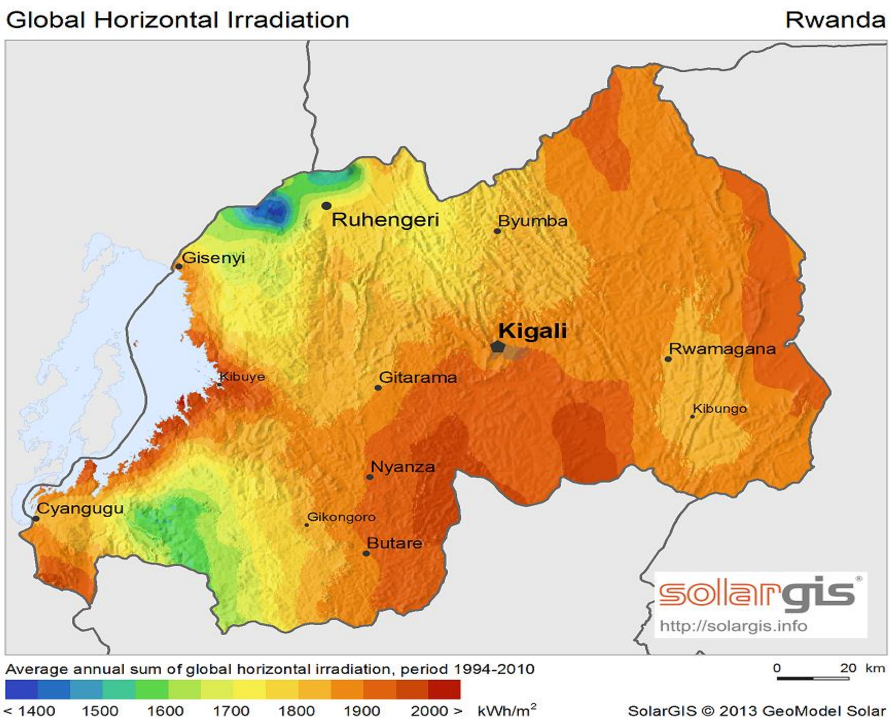


Figure 1. 2 Global horizontal irradiation map of Rwanda.

Source: PVGIS, 2018

1.2. Problem statement

The demand for food in Rwanda is growing dramatically due to the increasing country population while cultivated land is decreasing. The Government of Rwanda has committed to exploiting its irrigation potential by use of both surface and underground water sources to address food security with the goal of ensuring sustainable production of food, cash, export and industrial crops. Many irrigation projects were started with the principal objective of enhancing agricultural production while avoiding dependence on rain-fed agriculture and thus, decreasing production risk and volatility (MINAGRI, 2016). But irrigated area is still small (48,508 Ha) compared to the total national cultivated area (1.75 million Ha) (Bizimana C. et al., 2012).

Presently, electricity shortage in Rwanda is a major barrier to the national agriculture development. In fact, the agriculture is the most affected sector due to the fact that almost 80% of Rwanda population depend on agriculture (Mbonigaba, M.J.J., 2013) and irrigation system becomes expensive due to the lack of power for water pumping system. Generally, the common agriculture irrigation technologies used in Rwanda are watering with cans technology which is labour intensive and allows irrigation of only a small area (50 to 100 m^2) and Diesel motorized technology which causes air pollution while solar PV technology is still behind.

In 2014, Food and agriculture Organisation of the United Nations (FAO) stated that climate change, and the expected increase in the frequency and severity of extreme weather events, will affect the agriculture sector, thereby increasing the risks faced by the rural populations, the majority of which are dependent on agriculture for their livelihoods and food security.

Increasing of climate change and human population have increased the reduction of agricultural production due to droughts and the reduction of cultivated land and forced the farmers to find other alternative energy sources for water pumping system for irrigation. Therefore, that’s why this study was conducted to find out the least cost and suitable technology among the existing technologies, and to identify barriers and to suggest policy initiatives to overcome those barriers for Rwanda agricultural irrigation development.

1.3. The objectives of study

1.3.1 Main objective

The main objective of this study is to analyze economically and environmentally the cost of a Solar PV, Diesel and hybrid PV-Diesel water Pumping Systems for Agricultural Irrigation in Rwanda.

1.3.2 Specific objectives

To analyze economically and environmentally the cost of a Solar PV, Diesel and hybrid PV-Diesel water Pumping Systems for Agricultural Irrigation in Rwanda, it is necessary to take account the following specific objectives:

- To assess potential of solar energy and water within selected areas of Bugesera district for irrigation
- To determine with HOMER software the least cost technology among of these three technologies of water pumping for irrigation in Rwanda.
- To investigate environmentally the effects of diesel and PV water pumping systems.
- To identify the barriers and drivers of diffusion of water pumping system for irrigation in Rwanda.
- To assess existing policies supporting agricultural in Rwanda.

1.4. Research questions

- Is solar energy suitable to replace diesel as main source of water pump in (Bugesera) Rwanda?
- What is the least cost technology among of a solar PV, Diesel and hybrid PV-Diesel water Pumping Systems for agricultural irrigation in Rwanda?
- Are solar PV and Diesel water pumping systems having negative effects on environment?
- What are the barriers and drivers of diffusion of agricultural irrigation in Rwanda?
- Which are the policies supporting agricultural in Rwanda?

1.5 Scope of the study

This study aims to analyze economically and environmentally the cost of solar PV, Diesel and PV-Diesel hybrid water pumping systems for agricultural irrigation. The case study located in Rwanda, Eastern province, Bugesera district. This district has been chosen because it is a dry region in Rwanda, thus the irrigation system is needed in that region to regulate food issues. The study was undertaken in Rwanda (Bugesera) from March up to July 2018 for collecting data and making analysis of them.

1.6. Significance of the study

This project will help government for reinforcement agriculture policies to achieve the goals of economic development and poverty reduction strategy by improving the use of irrigation which leads to increase agricultural production. This study will also help people to know how they can use the renewable energy especially solar energy to pump water for irrigation that will lead to increase their agricultural income and also will create jobs for companies which purchase renewable energy materials and for youths who are interested in agriculture sector. The study will also help the future researchers to gain more knowledge about the use of solar energy as power sources of water pumping system for irrigation. And it will also help researchers to address the solutions of droughts consequences for farmers. These solutions will lead to fight against famine in rural areas by applying irrigation programs in agricultural activities.

1.7 . Justification of case study

There are three primary reasons why this case study has been chosen.

- This area has a significant interest in irrigation due to the long term of dry season, abundant water resources in this area, intensive population growth and increased in food demand.
- This area has a significant interest in using solar energy water pumping systems because it has a centralized power system that affect power distribution in rural areas which leads to the lack of energy for pumping system in rural villages . Therefore the use of renewable energy (e. g: solar) is one of the best solution of energy needed in irrigation.
- Bugesera district must be protected from hunger and/or high agricultural production price.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

This chapter reviews empirical works done by other scholars in the field of agricultural irrigation and renewable energy (Solar). The purpose of this literature review is fourfold. First part of this chapter deals with conceptual framework and overview of agriculture sector for Rwanda.

Second part, water pumping systems for agricultural irrigation were identified and discussed. This is important because this study aims to bridge the gap by combining information about the contribution of irrigation especially using solar energy in increasing crop production from both academic literature and real-world practitioners.

The third part reviews agricultural irrigation water resources and energy resources for irrigation. The four irrigation methods are also reviewed: water cans or traditional, surface, drip and sprinkler.

The final part is focused to irrigated sites and 'institutional policies,' which is a sensitizing concept that is needed for this master's thesis. Policies which support agricultural sector are reviewed. These policies were used to evaluate the gap in agriculture policy.

2.2. Conceptual framework

The access to reliable energy is the main input for the assessment of impacts on economic development of the country through sustainable agriculture production. Figure 2.1 shows a possible conceptual framework which includes availability of energy resources, government and institutions policies, availability of affordable water pumping technology, opportunity and challenges for adopting irrigation applications, and social and environment aspects. From a farmer perspective, availability of pumping technology does not automatically mean actual access. There are several barriers and drivers in the decision to take-up the new technology need to be considered. The review of existing policies and identify such drivers of and barriers to adoption is one of the objectives of this thesis. Other objective of this study is to assess the affordability and impacts of adopting irrigation systems on environment and household welfare.

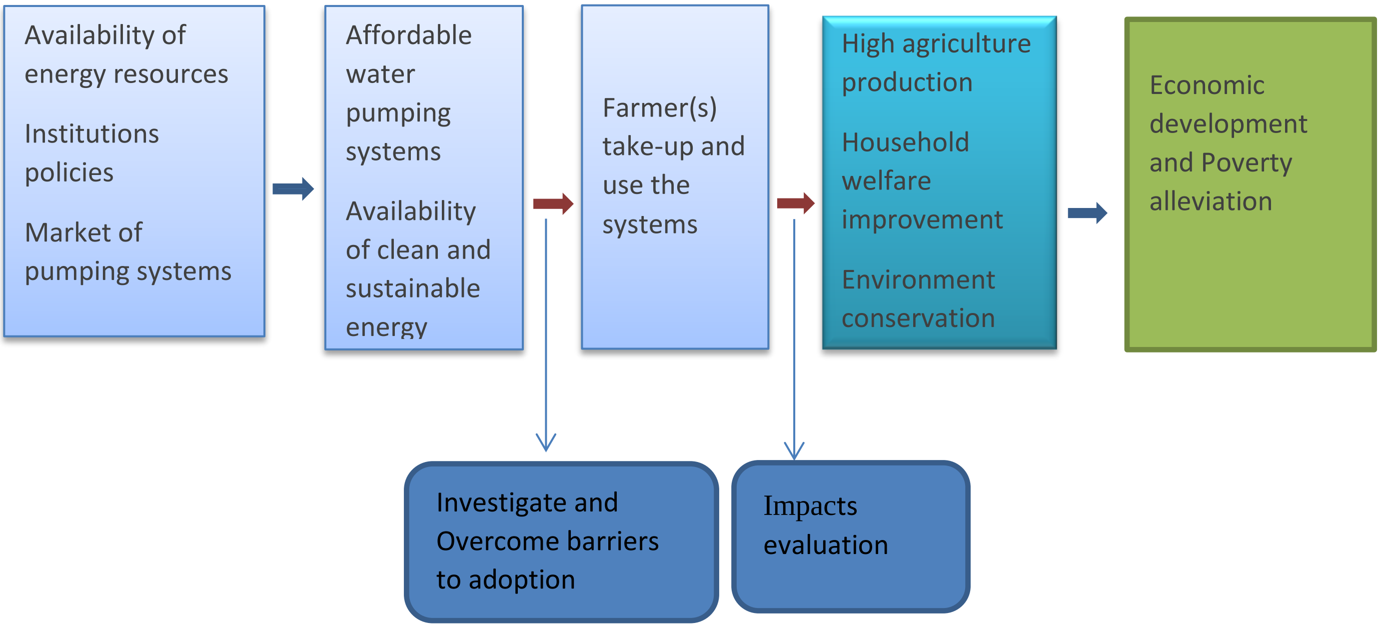


Figure 2. 1 Conceptual framework represents Relationship between objectives and research questions.

2. 3. Agriculture sector for Rwanda

2.3.1. Economic relevance of agriculture

Agriculture accounts for a third of the country's gross domestic product (GDP) (2009–2013) (World Bank, 2015). National economic growth projections are expected to depend heavily on the performance of the agriculture sector, which employs more than 80% of the country's population (FAOSTAT. 2014).

This sector also plays a key role for national food production where more than 90% of the food produced nationally is consumed in the country. Although agriculture contributes greatly to the country's export revenues, Rwanda is still a net agricultural importer. Generally, tea and coffee are leading export commodities concentrating more than 90% of the export crops value. The main crops grown in the country are beans, banana, cassava, and maize, accounting for 18.1%, 17.3%, 9.2%, and 9.5% of total harvested area (2008–2012). However, production of rice, maize, and beans does not meet the national demand, and therefore imports of these agricultural products are significantly higher (FAOSTAT. 2014).

There is an inclination for agricultural reinforcement due to heavy demographic pressure, resulting in a large amount of very small and scattered farms. In fact, small-scale farmers (less than 1 ha) account for 72.4% of total farmers in the country. Since more than 70% of agricultural land is on hills or the side of hills and commercial agriculture is more difficult (NISR, 2013).

Currently, Rwanda is finding a way to transform its traditional agriculture sector to modern method in order to have a sustainable management of natural resources, water and soil conservation. The strategies are being made to achieve the target include crop diversification and intensification and irrigation development (Boelee E. & Madsen H., 2006). In Rwanda, there are three agriculture seasons and each season has its specific crops grown in a certain portion as shown in table below.

Table 2. 1 Rwanda agriculture seasons and main crops grown

Season	Crop	Percentage (%)
Season A: starts in September of one year and ends February of the following year	Beans	27
	Bananas	19,7
	Cassava	12,6
	Maize	11,9
Season B: starts in Murch and ends in July of the same year	Bananas	17,9
	Beans	17,4
	Cassava	15,9
	Sorghun	14,6
Season C: starts in August and ends in September of the same year	Irishpotatoes	71
	Beans	14
	Vegetables	12

Source: (Basalike P., 2015)

2.3.2. Agricultural production systems and greenhouse gas emissions

Rwanda has a diversity of agriculture production systems spread throughout its various agro-ecological zones. The northern and western highlands are predominantly dedicated to monocrop cultivation, such as potatoes, tea, maize, wheat, climbing beans, and pyrethrum. The eastern lowlands are popular for banana, maize, bush bean, sorghum, and cassava production. In the central and southern regions, farmers cultivate sweet potatoes, bush beans, tea, coffee, cassava and wheat (World Bank, 2015).

Livestock farming is both small- and large-scale and includes cattle, sheep, goats, rabbits, pigs, chicken, etc., usually reared under zero-grazing systems. The farmers with relatively large land endowments (above 5 ha per farm) are located in the eastern savannah (Nyagatare, Gatsibo, and Kayonza districts). Sugar cane is grown in Nyabugogo, Kagera and Nyabarongo swamps located in Gasabo, Gicumbi, Kamonyi, and Bugesera districts.

Irrigated rice is grown throughout the country in swamps and extension of rice areas is ongoing. Agriculture industries include tea, coffee, pyrethrum, sugar processing plants and industries producing maize flour, soybean oil, packed milk and its sub-products are developing (World Bank; 2015).

Total greenhouse gas (GHG) emissions in Rwanda are relatively low compared to regional and global averages, but trends show a slight increase since 2010 (WRI, 2015).The agricultural sector contributes significantly (45.6%) to the country's total GHG emissions (FAOSTAT, 2014).

2.3.3. Rwanda Agriculture and climate change

The Rwandan agricultural sector is highly vulnerable to climate and weather-related risks, including prolonged droughts (especially in the eastern and Southeastern regions), mudslides (especially in the northern and western regions), unpredictable rains, floods and hailstorms. The variable rainfall in 2008 caused maize yield losses of 37% in the eastern province and 26% in the southern province. Milk production losses were estimated at 60% in times of a drought (Kagabo, D.M. & Ndayisaba, P.C., 2015). Research indicates that rainfall patterns are becoming more irregular and unpredictable with shorter rainy seasons negatively affecting Rwandan agricultural production (McSweeney, R., 2011).

Moreover, estimates from the fourth IPCC assessment report indicate that average surface temperature in Africa has increased by 0.2 to 2.0 °C in the last four decades (1970–2004), expecting an overall increase in annual temperatures (by 1.0° C–2.0° C) over the next century (2010–2100) in Rwanda (IPCC, 2007). For that reason, Rwanda has taken a proactive approach in mainstreaming climate change into its development policies and strategies. Main national development documents, such as Vision 2020, the Economic Development and Poverty Reduction Strategy (EDPRS), the Strategic Plan for the Transformation of Agriculture in Rwanda (SPTAR), and the Irrigation Master Plan (IMP), recognize climate change and variability as the greatest challenge and threat to the development agenda(World Bank; 2015).

2.4. Water pumping systems for agricultural irrigation

Water pumping system has a long history and many methods have been developed to pump water to use for different purposes like irrigation, domestic use, industries with a minimum of effort (Prakhar, M., 2013).The irrigation systems have the role of taking water from source, conveying it to individual fields within the farm and distribute it to each field in a controlled manner. Depending on elevation and location of water resources, two methods of irrigation can be used. When water surface is situated on higher slope, the gravity method is used while when source of water is underground or at low slop, the pumping system which is also known as pressure method is required to take water to the point of use (Basalike, P., 2015). About 85% of African water withdrawals are used for irrigation (James, 2012).

In Rwanda, many projects are being studied on how to improve agriculture productivity by combating the effects of climate change such droughts, irregular rainfalls and landslides. The one of measures taken to deal with these problems are to put much effort on providing irrigation to hillside farms (Derrel, L., 2011). There are some considerations such as land slope, soil permeability and type, plot size and crops, water availability, required labor inputs and economic costs/benefit have to be analyzed before carrying out irrigation. The most Rwandan cropped areas are irrigated using surface water resources by method of gravity especially for marshland areas.

However some regions of the country showed to have higher slope and so it is impossible to apply gravity method of irrigation. Those areas include Bugesera district with an altitude varying between 1,100 m and 1,780 m. Bugesera is hot district and is at the 17th position in the country to have a percentage of Households involved agriculture and livestock activities. Crop farming and livestock are important in the Bugesera district's economy where 77.8% of the population depend on agriculture against 72% for national average (Bugesera, 2012). Compared to other regions of the country, Bugesera district has dry climate with a temperature varying between 20°C and 30°C with an average ranging between 26°C and 29°C. In the past the district was turning into a dessert zone due to the long drought period that is why the sustainable agriculture is needed by enhancing irrigation system. In fact this district has abundant water resources (rivers and lakes) and good average solar irradiation of 5.6 kWh/m^2/day which may use for irrigation.

2.3.1. Solar PV water pumping systems for agricultural irrigation

Photovoltaic water pumping (PVWP) systems have been studied and installed for over 40 years in off-grid areas, especially for drinking purposes (Vick, B.D. & Neal, B.A, 2012). In spite of that, the expected fall in prices of PV modules due to the rapid worldwide growth of the PV market over past years, research on development of PV systems has boosted by encouraging larger system and new applications such as water pumping for irrigation

(Foster, R. et al., 2014). PV water pumping systems allow users to avoid the constraint of the high fuel costs for motorized pumps. The electric pumps linked to the solar energy units have proved reliable and have low maintenance costs. Energy outputs of solar panels are limited, however, and in most cases a solar-driven electric pump may irrigate only a small land area of 0.3 to 1 ha (FAO, 2014).

