



**MÄLARDALENS HÖGSKOLA  
ESKILSTUNA VÄSTERÅS**

# DESIGN, OPTIMIZATION AND ECONOMIC ANALYSIS OF PHOTOVOLTAIC WATER PUMPING TECHNOLOGIES, CASE RWANDA

**PIE BASALIKE**

School of Business, Society and Engineering  
*Course:* Degree Project  
*Course code:* ERA 401  
*Subject:* Energy Engineering  
*HE credits:* 30 credits  
*Programme:* M.Sc. programme in Energy  
Systems

*Supervisor:* Pietro Elia Campana  
*Examiner:* Jinyue Yan  
*Date:* 2015-06-25  
*Email:* [pbe13001@student.mdh.se](mailto:pbe13001@student.mdh.se)

## **ABSTRACT**

Today agriculture sector has a big contribution to the development of economy for many countries. Irrigation is a method which supplies amount of water required in proper time to the cropped land and contributes to the increases of agriculture productivity. Using diesel pump to deliver water to the place of use causes problems both in terms of profitability and environmental perspectives. Higher price of diesel increases operation costs of diesel water pumping system thereby reducing the incomes. In addition the use of diesel pump emits a huge amount of CO<sub>2</sub> emissions which cause global warming. A possible solution to those problems is to use solar energy, a source of energy which is environmental friend and available for free.

The main target of this thesis is to design and optimize a cost effective PVWPs considering three alternatives with tank storage, battery storage and a system without storages medium. The two areas in Eastern province of Rwanda were taken as case study to grow coffee and cassava with five hectares each.

To run simulations, different tools have been used. Those includes CROPWAT to determine water requirements for two crops; MS Excel to design a PVWPs directly connected to irrigation system, make economic analysis, evaluate CO<sub>2</sub> emissions and calculate other parameters. Furthermore in PVsyst software the design and simulation for PVWPs with storages medium has been carried out.

Results showed that using PVWPs directly connected to irrigation system is the most profitable way when compared to the rest two alternatives. They also showed that systems designed to irrigate coffee becomes the most profitable due to huge amount of electricity surplus and higher price per kilogram of coffee. Finally fully replacement of DWPs results in annual reduction of CO<sub>2</sub> emissions by 6.6 tonnes.

**Keywords:** Photovoltaic system, storages medium, pumping system, economic analysis, reduction in CO<sub>2</sub> emissions.

## SUMMARY

This master thesis entitled “Design, optimization and economic analysis of photovoltaic water pumping technologies” was done in a School of Business, Society and Engineering at Mälardalen University to successfully complete the Master program of Sustainable Energy Systems. The thesis work was focused on how to improve Rwanda irrigation system through use of alternative source of solar energy to pump water from underground to two fields with five hectares each and which are used to grow coffee and cassava. The areas selected were Gashora and Ngugu located in eastern province of the country. Due to a landlocked of the country, the price of diesel fuel mainly used in pumps becomes higher thereby making the agriculture sector not to be as much profitable as expected. Moreover CO<sub>2</sub> released from diesel fuel cause problems on environment and on life of people in general.

To achieve higher agriculture profitability in a sustainable manner, solar energy has been considered to replace diesel fuel. This was carried out by designing a complete PVWPs to convert available sun energy into power requirement of the pump. Both technical and economic aspects were taken into account in order to be able to choose the best configuration among three PVWPs: with tank storage, with battery storage and PVWPs directly connected to irrigation system without storage medium. Before designing a PVWPs the input parameters such as water requirements, solar irradiation and total dynamic head were determined using CROPWAT, PVsyst and Rwanda groundwater level respectively. The nearest station of Kampala (Uganda) were taken into account due to the lack of meteorological data for Rwanda in the PVsyst database. To ensure that energy and water are always available, PVWPs was designed on worst case month, the month where the ratio between water requirements and solar irradiations is the highest. The best Loss of Load (LOL) was obtained considering the intersection of PV powers and pump powers for the worst case and best case. It has to be reminded that the worst case is when groundwater level is at its maximum depth of 380m whereas the best case considered is 1m depth. In PVsyst, the design and simulation of PVWPs equipped with tank and battery storages medium was done while the design of PVWPs directly connected to irrigation system was performed using MS Excel tool. Furthermore, all PVWPs, in addition to DWPs, were compared in terms of economic perspective using MS Excel and the mostly utilized technics were: Life Cycle Costs (LCCs), Net Present Values (NPVs) and Payback Periods (PBPs). MS Excel was also used to determine the characteristics of the most efficient method for drip irrigation system and also used to assess the CO<sub>2</sub> emission reduction when DWPs is utilized to replace PVWPs technologies.

The results of this thesis showed that energy produced and exceeded depend on size of PVWPs and storage medium used. To this, higher energy was obtained for irrigation of coffee and when battery storage is incorporated in the system. Even though the PVWPs directly connected to irrigation system have to operate only when sun is available, it was selected to be the best configuration due to its low initial investment costs, higher NPVs and short PBP.

The CO<sub>2</sub> emissions for coffee irrigation becomes higher than CO<sub>2</sub> emitted when irrigation of cassava is made due to huge amount of diesel fuel to meet water requirements of coffee and in total 6.6tonnes are saved every year when both cropped lands are irrigated using PVWPs.

# TABLE OF CONTENTS

<b>1</b>	<b>INTRODUCTION .....</b>	<b>1</b>
1.1	Overview and thesis outlines .....	1
1.2	Background .....	2
1.3	Problem statement .....	3
1.4	Limitations .....	4
1.5	Scope .....	4
1.6	Purpose.....	5
1.7	Objectives of thesis.....	5
<b>2</b>	<b>LITERATURE STUDY .....</b>	<b>6</b>
2.1	Agricultural sector for Rwanda .....	6
2.2	Rwanda irrigation system .....	7
2.3	Use of solar photovoltaic energy in the agriculture sector .....	9
<b>3</b>	<b>METHODOLOGY .....</b>	<b>11</b>
<b>4</b>	<b>DESCRIPTION AND DESIGN .....</b>	<b>12</b>
4.1	Photovoltaic water pumping system (PVWPs).....	12
4.1.1	Design and implementation.....	13
4.1.1.1	<i>Design and simulation of PVWPs with tank storage .....</i>	<i>13</i>
4.1.1.2	<i>Design and simulation of PVWPs with battery storage .....</i>	<i>14</i>
4.1.2	Design of PVWPs directly connected to irrigation system .....	14
4.2	Drip irrigation system.....	15
4.2.1	Design and implementation.....	16
4.3	Environmental perspective .....	17
<b>5</b>	<b>ECONOMIC EVALUATION .....</b>	<b>18</b>
5.1	Economic assessment for PVWPs .....	19
5.1.1	Costs of PV system.....	19
5.1.2	Costs of pump-motor unit.....	19
5.1.3	Costs of storages .....	20
5.2	Economic assessment for DWPs .....	20

<b>6</b>	<b>RESULTS AND DISCUSSIONS .....</b>	<b>22</b>
6.1	Meteorological data.....	22
6.2	Crop water requirements .....	23
6.3	Irrigation system design .....	23
6.4	Selected Loss of Load (LOL) .....	24
6.5	Evaluation of systems energy production and systems energy for PVWPs equipped with tank and battery storages .....	26
6.6	Analysis of energy production for PVWPs directly connected to irrigation system.....	28
6.7	System profitability .....	33
6.8	Assessment of systems CO <sub>2</sub> emissions .....	38
<b>7</b>	<b>CONCLUSIONS .....</b>	<b>39</b>
<b>8</b>	<b>SUGGESTIONS FOR FURTHER WORK .....</b>	<b>40</b>
	<b>APPENDIX.....</b>	<b>45</b>
	Appendix 1. Rwanda groundwater level .....	45