The solar pump unit includes solar panels, a battery pack with current regulator unit for energy storage, and an electric motor linked to the water pump. To irrigate effectively, water needs to be stored in a water reservoir or tank and connected to a low pressure pipe system or drip system.

Figure 2. 2 Solar panels, pump and reservoir for drinking water and garden irrigation
Source: FAO, 2014

- **Principle of a solar water pump**

Solar water pumping system is based on PV technology that converts sunlight into electricity to pump water. The PV panels are connected to a motor (DC or AC) which converts electrical energy supplied by the PV panel into mechanical energy which is converted to hydraulic energy by the pump. The capacity of a solar pumping system to pump water is a function of three main variables: pressure, flow, and power to the pump. For design purposes pressure can be regarded as the work done by a pump to lift a certain amount of water up to the storage tank. The elevation difference between the water source and storage tank determines the work, a pump has to do. The water pump will draw a certain power which a PV array needs to supply (Chandel, S.S. et al., 2015).

A PVWP system for irrigation typically consists of five main components: PV array, power control unit, pumping system, storage unit, and irrigation distribution system (Gopal C. et al., 2013). In the case of the storage system being a battery bank, a charge controller interfaces the PV module with the battery and the power-conditioning unit.

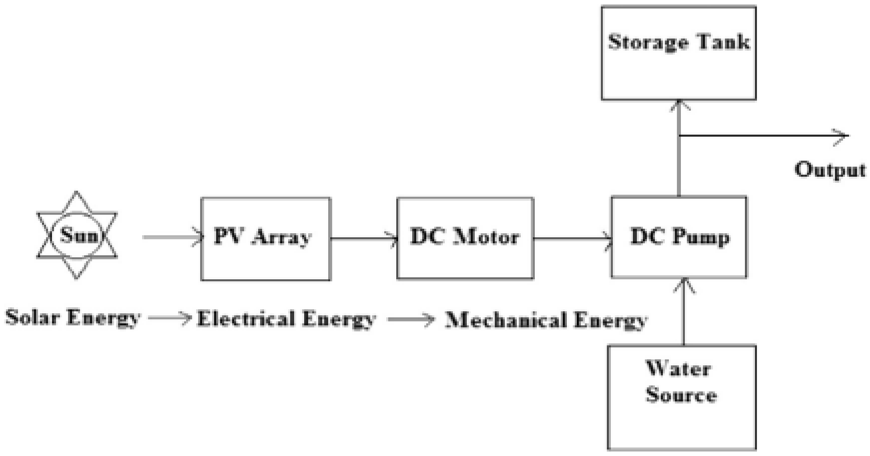


Figure 2. 3 Block diagram of a direct coupled PV DC water pumping system.

Source: Chandel S.S. et al. , 2015

Many researches have discussed the feasibility of using the PV and diesel generator in running the water pumping systems in remote or isolated areas in different locations in the world. Most of them have highlighted on how solar powered pump for irrigation can be considered an attractive application of renewable energy.

A study conducted by (Electric Light Fund (SELF), 2008) focused on a cost and reliability comparison between solar and diesel powered pumps, showed the advantages of Solar PV pumping system. The results indicated that solar pumping systems are more reliable and cost-effective than diesel powered systems. Although Solar PV powered pumps requires a higher up-front investment but its ongoing operation and maintenance costs are very low. Diesel pumps are the opposite; they are typically characterized by a lower first cost but a very high operation and maintenance cost. (Nazmul et al., 2015) analyzed the feasibility of replacing diesel irrigation pumps with solar PV powered motor-pump systems in HOMER and he stated that the use of diesel run pumping system is neither cost effective nor environment friendly.

In 2012, Teoh et al. analyzed the techno-economic and carbon emission for a 1MW grid-connected PV system in Malacca, Malaysia by using HOMER optimization software and demonstrated that the system has long-term benefits as compared to other stand-alone systems. (Hamidat et al., 2003) developed a model to test the performance of PV Water Pumping systems for irrigation in regions of the Sahara. The study showed that PVWP systems are suitable for irrigating crop in small-scale. (Kamel et al, 2005) analyzed economically the cost of hybrid power systems versus the diesel generation for a remote agricultural irrigation development and concluded that hybrid systems provide less costly electricity compared to diesel-powered systems as analyzed from their net present cost (NPC). (Jun et al., 2014) estimated the CO_2 emissions of a PV water pumping (PVWP) system over the project lifetime. The results showed that the PV technology has great potential for global warming mitigation, especially if used to irrigate degraded grassland.

Pie Basalike has conducted a design, optimization and economic analysis of photovoltaic water pumping technologies in Rwanda. The results demonstrated that using PVWPs directly connected to irrigation system is the most profitable way when compared to PVWPs connected with tank storage or battery. (Kelley et al., 2010) investigated the technical and economic feasibility of PVWP systems for agricultural irrigation; they concluded that there are no technical barriers for implementation of PVWP systems. The major challenge of PVWP systems is the high initial cost of PV modules. On other side, DWP systems have a much lower initial capital cost (ICC). Usually DWP systems have been considered to be the best techno- economic choice from many years ago, particularly when the decision making process based on low initial capital cost. Nevertheless, the decline in the price of PV modules will continue to help the boosting of the PV market and making PVWP systems more competitive with other pumping systems. The study conducted in India by (Chandel et al., 2015) was confirmed that solar water pumping is economically viable in comparison to electricity or diesel based systems for irrigation and water supplies in rural, urban and remote regions. And also it was found that the investment payback for some PV water pumping systems is to be 4–6 years.

Assessment study of economic viability of PV/wind/ diesel hybrid energy system in southern peninsular Malaysia has been examined by (Ngan, M. S. and Tan, C. W., 2012), the results confirmed that hybrid systems are the best option as a replacement to stand-alone systems due to their low cost of energy generation with significantly low CO2 gases emission, therefore, supports clean and green environment. (Foster et al., 2014), they have found that the overall upfront cost, operation and maintenance cost, and replacement of a diesel pump are 2–4 times higher than a solar photovoltaic (PV) pump. According to (Meier, 2011) PVWP overcomes all disadvantages such as greenhouse gas emissions, fuel price fluctuations, and fuel and oil spills. (Gao et al., 2013) confirmed that when taking into account overall investment costs, the PVWP system was shown to have a payback period of eight years, hence demonstrating an excellent economic return.

2.3.2. Hybrid PV-Diesel Systems

Hybrid systems can be a combination of renewable energy technologies (generally wind and solar) and conventional systems (diesel, kerosene/gasoline/ systems, storage batteries and grid connections). A combination of renewable energy systems with grid power for a water pumping system is not the best option especially in developing countries because grid power is normally reliable and the cheapest option for water pumping applications. The hybrids of solar PV, wind, and diesel/ gasoline/kerosene power generation systems are most commonly used to pump water in different rural areas of developing countries. However, in most developed countries utility companies combine hybrid systems with grid power supply to compensate for peak hour power demands because incentives are making renewable energy financially attractive (Argaw et al. , 2003).

Hybrid systems can provide a reliable power source for a village in many developing countries. These systems can supply power for community services (water pumping, phone charging, health clinics, school, home and street lighting etc.). For this reason, hybrid systems are becoming more interesting for stand-alone applications.

Generally, the possible hybrid systems for water pumping applications are PV with diesel generator, wind turbines and storage batteries with a backup diesel generator, PV and batteries, wind turbines and PV with batteries, or wind turbines with batteries. In this thesis, hybrid system of PV with diesel generator is chosen to be compared economically and environmentally with stand-alone PV and diesel pumping systems. The power sources of hybrid system are mutually independent for water pumping, for example, in cloudy days or night when solar energy is low or absent, diesel can be used to compensate. Therefore, hybrids present truly reliability for a water pumping system than wind and PV systems alone.

Hybrid systems are not designed for worst climatic conditions because power does not come from a single source. However, although these systems are helping in reliability of the system and are reducing the overall size of the power system, their initial costs are still high because of the costs of the required central control system and power conversion units such as DC–AC inverter, DC–DC converter and AC–DC rectifier. In addition, a highly skilled labour must be available to maintain the systems (Argaw et al., 2003).

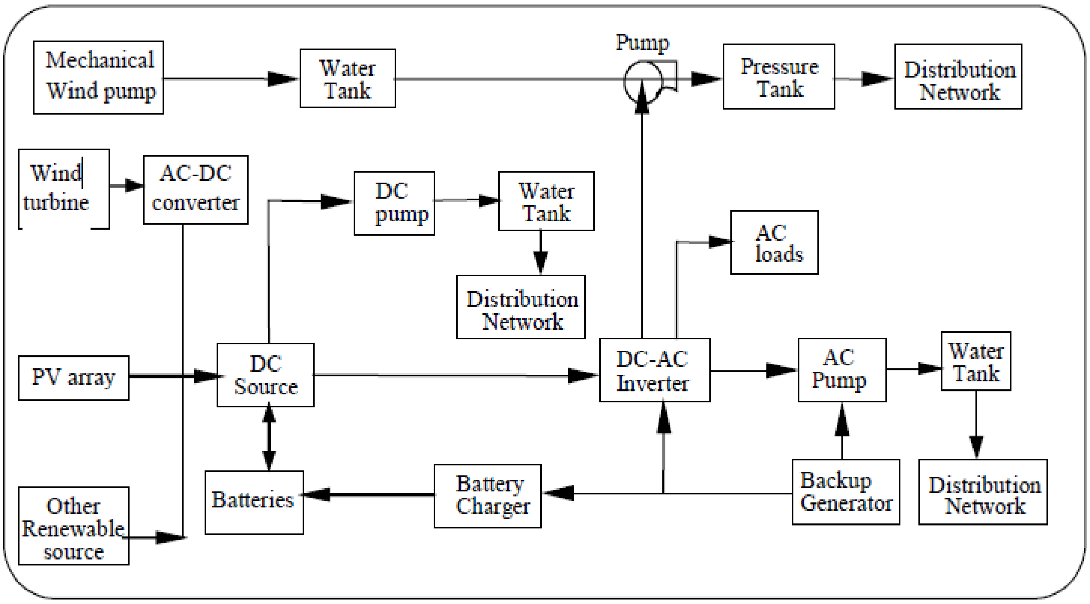


Figure2. 4 Schematic presentation of stand-alone hybrid power sources with a backup generator for water pumping applications

Source: (Argaw et al., 2003).

2.4. Agriculture water resources

The available water resource is an important criterion for choosing the kind of energy sources for any given water pumping application. Water can come either from groundwater or surface water. Surface water includes lakes, rivers, seawater, and rainwater whereas groundwater is found in underground aquifers, including springs. Spring and underground water does not commonly require treatment, except when it contains chemical substances such as salt and fluoride (Argaw et al., 2003). Generally, the water treatment is not the main issue for irrigation purposes as long as it does not contain chemicals harmful to the soil and the crops.

According to (Argaw et al., 2003) the quality of the water is another important factor in identifying water resources. If the water will be used as a domestic water supply, treatment may be needed. Nevertheless, water quality may be less important for irrigation and livestock watering except if it contains harmful chemicals. For example Saltwater can burn some crops and damage soils.

Usually, agriculture requires the use of fresh water to irrigate crops. On Earth, 2.5% of the total global water is the fresh water, 68.6% of which is in form of glaciers and ice caps, 30% lies under the ground in rock fractures and soil pores, and remaining 1.4% lies over the surface in form of rivers and lakes (Prakhar, M., 2013). Groundwater forms a major source of fresh water for agricultural uses. India and China inhabit about 37% of the world's population, but have only 9% of the world's groundwater resources. In China, groundwater is used to irrigate more than 40% of the total arable land and to supply 70% of drinking water. India alone accounts for over 56.1% of global groundwater withdrawal for irrigation every year (Prakhar, M., 2013).

The main water resources used for Rwanda irrigation system are runoff for small reservoirs, runoff for dams, direct river and flood water, lake water resources, groundwater resources and marshlands (IPAR Rwanda, 2009).

2 .5. Energy resources for water pumping system

Power sources are mainly selected based on the technical, environmental and economical aspects of the power source, location, and social factors. Although reliability of the power source is the main factor, the system's affordability is another important selection factor, especially in rural areas of developing countries where income levels are very low. There are different sources of power that are used to pump water, such as renewable energy (hydropower, wind, solar, biofuels etc.), human energy, and fossil fuels for small generators (Prakhar M., 2013).

In developing country like Rwanda the choice of power source depends on the capacity of people because some sources of energy can't be obtained easily. Although Renewable energy source have been known and used for thousands of years, the general concept of renewable energy was introduced in the 1970s as part of an effort to move beyond nuclear and fossil fuels (IEA, 2012). The most common definition is that renewable energy is energy taken from a resource that is replaced rapidly by a natural, ongoing process. Under this definition, energy sources such as peat, fossil fuels and nuclear power are not renewable (IEA, 2012).

According to (Mahir and Semih, 2012), 15% of total energy consumption in crop production is for pumping irrigation water. The big contributors to this figure come from the countries such as India and US who have the share estimated up to 43 % and 23% of the total direct energy use respectively (Mahir and Semih, 2012). Generally the amount of energy required varies depends on method of irrigation applied. For example; flood irrigation method becomes less energy consumptive when compared to pressurized irrigation method because pressurized method needs too much energy to lift water at certain height.

Currently, the energy used to pump water for irrigation in Rwanda is mainly from electric grid and fossil fuels. In fact, those types of fuels have some limitations such as depletion of resources in future, rising their prices day to day, and environmental degradation. For this reason many researches have been conducted about finding out other alternative sources to replace non-renewable energy resources and one of the best option was solar energy, as energy source which is environmental friend and require less maintenance costs during its production (Cabeza et al., 2011)

Table 2. 2 Comparison of potential power sources for use in water pumping.

Power Source	Advantages	Disadvantages
Generator	1. Cheapest 2. Easy to install and operate	1. Expensive fuel 2. Short life expectancy 3. Require frequent maintenance 4. Polluting (when using diesel)
Wind Turbine	1. Cheaper when compared to photovoltaic 2. No fuel required 3. Clean	1. Very high maintenance costs 2. Effective only in high wind areas 3. Lower performance in low to moderate wind conditions 4. Skilled labor required to install
Photovoltaic	1. Low maintenance requirements 2. No fuel required 3. Clean	1. High safety requirements from theft and vandalism 2. Investment required to expand to match the power needs 3. Low performance on cloudy Day

Source: Prakhar M., 2013

2.6. Use of solar energy in the agriculture sector

All energy forms derive either directly or indirectly from solar energy. The biomass, wind, ocean thermal energy, hydropower, and tidal energy are indirect forms of solar energy. The Crop drying, solar-thermal electric power generation, solar heat collection, and direct conversion of solar energy into electricity are direct forms. Solar energy can be directly converted into electricity using either thermoelectricity or PV cells (FAO, 2014). Due to the PV cells for direct production of electricity from the sun are currently the most promising and broadly available technology that is why is emphasized in this thesis. Producing energy from solar energy is an important research and development field recently because solar energy resources can produce energy required in different activities but also it is produced by clean methods. Therefore, solar energy can be possible to prevent global climate change (Bilal, G. et al., 2014).

The exception to the African countries located closer to equator which has low potential in solar irradiation due to their location, the rests have a huge potential in solar energy of about 4 to 6 kWh/m2/day (Kavitha et al., 2014). The PV technology could produce energy need for Africans and even exceeds demand by 2050. This technology has high prosperity because the cost of solar photovoltaic (PV) technology to convert solar energy into usable power is declining day to day due to rapid improvement of technology and dramatic reduction in price of PV modules products from China (Abu-Aligah, 2011). Egypt is one of the solar belt countries and its economy depends on irrigated agriculture. Development of a solar pump for irrigation is important and worth investigation in Egypt (Korayem et al., 1986).The need of solar pumping system in Egypt is evident because of the over-population that gives rise to the quick need of inhabiting the desert. In 2000, FAO recognizes the solar photovoltaic (PV) system as a technology that is already providing energy services in many sites around the world, mainly at the household level, new income-generating activities and agricultural production (Bart et al., 2000). According to (Nshimyumuremyi E., 2015), a solar-powered pumping system is more reliable and required less maintenance compared to the other systems used in pumping.

Rwanda is well benefited with solar energy, even during the months of the rainy seasons there is daily and sufficient sunshine as indicated on Figure2.5, the average daily global solar irradiation on the tilted surface has been estimated to be 5.2 kWh per m^2 per day. The long term monthly average daily global irradiation range from 4.8 kWh/ (m^2 day) (location

Burera, month of May) to 5.8 $kWh/m^2/day$) (location Nyanza, month of July) (Uwisengeyimana J. de D. et al., 2016).

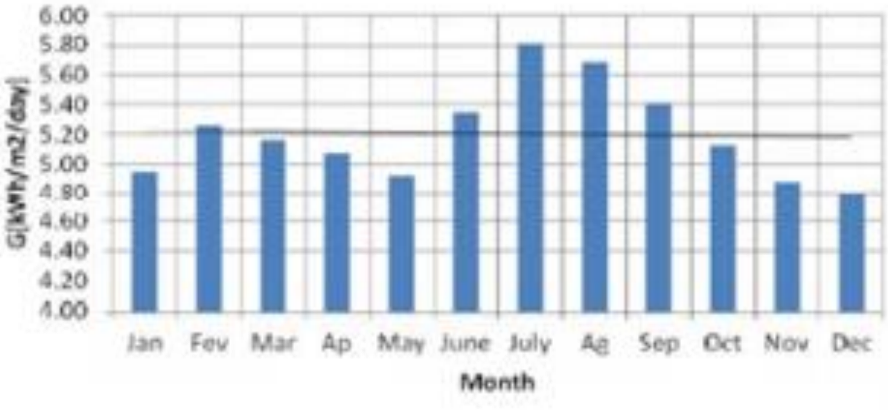


Figure 2. 5 Monthly average daily global solar irradiance in Rwanda

Source : Uwisengeyimana J. de D. et al., 2016)

Although Rwanda has higher potential, solar energy has very low contribution to the national agriculture sector. The most electricity produced from solar is connected to the national grid. Currently, Rwanda has 8.5 MW from on solar power plant located in Eastern Province which is the first utility scale solar farm in Sub-Saharan Africa outside of South Africa(Jerusalem Post, 2015). In additional, solar energy is used at the households, institutions and hotels levels as energy for lighting, water heating, TV, Radio and medical refrigerators operating (Harding, 2009).

Figure 2. 6 : Utility-scale of 8.5MW PV power plant constructed in Agahozo-Shalom Youth Village in Rwanda.
Source: Ministry of infrastructure, 2015

The above solar PV Power plant is 20 hectares of land and uses 28,360 photovoltaic panels and produces 6% of total electrical supply of the country. The project was built with U.S., Israeli, Dutch, Norwegian, Finnish and UK funding and expertise (Ministry of infrastructure, 2015).

Currently in Rwanda the mostly technology utilize to lift water for irrigation is diesel pumping system. The use of diesel pump to pump water causes different problems on human life and environment because it emits a huge amount of CO_2 emissions which cause respiratory diseases and global warming. According to (Mahir and Semih, 2012), different researches are being made with a focus to design solar photovoltaic water pumping systems which can provide electricity in isolated area that can be used for crop irrigation and in different home activities. In 2015 (Nazmul et al., 2015) stated that if there no big water storage tank, PV can produce excess electricity up to 84% which can be used in residential needs or can be used in other agricultural needs. The increase of oil price by 400%, rapid reduction in price of PV modules and higher solar insolation are the important factors which can accelerate the growth of solar power market and play a key role in studying the feasibility of harnessing solar energy in agriculture sector of Rwanda (Basalike P., 2015).

2.7. Types of agricultural irrigation methods

To warrant that the plants do not suffer from stress of over or less watering, it is essential to design a suitable irrigation system which delivers a predefined amount of water at the root zone of plant at regular time intervals. The design is made based on different factors. Those factors include water source, type of crop, power source, spacing of distribution system and peak water requirement. It is also to consider climate data such as rainy fall, temperature, humidity, and evaporation. In addition, the topography of the land (type of soil, clay or sands) and water quality are also additional input parameters to be taken into account (Kharagpur, 2015).

The main factors considered to choose the method used for irrigation are type of crop grown for example rice, the rice require standing water depths at almost all stages of its growth. On the other hand, potatoes suffer under excess water conditions and require only some amount of water to be applied at the right time. Another main factor determining the way water is to apply to the plants, the source and quantity of water available at the field. If water is scarce, it is necessary to be applied through carefully controlled methods with minimum amount of wastage. Usually these methods use pressurized flow through pipes in order to deliver water carefully near the plant roots (Kharagpur, 2015). On the other side when water is unlimited during the crop growing season, the river flood water is allowed to overflow as much area as possible as long the excess water is needed.

Generally, irrigation is an artificial application of water to the soil usually for assisting in growing of crops. Some types of irrigation methods include:

• Surface Irrigation
• Sprinkler Irrigation
• Drip Irrigation
• Manual Irrigation - using buckets or watering cans

2.7.1. Surface Irrigation

In surface irrigation, water moves over and across the land by simple gravity flow in order to wet and infiltrate the soil. Surface irrigation can be divided into furrow, border strip or basin irrigation. It is also called flood irrigation when it results in flooding or near flood of the cultivated land. Here, land leveling is required to avoid less flooded for high slope or over flooded for low slope. Therefore, the surface irrigation system should be able to apply an equal depth of water all over the field without causing any erosion. In this irrigation method, the water is applied directly to the soil from a channel located at the upper reach of the field (Maimbo, M.M.et al., 2010). It is essential in these methods to construct designed water distribution systems to provide adequate control of water to the fields.

Flooding method has been used in Rwanda for many years ago without any control, for that reason sometimes this method is called uncontrolled flooding. In Rwanda, flooding method is mostly used for irrigating rice and sugar cane. When the water inundates the flood area, the water distribution is quite unbalanced because a lot of water is wasted as the soil is excessed by water and sometimes causes the serious losses of crop production. Hence this method is not very efficient but also the adaptation of this method doesn’t cost much. In fact, due to the abundant surface water resources of the country, water drainage occupies the most applied method of irrigation with a proportion of 57.7%. Other method used but with less proportion of 26.9% is pumps/tube wells irrigation machine (Maimbo M.M.et al., 2010).

Figure 2. 7 Irrigation by surface irrigation at Kagera valley, Bugesera

2.7.2. Manual irrigation using buckets or watering cans

The watering can provides a simple and accessible irrigation technique that is understandable and widely practiced by small-scale farmers for vegetable production. This technology requires low investments, but is labour intensive and allows irrigation of only a small land (50 to 100 m^2) (FAO, 2014).Irrigation by watering can or bucket (see figure 2.8) is mostly used by many small-scale farmers with a simple way of growing irrigated crops. In most countries the watering cans are locally produced from galvanized irons or plastics. Carrying the cans from the water source to the crop is labour-intensive and daily watering is required.

Normally, the water source should not be more than 50 m away from the area to be irrigated; not be too deep; and allow easy access for filling the watering can (FAO, 2014).Usually, irrigated fields are mostly found along rivers, lakes and streams or where any surface and groundwater can easily be reached. In general, these systems have low requirements for infrastructure and technical equipment but due to the amount of labour required to carry water from source to field, this technology is suitable for irrigating areas which are between 50 and 100 m^2 (FAO, 2014).

Figure 2. 8 vegetable irrigation by cans at Rumira valley, Bugesera

2.7.3. Drip Irrigation

In drip irrigation method, water is applied to each plant separately in small, frequent and precise quantities through dripper emitters. It is the most advanced irrigation method with the highest application efficiency. The water is delivered continuously in drops at the same point and moves into the soil and wets the root zone vertically by gravity action.

Drip irrigation is sometimes called trickle irrigation, operates as its name suggests. Usually, water is delivered at or near the root zone of plants, drop by drop. For that reason, this method can be the most water-efficient method of irrigation, since evaporation and runoff are minimized. In modern agriculture, drip irrigation is often combined with plastic mulch, further reducing evaporation, and is also a means of delivery of fertilizer. The process is known as fertigation (Kharagpur, 2015).

Drip Irrigation involves dripping water onto the soil at very low rates (2-20 litres per hour) from a system of small diameter plastic pipes filled with outlets called emitters or drippers. Water is applied close to the plants so that only part of the soil in which the roots grow is wetted, unlike surface and sprinkler irrigation, which involves wetting the whole soil profile. This method provides a very high moisture level in the soil which makes drip irrigation to be more efficient than other methods. A 10–15 L bucket reservoir or 200–300 L fuel drum is placed at an elevated height (1–2 m) above the field and is connected to the small tubes and drippers to irrigate a small vegetable garden area of 50 m^2(FAO, 2014).

The drip irrigation system is mostly suitable to areas where water quality is marginal, land is horizontally or of poor quality, where high value crops require continuing water applications, or where labour or water is expensive. Drip irrigation is more economical successfully for fruit or orchard crops and vegetables rather than other crops since in the fruit plants as well as rows are widely spaced. The irrigation efficiency of a drip irrigation system is more than 90 percent (Kharagpur, 2015; FAO, 2014).

Figure 2. 9 Installation of drip irrigation lines

Source: FAO, 2014

2.7.4. Sprinkler Irrigation

Sprinkler irrigation is another popular irrigation method, which pipes a set amount of water to the fields, and then sprays this directly over the crops with high pressure sprinklers. The amount of water can be closely controlled, which is a huge benefit. Usually Sprinkler irrigation is a method of applying water which is similar to natural rainfall but spread uniformly over the land surface just when needed and at a rate less than the infiltration rate of the soil in order to avoid surface runoff from irrigation.

This method is achieved by pumping water through a system of pipes, and then water pumped is sprayed into the air through sprinklers so that it breaks up into small water drops which fall to the crops. This method of irrigation is suitable for sandy or shallow soils, with poor water availability, or where uniform application of water is desired. Here, there no land leveling is required as with the surface irrigation methods (Kharagpur, 2015). The water that is pumped through sprinkler system must be free of suspended sediments otherwise sprinkler nozzles would be blocked.

The sprinkler irrigation method is also suited for most crops planted on rows, field as tree crops and water can be sprayed over or under the plants. However, large sprinklers are not recommended for irrigation of vegetable crops such as lettuce because the large water drops produced by the sprinklers may damage the crop. Sprinkler irrigation has high efficiency compared to the surface irrigation method. This efficiency varies according to climatic conditions; 60% in warm climate; 70% in moderate climate and 80% in humid or cool climate (Kharagpur, 2015).

Figure 2. 10 Installation of sprinkler irrigation

2.8. Overview of agriculture irrigated sites in Rwanda

In Rwanda, the Ministry of Agriculture and Animal Resources (MINAGRI) understands that increasing land under irrigation is not an end in itself but what is of greater concern are the harvests realized from the irrigated land and the profitability derived. While many irrigation projects are focused on individual (smallholder) producers, MINAGRI recognizes that larger (commercial) operators need to be significant participants in the agricultural sector and using renewable energy as power for water pumping system. Consequently, the Government of Rwanda (GoR) and MINAGRI encourage private sector investments as a critical part of the mixture that is required to create a vibrant and profitable agricultural economy within the country (MINAGRI, 2016). According to Rwanda Agriculture Board (RAB), the government of Rwanda has ambition to irrigate 100,000ha by 2020 but currently irrigated land is around 48,508 ha (See Table 2.4). But irrigated area is still small (48,508 Ha) compared to the total national cultivated land (1.75 million Ha) (Bizimana C. et al., 2012).

The ten sites that MINAGRI has identified as being currently available to interested investors are described in summary below. Individual and detailed information for each site is in the following table.

Table2. 3 Geographic Location of irrigated sites

ID-site	SITE NAME	PROVINCE	DISTRICT	SECTOR	TOTAL SITE AREA	IRRIGATED AREA	Ha AVAILABLE	% Offered
71	Nasho Phase I	Eastern	Kirehe	Mpanga	600	502.7	400	80%
12	Rurambi	Eastern	Bugesera	Mwogo	1,000	850	400	47%
41	Nyanza 23	Southern	Nyanza	Nyagisozi	471	301	301	100%
6	Mukunguri	Southern	Kamonyi	Nyamiyaga	711	400	250	63%
70	Matimba	Eastern	Nyagatare	Matimba	402	398	200	50%
50	Cyili	Southern	Gisagara	Gikonko	460	271.8	150	55%
34	Rwagitima-Ntende	Eastern	Gatsibo	Gitoki	590	525	100	19%
27	Muvumba 4	Eastern	Nyagatare	Nyagatare	345	254	86	34%
4	Rusuli Rwamuginga	Southern	Huye	Ruhashya	179.8	140.5	86	61%
49	Karongi 12	Western	Karongi	Rubengera	145	94.4	80	85%

Source: MINAGRI, 2016

Table 2. 4 Current irrigated area in Rwanda

Indicators	**Units**	**Baseline 2013**	**2014**	2015	2016	**Achievement 2017**
Area covered by radical terraces	Ha	46,246	64,590	82,565	103,918	110,041
Area covered by progressive terraces	Ha	802,292	846,476	894,213	913,212	923,604
Area under hillside irrigation	Ha	3,075	4,807	5,710	5,948	7,413
Area under marshland irrigation	Ha	24,721	24,721	29,277	35,161	36,521
Area under small scale irrigation	Ha		-	420	2,444	4,574
Total area under irrigation	Ha	27,796	31,812	35,407	43,553	48,508

Source: MINAGRI

2.9. Rwanda policies which supporting investment in agricultural sector

The policy is a framework developed to guide a process. Agriculture is an engine for country development. Rwanda agriculture sector is one of the leading sectors need more attention due to its significant role in country's economic development and target achievement toward vision 2020.

Rwanda agricultural policy has been developed with aim of guiding and influencing decisions related to extraction, development, and use of Rwanda's energy and water resources in a way that agriculture sector can contribute to country's development and socio-economic transformation.

2.9.1. Transaction Structures and Considerations

i. Land Acquisition

MINAGRI is very flexible and willing to work with investors on any structure that is mutually beneficial. In most cases, land is acquired under a lease agreement. Leases usually run for five to ten years and may contain renewal provisions. In most situations, the investor will not be acquiring the entire land area of a specific site. However, the land to be acquired will be contiguous, thus allowing the investor the ability to achieve efficiencies in all production aspects. While MINAGRI will entertain offers for land areas less than the total available at a given site, preference will be given to offers for the entire available land area. In those cases, where the government is the owner of the land, contractual agreements are between the investor and the government. However, some sites contain privately owned land. In the majority of these cases, the owners are smallholder farmers.

ii. Investment considerations and climate

- **Legal environment**

The Rwanda Development Board (RDB) offers support to investors to ensure their investments are carried out within the existing legal framework. Overall, government facilitates the existence of an enabling legal environment within which investors operate.

- **Capital Controls, Taxes and Repatriation**

The country offers tax waivers/exemptions on manufacture /importation of various commodities seen as strategic to the growth of agriculture sector. The Rwanda Development Board and Rwanda Revenue Authority often guide investors on which commodities are tax exempt.

- **Markets: Domestic market and Export**

Rwanda has a growing middle income population, creating a ready market for various consumer goods. The economy is liberalized, with prices being determined by the market forces of demand and supply. There are also trade agreements between Rwanda and the EU, EAC and United States ensure that our high-value export products reach destinations in EAC, Europe and North America with ease.

- **Infrastructure**

Government has been investing heavily in soft and hard infrastructure to support the agriculture sector. This includes investments in main roads, feeder roads, electricity and other forms of infrastructure such as construction of dams and other irrigation infrastructure.

- **Investment Incentives**

Rwanda offers a range of incentives, including:

- Free initial work permit and visa for investors and foreign workers
- Acquisition of permanent residency (An investor who deposits an amount equivalent to 500,000 US $ on an account in one of the Rwandan commercial bank for a period of not less than 6 months is entitled to a permanent residency status).
- Aftercare services from RDB.
- Tax exemption on imported goods (Machinery and raw materials, privileges on movable properties and equipment).

2.9.2. Small Scale Irrigation Technology (SSIT)

According to Rwanda Agriculture Board(RAB), in order to reduce climate change induced droughts which are now threatening Rwanda's twin goals of food security and poverty reduction, Rwanda has been obligated to accelerated the development of sustainable, affordable, farmer owner irrigation systems. The government of Rwanda, in its cabinet resolution of 27th July 2014, adopted the subsidized farmer led small scale irrigation development program. The usage of SSIT farming as a business enterprise is expected to lead to increases in crop production and production and productivity of food and cash crops in Rwanda.

Through a Government subsidy program, Rwanda provides subsidy of up to 50% of the total required investment cost to farmers. This subsidy is reserved for the farmers having land ranging between 0.5 to 10 hectares, with total pumping not to exceed 5bars pressure requirements. The small scale irrigation technology includes ready to use 1ha, 5ha, and

10ha complete sprinkler and drip kits with portable diesel/petrol motor pump and pipes and rain-water harvesting through tanks (plastic and concrete).

2.10. Summary of the Literature Review

In summary, based on the literature reviewed, the importance of water in human life is unlimited; water can used in irrigation, domestic use, industries, and others human daily activities. Here in this master's thesis, it is focusing the use of water to irrigate agricultural crops. The irrigation pump system needs some power for pumping water from underground or surface. It is clear that there is a relationship among water, irrigation, environment and energy power. Today the demand and consumption of water, food and energy are increased in the day to day as the population growth increased. Several researches have been done for comparing different water pumping systems for agricultural irrigation, particularly PV water pumping (PVWP) versus diesel water pumping (DWP) systems. Many studies have proved that PVWP systems have more advantages compared to DWP systems.

However, most studies conducted on the use of PVWP systems for irrigation fail to show disadvantages of using solar PV systems on the wildlife, forest and soil, in particular at the phase of installation. There is still a gap in comparison between PVWP and DWP systems, especially for irrigation where there are no previous detailed studies that consider the effects of PVWP on environment especially for farmland and grassland and forested areas. Most Previous studies on environmental analysis of PVWP systems in Rwanda were only focused on CO_2 emission reduction. However a deep analysis for suitability of PVWP systems, including all potential effects and benefits either technically or economically or environmentally is advised. The previous researchers also didn't clearly show the policies which can support small farmers in Rwanda.

In addition, the previous researchers fail to mention clearly the link between renewable energy especially solar energy and agriculture irrigation in Rwanda, how available water and energy resources can be used efficiently to solve the issue of food security. Most scholars have been concentrated on the use of solar energy for electrification. Therefore, more studies are needed to identify the cost-effectiveness of solar energy and how it can be involved in Rwanda agriculture sector.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction

Research methodology is a chapter that is included all techniques and methods that are used for conducting research. This section describes the methodology that followed in study to answer the research questions. In this master's thesis several commercial tools have been used to simulate the water pumping systems such as Homer software and Excel Software. The information about the average monthly solar radiation on the selected site and the characteristics of PV system components were provided by Rwanda meteorology agency, PVGIS (Photovoltaic Geographical Information System) for Africa, different internet websites, different books, scientific research papers and journals. The other line of this research included quantitative and qualitative interviews with different participants. These interviews comprised the practice portion of the study. The responses from the interviews were used to modify the preliminary policies developed in the literature review. This chapter thus provides an overview on how to design, optimize, and assess the environmental and economic feasibility of proposed pumping systems.

3.2 Research design

This study uses both a qualitative and quantitative research design. Qualitative as well as quantitative approaches employed to collect data. The study was used both qualitative and quantitative approaches during sampling, data collection, and analysis. At data collection stage, Qualitative approach used to collect ideas and opinions from farmers in open ended interview to the respondents where people provided their experiences in agriculture, while quantitative approach was used to collect responses from government institutions and non-government organizations in closed ended interview and also questionnaire has been used to collect numerical data.

3.3 Population and target population

This study was conducted in Bugesera district which selected depending on high solar potential and abundant water resources. This study used sampling in order to obtain data from the field. Sampling helped to simplify wok of the researcher by concentrating on few respondents instead of covering many respondents and also sampling helped to make generalizations due to the limited time of research.

3.2.1 Sampling procedure and data collection

The study was conducted based on the survey in Bugesera district, Eastern Rwanda. The sample households were selected by utilizing random and purposive sampling techniques.

From the total number of households that are using agriculture as main incomes sources in the selected study areas, 60 farmers were taken from Rilima and Gashora sectors, Bugesera by systematic random sampling technique. Generally, based on the multistage sampling process, a total of 68 participants were selected by systemic purposive and random sampling technique. The summary of the number of respondents selected from study area is presented in Table 3.1.

To carry out this study, both primary and secondary data sources were employed. The primary data were collected by employing method such as key informant interview using semi structured checklist, expert interview; focus group discussion, semi structured household questionnaire and observation of events. Secondary data that could supplement the primary data were collected from published and unpublished documents obtained from different sources. These included country policy statements, strategies regulations, reports, papers and journal on irrigation practices. Items covered during the data collection were socio-economic situation of sampled households, irrigation practices, opportunities and barriers of irrigation activities, crops grown, demographic features, irrigated land and the livelihood impact of irrigation activities. Discussions were also held with irrigation experts at the Rwanda Agriculture Board (RAB) and at sites.