# LIST OF FIGURES

Figure 1. Rwanda map [15]..... 3

Figure 2. Layout of sprinkler irrigation system [20]. ..... 7

Figure 3. Layout of drip irrigation system [23]..... 8

Figure 4. Meteorological characteristics of the region under study. .... 22

Figure 5. Water requirements for coffee and cassava. .... 23

Figure 6. Required LOL to design PV water pumping system for coffee irrigation. .... 25

Figure 7. Required LOL to design PV water pumping system for cassava irrigation. .... 25

Figure 8. Solar irradiances for a PVWP system equipped with tank and battery storages to satisfy water need for coffee plantation when a solar panel is mounted on fixed tilt angle and tracking array, respectively. .... 27

Figure 9. Unused energy of tank and battery for PV water pumping system designed to meet electricity requirements for coffee plantation when solar panel is mounted on both fixed tilted angle and tracking system array. .... 27

Figure 10. Unused energy of tank and battery for PV water pumping system designed to meet requirements of cassava plantation when solar panel is mounted on both tilted angle and tracking system. .... 28

Figure 11. Design month for coffee irrigation. .... 30

Figure 12. Design month for cassava. .... 30

Figure 13. Power peak requirement for PVWPs directly connected to irrigation of coffee land obtained by varying different parameters by 10 % from -30% to 30%..... 31

Figure 14. Power peak requirement for a PVWPs directly connected to irrigation of cassava land obtained by varying different parameters by 10% from -30% to 30%. .... 31

Figure 15. Monthly electricity surplus obtained during irrigation of coffee land and cassava land using PVWPs with tank, battery storages and PVWPs directly connected to irrigation system. .... 33

Figure 16. Comparison of NPVs for PVWPs with battery and tank, PVWPs directly connected to irrigation and DWPs to meet water requirements of coffee and cassava..... 34

Figure 17. NPVs for PVWPs with storages medium, DWPs and PVWPs directly connected to irrigation system when the actual production of both coffee and cassava is increased by 20%..... 35

Figure 18. NPVs for PVWPs with storages medium, DWPs and PVWPs directly connected to irrigation system when the actual production of both coffee and cassava is increased by 40%..... 35

Figure 19. Comparison of LCCs for all the systems..... 36

Figure 20. Impact of LCCs and NPVs on Payback period for different systems when actually productivity is increased by 40%. .... 37

Figure 21. CO2 emissions when DWP is used to irrigate both coffee and cassava. .... 38

# LIST OF TABLES

Table 1. Agriculture seasons and crops grown ..... 6

Table 2. Characteristics of drip irrigation system. .... 24

Table 3. Summary of power produced by PV modules and power need by pump for PVWPs  
equipped with tank and battery to irrigate both cassava and coffee. .... 26

Table 4. Reference case for coffee. .... 29

Table 5. Reference case for cassava..... 29

Table 6. Total annual electricity surplus for PVWPs technologies. .... 32

# LIIST OF EQUATIONS

Equation 1.....13

Equation 2 .....14

Equation 3 .....14

Equation 4 .....14

Equation 5 .....15

Equation 6 .....16

Equation 7 .....16

Equation 8 .....16

Equation 9 .....16

Equation 10 .....16

Equation 11 .....17

Equation 12 .....17

Equation 13.....17

Equation 14 ..... 18

Equation 15..... 18

Equation 16 ..... 18

Equation 17.....20

Equation 18 .....21

Equation 19 .....21

Equation 20.....21



## ABBREVIATIONS AND TERMS

PV	Photovoltaic
CSP	Concentrating Solar Power
LOL	Loss of Load
GDP	Gross Domestic Product
DC	Direct Current
AC	Alternative Current
BOS	Balance of System
NPV	Net Present Value (\$)
PBP	Payback Period (Year)
SRE	Standard reference environment
kWh	Kilowatt-hour
€	Euro
\$	United State Dollar
$W_p$	Watt Peak
$kW_p$	Kilowatt Peak
$MW_p$	Megawatt Peak
$S^*$	Optimum tilt angle ( $^{\circ}$ )
$\phi$	Latitude angle facing south of location ( $^{\circ}$ )
$P_h$	Hydraulic Power (kWh)
<i>TDH</i>	Total Dynamic Head (m)
Q	Water flowrate (liter/sec)
$IWR_p$	Peak water requirement ( $m^3/day\ ha$ )
$T_h$	Total hour of operation per day (hours)
PVWP	Photovoltaic Water Pumping
$P_{p,pvwp}$	Peak power of Photovoltaic Water Pumping System directly connected to irrigation system ( $kW_p$ )
DWPs	Diesel Water Pumping System
$IWR_t$	Total monthly average daily water ( $m^3/ha\ day$ )
$IWR_{t,m}$	Water requirement at design month ( $m^3/ha\ day$ )
$f_m$	Matching factor (0.9)
$\alpha_c$	Photovoltaic temperature coefficient (0.45%/C)
$T_0$	Reference temperature ( $25^{\circ}C$ )
$E_{sm}$	Monthly average daily irradiation hitting the array ( $kWh/m^2\ day$ )
$T_{cell}$	Cell temperature ( $^{\circ}C$ )
$\eta_p$	Pump efficiency
$T_{air}$	Ambient air temperature ( $20^{\circ}C$ )
G	Global irradiation ( $1000W/m^2$ )

NOCT	Nominal Operating Cell Temperature (°C)
$N_e$	Total number of emitters
$D_e$	Spacing between two emitter (m)
$N_l$	Number of lateral pipes
$L_l$	Length of lateral pipes (m)
$W_C$	Width of cropped land (m)
$N_s$	Number of sub-mains
$L_{land}$	Length of land (m)
$D_l$	Spacing between laterals pipes (m)
$N_{l'}'$	Total number of laterals pipes
$Q_m$	Sub-main flowrate (liter/sec)
$Q_l$	Lateral flowrate (liter/sec)
$\Delta H$	Friction head loss (m)
$H_p$	Total head pump (m)
$L$	Length of pipe (m)
$D$	Inside pipe diameter (mm)
$C$	Friction coefficient of the pipe
$K$	Constant equals to $1.21E^{10}$
$PE$	Polyethylene
$P_n$	Power pump considering friction losses (kW)
$LCC$	Life cycle costs (\$)
$ICC$	Initial investment costs (\$)
$PW(C_R)$	Present Worth costs for replacement (\$)
$PW(C_{O\&M})$	Present Worth for operating and maintenance costs (\$)
$PW(C_F)$	Present Worth of annual costs (\$)
$CF$	Cash flow registered from year 1 to year N (\$)
$i$	Discount rate (%)
$Ba$	Annual income (\$)
$m$	Percentage of annual operation and expenses (%)
$H_e$	Hydraulic energy (kWh)
$P_d$	Power rating for diesel engine (Kw)
$C_d$	Capital cost per installed kW (\$/kW)
$C_t$	Total costs of pumping system (\$)
$T_d$	Total number of annual running hours (hours)
$C_f$	Specific cost of fuel consumption (\$/liter)
$f_d$	Specific fuel consumption (liters/\$)
$AFC_d$	Annual fuel consumption (liters)
$H_{e,tot}$	Total annual hydraulic energy (kWh)

## **ACKNOWLEDGEMENTS**

This section is to give value and demonstrate my gratitude to all people who helped me, motivated me and supported me in the best way during my studies at Mälardalen University (MDH).

First, I want to thank the government of Rwanda through the Ministry of education for giving this opportunity and providing me all the requirements in terms of financial support. To this point, I can't forget the everyday assistance of the Ambassador of the Republic of Rwanda here in Sweden, Venancia Sebudandi and her coworker Taifae Eduard. I thank them so much.