The sample size of the study was 68 respondents. This therefore means that the sample shall include 60 formers, 2 agronomists, 2 irrigation experts and 4 administrative staffs (Davis & Shirtliff Company, RAB, MINAGRI and Rwanda Meteorology Agency). The sample sizes are summarized in Table below.

Table 3. 1 Population sample and sampling techniques

Category of respondents	Sample population	Sample Size	Sampling techniques
Farmers	150	60	Simple random sampling
Agronomists	15	2	Purposive sampling
Irrigation Experts	8	2	Purposive sampling
Administrative staff	20	4	purposive sampling
Total	**193**	**68**	

3.3.2 Sample and sampling techniques

Simple random and purposive sampling techniques were used to ensure that each member of the target population has an equal and independent chance of being included in the sample. Simple random sampling used to select farmers in selected district. This technique was chosen because the category of farmers has a large population size and as such warranted simple random sampling to minimize sampling bias. Purposive sampling employed to select agronomists, experts and administrative staff. This technique was used because sampling has to be done from smaller groups of informants therefore researcher needs to choose one by one purposively.

3.4 Data Collection methods

Field studies are necessary to define quantitatively the irrigation system performance in relation not only to its physical features but also to its design and management. The researcher has used questionnaires, documentaries and interviews as the main tools for collecting data. The selection of these tools was guided by the nature of data collected, the time available as well as by the objectives of the study. The study used a physical survey method of research; this included observing and personal interviews (See appendix V). This involved carrying out an energy demand and cost survey for agriculture irrigation system in different rural areas of Rilima and Gashora. The areas were selected because high agriculture activities items and good resources are found in these areas. These areas were selected purposively in Bugesera by considering availability of solar energy, water sources and climate's characteristics.

3.4.1 Interviews

The interviews were used to collect primary data from farmers, experts, agronomists and administrative staff. It was guided by questions that prepared before as shown in Appendix VI

3.4.2 Documentary Review

This method used to collect secondary data and was guided by a documentary review checklist. Those secondary data were collected from documents and reports from Rwanda Ministry of Agriculture and Animal resources(MINAGRI) , Rwanda Meteorology Agency, Rwanda Agriculture Board (RAB), Photovoltaic Geographic Information System(PVGIS), International organizations, Non-Government Organizations (NGOs), and other public and private companies related to solar energy and agriculture, published books and journals.

3.5 Data collection instruments

The instruments that were used include; interview guides, questionnaires, and documentary checklist.

3.5.1 Interview guide

An interview guide was prepared in order to conduct interviews with respondents. This instrument used as being method of asking questions, the researcher utilized it for interviewing individuals as well as groups of key informants. The interview guide is more flexible method of interviewing useful areas where the researcher has little knowledge of situation under investigation.

3.5.1.1 Participants' selection

In order to collect enough information, it was decided by researcher that a larger range of knowledge and opinions could be gathered if interview participants were selected from different farmers of different areas of the district. For these reasons, interview participants were sought from around the different areas, to provide a sufficient number of interview participants to gain a range of opinions. Potential interview participants were chosen by purposive sampling and by simple random sampling in government institutions, farmers, experts and private companies, in the study area.

3.5.1.2 Interview structure

The interviews were conducted using a semi-structured format. Semi-structured interviews use prepared questions to guide the interview process but these questions are also open-ended to allow interview participants a maximum of freedom to answer. The benefit of this methodology is that it permits a deeper level of communication, allowing the researcher to access the interview participants' opinions and feelings (Sekaran, U., 2003). The open-ended nature of the interview questions follows this procedure by allowing the interview participants a maximum of flexibility about how to answer the questions without the interference of the questioner. Furthermore, the framework of questions asked in the interviews was prepared before the interview happen.

3.5.2 Questionnaire

The questionnaires has been used to enable the researcher to balance the quantity and quality of data collected and also to enable respondents to provide information about a particular questions with a freedom by writing their opinions, views, perceptions, feelings, and experiences. And also questionnaire used to know the costs or amount of different systems' items

3.5.3 Documentary checklist

This instrument was used to collect primary data that will be used to compare findings. The researcher reviewed secondary data to enable verification of the primary data.

3.6 Data processing and analysis

Data was analyzed both quantitatively and qualitatively. The Answers/responses grouped and analyzed using HOMER software and Excel programs. The information grouped under excell micro-software has been interpreted both quantitatively and qualitatively.

3.6.1 Qualitative data analysis

Qualitative data analysis was done during data collection by assigning different categories to different information. Content analysis was carried out by checking questions to ensure validity and authenticity of the answers given (Amin, 2005). All the information was analyzed according to the research question and the information available.

3.6.2 Quantitative data analysis

After collect data, the following methods will be used to analyze and present data.

i) **HOMER Software:** It has been used to analyze the cost of Solar PV, Diesel generator and PV-Diesel hybrid pumping systems.

ii) **Microsoft Excell:** Ms Excell was used to calculate average of collected data and plot the graphs

iii) **Graphs:** The graphs were also used to present data.

iii) **Simple tables**: The simple tables have been used to present collected quantitative data.

3.7. Ethical considerations and limitations

The researcher followed ethical guidelines in order to get full information needed from the participants. This included undergoing an ethics review process before engaging interview participants to ensure that procedures were fair and unbiased to all involved. Great care was taken to ensure that these participants were kept completely anonymous in the research.It was decided that the interviews should be anonymous so that the reader cannot find out who was interviewed in order to keep security of respondents. The benefits of assuring the participants of anonymity were that they would be more willing to give higher quality information, including personal opinions and perceptions. Participants were also given the time of asking questions. And also Participants were thanked for their help.

When doing this study, time limit was a major limitation to interview many participants as much as possible from different cells and villages. The researcher also struggled to get on time authorization letter from institutions because it took at least two weeks to get feedback. Projects documents from different institutions both private and public are so secret to share.

3.8. Description of the site

3.8.1. Demographic features of Bugesera district

Bugesera district is one of the thirty (30) districts of the Republic Rwanda and one of the seven Districts that make up the Eastern Province of Rwanda. It neighbors the City of Kigali and is at a frontier to the Republic of Burundi. The district is composed of 15 Sectors, 72 Cells and 581 Villages with a total Population of 363,339 people, where 177,404 are males and 185,935 are females (General Population census: 2012). Bugesera district covers a total surface area of 1337 km² of which arable land is estimated at 91,930.34 ha. Its Population Average Annual Growth Rate is 3.1%, with a population density of 282 people per km^2. The average size of land cultivated per householder (HH) is 0.59ha. The population of Bugesera district is estimated at 13.9% of the whole Eastern province population, and at 3.4% of the total population of Rwanda (General population census 2012) (BUGESERA, 2013). It is located at 2° 8' 44" south the equator 30° 5' 29"East of Greenwich Meridian at altitude of 1429m (newstrackindia, 2018). Below is an illustrative table showing demographic characteristics of Bugesera in the context of Eastern Province and Rwanda

Table 3. 2 Demographic characteristics of Bugesera

District	2002 Total Population	2012 Population			Population change (2002-2012) (%)	Average Annual Growth Rate (2002-2012) (%)	Population Density (sq.km)
		Male	Female	Total			
Bugesera	266,775	177,404	185,935	363,339	36.2	3.1	282
Eastern Province	1,700,137	1,257,750	1,343,064	2,600,814	53.0	4.3	275
Rwanda	8,128,553	5,074,942	5,462,280	10,537,222	29.6	2.6	416

Source: (BUGESERA, 2013)

Figure 3. 1 Administrative Map of Bugesera District with all different sectors and rivers.

Source: (BUGESERA, 2013)

3.8.2. Hydrography

Bugesera district hydrographical network is mainly characterized by 3 rivers (Akanyaru, Akagera and Nyabarongo). Apart from these rivers, Bugesera has 9 lakes which are namely as following: Lakes Cyohoha North, Cyohoha South (630 ha on Rwandan side), Rweru (1857 ha on Rwandan side), Rumira (280 ha), Mirayi (230 ha), Kidogo (220 ha), Gashanga (232 ha), Kirimbi (230 ha) and Gaharwa (230 ha). The seven lakes were formed as a result of Akagera river over flow, except lake Cyohoha South and lake Rweru (BUGESERA, 2013). These lakes have little effect on irrigation and rainfall formation. Nevertheless they are mainly used for fishing, farming and tourism.

3.8.3. Climate

Compared to other regions of the country, Bugesera climate is dry with temperature varying between 20 and 30°C. The temperature average of this district is between 26 and 29°C. In the past years Bugesera district was turning into a dessert zone due to the long droughts period. However with increased government effort, the district had been afforested. This effort improved climatic conditions of this district (BUGESERA, 2013). The situation of the average rainfall for Bugesera district obtained at Kayonza station from Rwanda Meteorology Agency. This meteorology station was selected because Kayonza district has the same climate characteristics as Bugesera district (See appendix II). It is clear that in this region faces droughts. Because in January up to May they expect to get enough rainfall as Appendix II shows that the rainfall is little particularly in February, March and May. From June up to September, it is the dry season but if irrigation system is adopted, crops may be grown all times in this district so that to fight against famine and poverty in this region.

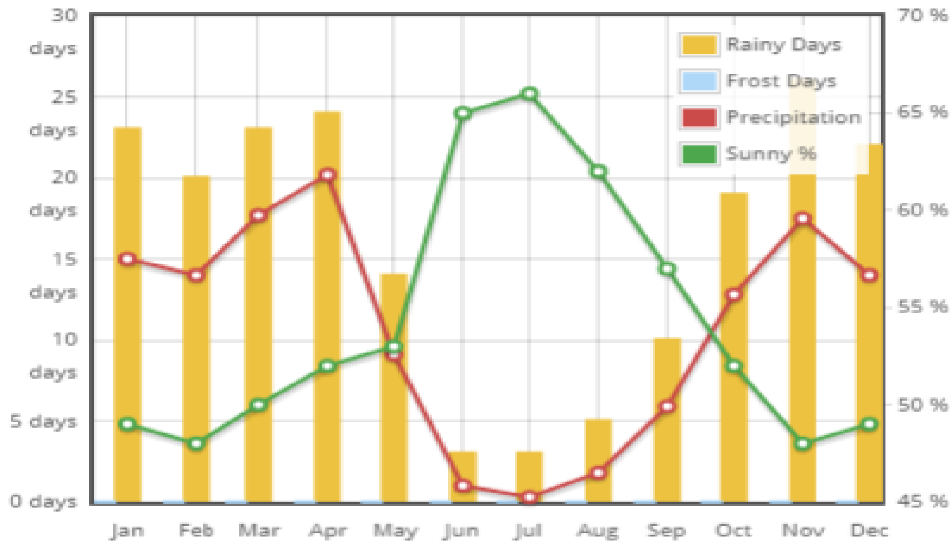
The district has two dry periods and two rainy periods. The table below shows Bugesera's climatic seasons

Table 3. 3 climatic seasons of Bugesera district

Climatic season	Duration	Local name for the period
A short dry season	January to mid march	*Urugaryi*
Long rainy season	Mid march to June	*Itumba*
Long dry season	Mid June to September	*Impeshyi*
A short rainy season	Mid October to December	*Umuhindo*

Source: BUGESERA, 2018

The time around July is driest. Rainfall and other precipitation peaks around the month of April as shown by the Figure 3.2 below.



Average rain days, frost days, precipitation and sunshine %
over the last 20 years in Bugesera, Kigali, Rwanda (populated place).

Figure 3. 2 Monthly average values of various climate data for Bugesera District

Source: Uwibambe J., 2017

3.8.4. Agricultural sector

Bugesera district is at the 17th position in the country to have a percentage of Households involved in agriculture and livestock activities. Crop farming and livestock are the district's economy's backbones where by 77.8% of the population depend on agriculture against 72% for national average (EICV3, 2012). According to (EICV3, 2012) 72.3% of the HH of the district have less than 1ha of land to be cultivated. The system of agriculture practiced in the district is a mixed and involves livestock and crop farming on small parcels.

The key challenges in this agricultural sector of Bugesera include; poor agricultural techniques, hill side irrigation is still low, failure to irrigate 3,550 ha of marshlands, insufficient use of organic fertilizers (3.1% only) (EICV3, 2012). In addition, farmers still use traditional tools like hoes and pangas, and the use of fertilisers and improved seeds is still low. Value addition is still poor, most products are sold in primary form, and livestock transformation still has a long journey where profitable non-traditional livestock like chicken rearing, rabbits, crocodile and beef farming is still under developed in Bugesera

District. For these reasons, agriculture has not benefited much Bugesera in the last five years (BUGESERA, 2012). In this study, agricultural irrigation will be discussed in more details.

3.8.5. Solar potential

Bugesera district receives a large amount of sunlight all over the year with an annual average solar radiation of 5.6 kWh/m^2/day. This solar irradiation level can be considered as one of the highest irradiation levels over the world compared with its value in Europe (1 kWh/m^2/day) and (1.7 kWh/m^2/day) in Greece (Khashab and Ghamedi, 2015) .In addition, Bugesera district is one of the driest sites among other districts of the eastern province of Rwanda since its average temperature is high, with the values above of 21°C and the precipitation amount in this area is the lowest in the whole country, with values below 900 millimeters per year (Uwibambe J.**,** 2017). Therefore, the above factors have been taken into consideration while selecting Bugesera district as an interesting site on which this study will be performed, using solar energy to pump water for agricultural irrigation.

The daily global irradiation levels and the clearness index for the location of Bugesera, Eastern province of Rwanda in kWh/m2/day are shown in Figure3.3.

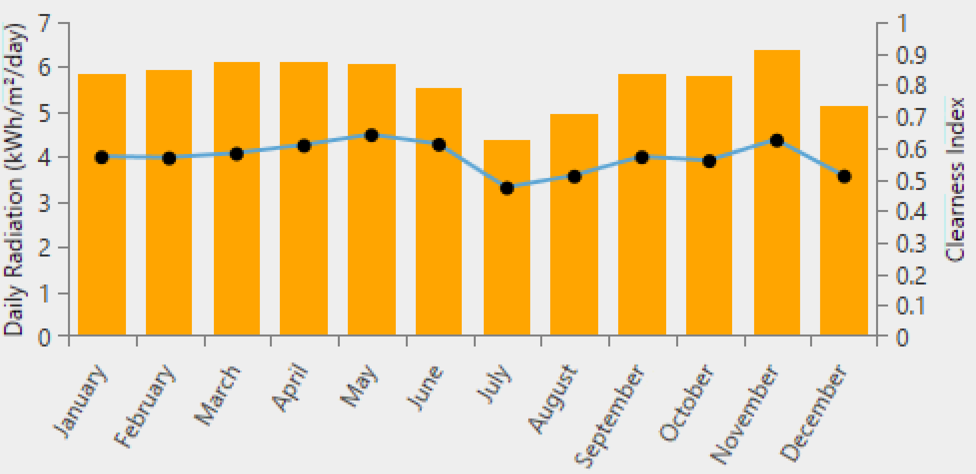


Figure 3. 3 The Daily solar radiation and the clearness index for the location of Bugesera

3.9. Overview on HOMER Software

HOMER means Hybrid Optimization Model for Multiple Energy Resources (Uwibambe J., 2017). The HOMER optimization software is used to evaluate, both the technical and economic viability of the proposed energy system by taking into account the variations of both the diesel prices and solar radiation, as experienced in most parts of Rwanda.

HOMER is a powerful modelling tool which uses to simplify the design, analysis, and evaluation of both grid and off-grid connected hybrid power system for distribution generation, standalone and remote applications (Homer, 2018). It performs three basic functions which includes simulation, optimization, and sensitivity analysis.

The word HOMER came from the abbreviation of "Home Energy". It simulates the operation of a system by calculating energy balance equations for 8,760 hours in a year and compares the solutions with different possible configurations and finds the best possible and economically suitable solution among of those configurations (Nazmul at al., 2015). HOMER simulates thousands of system configurations, optimizes for lifecycle cost, and generates results of sensitivity analyses on most input parameters. This software was developed by the United State National Renewable Energy Laboratory (NREL) and can be used to design varieties of energy system including solar PV, convention generators, hydro power, biomass and wind turbines (Olasunkanmi et al., 2014).

In this study, the HOMER software was used to analyse the optimal design configuration for the hybrid photovoltaic/diesel energy system in Eastern province of Rwanda, Bugesera district. The software first estimates the technical feasibility of the proposed pumping systems and later ranks the systems based on the total NPC, COE, O&M and OE. The analysis performed in order to determine the optimal configuration for the proposed site with the aim of minimizing the dependency on fossil fuels. In addition, all possible stand-alone systems involving diesel generator and photovoltaic energy systems are also analyzed and their viabilities assessed.

3.10. Economic assessment of pumping systems

This section contains a guide for estimating the costs and benefits of alternative water pumping options. The economic assessment of a project is quantified in term of the amount of money saved per certain time of period. An economic evaluation is used to identify which alternative water pumping option achieves the maximum benefit for the least cost.

Net present Cost (NPC), Operation cost (OC), Operating and maintenance cost (O&M) and Cost of energy (COE) used to compare different water pumping technologies by evaluating the capacity of producing the benefits. An economic evaluation of water pumping systems is based on the monetary values of the system. Generally the economic analysis of alternative systems is undertaken to find out the most profitable among the possible energy source alternatives. When performing economic evaluations, the alternative systems must provide the same level of service as the conventional ones. For example, water pumped by using diesel generator should also have similar water delivered by the other alternatives (PVWP and hybrid Diesel-PV etc.).

Although, economic approach cannot convert all relevant factors to monetary values, the environmental (external impacts) evaluation approach emphasizes to non-monetary values that can effect directly or indirectly the selected water pumping system. These two evaluation approaches/methods (economic and environmental) and a technical evaluation are the main criteria in selecting the best alternative energy source for water pumping systems. However, the final decision must be made after all the technical, economical, environmental, and other related external impacts are considered. In fact, these costs are evaluated to determine the most viable system among all available alternatives. All the expenses costs of water pumping systems correspond to Rwandan market.

3.10.1. Determination of economic parameters

This study introduces an economic analysis and comparison among three technologies using a standalone PV system, a hybrid PV-Diesel system and a Diesel generator for water pumping for irrigation purposes in Bugesera, Rwanda within (Lat.1° 57' south, Long. 30° 04' East). The study took into account the parameters which affecting the cost of these systems such as; initial capital cost of the components, installation, operating and maintenance (O&M), structures and fuels costs. The economic analysis and the comparison of these systems have been concluded for the following parameters (NPC, O&M, OC, and COE);

- Net present cost (NPC); describes the total cost of the system over its lifetime including the capital, installations, running and, operating and maintenance costs.
- Operating and maintenance cost (O&M); describes the total cost for running and maintaining the systems.
- Operation cost (OC); describes the yearly cost of operation in $/year.

- Cost of energy (COE); describes the total average cost of the system for generating electrical energy of one kWh. COE is the main parameter in comparing different technologies and it is expressed in $/kWh.

3.10.1.1. Determination of Levelezed Cost of Energy (LCOE)

The Levelezed Cost of Energy is the cost of production of one kilowatt-hours (kWh) of electricity. LCOE indicates in term of money what it would cost the owner of the facility to produce one kWh of energy, including the total construction, central production costs of the power station during its economic lifetime. The LCOE is a method used to compare renewable energy technologies adopted to produce electricity (Wagner and Jorge, 2012).
The Levelezed Cost of Energy can be calculated by using the equation below.

$$\mathrm{LCOE} = \frac{\mathrm{FCR} \times \mathrm{ICC} + \mathrm{LRC}}{\mathrm{AEP_{net}}} + \mathrm{O\&M} + \mathrm{PTC} \qquad (3.1)$$

Where, FCR = Fixed Charge Rate; ICC = Initial Capital Cost; LRC = Levelezed Replacement Cost; O&M = Operations and Maintenance; PTC = Production Tax Credit and AEPnet = Net Annual Energy Production.

3.10.1.2. Net Present Cost

The Net Present Cost (NPC) of an energy project is the sum of the current value of all costs over its lifetime, including residual values (Blackler and Iqbal, 2006). The net present cost of a project is the sum of all cost components, including:

- The investment of capital or initial capital cost
- O&M costs
- Costs of major replacements
- Fuel costs (if applicable)
- Any other costs such as rent fees and legal fees.

If a series of projects or investment options are being considered, the lowest net present cost is the best option (Olasunkanmi et al., 2014). The NPC is mathematical defined as:

$$NPC = \frac{Co_1}{(1+i)} + \frac{Co_2}{(1+i)^2} + \cdots + \frac{Co_t}{(1+i)^t} + \frac{D_v}{(1+i)^N} = \sum\left(\frac{Co_t}{(1+i)^t} + \frac{D_v}{(1+i)^N}\right) \qquad (3.2)$$

Where; NPC = Net Present Cost, Cot = Cash outflows in period t, i = Discount rate, t = Number of periods of outflows, N = Lifetime of energy park and Dv =disinvestment value.

3.10.1.3. Operation and maintenance cost

The costs of operation and maintenance (O&M) include costs normally associated with recurrent routine operation of the plant installed (Wagner and Jorge, 2012). The O&M costs do not include the major repairs of energy systems. The major repairs costs are included in the Levelezed Replacement Costs (Walford, 2003).

In general, the cost of operations and maintenance may also include:

- Taxes on property where the solar farm operates
- Payment of land use
- Miscellaneous insurance
- Access to transmission and distribution rates
- Management fees and administrative expenses.

3.10.1.4. Payback period

If annual cash flows or annual Savings are equal over life time of power plant, the payback period (PBP) is found by dividing the initial investment by the annual savings.

$$\text{Payback Period(in years)} = \frac{\text{Initial Investment Cost}}{\text{Annual Operating Savings}} \qquad (3.3)$$

3.11. Key assumptions

Obtaining all the necessary parameters and cost data for economic calculations can be difficult. Most of the time, recording actual financial (all expenses) information is impossible. In such cases, making assumptions is the common practice. And assumptions of investment costs, even for similar systems, may vary because of variations in transportation, manufacturer and labor costs. In fact, using an incorrect assumption for long-term economic analysis can lead to inaccurate results, which can affect viability of project. For this reason, actual cost information should be used as much as possible and realistic assumptions made to help to reduce the risks in economic analysis. When performing economic comparison, the all systems must provide the same level of services.

The common assumptions in economic analysis include inflation rate, discount rate, and fuel escalation rate. The key technical assumptions include component lifetime, major maintenance and operating cost. The worst case is developed analysis using the extremes of assumptions ranges. In order to avoid these difficulties, it is important to take the highest fuel cost, the highest discount and interest rates, the shortest system lifetime, and the lowest average daily solar radiation. Homer software will be used for modelling and simulation of the entire system. Therefore the interest, inflation, and fuel escalation rates must often be assumed. The performance evaluation of the system has been done by taking into consideration the following assumptions:

- The PV life time was estimated based on the guarantee of PV panels which is assumed to be around 20 years whereas Diesel generator's life time is estimated to 15,000 hours.
- The inflation and discount rates are assumed to be 5 percent and 7.42 percent respectively. While the price of one liter of diesel is assumed to be 1120 Rwandan francs (RWF) which equivalent to 1.28 United States Dollar (USD).
- The average solar radiation (5.6kWh/m^2/day).
- The annual solar resources input and the primary load profiles are assumed to remain constant throughout the project lifetime.

3.12. Design and optimal sizing of PV water pumping system

A water pump needs a certain power to produce a certain amount of pressure and flow. Therefore the PV array size has to be optimized for the required amount of power to pump the irrigation water requirement (IWR).

To develop a solar-powered water pump system it is necessary to determine the size of the system needed, these including PV panels size, the pump, water storage tank size, pipe length, mounting structure, etc. Furthermore, in order to design the pumping system and calculate the power needed correctly, it is important to know the following information:

- The ambient temperature
- The solar irradiation potential(Kwh/m^2/day)
- Number of sunshine hours
- The quantity of water needed to irrigate a selected crop land
- The type of the water source (a stream, river, well or lake).
- When the water is needed
- Quantity of water flow rate/discharge(m^3/hour)
- The total dynamic head (m)
- The capacity of storage tank (m^3)

The size of PV system required for driving the water pump can be calculated by using the following equation (Ahmad, 2002);

$$PV_P = PV_A \times 1000 \times \eta \qquad (2.4)$$

$$PV_A = (L_{wh})/(G \times C_T \times \eta_C \times \eta)$$

Where: PV_P is PV power (W), PVA is PV Area (m^2), L_{Wh} Required electrical energy (kWh/day), G is Daily irradiance on the PV surface (kWh/m2/day), C_T PV is temperature coefficient, η is PV efficiency and η_C is Controller efficiency

A water pumping system must be sized vigilantly and realistically. Because an oversized system is a waste of financial resources while an undersized system will disappoint the owners. Sizing a system for the worst seasonal variation of the energy resource such as solar is recommended to ensure that farmers have enough water.

After the power source of system is identified, the total pumping head and the water demand can be used to size the system. The total pumping head is the total head required to pump water from the water source to the storage tank. That is the sum of the pumping head, the friction, and the discharge head. The discharge head is the height from the surface of the ground to the storage pipe outlet. The pumping head, in case of groundwater from boreholes, is the static water level plus the drawdown. The friction head is the energy loss in pipes and fittings. The figure below shows schematic diagrams of electrical wind pump which has setups similar to PV or diesel pumps.

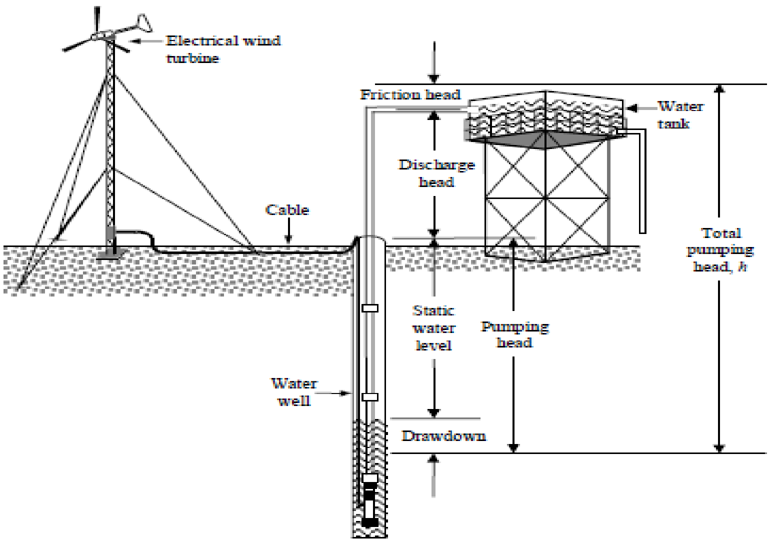


Figure 3. 4 Schematic diagram of electrical wind pumps.

Source: Argaw et al., 2003

PV unit of a solar pump consists of PV modules connected in series and parallel combination. A PV module composed by solar cells which convert solar radiation into electricity. The figure below shows the arrangement of a PV array

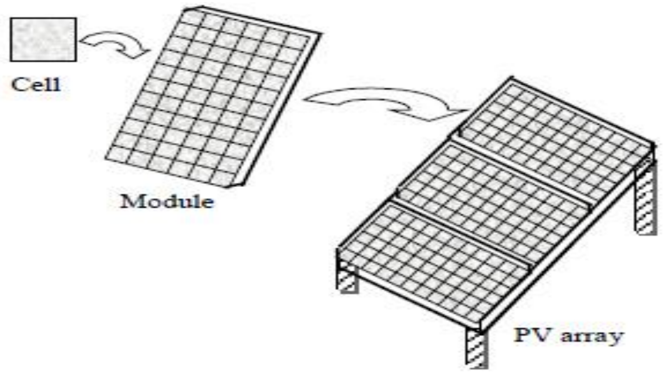


Figure 3. 5 Arrangement of a PV array generator.

Source: Argaw et al., 2003

The PV array can be a fixed, flat-plate module, or it can consist of various types of collectors, either tracked or untracked. Flat-plate arrays are normally fixed with the module supported by a structure so they are oriented due south (in the northern hemisphere), or north (in the southern hemisphere), and inclined at about the angle of latitude to maximize the amount of solar radiation received annually.

Most arrays are designed to carry the modules at a fixed tilt angle, which maximizes the amount of sunlight received over the year. The rotation of the Earth positions the sun up and down in the sky, depending on the time of year. Mounting the array at 0° from the horizontal (flat) position can be optimal at the Equator. Mostly it is recommended that the PV array be mounted at 10° at least so there will be good rainwater runoff, which helps keep the array clean. Furthermore, the PV array can also be manually adjusted, daily, monthly or seasonally, to allow for changing the solar elevation at noon. This is a relatively simple way to increase the power output without adding significantly to the cost.

3.12.1. Assessment of Water Pumping Systems

The assessment and analysis of the water pumping system using different technologies such as photovoltaic, Diesel or both can be affected by a various parameters such as location of selected field, meteorological conditions, water demand, water head or levels, cost of components and also cost of maintenance and operation.

This study analyses economically the cost of the water pumping system under three technologies, PV and Diesel and hybrid PV-Diesel. These proposed systems are different in the source of electrical energy which driving the water pumps.

Those water pumping systems are;

- Diesel water pumping (DWP) system; in which the Diesel generator only gives the required energy to water pump motor.
- PV water pumping (PVWP) system, in which the required energy to drive water pump is produced by solar photovoltaic.
- Hybrid PV-Diesel water pumping system; in which the required energy for pumping water is generated from two different sources (photovoltaic and Diesel generator). The PV gives 75% of the required energy while Diesel gives 25%.

The design and optimization analysis of these three water pumping systems are obtained using both HOMER software and Excel Software. Based on the all costs of each system, the study analyzes the operation of these systems from the economical view (NPC, OC, COE, and O&M) and environmental view (CO_2 emission, and farmland and grassland conservation).

The table below presents the parameters of the pumping system and the water demand.

Table 3. 4 Parameters of water pumping system

Parameters	**Value**
Pump power	10 kW
Pump flow rate	9 liter/sec
Water demand	240 m^3/day
Pump & motor efficiency	85 %
Hours of operation	8 hours
Water head	80 m
System lifetime	20 years

3.12.1.1. Diesel water pumping Systems

Diesel water pumping (DWP) system is a system used the diesel fuel to drive the water pump for operation. In areas without electricity facilities, a small generator provides the electric power for the system operation. The introduction of diesel-powered generating set in this study can be considered important as it can serve as backup because the duration of sunlight tends to reduce during the rainy season and also can serves as supplementary energy system during night.

DWP system has four main components such as diesel engine, water pump, water head and storage tank. The economic evaluation of DWP has to be investigated taking into account the same lifetime of 20 years as PVWP. The total cost of the diesel system includes the cost of the diesel unit, replacements, fuel, and O&M. The cost of diesel pump depends on its size while the efficiency varies with the running condition of the pump. The cost of diesel pump is estimated to be in range of 800 to 1000$ per kW for diesel pump size less or equal to 10kW whereas for larger scale is 7000 to 9150$ per kW. In addition, the maintenance and operating costs of diesel pump are higher and can even equal or 50% more than the capital cost (Miron, Z., 2015). And also, the fuel efficiency of diesel generator per liter varies from 2.5 to 3kWh (Jimenez and Lawand, 2000). According to (Phocaides, 2007) the cost of each generator system unit is relatively high and varies from US$2 500–US$750 per ha depending on the size of the area. Diesel pumps are best for higher water demands and larger irrigation applications. They are more economical with a hydraulic equivalent load greater than 1,500 m^3/d.

During economic assessment of diesel water pumping (DWP) system, many assumptions was made. It was assumed that pump is replaced every 10 years, the pump operates 8hours per day and the pump efficiency is 85%. It is assumed the maintenance cost for diesel pump to be $1035 per year. The inflation and discount rates are assumed to be 5% and 7.742 % respectively as the same as for PVWP system.

Figure 3. 6 Diesel water pumping system at Gashora site

3.12.1.2. PV water pumping System

A pumping system powered by directly converting solar energy into electricity is called a PV pumping system, and is one of the most reliable technologies for pumping water in remote areas.

The PV water pumping system consists of a PV array, a DC/AC motor –pump set, pump controller or inverter, cables, mechanical structure, and water storage tank. The PV array converts the solar energy into DC electricity while the motor and pump converts the electrical energy output into hydraulic power. The PV array can be directly coupled to a DC motor, or to an AC motor through an inverter. AC PV pumps are suitable for a hydraulic equivalent load of 1, 500m^3/d. The hydraulic equivalent load of PV pumps depends mainly on the amount of solar radiation of the field location and the size of the PV array. DC PV pumps are recommended for smaller applications up to a hydraulic equivalent load of 600 m^3 /d. (Argaw et al. , 2003)

The PV array/panel is mounted on a suitable structure with a provision of manual or automatic tracking. Water is pumped during day and stored in tanks, for use during day time, night or under cloudy weather. In fact the water tank acts as energy storage and battery is not necessary used for storage of PV electricity except for specific requirements it can be used (e.g when surplus electricity is needed for lighting purpose).

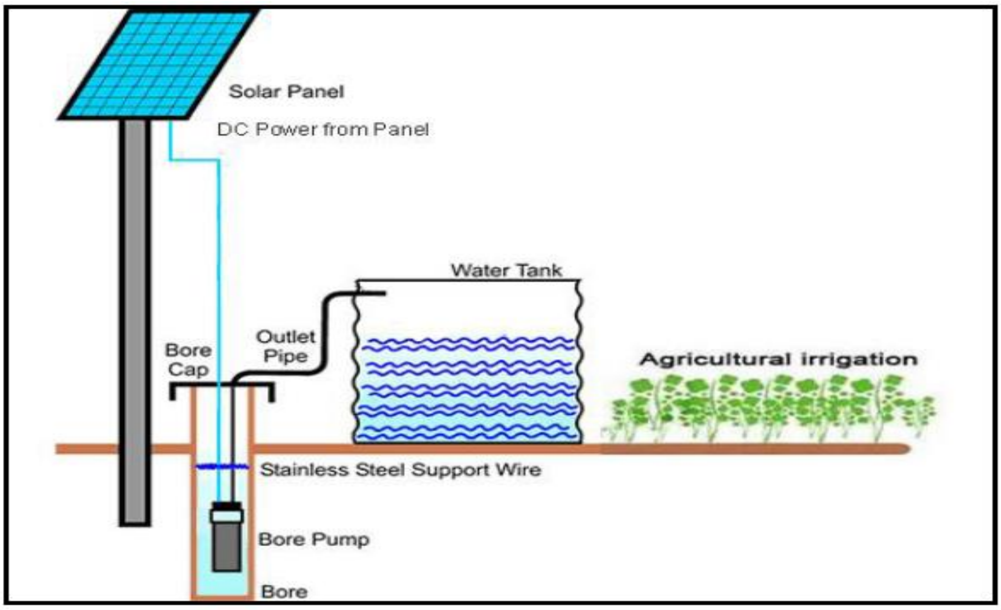


Figure3. 7 A Schematic diagram of the PV water pumping system

Source: ALLaham et al., 2014

3.12.1.2.1. Assessment of the costs of PV system

PV solar system is a combination of many modules grouped together to generate power by using solar irradiations as source of energy. To know how much does a PV system cost depends on many factors such as manufacturer industry, retailer, installer or PV system grade but the major factor is the size of PV array. In general, the cost of PV system is calculated per Watt Peak produced and the bigger in the size, the higher the costs of PV system (Jimenez and Lawand, 2000). According to (ALLaham et al.2014), the cost per Watt Peak of PV module has been dropped from $76.6 to $0.36 in the years 1997 to 2014 due to rapid growth in use of solar energy and many manufacturing companies of solar PV entering the market. This decline in price of PV system is significantly affects the overall cost of the pumping system since PV modules represent 60–80% of the total cost of a PV system. The global weighted average Levelized cost of electricity (LCOE) of utility scale solar PV has fallen 73% since 2010, to USD 0.10/kWh for new project commissioned in 2017 while average installed cost of utility scale solar PV was USD 1 388/kW (IRENA, 2018).

The size of the photovoltaic array is estimated to be 12 kWp which was considered adequate enough to meet the peak electricity demand of 10kWp required by the system. The excess production from the PV is expected to be use to pump reserved water or charge the battery backup. The PV-MF100EC4 (36-cell polycrystalline) module rated power of 100Wp was selected which has an area of 0.81m^2/module (bdt, 2018). Therefore, a total number of 120 modules are required to generate 12kWp which would cover a total area of 97.2 m^2.

In this study, each PV module initial cost has assumed of $220 with a lifetime of 20 years while the operating and maintenance cost is taken as $10 /yr. The remote area chosen for this study (Bugesera) enjoys sunshine for an average range of 10–12 h and since the output of PV modules depends on sunlight; therefore, the solar PV system requires either big tank or battery or generator to ensure continuous energy supply when the sun has set or the raining period. Temperature is another factor that must be considered because it makes the PV module less efficient as it increases (P. Nema et al., 2009). Therefore, temperature coefficient of 0.5%/ ^{0}C was utilized for the simulation. This means that there will be a reduction of 0.5% power output from the PV module at every 1^{0}C increase in temperature. The efficiency of the PV module was specified as 11.9% by the manufacturer under standard test condition with 47.5^{0}C nominal operating temperature (bdt, 2018). System costs are based on US dollar as HOMER software allows for US currency. However, it can be converted to Rwandan Francs based on the exchange rate of US$1 equivalent to 870RwF as on July 2018.