Secondly I would like to express my sincere appreciation to my supervisor Dr. Pietro Elia Campana and examiner Prof. Jinyue Yan for review of this thesis in detail and their important feedback.

I would like also to thank all staff in Master program of Sustainable Energy Systems, especially Program Coordinator, Elena Tomas Aparcio for her assistance.

Finally, none of this would have been possible without the love and support of my parents and immediate family, who have always encouraged and believed in me, in all my endeavors.

# 1 INTRODUCTION

## 1.1 Overview and thesis outlines

In order to solve food security issue for rapid increases of population and make their economy on higher level, agriculture is one of the sectors which needs to be developed. Water and energy are the main drivers and form an engine to the development of agriculture. For total water and energy consumption worldwide, agriculture occupies a big portion where about 70% of freshwater withdrawals are utilized in that sector while energy used accounts 30% of energy consumption [1]. However those figures will keep increasing with expected population growth [2]. Water is provided to crops through irrigation to increase crops productivity up to 5 times more than the crops harvested without application of irrigation [3]. 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 [4]. The profitability of two water pumping technologies using different sources of power to pump water to the irrigation place can be evaluated both in terms of CO<sub>2</sub> emissions saved and money saved. Two systems such as DWPs and PVWPs can typically fulfil the irrigation water needs in off-grid areas. However in long term, DWPs becomes less profitable due to higher operating and maintenance costs [5]. In addition solar energy is environmental friend and a source which can be found all over the world for free [6].

In term of environmental perspective, agriculture is among the sectors mostly causing global warming due to the use of fossil fuels to power machines. Worldwide, the total energy consumed by agriculture sector is estimated to  $7.7 \times 10^6$  GWh per year. Only 29.6% of renewable energy such wind, photovoltaic, hydroelectricity and biomass contribute to the total energy use [7]. Solar when it is exploited at optimum level can replace fossil fuels and even produce more energy than the actual energy needed in agriculture. Furthermore the production of solar energy requires small land compared to the land of cultivation. [7].

In exception to the African countries located closer to equator which have low potential in solar irradiation due to their climate, the rests have a huge potential in solar energy of about 4 to 6 kWh/m<sup>2</sup>/day [8, 9]. 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. The PV technology could produce energy need for Africans and even exceeds demand by 2050 [6]. Those two factors, higher insolation, and rapid reduction in price of solar PV technology play a key role in studying the feasibility of harnessing solar energy in agriculture of Rwanda.

This master thesis seeks to determine the best PVWPs among three configurations. Those include PVWPs with battery storage, PVWPs with water storage and PVWPs directly connected

to irrigation system. The design of irrigation system required and economic analysis are also included. The work is briefly summarized in the following 8 chapters:

Chapter 1 provides a general overview of agriculture sector, water and energy consumption. It also describes the background information of the country under investigation, sets the objectives, formulation of problem statement, and gives limitations, scope of the study and purpose.

In order to know the current state of art and knowledge gaps, the literatures study about agriculture of Rwanda, irrigation system applied by the country and use of solar energy in agriculture sector are presented in Chapter 2.

The main target of Chapter 3 is to describe and give detailed methods used to design three different alternatives of PVWPs, their economic evaluations and provides some explanations why the regions and irrigation system were selected.

In Chapter 4, the detailed description, design and implementation of all three PVWPs and irrigation system to fulfill water needs are provided. The considerations for assessing CO<sub>2</sub> emissions are also illustrated in this chapter.

Chapter 5 describes assumptions made to carry out economic analysis of three PVWPs technologies, DWPs and drip irrigation system.

In Chapter 6, the technical and economic results are presented and discussed.

The conclusion of the thesis has been taken by summing up all the findings and summarize them in Chapter 7.

Finally, further works is clarified in Chapter 8.

## **1.2 Background**

Rwanda is a country located in central Africa and whose geographical coordinates are between 10°4' and 2°51' latitude South and between 28°45' and 31°15' longitude East [11], as it is shown in Figure 1. The country has higher density of population where for a total area of 26338 km<sup>2</sup>, 376 residents live on only one km<sup>2</sup> [12]. Agriculture sector has a significant impact on Rwanda's economy whereby 90% of the total population is practicing agriculture. Poor performance of agriculture sector affects economic development in different angles as 91% of food consumption, 36% GDP and 70% of the revenue are from national agriculture [13]. Rwanda has three agricultural seasons namely, "A" which starts in September and ends in February of the following calendar year, "B" which starts in March and ends in July of the same calendar year, and last season "C" which starts in August and ends with September of the same calendar year [3]. The annual average temperature is ranging between 16°C and 20°C with an annual average rainfall of about 1,250 mm [14]. Due to its climate, Rwanda is known to have abundant water resources however those resources are not shared in the same way for the entire country. Water availability helps the farmers to irrigate their fields and hence obtaining higher crop

yields. 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 [12]. In order to take water from sources to the point of irrigation, manual (human) power has a significant share, while centrifugal pumps are typically powered by diesel fuels and in some case electricity. The researchers are being conducted to design a small PVWPs to solve problem of potable water for people living in villages and also to provide water for irrigation on small pieces of lands.



Figure 1. Rwanda map [15].

### 1.3 Problem statement

Currently, electricity shortage in Rwanda is a major barrier to the national development. The agriculture is the most affected sector due to the fact that almost all Rwandan people depend on it and irrigation system becomes expensive as result of lack of power powered pumps. The country increases its energy need through imports of petroleum products from outside the country. However due to a landlocked of the country, the price of diesel fuel mainly used in pumps becomes higher. The use of diesel not only looked in term of cost but also in term of

environmental perspective whereby the CO<sub>2</sub> emissions released have negative impact on environment and life of people in general. Furthermore, selecting the best option among three available configurations of PVWPs technologies, with tank storage, with battery storage and PVWPs directly connected to irrigation is an issue which needs to be addressed.

## **1.4 Limitations**

Most of Rwandan irrigable areas use surface irrigation to water their crops and this mode of irrigation do not require pumps to take water from source to the field. However in some regions method of gravity is practically impossible. Therefore water pumping mode is required to deliver water where it is needed. In order to see the impact that the PVWPs could have on Rwandan irrigation system, this master thesis focuses on the following regions: Gashora and Ngugu, near Lake Rwampanga in Kirehe district. The two sites considered as case study have five hectares each and are used to grow cassava and coffee. For the design and simulation of PVWPs technologies, the nearest station of Kampala in Uganda have been used due to the lack of meteorological data for Rwanda in the PVsyst database.

## **1.5 Scope**

The research is intending to answer with clear facts to the following five questions:

- Is solar energy suitable to replace diesel as main source of power powered pump in Rwanda?
- If solar energy is available enough, in which optimum way can this be converted into usable power for pump?
- Is the entire system, PVWPs economical viable?
- What is the most efficient irrigation system to supply water to cropped land?
- What are the environmental contributions associated with use PVWPs in place of DWPs?

## **1.6 Purpose**

The purpose of this Master thesis is to present the benefits of replacing DWPs by PVWPs in irrigation system of Rwanda. The benefits are demonstrated both in terms of economic and environmental perspectives to show how much earning and how much reduction in CO<sub>2</sub> emissions is achievable when PVWP technologies are used to replace DWP technology. Due to the fact that PVWPs could be used with different configurations, the purpose is also to select the best configuration among three configurations available.

## **1.7 Objectives of thesis**

The main objective of this thesis is to design and optimize a cost effective of PVWPs technologies taking into account three different scenarios for:

- PVWPs with storage tank
- PVWPs with battery storage
- PVWPs directly connected to irrigation

Those three different configurations have been compared both under a technical and economic viewpoint. Moreover, the comparison between PVWPs technologies and DWPs for irrigation has been conducted in this work.