3.12.1.2.2. Assessment of the cost of energy storage systems

The total electricity production from PV system is not direct fully utilized by the pump for irrigation that is why energy storage systems are needed to store that excess electricity. The electricity surplus values depend on the method of storage used either to store electricity in form of water or in form of chemical energy. The role of storage is to store energy for later use when the system fails or there is no sun during night or cloudy day. The battery is used to store energy from PV panel in chemical form while tank stores energy in form of water. Depending on choice of farmer, storage tank can be installed or constructed underground, on the surface or at certain height above the ground (Bates et al., 2009). In this study, elevated water storage tank will be considered in order to obtain the pressure requirement for agricultural irrigation. Usually, 3 days of storage is recommended for renewable energy water pumping systems.

Figure 3. 8 Water storage for agricultural applications at Gashora

The cost of tank depends on its size and it is assumed to be $0.2/litre (VZP, 2018). The time of operation of lead acid battery is ranging between 5 to 7 years and is considered as the cheaper compared to Nickel cadmium battery where their costs are 160-200€/kWh and 690-1590€/kWh respectively (farmers.org.au, 2018). However in terms of economic perspective, battery storage costs too much compared to the tank storage.

The study conducted by (Rohit et al., 2013) showed that the tanks can be used for water storage in place of requirement of batteries for electricity storage. Moreover, energy storage costs can be ignored when PV system is directly connected to the pump system and delivering water directly to the crops. The batteries are not recommended in solar power pumping system because of the following reasons:

- It increases the cost of the system
- It reduces the overall efficiency of the system
- It increases maintenance cost

3.12.1.2.3. Inverter

The selection of the inverter depends on the overall capacity of the PV Array. In this case, an inverter rated 12kW was considered in order to be fully capable of converting the maximum output of the PV module. The overall efficiency of the inverter was specified by the manufacturer as 97.5%. The expected lifespan of the inverter was assumed 15 years; it means that this inverter must be replaced at least once during the project life-time of 20 years. The replacement cost of this converter was assumed to be the same as the initial cost at $400 /kW ($4800) while its operating and maintenance cost is zero (Hafeez Olasunkanmi et al., 2014).

3.12.1.2.4. Assessment of the cost of water pump- motor

The pump-motor set is subsystem of water pumping system. A solar pump is powered by solar energy, either directly by converting the solar resource into electricity or indirectly by using solar-thermal heat collectors. However, water pumping system using solar-thermal heat collectors is not suitable for irrigation and is not in scope of this study.

Water pump require power conditioning devices such as DC–DC converters, DC–AC inverters, AC–DC rectifiers, MPPTs, switch controllers, and charge controllers in order to function optimally. Power conditioners are generally used to suppress electrical power disturbances resulting from under or over voltage and electromagnetic interference. Charge controllers are used to prevent batteries from discharging and overcharging. DC–DC converters, DC–AC inverters, and AC–DC rectifiers are called the power processors. The DC–DC converters are used to regulate the DC power supplies in DC motor drive where they convert a DC input voltage into a DC output voltage; DC–AC inverters invert the DC input voltage into AC output where AC–DC rectifiers convert an AC voltage or current into a DC out voltage. Generally a DC–DC converter is a combination of an inverter and a rectifier. The pumps are constructed from high quality lead marine grade bronze and stainless steel and are also designed for corrosion-free (Argaw et al., 2003).

The pumps are classified into three types according to their applications: submersible, surface, and floating water pumps. A submersible pump draws water from deep wells, a floating water pump draws water from reservoirs with adjusting height ability and a surface pump draws water from shallow wells, springs, ponds, rivers or tanks. The motor and pump are built in together in submersible and floating systems. In the surface system, pump and motor can be selected separately to study the performance of system along with controller and PV panel.

The assessment of pump- motor costs is necessary in order to know the pump size needed. The cost of pump motor depends on the amount of water required and dynamic water head to which water is to be pumped. In this study, the water head is assumed to be 80m. A DC pump motor has been preferred due to its permanent magnet which is created in DC motor and also increases it's efficient up to 100% more than AC motor (ALLaham et al., 2014). The pump which needs to be bought to deliver water required for irrigation is of type Lorenz, PS 20-HR-04-MPPT. The total cost of pump system is $1650 and this includes $1000 of pump, $600 of pump controller and $50 of water level sensor for tank (Bates et al., 2009).

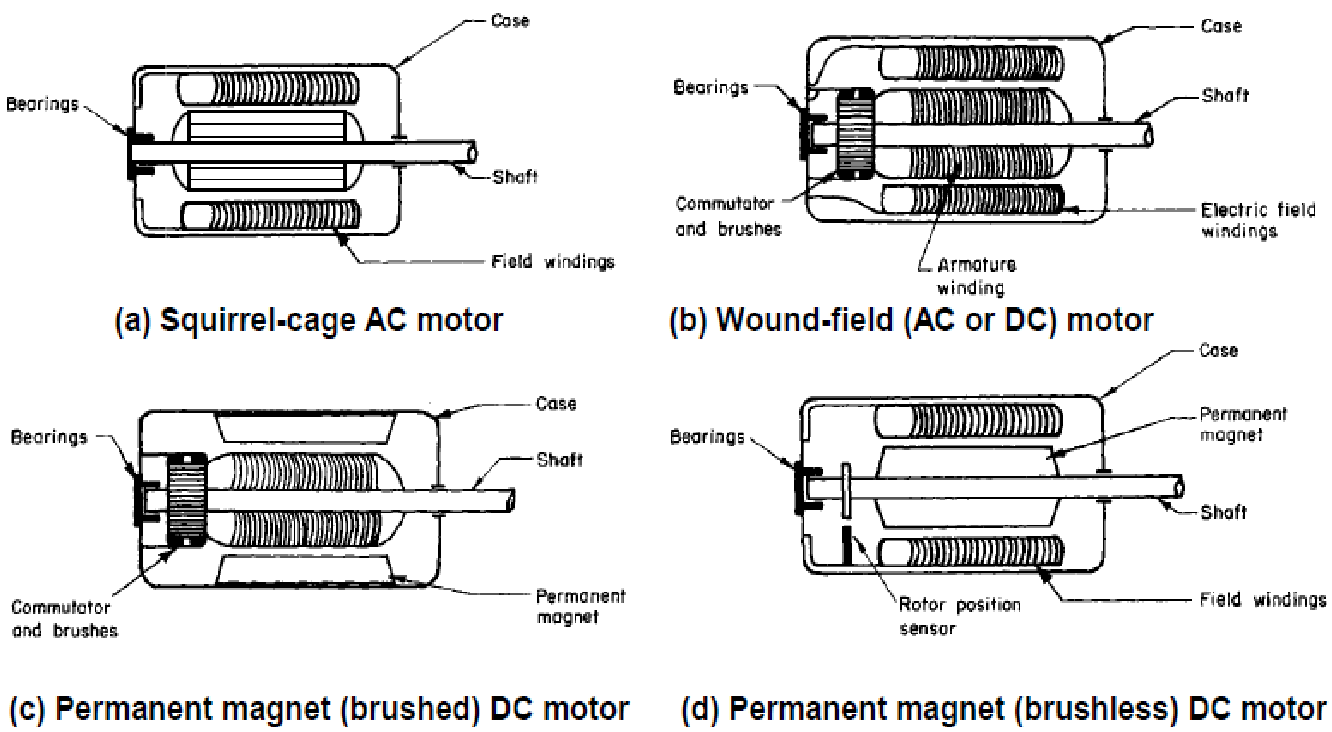


Figure 3. 9 Schematic diagrams of the four main types of electric motors.

Source: **Argaw et al., 2003**

The main advantages of permanent magnet DC motors are their simplicity and efficiency for smaller applications and no complex control system is required. Maintenance in brushless DC motors is minimal. However, AC motors are less efficient than DC motors and require inverters for PV applications which increase cost and breakdown risk.

3.13. Performance parameters of a PV water pumping system

The performance of PV water pumping system mainly depends on the water flow rate which is influenced by weather conditions at the selected location, especially solar irradiance and air temperature variations. The performance of solar pump depends on the head (m) by which water has to be lifted, the water requirement, size of water storage tank, water to be pumped (m^3), PV array virtual energy (kWh), Energy at pump (kWh), pump efficiency (%), and system efficiency (%) and variation in pump pressure due to change in irradiance and pressure compensation (Foster et al., 2014).

The performance of solar water pumping system mainly depends on the following parameters:

- Solar radiation availability at the location
- Total Dynamic Head (TDH): Sum of suction head (height from suction point till pump), discharge head (height from pump to storage inlet) and frictional losses(m)
- Flow rate of water
- Hydraulic energy: potential energy required in raising the water to discharge level
- Total quantity of water requirement

Hydraulic energy E_h (kWh/d) required per day to supply a volume (V) of water (m^3) at TDH is calculated as following (Foster et al., 2014).

$$E_h = \rho \times \mathrm{g} \times \mathrm{V} \times \mathrm{TDH} \tag{3.5}$$

Where ρ is the water density, g is the acceleration due to gravity (9.81 m/s^2), V is volume of water (m^3),TDH is the total dynamic head (m) which is the sum of static head (m) and friction losses (m).

Solar photovoltaic array power P_{pv} required is given by

$$P_{Pv} = E_h/(I_T \times \eta_{mp} \times \mathrm{F}) \tag{3.6}$$

Where I_T is the average daily solar irradiation ($kWh/m^2/day$) incident on the plane of array, F is the array mismatch factor, η_{mp} is the daily subsystem (motor-pump) efficiency. The efficiency of the system can be increased by selecting the size of PV array, its orientation and motor-pump system.

The amount of water delivered by the PV array depends mostly on the amount of the solar radiation received on surface of PV array, the size of the PV array, and the performance of the subsystem.

The amount of water pumped V (m^3) is given by the following equation:

$$V = (P_{pv} \times I_T \times \eta_{mp} \times \mathrm{F})/(\rho \times \mathrm{g} \times \mathrm{TDH}) \qquad (3.7)$$

Where ρ is the water density, g is the acceleration due to gravity (9.81 m/s^2), TDH is the total dynamic head (m).

The efficiency of the motor-pump system η_{mp} is given as follows:

Efficiency = hydraulic energy output / input energy

Efficiency of PV array (%) is given by

$$\eta_{pv} = \frac{P_{pv}(W)}{I_T(W/m^2) \times A_c(m^2)} \times 100 \qquad (3.8)$$

The overall solar water pump system efficiency is calculated as follows:

$$\eta_{total} = (\eta_{pv} \times (\eta_{mp}) \qquad (3.9)$$

Where η_{pv} is efficiency of PV array (%), η_{mp} is efficiency of the motor-pump subsystem (%)

3.14. Assessment of irrigation water requirement (IWR)

The assessment of IWR is complex because it is affected by many factors, such as climatic parameters (solar radiation, temperature, and humidity), crop characteristics (type, variety, and development stage), and environmental conditions. The amount of water required for irrigation is mainly depends on the type of crop and the size of field to be irrigated.

The amount of pumped water by a PVWP system is also depend on the dynamic variability of the solar radiation, temperature, and performances of the inverter and the pump system. The solar radiation and temperature primarily affect the power output of the solar PV array. In general the energy extracted from a PV module is mainly dependent on weather conditions. The research conducted by (Gad ; 2009) has developed a methodology for performance prediction of a direct coupled PV water pumping system in South Sinai, Egypt by using a computer simulation program. The system is found to be capable of pumping water of 24.06 l/day, 21.47 l/day and 12.12 l/day in summer solstice, equinoxes and winter clear sky days respectively.

In agriculture, water demand for crop irrigation is seasonal, because some crops need a maximum water supply for a short growing season. In general, all irrigation systems need to be designed for peak water demands. Irrigation water pumps are characterized by the need for large quantities of water. For this reason, producing high value cash crops is advantageous that making the systems to be more economically viable.

Usually, water demand for irrigation varies from crop to crop and changes with the meteorological factors, type of soil, irrigation methods and rainfall scheme. Although, estimating the water demand for irrigation use is complex, local practice and field experience are the best guides to estimate water requirements for a specific application. The following table shows the estimated daily water requirements for various types of crop irrigation.

Table 3. 5 Estimated maximum daily water demand for various types of crop irrigation

Crops	Daily Water Requirement (m^3/ha)
Rice	100
Rural village farms	60
Cereals	45
Sugar cane	65
Cotton	55

Source: (Argaw et al. , 2003)

1.14. Environmental assessment

The main cause of global warming is CO_2 emission released from different sources of energy. The amount of CO_2 emitted varies depends on energy produced and power technology used for conversion.The environmental advantages of using PVWP systems was analysed in terms of CO_2 emission reduction.

The utilization of PVWP systems for agricultural irrigation can reduce CO_2 emissions in two possible ways: use of PV modules instead of diesel to power irrigation system and selling surplus electricity from solar energy systems through feed in-tariff scheme. The revenues that can be generated through the using of the PVWP irrigation systems come from the fuel savings, the available incentives for renewable energy production and selling surplus electricity generated during the non-irrigation period. The reduction of CO_2 emissions that achieved in this way can be monetized and traded through carbon credit market. At the same time, the study was highlighted the effects of PV systems on grassland and farmland, soil and wildlife.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

This section presents the results from the site and simulation results from HOMER software. These results are included all environmental and economic parameters which can express the performance of irrigation systems. The NPC, COE, OC and O&M of selected water pumping systems are presented and discussed in this chapter. Finally evaluation of environmental effects of these water pumping systems especially CO_2 emissions, soil, wildlife, and farmland and grassland degradation are also presented in this section.

4.1. Analysis of Bugesera solar energy potential

Table 4.1 shows the situation of the average solar radiation obtained in Bugesera district. The average solar radiation data was collected from Rwanda Metheology Agency and by using Microsoft office Excel, the average solar radiation was calculated by considering data shown in appendix I**.**

Table 4. 1 Average solar radiation at Mayange station (Bugesera district).

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Average solar radiation(kWh/m^2/day)	5.83	5.94	6.10	6.12	6.06	5.54	4.35	4.97	5.86	5.81	6.39	5.14	5.67

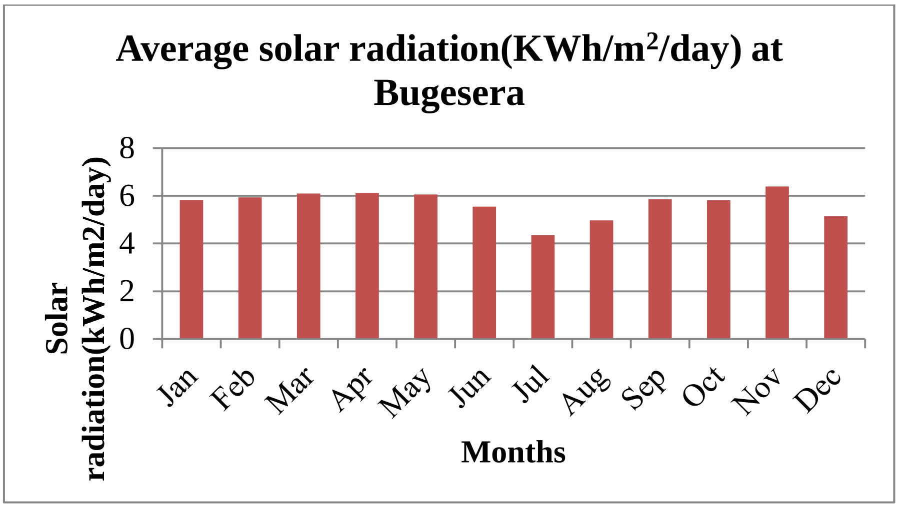


Figure 4. 1 Variation of solar radiation for the location of Bugesera district

Figure 4.1 shows that enough solar radiation is available in Bugesera district and this ensures that the system which needs solar energy to operate will work without any uncertainty. Therefore the use of solar PV to capture energy for pumping water is more feasible in this region.

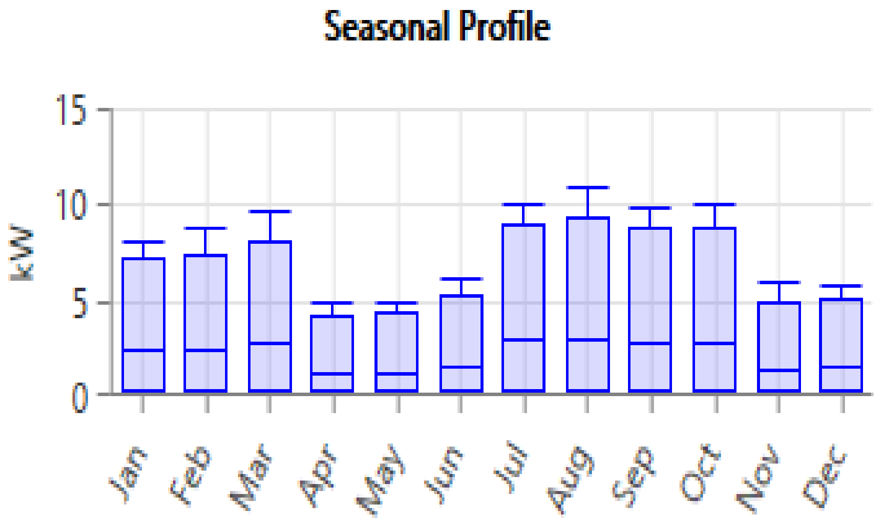


Figure 4. 2 Seasonal load profile for irrigation at Bugesera district

Figure 4.2 shows that irrigation is highly needed in July and August (summer season). While April and May are the months of heavy rainfall it means irrigation is not needed in this period. For that reason it is important to find other applications of energy produced by PV system when irrigation is not required.

4.2 Analysis of energy produced by PVWP system

The energy produced by solar photovoltaic is directly proportional to solar irradiation available and the size of panel. The quantity of solar energy production also varies depends on how solar panel is installed to capture solar irradiations. Moreover energy requirement for pump is a result of solar radiations hitting the solar panel. Solar panel can be mounted either on fixed tilt angle or on system which tracks the sun. In order to capture maximum power from a PV panel, it is important to connect it to the structure controlled by maximum power point tracking (MPPT) system. Tracking the sun reduces the physical size of PV panel area required for a given output, increases overall efficiency of the system, improves power production, and return on investment. The results from the field through manual tracking by changing the orientation of PV array at least four times a day to face the sun, the output obtained is 22% more as compared to the fixed tilted PV array. According to (Chandel S.S. et al., 2015) tracking of a solar pumping system extends the time for peak water supply

In general to get optimum energy production, tilt angle have to be properly determined and this takes into account the latitude of the area under investigation. Based on the benefit of tracking system, it could be preferred as a best option to use due to its higher performance.

Nevertheless in terms of economic perspective, tracking system cost too much compared to the solar panel mounted on fixed tilt.

The total electricity production from PV system is not always fully utilized by pump to meet water requirement for irrigation. The excess of electricity varies depends on method of storage used either to store electricity in form of chemical energy into battery or in form of water into tank. However, more electricity surplus is obtained for a PV panel directly connected to irrigation system without storage. Furthermore, significant increases in electricity surplus are obtained when there is no irrigation required. In fact there are some months do not need electricity for pumping water (see figure 4.2) while solar panel keeps producing it from the available solar energy source.

4.3 Economic analysis of proposed water pumping systems

The economic analysis of alternative systems is undertaken to find the most profitable among the possible energy alternatives.Table 4.2 shows that the capital cost of the systems increase with the use of renewable energy system (solar PV) compared with the conventional systems (Diesel) due to the higher initial capital costs of the renewable energy technology. But the operating cost of the PV systems is very low compared to diesel system which leads to be more economical for long term. By the fact that the PV costs decreases with the increasing of its efficiency, one can consider the great advantages of using this kind of energy in the future. Table 4.3 summarizes the NPC, O&M, OC and COE for the three used systems. The interest rate and the annual inflation rate were set equal to 7.42 percent, and 5 per cent, respectively (tradingeconomics.com/Rwanda, 2018).

Table 4. 2 Cost of the pumping Systems.

Parameters	Solar PV	Diesel	Hybrid PV-Diesel
System	34400$	16600$	47850$
Fuel	0$	24742$	7513$
Replacements	20$	15700$	5069$

Table 4. 3 NPC, M&O, OC and COE for the three proposed water pumping systems

Parameters	Solar PV	Diesel	Hybrid PV-Diesel
NPC	37743$	62765$	67603$
OC	150$/yr	5560$/yr	1401$/yr
O&M	229$	10359$	3210$
COE	0.192$/kWh	0.367$/kWh	0.289$/kWh

4.3.1. Net present cost (NPC) and operation and maintenance (O&M)

Figure 4.3 and figure 4.4 show the NPC and O&M costs for the PV, hybrid PV-Diesel and Diesel unit systems. The NPC of the PV system is the lowest one due to a very low running costs and long life of the PV panels (more than 20 years) compared with the Hybrid and Diesel systems.

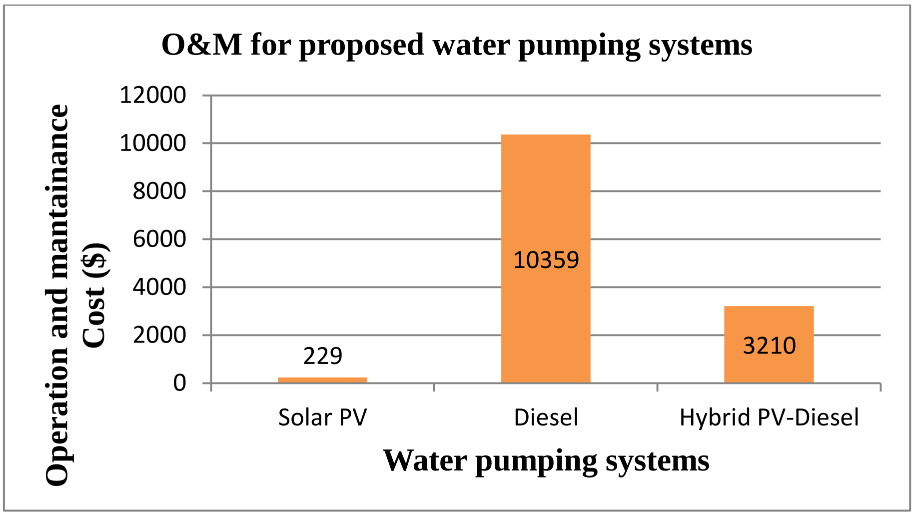


Figure 4. 3 O&M cost for PV, hybrid PV-Diesel and Diesel water pumping systems

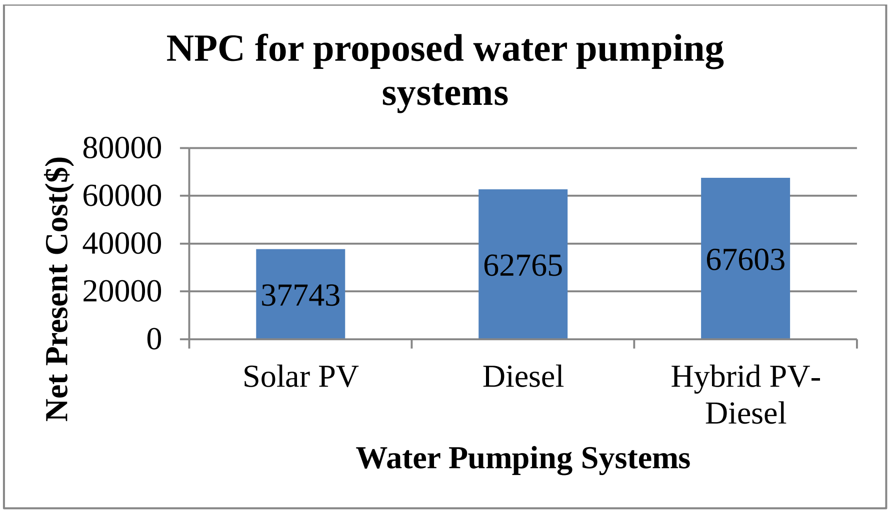


Figure 4. 4 NPC cost for PV, hybrid PV-Diesel and Diesel water pumping systems

The costs of diesel systems for irrigation are increasing sharply due to the lack of availability of diesel fuel in the markets. According to Rwanda National Bank (BNR) oil prices is the major drivers of inflation, are expected to rise by 23.8% in 2017 against a 15.7% fall in 2016 (National Bank of Rwanda(BNR), 2017). This issue of scarcity of fuel affects heavily the O&M costs of diesel system.

Furthermore, the use of diesel fuel is more expensive in the rural areas due to the transportation difficulties. Currently, diesel cost is already unfordable to the world's poorest people especially in Rwanda due to taking into account the costs of transportation of diesel. In Rwanda, the diesel prices are heavily subsidized by the government, but this will not be the case in the future. In fact, no one knows what the price will be next year or 10 years from now but all indications suggest that oil will only continue to increase in cost as global oil production will drop down due to the decline in resource and rapidly increasing demand due to the high population growth.

In general, diesel prices will evidently increase in the future since Rwanda will continue to import all quantity of oil derived fuels needed in day life. However, this fact explains the importance of using PV water pumping systems in rural and remote areas where connecting to the electricity grid is difficult.

As shown in table 4.2, the fuel cost is approximately 39.42% and 11.11% of the NPC for Diesel and hybrid PV-Diesel systems respectively. Moreover, the less fuel cost in hybrid PV-Diesel system than the Diesel system results from low operation periods of Diesel generator with respect to PV (75% PV and 25% Diesel). However, the increase in NPC for hybrid system is arising due to the replacements of the diesel components with small operating periods. The O&M costs showed that the Diesel systems take a lot of costs due to operation principles where they are heavily dependent on fuel, which arise the advantageous of using PV with almost maintenance free, no rotating part and silent. Usually, maintenance and overhauling of diesel generators are needed regularly because of its rotating parts. In both cases either NPC or O&M, a PVWP system shows to be a profitable investment.

4.3.2. Operation cost and cost of energy

The OC and COE for the three systems are shown in figures below.

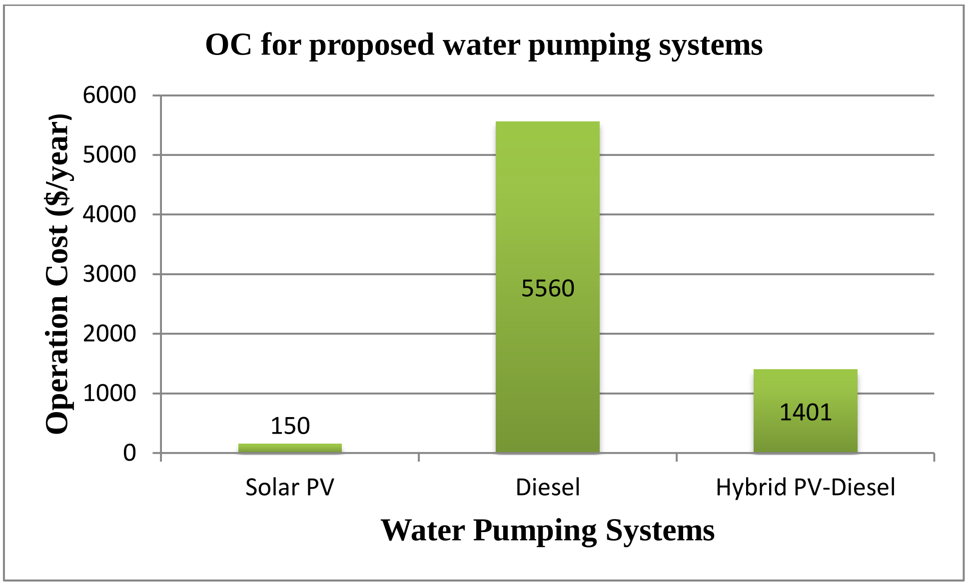


Figure 4. 5 OC for PV, hybrid PV-Diesel and Diesel water pumping systems.

As shown in figure 4.5 the operation costs (OC) of the systems decrease with using PV water pumping system. OC cost of PV system is about 2.69% of the Diesel system and 25.19% of the hybrid PV-Diesel system. It is clear that due to a very high running cost of diesel system, OC of the Diesel unit is higher than that of the PV and hybrid PV-Diesel systems (see Table 4.3).

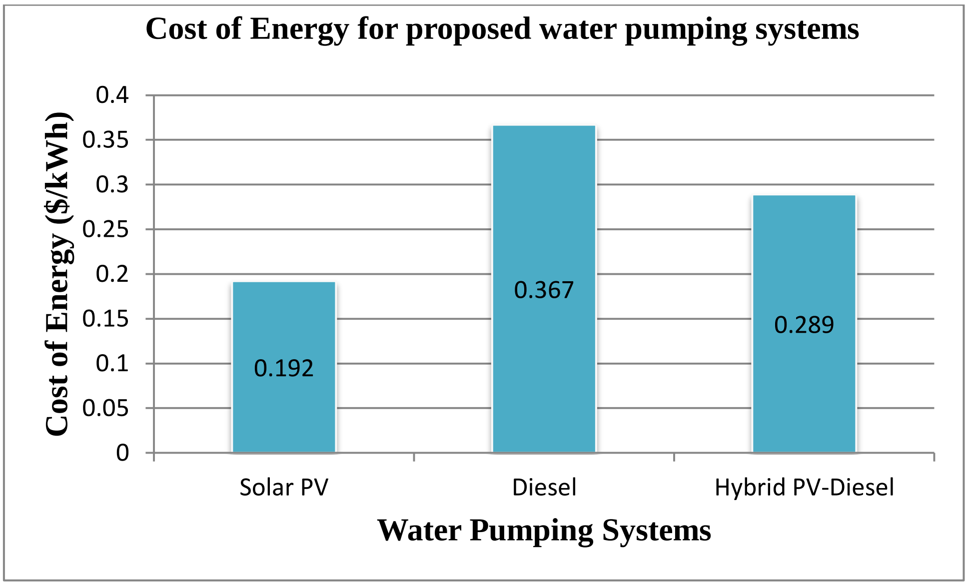


Figure 4. 6 COE for PV, Diesel and hybrid PV-Diesel water pumping systems

The comparison of the renewable (solar) and conventional energy resources can be examined from the COE, which represents the total cost required for generating one kWh as unity of electricity. As shown in figure 4.6 above, the COE for PV system is lower than the rest two systems. The HOMMER results show that COE for solar PV, Diesel and hybrid PV-Diesel systems are 0.192, 0.367 and 0.289 $/kWh respectively. COE of PVWP system is lower because it requires a minor maintenance and it is fuel independent. The PVWP system has low PBP varying between 7 and 8 years showing high economic profitability.

From the above economic analysis, PV systems can be an attractive and suitable energy source deployed alongside diesel pumps in different areas with good of solar radiation and where the cost of transmission system to on-grid is very high.

4.4 Analysis for irrigation methods costs

The high cost of irrigation methods (see table 4.4) has discouraged many private farmers from investing in irrigation. In fact this high cost is the main factor which affects development of irrigation in Rwanda.

Table 4. 4 Average investment cost for irrigation method ($/ha)

Technology	**Rwanda Cost/ha**	**Serviceable Lifespan**
Drip	4000USD/ha	10years
Sprinkler	14000USD/ha	25years
Center Pivot	14000USD/ha	40years

According to RAB, the high costs of irrigation development in Rwanda (compared to average international costs of 5000USD/ha) are related mostly to the hilly topography of Rwanda which requires bigger pumping systems which have to be imported. Despite the fact that Rwanda is blessed with many lakes, its rural communities living around these water bodies, have not fully benefitted from irrigation and are constantly exposed to food insecurity and poverty due to drought. It is obligatory for the Government of Rwanda to find mechanisms of encouraging private sectors to investment in agricultural irrigation.

4 .5. Environmental analysis for water pumping systems

4.5.1. Greenhouse gases (GHG) emission

The main cause of global warming is CO_2 emission released from different sources of energy. The amount of CO_2 emitted varies depends on energy produced and power technology used for conversion. The one of conversion technologies is diesel generator which is the most usefully in different areas of the world for power generation. The operating principle of diesel-powered generator involves the injection of diesel fuel in mix ratio with the compressed air into combustion chamber. The burning of this mixture produces unburned hydrocarbon and other poisonous particulates such as, Carbon dioxide (CO_2), Carbon monoxide (CO), Sulfur dioxide (SO_2) and Nitrogen oxides (NOx) which are very dangerous to our health especially lungs. In this analysis, it was chosen CO_2 gases in comparison of the proposed water pumping systems. Table 4.4 shows details of pollutant emissions for all the system configurations which are quite dangerous to both human and atmosphere.

Table 4. 5 Pollutants emission for Diesel energy systems.

Emission (kg/yr)		
Pollutant	**Diesel**	**Hybrid PV/Diesel**
Carbon dioxide	14106.50	1218
Carbon monoxide	29.82	2.99
Sulfur dioxide	28.30	2.57
Nitrogen oxides	312.71	28.42
Unburned hydrocarbons	3.66	0.35
Particulate matter	2.83	0.23
Total emission	14483.82	1252.56

From the environment point of view, PVWP system contributes to the reduction in greenhouse effect as shown in table 4.5, it extreme decreases in generation of pollutant gases. Table 4.5 presents the comparison between these systems where the total emissions for standalone diesel system is 14483.82 kg/yr while the introduction of PV system as hybrid system can lower the total emission to 1252.56 kg/yr.

In Rwanda, there is no specific penalty imposed for pollution (CO_2 emission) from agricultural. For that reason, this has indirectly encouraged citizens to operate various forms of combustion engines as their electricity generating tool. However, most developed countries in Europe and USA imposed penalty on this emission where carbon trading (the CO_2 emissions reduction) are considered as offsets at 100 $/tonne (Pietro E., 2015). This means if penalty imposed for pollution in Rwanda, PVWP system can help people to save USD 1448.382 per year over DWP system and USD 125.256 over hybrid PV-Diesel system.

4.5.2. Analysis of the impacts of solar power plants on Wildlife and land

Although PVWP has more advantages for reducing CO_2, there are also some disadvantages such as wildlife, soil, and farmland and grassland degradation. In fact PV system needs some land to be installed on. Most installations of PV array are supported by fixed structure metal, if those systems are not movable it means that all area occupied by the systems is useless up to the end of lifetime of the system. This issue affects crop-rotation system and growing of natural threes. In addition, installation of solar power plant equipments requires removing trees which are around the selected area to avoid shade of the plants. This action affects the life of wild animals which are living in that area. Generally, a major motivation for promoting solar power is to reduce emissions of carbon dioxide from traditional power generation. When the solar power is installed in forested regions, this motivation needs further research because trees and bushes must be removed to prevent shading of solar panels. Typically, any plant taller than ∼0.5 m is removed, and tree roots are removed to allow posts to be driven into the ground (US-BLM, US-DOE, 2010). Due to the small land per HH in Rwanda, where the average size of land cultivated per household (HH) is 0.59ha, it is necessary to install the movable support of PV array.

In fact, large-scale solar power plants are possible impacts to species of flora or fauna include the soil erosion, since soil and local biota is removed during the construction phase of a solar power plant. Nevertheless, ecological impacts of solar power plant technologies are minor, as was confirmed by (Turney, D. and Fthenakis V., 2010), who found that the removal of forests to make space for solar power causes CO_2 emissions as high as 36 g CO_2 per kWh, which is a significant contribution to the life cycle CO_2 emissions of solar power, but is still low compared to CO_2 emissions from coal-based electricity that are about 1100 g CO_2 per kWh. But attention for site selection for each solar power plant projects is advised and should be taken into account with extra care.

4.6. Respondents Vs. agricultural irrigation

During the survey, about 45% of 60 respondents were confirmed that irrigation activities are improving their agricultural production and their income from the sale of agricultural products which leads to improved standard of living of their families. Whereas the rest (55%) of respondents responded that they never use to irrigate their crops. The survey results indicated that those farmers who irrigate their crops, 33% of respondents use water cans and 52% flood irrigation method to watering their crops whereas the rest use modern technologies (drip and sprinkler).

The main agricultural products produced by the sample respondents in 2018 were classified into two categories namely vegetables (onion, carrot, tomato, sweet potato, bean, cabbage and others) and cereal crops (maize, sorghum, rice, etc.). The majority cultivated fields are located in marshland and near to the valley where the farmers can get water easily. Based on the information from the Rwanda Agriculture Board (RAB) and Ministry of agriculture (MINAGRI), the total area covered by irrigation scheme is about 48,508 ha.

The results from survey also shows that producing agricultural products through small-scale irrigation technologies(SSIT) are becoming better solution for climate change effects including drought and they are increasing income of farmers from the sale of agricultural products and this leads them to improve their standard of living. Furthermore, this was confirmed during the discussion with the farmers. They confirmed that SSIT helps to ensure food security and getting additional income where they obtain 3 to 4 times of crop production rather than none irrigated crops' land.