## 2 LITERATURE STUDY

### 2.1 Agricultural sector for Rwanda

Reducing global poverty level thereby combating the problem of hunger is among the Millennium Development Goals to be achieved by the year 2015. About one third of the world's total population gets their income and subsistence from agriculture sector. Rwanda has known an improvement in its agriculture sector because of measures taken by the government to increase national food production [16]. The main crops during pre-colonial time were sorghum, finger millet, taro, peas, cowpeas and bananas. As the big part of country was covered by grass and trees, method of cultivation applied was to burn the field before plantation. This method had an advantage of rapid growth of grass pasture for the livestock on one hand but on other hand it is disadvantageous due to reduction of soil's fertility and soil's wetness. During colonial period, the focus was to fight against a serious famine which took place. The people were forced to grow crops to face the starvation. Recently, the method which were introduced by colonials are stopped and people got back to their original way of cultivation. Currently Rwanda is seeking 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. Among the strategies in which an effort is being made to achieve the target include crop diversification and intensification and irrigation development [17]. Crops do not consume the same amount of water during irrigation and some need a huge amount of water requirement whereas others need to absorb fewer amounts. In addition, availability of water depends on the season. It is obviously understandable that the quantity of water during rainy season is higher compared with that of summer. As presented in Table 1, Rwanda has three agriculture seasons and each season has its specific crops grown in a certain proportion to the available land.

Table 1. Agriculture seasons and crops grown

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

## 2.2 Rwanda irrigation system

Irrigation has 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 [18]. Depending on elevation and water resources available, two methods of irrigation can be used. The case with which water surface is situated on higher slope, the gravity method is used whilst when source of water is underground the pumping mode which is also known as pressure method is required to take water to the point of use. Alternatively, the pumping method is also used for surface water resource located at low slope [18]. Pressure method in turn can be operated under two different systems of irrigation namely sprinkler irrigation system and drip irrigation system. Sprinkler irrigation is a method of applying irrigation water which is similar to natural rainfall. Water is distributed through a system of pipes usually by pumping. It is then sprayed into the air through sprinklers so that it breaks up into small water drops which fall to the ground. As shown in Figure 2, the system is composed of mainline and sometimes sub-mainlines; laterals, sprinklers and centrifugal pump which takes water from the source and delivers it to the pipe system with predefined pressure [19].

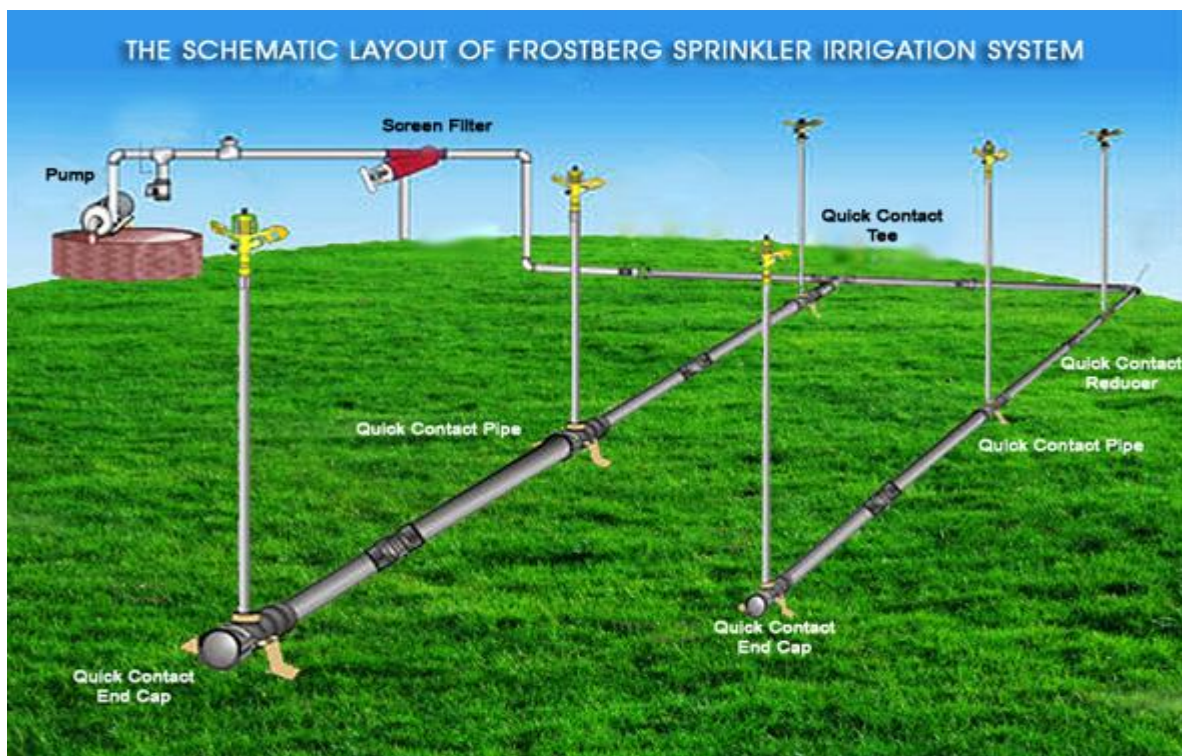


Figure 2. Layout of sprinkler irrigation system [20].

The method of drip irrigation system shown in Figure 3, also known as trickle irrigation or micro irrigation or localized irrigation, is an irrigation method used to distribute water directly to the soil at very low rate from a system of small diameter plastic tubing fitted with outlets called emitters or drippers. The water is also applied close to the plant root zone providing a high moisture level in the soil in which plant can thrive [21]. For better efficiency, drip has shown to be the best choice due to its higher water savings of up to 50 % compared to sprinkler.

Moreover drip has shown to be most efficient in terms of energy consumption whereby about 0.2 kWh/m<sup>3</sup> is less consumed when compared to sprinkler irrigation system [22].