4.7. Barriers and Drivers of agricultural irrigation development

4.7.1. Barriers

During interview and survey with farmers of Bugesera district and RAB staff, there are some problems raised as the barriers for harnessing agricultural irrigation.

- Farmers' financial capacity especially for the purchase of pumping systems and skills about the use of modern irrigation technology especially solar PVWP system are considered to be the main limitations for most of farmers.
- Insufficiency of incentives and subsidies for small farmers (Poorest people)
- The farm size seems affect the adaptation of PVWP systems in Rwanda, where the average size of land cultivated per household (HH) is 0.59ha.

- Lack of infrastructure (road, ponds, dams and storage) and advisory services are seen to be the other barriers for the adoption of pumping systems for irrigation.
- The quality standards along the agro-food chain and insufficient market information and market networks are considered as limitations.
- Lack of strong legislative framework, practical policy, legal and regulatory environment for the private sector to be attracted to invest in solar energy technology.
- shortage of agricultural inputs such as improved seeds and pesticides
- Lack of strong and sustainable training program for farmers and technicians in SSIT.
- Low purchase capacity to afford SSIT kits even at 50% subsidy due to the expensive of SSIT equipments because the most of irrigation equipments are imported (see appendix IV).

4.7.2. Drivers

- From the results of survey with farmers, all of the respondents confirm that the adoption of pumping systems is helpful to increase crop production and their incomes.
- The Government of Rwanda adopted subsidy program of up to 50% of the total required cost for small scale irrigation technology (SSIT) to the farmers.
- The global cost reduction in solar PV prices; the price of PV modules will be continuing to decline due to technology improvements, competitive procurement and prolonged support from international donors and favourable framework conditions provided by governments. Recently, the rapid decrease in the price of solar PV panels and rising oil prices made solar PV technology increasingly competitive with conventional technologies, such as diesel-fired generators, which are widely used throughout Africa (Hansen U.et al., 2015). The fall in electricity costs from utility-scale solar photovoltaic (PV) projects since 2010 has been remarkable by IRENA. The global weighted average Levelized cost of electricity (LCOE) of utility scale solar PV has fallen 73% since 2010, to USD 0.10/kWh for new project commissioned in 2017. IRENA has confirmed that cost reductions are set to continue through 2020 and beyond up to USD 0.03/kWh from 2018 onward (IRENA, 2018)
- Availability of solar energy potential; Bugesera (Rwanda) is located just a few degrees of the Equator that makes it a prime candidate for the development of solar PV plants. Bugesera has monthly average daily global irradiation of 5.6 kWh/ (m^2 day) on a

horizontal surface. This level of solar insolation is quite favorable, for the application of a number of solar technologies.

- Financial and technical support; International donors and investors are interested to promote solar energy use due to the geographic location of country. Furthermore, the government programs are also used to promote the diffusion of solar PV market either direct or indirect. These are, import duty and VAT exemptions for imported PV components and feed-in tariffs for investors of large-scale solar power plant.

4.8. Suggestion policies

After collecting information from observations, interview and survey with respondents, the following policies were suggested to overcome the barriers of development of agricultural irrigation applications:

- Improve access to credit and long-term loans especially for small farmers, in order to lift millions of people out of poverty. These will help small farmers to be more productive and bring agricultural transformation shift from traditional towards modern agricultural production oriented towards the market or other systems of exchange.
- Organizing/ strengthening cooperatives of agricultural irrigation, in fact attention should be given for the encouraging of irrigation cooperatives so that farmers can join together in dealing with irrigation activities based on cooperative values and principles, and solve their problems for the common benefit through members' participation.
- Improve access and supply of components of pumping system (PV or generator, motor pump, spare parts etc.) at sector level.
- Facilitating training and experience sharing between farmers
- Improving access to timely market information and market networking
- Strengthening crop value chain and supply of processing materials
- Improve conservation of soil, energy and water by utilizing resources efficiently.
- Improving availability of agricultural inputs especially seeds, pesticides and agro-chemicals and fertilizer at village level.
- Improving mobilization about land consolidation program in order to encourage farmers to combine their small lands together.
- Introducing subsidy program for solar PVWP systems for agricultural irrigation because currently the available subsidy is reserved for diesel motor pumps.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Like many countries of the world, agriculture sector has a significant impact on Rwanda's economy whereby 80% of population depend on agriculture. The irrigation system is promoted to increase crops productivity up to 5 times more than the crops harvested without application of irrigation. The main purpose of this master's thesis was to analyze environmentally and economically the cost of solar PV system, Diesel and hybrid PV-Diesel water pumping systems for agricultural irrigation. The HOMER software was used for optimizing and simulating the pumping systems in terms of NPC, OC, O&M and COE. These three pumping systems are designed to operate at Bugesera district, Rwanda.

The economic analysis showed that a solar PVWP is more profitable compared to others two systems due to its free fuel dependent and very low maintenance cost, and long life of the PV system. The HOMER results show that COE for PV system, Diesel unit and hybrid PV-Diesel systems are 0.192, 0.367 and 0.289 $/kWh respectively while O&M costs are 229 $, 10359 $ and 3210 $ respectively.

From the environment point of view, a replacement of DWP systems by PVWP systems results in CO_2 emissions reduction of about 14.48 tonnes while for hybrid solar PV-diesel is about 1.25 tones. It was also found that large-scale solar power plants are indirectly CO_2 emitters as high as 36 g CO_2 per kWh, since forests and bushes have to be removed to make space for solar power plant. These power plants also negatively affect wildlife, soil quality and farmland and grassland. For that reason, a deep investigation is needed to avoid those negative effects of large-scale solar power plants.

The problems identified during the survey include financial constraints especially for the purchase of motor pumps, shortage of agricultural inputs, insufficient market information and lack of infrastructure facilities. Furthermore, even if the research show that the policy of SSIT project is become an intervention instruments for drought mitigation in Rwanda, but many farmers are struggling to pay their 50% of investment cost, and this is affecting the performance of this project. Therefore, in order to improve and expand irrigation activities, it is necessary to solve the above mentioned problems through the involvement of all stakeholders including government institutions, the farming communities, researchers, private sector and non-government organizations to fill the capacity gaps.

Finally, relying on an interview, software results and observations, it is concluded that Bugesera district has abundant resources for irrigation schemes especially using PVWP systems that could significantly improve agricultural production and the status of food security which lead to improve standard of living of farmers and country's economy development.

5.2. Recommandations

This master thesis represents the environmental and economic cost analysis of a solar PV, diesel and hybrid PV-Diesel water pumping systems for agricultural irrigation for supporting the sustainable development of agriculture production in Rwanda. This section discusses some recommendations and the issues that require further investigation.

- The storage systems of solar PVWP systems need to be evaluated in deep because battery is too expensive. However, more investigations are also required to study the possibility of harnessing the entire power system for multiple applications, such as providing power for irrigation as well as for other off-grid loads, which were not taken into account in this current study. This could be more economically profitable, since irrigation is required only for some months of the year.
- The environmental feasibility of PVWP systems has to be further analysed. The assessment of the most suitable areas for implementing solar PVWP project is another crucial aspect that needs to be investigated for wide and sustainable applications of the technology. It is important to identify all economic and environmental constraints that can negatively affect the suitability of PVWP systems. Moreover, due to the small land per HH in Rwanda, it is necessary to use sun tracking system to maximize power output, marginal land or install the movable PV array in order allowing the connection of the systems to the grid or other loads when irrigation is not required. This also will allow the farmers use crop-rotation system.
- Although, the policy of land consolidation was introduced by the government of Rwanda, in Bugesera district is still low applicable. For this reason, more sensitization is needed to improve the skills of people about the use of land together (cooperatives). This also will help the farmers to put together their finance power to afford water pumping systems.

- The government of Rwanda is highly recommended to introduce the incentives and subsidies for PVWP systems in spite of DWP, because currently the available subsidy is reserved for only diesel motor pumps which contribute to CO_2 emissions. In addition, Government needs to introduce a fully grants program for destitute and poorest people to buy solar PVWP systems.
- Furthermore the private sector needs to be involved in land irrigation especially using PVWP systems. The government needs to find ways to motivate private agricultural producers and encourage the availability of finance for business start-up in the agriculture sector.
- This research for PVWP systems was limited to the agricultural irrigation, but it could be extended to the crop drying, crop conservation, crop value-added processing and rural electrification in Rwanda. It is recommended for researchers to think about that.
- Finally, agricultural Policy developers should work closely with country's statisticians, researchers and all stakeholders for better outcomes. In addition to this, it will help to make a better realistic plan and projection toward the country's target of irrigated areas (100,000ha by 2020).

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APPENDICES

APPENDIX I: Average solar radiation available at Mayange station (in Bugesera district) for 2016-2017.

Months	Average solar radiation(W/m2)	Maximum (W/m2)	Minimum (W/m2)
January	486.29	1715.3	10.9
February	521.84	1698.5	10.8
March	566.59	1788.1	102.7
April	610.25	1789.7	12.1
May	530.23	1790.8	11.8
June	461.77	1638.7	10.9
July	363.33	1390.9	10.8
August	414.73	1729.2	10.9
September	555.42	1784.8	23
October	602.96	1790.6	16.3
November	674.93	1769.4	161.1
December	478.6	1786	10.7

Source: Data from Rwanda Metheology Agency

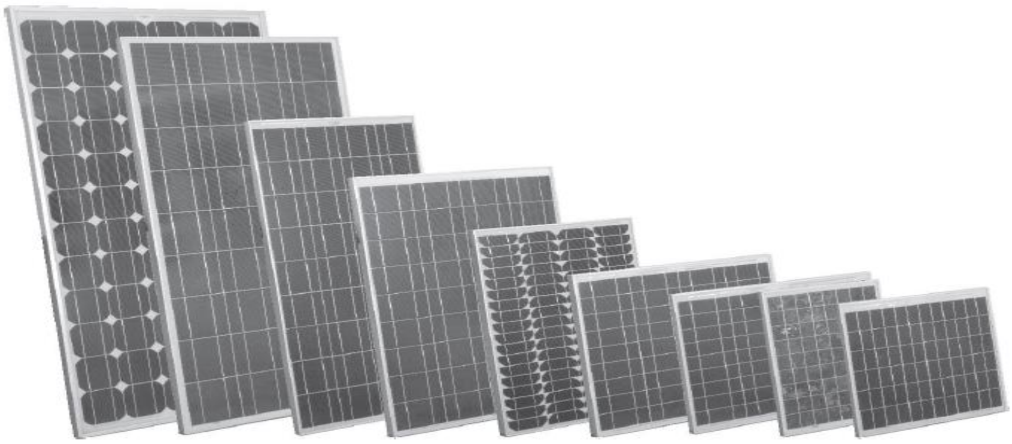
APPENDIX II: Average rainfall at Kayonza station for 2016-2017

Station_Name	Lat	Lon	Elev	Year	Month	Rainfall in(mm)
KAYONZA	-1.9	30.51	1575	2016	1	15
KAYONZA	-1.9	30.51	1575	2016	2	45.6
KAYONZA	-1.9	30.51	1575	2016	3	40.6
KAYONZA	-1.9	30.51	1575	2016	4	76.2
KAYONZA	-1.9	30.51	1575	2016	5	25
KAYONZA	-1.9	30.51	1575	2016	6	0.2
KAYONZA	-1.9	30.51	1575	2016	7	0
KAYONZA	-1.9	30.51	1575	2016	8	0
KAYONZA	-1.9	30.51	1575	2016	9	6.2
KAYONZA	-1.9	30.51	1575	2016	10	78.6
KAYONZA	-1.9	30.51	1575	2016	11	0

KAYONZA	-1.9	30.51	1575	2016	12	28.6
KAYONZA	-1.9	30.51	1575	2017	1	3.6
KAYONZA	-1.9	30.51	1575	2017	2	36.8
KAYONZA	-1.9	30.51	1575	2017	3	20.8
KAYONZA	-1.9	30.51	1575	2017	5	21.6
KAYONZA	-1.9	30.51	1575	2017	7	0
KAYONZA	-1.9	30.51	1575	2017	8	65.8
KAYONZA	-1.9	30.51	1575	2017	9	19.4
KAYONZA	-1.9	30.51	1575	2017	10	60.6
KAYONZA	-1.9	30.51	1575	2017	11	59.2
KAYONZA	-1.9	30.51	1575	2017	12	37.6
KAYONZA	-1.9	30.51	1575	2018	1	112.8

Source: Data from Rwanda Metheology Agency

APPENDIX III: different size of solar panels available at Davis & Shirtliff Company



Appendix IV : Equipment Pricing and subsidized rate

SN	Description of equipment	Market Price (Frw)	50% Subsidized Price (Frw)	Serviceable Life Span
	Complete Portable Irrigation Kits			
1	1ha Portable Rain gun sprinkler system (diesel pump, HDPE pipes)	2,710,000	1,355,000	10
2	5ha Rain gun sprinkler system (diesel pump with HDPE pipes)	TBA	TBA	10
3	10ha Rain gun sprinkler system (diesel pump with HDPE pipes)	TBA	TBA	10
2	5ha conventional sprinkler system (diesel pump with HDPE pipes)	12,000,000	6,000,000	10
4	10ha conventional sprinkler system (diesel pump with HDPE pipes)	19,535,720	9,767,860	10
5	Drip and Treadle pump kit complete with 250m2 dam sheet	TBA	TBA	5
6	Drip and Treadle pump kit complete with 500m2 dam sheet	TBA	TBA	5
	Irrigation Fittings and spares			
5	Rain gun set with tripod stand (without pump unit)	450,095	225,048	-
6	75mm diameter HDPE pipe with latch fittings (6m lengths)	43,648	21,824	-
7	50mm diameter lay-flat hose PN 4bars (100m lengths)	31,774	15,887	-

8	6.0HP diesel pump units TDH 50m, Q=9m3/hr	1,164,500	582,250	-
9	6HP gasoline pump units TDH 30m, Q=9m3/hr	341,783	170,892	

Appendix V: Picture at field irrigation data collection (Gashora, Bugesera)

Appendix VI: General interview questions

Jean Baptiste RUTIBABARA

25th May 2018

Dear Respondents,

Greetings to you! I am a Master's degree student at the Pan African University Institute of Water and Energy Sciences (including Climate Change) (PAUWES), Energy Policy Track. In halfway satisfaction for the honor of this degree, I am carrying out a research on environmental and economic Cost Analysis of a Solar PV, Diesel and Hybrid PV-Diesel water Pumping Systems for Agricultural Irrigation in Rwanda: Case of Bugesera district

However, I am utilizing Bugesera district as case of study because of its high water and solar potential so that can be used for irrigation. This questionnaire aims to collect data to be used purely for academic research purpose. Although your participation is voluntary, we hope you will participate well in this important survey about agricultural irrigation. Your honest responses and the best of your knowledge would make this research a win.

This research will provide many benefits on agricultural irrigation development by mentioning the least cost and suitable water pumping system among of these three systems. It will also identify the barriers for diffusion of agricultural irrigation applications in order to achieve to sustainable crop production.

Yours faithful

Jean Baptiste RUTIBABARA

A. QUESTIONNAIRE FOR RAB

1. What is the current agricultural irrigation rate in Rwanda and the Government ambition or target to increase irrigation programme?

   …………………………………………………………………………………………
   …………………………………………………………………………………………

2. Is there any strategy and policies available for promoting solar PV water pumping applications especially for agricultural irrigation in Bugesera district as one of dry regions?

   …………………………………………………………………………………………
   …………………………………………………………………………………………

3. What are the subsidies and incentives for the farmers who want to promote agricultural irrigation?

   …………………………………………………………………………………………
   …………………………………………………………………………………………

Thank you for your response

B. QUESTIONNAIRE FOR RWANDA METEOROLOGY AGENCY

1. What is the solar irradiation of Bugesera district from 2016 to 2018?

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…………………………………………………………………………………………

1. What is the mean temperature of Bugesera district from 2016 to 2018?

…………………………………………………………………………………………
…………………………………………………………………………………………

3. What is the rainfall of Bugesera district from 2016 to 2018?

…………………………………………………………………………………………
…………………………………………………………………………………………

Thank you for your response

C. **QUESTIONNAIRE FOR BUSINESSES AND TECHNICIANS OF WATER PUMPING SYSTEMS (Davis & Shirtliff Company)**

1. What is the price of PV and diesel water pumping systems of 12 Kw?

   …………………………………………………………………………………………
   …………………………………………………………………………………………

2. What are the costs of all accessories of PV and diesel water pumping systems of 12 Kw?

   …………………………………………………………………………………………
   …………………………………………………………………………………………

3. What are the maintenance costs of PV and diesel water pumping systems of 12 Kw?

   …………………………………………………………………………………………
   …………………………………………………………………………………………

Thank you for your response

D. **QUESTIONNAIRE FOR INTERVIEW WITH FARMERS**

1. What do you think about irrigation?

2. What is your favourite type of irrigation method?

Water can

Sprinkler

Drip

surface

No idea

3. What is your favourite type of irrigation technology?

PV Water pumping system(PVWP)

Diesel water pumping system(DWP)

Hybrid PV-Diesel water pumping system

No idea

4. How do you rate the cost of irrigation technology/system in Rwanda?

Very expensive

Expensive

Moderate

Cheap

5. When irrigation system is mostly needed in agriculture sector?

Summer season

Winter season

No idea

6. Have you ever anticipated using any irrigation system?

Always

Occasionally

Never

7. Have you ever been worried about the climate change?

Always

Not satisfied

Never

8. Do you know that solar energy can be used to pump water for irrigation?

Yes

No

9. What are the main crops you irrigate in this sector?

…………………………………………………………………………………………………

…………………………………………………………………………………………………

10. What are the advantages of agricultural irrigation?

…………………………………………………………………………………………

…………………………………………………………………………………………

11. What are the challenges/barriers to apply irrigation applications in this village?

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…………………………………………………………………………………………

12. Please feel free to add any comment

…………………………………………………………………………………………

…………………………………………………………………………………………

Thank you for your cooperation. Your response is very important to this research. If you have any questions or comments, please feel free to contact Jean Baptiste RUTIBABARA

At : Phone : +250782397894

E-mail: baptiste0249@gmail.com

Thank you for your participation

Appendix VII: Thesis budget report

Nº	Item Description	Total amount(US$)
1	Flight ticket + ticket from airport to Home and Home to Airport	1000
2	Data collection expenses(local and international call, seminars and conferences, field trips, internet bundle)	650
3	Local Transport(in Kigali) to internship and thesis study area	380
4	Photocopying and Printing fees	250
5	books binding fees	50
6	Software fees	370
7	Data analysis training fee	300
Total		3,000