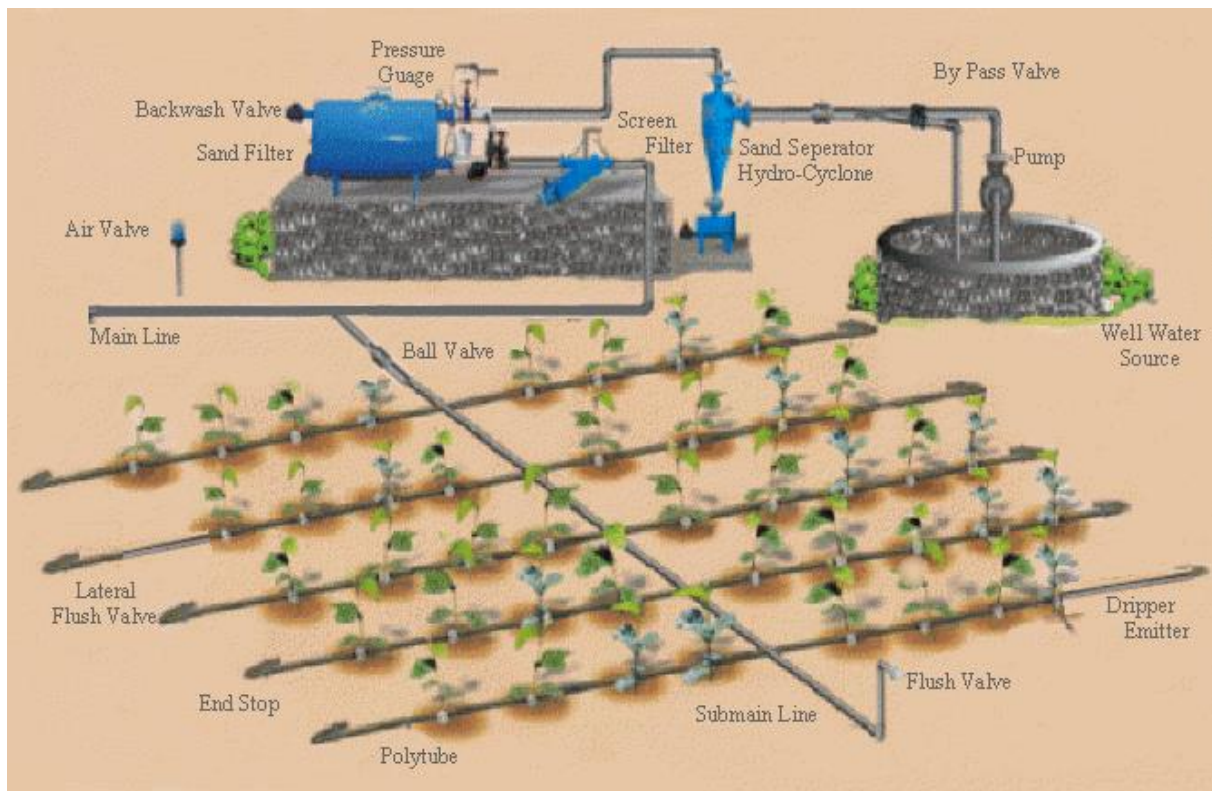


Figure 3. Layout of drip irrigation system [23].

The method of irrigation began since the civilizations of Mesopotamia, Sumeria and Babylon and the following century after that time, the application kept on increasing up to 17 percent of the total world croplands. However the method used was most efficient for large scale and became barrier to farm cultivating on small plot due to higher initial investment cost. In order to remove the barriers thereby making irrigation affordable to small holders, researchers were focusing on new approach to design irrigation systems which can cost as less as possible up to \$ 200/ha. The target was also to design the system to be used for any size of cropland, increase yields and raise income for poor people. About 85% of African water withdrawals are used for irrigation. However the use of water withdrawal varies depends on both location and climate of the region. The region with higher potential in rainfall uses less water withdrawal compared to the one where rains are unavailable and is estimated to 43 % and 99 %, respectively [18]. Water scarcity is a major barrier to irrigation of Sub-Saharan Africa. Except three countries, such as Niger, Mauretania and Djibouti which get water from upstream countries thereby reducing water stress and leads the irrigation much more feasible, the rest are suffering from water shortage. The lack of water resources in most Sub-Saharan countries makes the region to be the least in practicing irrigation and only 4 % of the total cultivated area is irrigated. Since 1960s up to 1990s different governments and private sectors from Sub-Sahara countries launched a plan to develop irrigation and this was funded by World Bank [24]. With help of funds from different organizations, many projects are being studied on how to improve Rwandan agriculture thereby combating factors such droughts, irregular rainfalls, landslides

and climate change which could affect the productivity. The measures taken to handle the problem are to put much effort on providing irrigation to hillside farms and increasing the water retention capacity of watersheds [25]. Based on recent literatures, the country's ambition was to increase the irrigated areas up to 100000 ha by 2015. Two years before the set time only one fifth of targeted area was achieved with all required infrastructures and water management facilities [21]. The irrigation is mainly used by large scale farmers who apply different methods depending on region and water resources available. The availability of resources in turn determines the kind of water supply system to be used to take water from source to the field of irrigation. Moreover other considerations such as land contour/slope, soil permeability and type, plot size and crops, required labor inputs and economic costs/benefit have to be analyzed before carrying out irrigation. Almost all Rwandan cropped areas are irrigated using surface water resources by method of gravity to direct water into furrows, basins or borders depending on surface irrigation design adopted. However some regions of the country showed to have higher slope and it is practically impossible to apply gravity method of irrigation instead pressure method is used. Those areas include Gashora and Ngugu near Lake Rwampanga in Kirehe district [12]. Due to 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 [3]. The pumps are mainly powered by diesel fuel and electricity when available. Diesel fuel consumed by pump when taking water to the field is evaluated in terms of number of gallons. According to [26], 40 gallons of diesel per year are used in pumps to irrigate the area equivalent to 0.4 hectares. This could result in 400 of gallons every year if considering that the entire irrigable area of 10hectares is to be irrigated using pumps powered by diesel.

### **2.3 Use of solar photovoltaic energy in the agriculture sector**

In order to get higher yields and profit, energy is a primary input of the agriculture sector. In agriculture, energy is consumed as results to develop technology and level of production from a system. Energy is used in both direct ways to power pumps during irrigation and indirectly to produce equipment, goods and services required on farm. Worldwide 15% of total energy consumption in crop production is for pumping irrigation water [27]. A big contributor to this figure comes from the countries such as India and US where the share was estimated up to 43 % and 23% of the total direct energy use respectively [27]. The amount of energy required varies depends on method of irrigation applied. Flood irrigation method becomes less energy consumptive when compared to pressure irrigation method and this is due to the fact that much energy is needed to both lift water at certain height and achieve the level of operating pressure of the irrigation. However the energy requirement can be minimized by reducing operating pressure and pumping volumes in method of pressurized micro-irrigation [28]. Currently energy used to pump water for irrigation is mainly from fossil fuels and electric grid. Those type of fuels have some drawbacks such rising their prices day to day, depletion of resources in future and hazards that they cause on environment. Many researches have been conducted about seeking other alternative sources to replace non-renewable energy resources and one of the best option was solar energy, a source which is environmental friend and require less maintenance costs during its production [28]. Solar is a source of energy which can be

found all over the world but the energy produced differs region by region depending on meteorological condition and demand for energy service [29]. Rwanda has a huge potential in solar energy compared to the countries of the same region. The average annual solar radiation of  $5.2\text{Wh/m}^2/\text{day}$  is obtained whereas that for the neighboring countries, such as Tanzania, Burundi and Democratic republic of Congo in cloudy season decreases even below  $4.5\text{Wh/m}^2/\text{day}$ . Even though it has higher potential, solar energy has very low contribution to the national electricity use due to its highest initial costs. The total electricity produced from solar energy accounts only  $1\text{ MW}_p$  [30]. The electricity produced from solar is mainly used in lighting, TV and Radio and operating medical refrigerators [13]. Currently the use of solar energy in pumping water for irrigation seems to be non-existing as the mostly method utilizes diesel pump to lift water [26]. However different researches are being made with a focus to design PVWPs which meets a lack of potable water for people living in isolated area to electricity and also to apply it in irrigation on small pieces of lands of about  $100\text{m}^2$ . [26, 27]. In all researches being conducted, there is a lack of expanding the use of PVWPs in large scale. Moreover economic assessment and  $\text{CO}_2$  emissions analysis are not considered. The increase of oil price by 400% and a considerable reduction in price of PV modules, are the two important factors which can accelerate the growth of solar power market in Rwanda [31]. The national total electricity from different resources is estimated to  $111.08\text{ MW}$  and this is not even enough to serve 92% of the total population. Through donors, Rwanda's ambition is to increase its power production from solar energy up to  $560\text{MW}_p$  by 2017 [32]. With the solar electricity production of five times that of the current available, this will undoubtedly push the planners not only focusing on administrative units such as schools, hospitals and health centers but also directing energy in agriculture sector.



### 3 METHODOLOGY

To design, optimize and simulate a cost effective of PVWPs and answer to the research questions, there are some important input parameters which need to be known before carrying out the study. Those include: solar irradiation of the region under investigation, source and quantity of water required to irrigate crops; the source of water can be surface water or subsurface water. In case of subsurface water, the total head through which water is to be pumped from the deep well to the storage tank or directly to the point of use, is also another input parameter and it has been assumed to 60m. The assumption of total dynamic was made based on spatial variation of the underground water level of the country [33]. Before doing design and simulation of PVWPs with tank and battery storages, LOL has been determined. The loss of load (LOL) is the probability time fraction at which the battery is disconnected due to low charge regulator security. In other hand it can be defined as probability time fraction at which tank becomes empty due to low pump power [34]. The selection was carried out considering best and worst case to determine the PV power and pump power. The design and simulation of PVWPs with both tank storage and battery storage has been performed using PVsyst software. Furthermore MS Excel was the main tool for conducting the economic analysis, design of irrigation system, evaluation of CO<sub>2</sub> emissions and also used to calculate some important input parameters such as hydraulic energy and power of pump. The two regions selected for irrigation are located in Eastern part of the country and are used to grow coffee and cassava respectively. Those regions were adopted because there are situated on higher slope and groundwater is the only source used to irrigate crops. In addition, the use of pumping systems is the main method to take water from source to the cropped area or to the water storage capacity. Using CROPWAT [35], water requirements for the two specific crops for the two specific locations were obtained.

The pump design leads to the design of PV array capable of converting available sun energy into hydraulic energy. The PV panel has to produce more power than the exact amount of power needed by pump in order to overcome the losses occurred in the system. The energy produced by PV modules is stored in two different forms [12, 36]. In the first case, the PV system is directly connected to the direct current (DC) pump and the energy stored in tank in form of water. Due to the fact that the energy of sun is changing time to time, converter is put between motor and PV system to match the DC generator with DC required by pump. When an alternative current (AC) pump is used, inverter is included to convert DC of PV modules to the AC of the pump.

The design month has been determined as the month whereby the ratio between monthly water requirement and monthly solar irradiation is the highest. To assure the water for irrigation is available all the season, the tank was chosen to hold amount of water to be used for at least three days to overcome the problems related to cloudy days. In the second case, the PVWPs took into consideration the battery as mean to store electrical energy of PV generator and be used later when water is needed. In this case a charge controller has to be installed between the battery, the PV modules and the load in order to avoid overcharging or undercharging.

Different irrigation methods such as surface and localized methods can be utilized to water the crops. With higher irrigation efficiency and lower power consumption compared to other

methods, localized method was selected as one of the best option [37]. Localized irrigation approach can be achieved with micro-drip and sprinkler irrigation systems. Due to the fact that drip irrigation is suitable to many different type of crops, any farmable crop and also suitable to any type of soil, it has been chosen as the one to apply, also due to its high irrigation efficiency [38]. There were two separate regions growing two different types of crops and the water requirement is not the same. The thesis work was carried considering two different scenarios: one for coffee plantation and another one for cassava plantation. The reasons for having two scenarios are because the system design is affected by the crop irrigation requirements that vary according to different crop. Accordingly, energy requirement to run the two pumps will be different and hence the PV array.

For every project, there is need to perform economic evaluation to make sure that it is viable or not. During economic investigation, the investment costs of standalone PVWPs have been estimated considering initial investment costs, and maintenance and operating costs. The costs of drip irrigation were determined taking into account initial investment cost per hectare, canal and delivery maintenance cost per cubic meter of water and on farm operation and maintenance cost per hectare. To see the impact that the PVWPs has on irrigation system of the regions, the methods of the life cycle cost (LCC), net present value (NPV) and payback period (PBP) have been applied. PVWPs were compared with DWPs which is currently used to provide water for irrigation. The project was not looked only in term of economic perspective but also in term of environmental perspective. The reduction of CO<sub>2</sub> emissions when PVWPs is used in place of DWPs were estimated per liter of diesel consumption.

## **4 DESCRIPTION AND DESIGN**

### **4.1 Photovoltaic water pumping system (PVWPs)**

A PVWPs is a combination of different components connected together to fulfill the water requirement. The power from sun converted by PV module is transferred to the pump which in turn deliver water to where it is needed. The main components of the system are PV array, controller or inverter (s) and motor-pump unit. Depending on storage mode adopted, the system can either use tank to store water or battery to store energy in form of chemical energy. Both methods have the same purpose of storing energy for using it when sun is not available. However, the system can also be designed without storages medium and water is directly pumped through pipes into the irrigation system. The drawback for using this configuration is that it operates only when there is sun. Environmental conditions in which the system is installed and its configuration, are two factors affecting the performance and efficiency of the system.

#### **4.1.1 Design and implementation**

Except for the PVWPs directly connected to irrigation which is designed in MS Excel to determine the power needed, the two other PVWPs technologies equipped with tank and battery were designed and simulated in PVsyst software. In PVsyst, the inputs parameters for system equipped with water storage tank are the water requirement, tilt angle and hydraulic head to which water should be lifted by the pump. Whereas, the tilt angle and electric load requirements have to be defined to design and simulate the system equipped with battery storage. The location of the area under investigation is also another important input parameter to be defined first to assess the locally available solar irradiation and the potential electric generation. The simulation were run on hourly basis and then aggregated on monthly basis.

##### *4.1.1.1 Design and simulation of PVWPs with tank storage*

In PVsyst, the primarily inputs parameters to design and simulate a PVWPs with tank storage are: the location in which the project is to be carried out, crop water requirement and the tilt angle to which the PV modules should be mounted to optimal convert available solar irradiation into electric power. The tilt angle is the same for all PVWPs technologies and is calculated according to the equation provided by [39]. The optimum tilt angle  $S^*(^\circ)$  for the fixed plate collector is determined taking into account the latitude of the area under consideration and is given the relationship:

$$S^* = 2.9489 + 1.4050\phi - 0.0190\phi^2, \text{ for } 4.858 < \phi < 13.017 \quad \text{Equation 1}$$

Where  $\phi$  [o] is the latitude angle facing south of the location.

The amount of water required for irrigation depends on many factors. The type of crop is one of important factor determining the irrigation water requirement. Moreover, the size of field to be irrigated is another parameter that affect the water requirement. Two separate fields with total size of 10hectares were selected whereby 5 hectares are for coffee plantation and the remaining 5hectares are for cassava. The specific water requirement for each type of crop was obtained on monthly basis using CROPWAT software.

The head requirement was assumed based on groundwater depth map taken from [35] and it attached in Appendix 1

Once all the inputs are known, the design is done step by step as described below:

- Definition of the user's water needs, which may be constant during the year, or having seasonal or monthly variation;
- Characterization of the storage tank;
- Dynamic behavior of the well;
- Photovoltaic system;
- Motor-pump device;
- Power regulation method.



#### 4.1.1.2 Design and simulation of PVWPs with battery storage

Before designing and simulating a system with battery storage, it is required to have information about hydraulic power. According to [40], the hydraulic power ( $P_h$ ) is obtained from the equation 2 below.

$$P_h = 9.81QT DH \quad \text{Equation 2}$$

Where TDH is the total dynamic head (m) to which pump should take water from deep well to the place of use and it is assumed taking reference to groundwater map.

Q is the flowrate (liters/sec) computed considering the peak crop water requirement ( $IWR_p$ ) and total hours of operation per day ( $T_h$ ) in the equation 3

$$Q = \frac{IWR_p * 1000}{T_h * 3600} \quad \text{Equation 3}$$

The size of battery is determined by its capacity to store energy when it is cloudy days. It is obviously understandable that energy stored is that required by the pump to keep the system operation when no sun is available.

In PVsyst, the following adjustments were made:

- Define user's needs: the user's needs includes the monthly hydraulic power needs
- System definition: both battery and PV modules types are selected. In addition the arrangement in series and parallel is set in order to fulfill the electric requirement.
- Regulator: the power produced by PV modules has to be controlled before entering the battery. The same regulation need to be done for the power output of the battery to pump motor.

#### 4.1.2 Design of PVWPs directly connected to irrigation system

The choice of PV module to convert sun into required power used in irrigation system is determined considering the worst month condition. The worst month in turns is evaluated taking into account the highest ratio between monthly water requirement and monthly available solar irradiation. Having known the worst month, available solar irradiation and crop water requirement, the PV peak power  $P_p$  ( $kW_p$ ) is calculated using equation 4 [41]:

$$P_{p,PVWP} = \frac{0.0027 TDH}{f_m [1 - \alpha_c (T_{cell} - T_o)] \eta_p} \max \frac{IWR_{t,m}}{E_{S_m}} \quad \text{Equation 4}$$

where, 0.0027 is a conversion factor that takes into account the density of water ( $1000 \text{ kg/m}^3$ ), the gravity acceleration ( $9.8 \text{ m/s}^2$ ) and the conversion between Joule and kWh ( $1/(3.6*10^6)$ ) to calculate the daily hydraulic energy;  $f_m$  is the matching factor assumed equal to 0.9;  $\alpha_c$  is the PV modules temperature coefficient equal to 0.45 %/°C;  $T_o$  is the reference temperature equal to 25°C;  $\eta_p$  is the efficiency of the pump;  $IWR_t$  represents the total monthly average daily IWR ( $\text{m}^3/\text{ha}/\text{day}$ ) given by the sum of the IWR of the n-th crops; TDH is the total dynamic head that takes into account the contributions of the groundwater depth, drawdown, operational head of the irrigation system and hydraulic losses (m);  $E_s$  is the monthly average daily solar irradiation

hitting the array (kWh/m<sup>2</sup>/day); the function max indicates that the design of the PVWP systems has to be conducted for the month *m* marked out by the highest ratio (design ratio) between monthly average daily IWR<sub>t</sub> and monthly average daily solar irradiation energy.  $T_{cell}$  is the cell temperature (°C) obtained using the following relationship [42]:

$$T_{cell}(C) = T_{air} + \frac{NOCT-20}{800} * G \quad \text{Equation 5}$$

Where  $T_{air}$  is the ambient air temperature in °C; *G* is the global irradiation of 1000W/m<sup>2</sup> and NOCT the nominal operating cell temperature. NOCT is the temperature of the cell at standard reference environment (SRE). The standard parameters are: ambient temperature of 20°C, an irradiance of 800W/m<sup>2</sup>, a wind speed of 1m/s and an open near surface mounting (the module is tilted at 45°).

## 4.2 Drip irrigation system

To ensure that the plants do not suffer from strain or stress of less and over watering it necessary 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 as input parameters. Those include water source and its availability, power source, agronomical details such as crop, spacing, age, peak water requirement and row direction for row crops. The design also considers climate data such as temperature, humidity, rainy fall and evaporation. Moreover type of soil, water quality and existing resources such as pump and main line are additional input parameters to be taken into account [43]. In chronological order from source to the end user, the components of drip irrigation system are pump which take water from source to the main line. The main line is connected to the sub-main pipe whose number is directly the same as number of subsections created in the field. The sub-main pipe is placed inside each subsection and then water of that pipe is shared across the rest of field part by lateral pipes attached to it. To ensure the predefined water on root zone and uniformity distribution, drippers with emitters are fixed on lateral pipes with a certain distance from one another [44]. The knowledge of input parameters stated above helps to design each component of the system starting backward, from emitter to pump. Based on type of crop, water requirement, operating time, soil type and water quality, emitter suitable for irrigation is selected. The length and size of lateral lines are determined based on the lateral line flow rate and field size. Similarly, the size and length of the sub-main pipe is determined. Each sub-main is an individual unit with its own control valve. The whole area is then divided into different sub-main units and the number of sub-main units that can operate at any one time is based on the existing pumping or water source capacity. Sections should be designed such that the discharge provided is the same for each one. The appropriate length of the sub-main pipe is determined taking reference in the predesigned allowable length. The main line is then planned connecting all the sub-mains by taking the shortest possible route [45]. The length of the main pipe can be determined based on the flow rate so that frictional head loss is within specified limits and total pressure head required for the system is within pump or water source capacity. Similarly to the determination of proper length of sub-main, the length of main line is determined taking reference on allowable length of main line. When gravity is used, then the

pump requirement is worked out from total discharge and pressure head required for the system. Depending on the flow rate and water quality, a suitable filtration device is selected.

#### 4.2.1 Design and implementation

To insure that the system is operating with higher efficiency, the system components have to be selected with proper sizes to meet the pressure and water required for irrigation. The procedures used to design a drip irrigation system are common for the area and type of crops to be irrigated. However the size can vary depending on type of crop which determines the water requirement and cropping area. The two separate regions adopted are used to grow different crops: coffee and cassava, but the irrigation areas have the same size. Common drip emitters have discharge in range 1-15l/h at the standard pressure of 1bar. The purpose of those emitters is to distribute the water uniformly. Moreover the variation of discharge between emitters in whole field should not exceed 20%. The operating pressure of drip tube is 0.41 – 0.82bar whereas the spacing between two emitters ( $D_e$ ) varies from 0.15-0.91m. This information in addition to total number of laterals pipes ( $N_l$ ) leads to the calculation of number of emitters  $N_e$  fitted on lateral pipe of length  $L_l$  given by [46].

$$N_e = N_l \frac{L_l}{D_e} \quad \text{Equation 6}$$

Where the length of lateral pipe  $L_l$  is determined considering the width of cropped area ( $W_c$ ) and the number of sub-mains ( $N_s$ ):

$$L_l = \frac{W_c}{N_s} \quad \text{Equation 7}$$

Given the lateral spacing ( $D_l$ ), length of cropped land ( $L_{land}$ ) and total number of sub-mains ( $N_s$ ), total number of ( $N_l$ ) is obtained using the relationship below:

$$N_l = N_s \frac{L_{land}}{D_l} \quad \text{Equation 8}$$

To have uniform distribution of water, the discharge through each lateral pipe ( $Q_l$ ) has to be the same and this is determined from the discharge of sub-mains ( $Q_m$ ) and total number of lateral pipes ( $N_l$ ) as follow:

$$Q_l = \frac{Q_m}{N_l} \quad \text{Equation 9}$$

The number of sub-mains ( $N_s$ ) is decided by designer according to the available land area and then the flow rate through those pipes ( $Q_m$ ) is determined through a division between flow rate of main line ( $Q$ ) obtained in stand-alone design and number of sub-mains ( $N_s$ ). The flow rate  $Q_m$  is expressed in l/h. For number of sub-mains equals 1, the discharge of the main line is the same for sub-main.

$$Q_m = \frac{Q}{N_s} \quad \text{Equation 10}$$

Once the emitters, laterals pipe and sub-mains pipes are selected, it will be possible all of them to the main line. The main line is directly connected to pump which takes water from source to the surface of irrigation. Alternatively the main line should also be connected to the storage and at this stage there is pump needed instead gravity method is used. Beside the total dynamic head (TDH), friction losses ( $\Delta H$ ) induced in pipes when directing water from delivery point to the real place of irrigation should also be taken into account. The total head used by the pump ( $H_p$ ) can be summarized using mathematical formula as follow:

$$H_p = \Delta H + TDH \quad \text{Equation 11}$$

Where  $\Delta H$  is expressed in m and is calculated using formula below:

$$\Delta H = K \frac{\left(\frac{Q}{C}\right)^{1.852}}{D^{4.87}} L \quad \text{Equation 12}$$

The terms, Q represents the water flow rate in l/s; L is the length of pipe line in m; D is the inside pipe diameter in mm; K is a constant equals to  $1.21E^{10}$  and C is the friction coefficient of pipe which varies from 100 to 160 depending on the material from which the pipe is made. In case of PE pipes, the coefficient is equals to 140. As head is increased, additional power of pump is required thereby increasing the power actual needed by pump to only take water from source to the surface. The new size of pump ( $P_n$ ) expressed in kW is described in the mathematical relation below:

$$P_n = \frac{Q * H_p}{45} \quad \text{Equation 13}$$

### 4.3 Environmental perspective

The main cause of global warming is CO<sub>2</sub> emission released from different sources of energy. The amount of CO<sub>2</sub> emitted varies depends on energy produced and power technology used for conversion. The calculation of CO<sub>2</sub> emissions was done considering the mainly method of DWPs used to pump water for irrigation purpose. The CO<sub>2</sub> emissions from DWPs was obtained per liter of diesel consumed and it is equivalent to 2.68kg of CO<sub>2</sub> emissions [47].

## 5 ECONOMIC EVALUATION

The choice of any system design and project in general depends on many factors. One of the most important factors to consider is determining the costs required to start and operating the system during its entire lifetime. The economic analysis is done using the so called Life-Cycle Costs (LCC) method which is used to compute all possible costs of the system. The analysis included the costs of drip irrigation system installed on two different cropland areas with 5hectares each. The assumptions made for different costs of drip irrigation system are: investment cost of \$1000 per hectare, canal maintenance and water delivery cost of \$0.0025 per cubic meter and on farm annual operation and maintenance cost of \$4 per hectare. Economic analysis of a PVWPs directly connected has been carried out ignoring the costs of storages. Other costs such as cost of PV system and cost of pump-motor unit are the same as for PVWPs equipped with storages medium and they described in sections below. However the amount of \$500 and \$100 have been assumed to be the cost of control valves and annual operation and maintenance costs respectively. In all water pumping technologies, the discount rate was assumed to be 10% while 38% of profit before taxes was taken as tax provision. In LCC analysis all the costs are brought back to present, whereas using Net Present Value method (NPV) all the incomes costs are brought back to present. To compare the two systems, it is important to take into consideration the time period to which, the project is financed itself and this is known as Payback Period (PBP). Different parameters such initial investment costs (ICCs), Present worth of the replacement costs  $PW(C_R)$ , Present worth of annual operation and maintenance costs  $PW(C_{O\&M})$  and Present worth of annual costs  $PW(C_F)$ , cash flow (CF) registered from year 1 to year N, obtained making annual difference between incomes and expenses, discount rate  $i$ , annual incomes  $B_a$  and the percentage of annual operation and maintenance costs on ICC need to be determined in order to get LCCs, NPV and PBP. Mathematically, LCC, NPV and PBP are calculated using equations 14, 15 and 16 below [48, 49].

$$LCC = ICC + PW(C_R) + PW(C_{O\&M}) + PW(C_F) \quad \text{Equation 14}$$

$$NPV(I) = -ICC + \sum_{t=1}^N \frac{CF}{(1+i)^t} \quad \text{Equation 15}$$

$$PBP = - \frac{\ln(1 - \frac{iICC}{B_a - mICC})}{\ln(1+i)} \quad \text{Equation 16}$$

The annual incomes were calculated considering the harvested crops with and without irrigation. The total yield without irrigation for both types of crops; coffee and cassava grown on area of 5 hectares for each were assumed to be 7tonnes while with irrigation a sensitivity analysis was made by increasing production without irrigation to 20% and 40% According to Rwandan market, the prices per kilogram for coffee and cassava are 1.4 and \$0.02, respectively [50, 51]. In addition to the annual incomes from yields, the excess of electricity produced increased the incomes of the systems which incorporate PV modules as source of power. The annual incomes of PVWP technologies are increased by electricity surplus produced and which is sold at \$0.22/kWh [52].

## **5.1 Economic assessment for PVWPs**

There are different factors which need to be known before carrying out the economic assessment of PVWPs. Those include economic factors such as the system lifetime, discount rate and differential inflation rates of certain items if there are. Another factor to consider is of technical nature and connected to the lifetime of PVWPs main component. The life cycle of the entire system is decided considering the component of system with longest replacement interval. In PVWPs, PV system should last 20-30years, whereas the pump and inverter may have to be replaced every 5-10 years [53]. Once the above two factors are known; the capital costs for complete system, costs for replacement components, annual maintenance and repair costs and installation costs are determined. In fact evaluation of capital and installations costs of PVWPs is performed in details in the following subsections.

### **5.1.1 Costs of PV system**

PV solar system is a combination of many modules grouped together to generate power. In order to match the power generated by PV panel with the power needed by the user, additional components are required for regulations. The components can be either converter when a direct current (DC) pump is used or Balance of system (BOS) in case an alternative current (AC) pump is required. To know how much does a PV system cost depends on many factors such as PV system rating, manufacturer, retailer and installer but the most important factor is the size of PV system. Moreover the cost of PV system is calculated per Watt Peak produced and the bigger the size, the higher the costs of PV system [59]. According to [54], 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 as a source of renewable and many manufacturing companies of PV plants entering the market. The total costs are broken into seven sub-costs such as capital cost (29%), PV module (19%), Inverter (5%), Balance of systems (14%), engineering& procurement and construction (12%), and operation and maintenance cost (16%) and 5% for other miscellaneous costs [55]. The operating and maintenance costs for PV pump were assumed to be  $0.01\$/W_p$ .

### **5.1.2 Costs of pump-motor unit**

The costs of pump-motor depend on the amount of water required and head to which water is to be pumped. The pumps required have to deliver the corresponding amounts of water for irrigation of coffee and cassava. In the irrigation of the selected two crops, water is pumped through the same head of 60m. A DC pump has been selected due to permanent magnet which is created in DC motor and increases it's efficient up to 100% more than AC motor [54]. The pump is also selected considering optimum water requirement of the month. The pump which needs to be bought to deliver water requirement for both cassava and coffee is of type Lorenz, PS 20-HR-04-MPPT. Typically 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. Due to the fact that components are imported from outside, extra cost of \$1000 was assumed as cost for shipping both solar and pump components. The amount of \$15 in addition to 0.01\$/Wp per year was assumed to be the amount required to maintain the pump [56].

### 5.1.3 Costs of storages

Two types of storage capacity, tank and battery are used together with PVWPs to store energy for later use when there is no sun available. Depending on choice, tank can be installed underground or at certain height above ground level [56]. In this thesis, elevated water storage tank was considered in order to obtain the pressure requirement for irrigation. The tank required is mainly the one to store the water to be used for at least three days. The cost of tank depends on its size and it is assumed to be \$0.2/liter [57]. Battery is used to store energy of PV module in chemical form. Depending on subtypes, both lead acid battery and Nickel cadmium battery can be used in combination with PV systems. The economic evaluation took into consideration the lead acid battery because of its lowest price when compared to Nickel cadmium and it is 160-200€/kWh and 690-1590€/kWh, respectively. The time of operation for this battery is ranging between 5 to 7 years [58].

## 5.2 Economic assessment for DWPs

As has been done in the previous section, economic evaluation of DWPs has to be investigated taking into account the same lifetime of 20 years. In contrary to the PVWPs which can be either underground or above, the diesel pump is always installed above ground. DWPs is made up with four main components such as diesel engine, pump element, pump head and rising main. However the detailed design of the system is not included in the scope of this thesis. The cost of diesel pump depends on its size whereas 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 and 7000 to 9150\$ per kW for diesel pump size less or equal to 10kW and for larger scale, respectively. The fuel efficiency of diesel generator per liter varies from 2.5 to 3kWh [59]. Moreover the maintenance and operating costs of diesel pump are higher and can even equal or 50% more than the capital cost [60]. The most important factor to consider when computing the costs of diesel pump is the required hydraulic energy ( $H_e$ ). The required hydraulic energy determines engine size and is obtained through equation (8) above. Due to larger scale of diesel engines suitable for pumping, the minimum size starts at 2.5Kw. The required power rating of the diesel engine ( $P_d$ ) is then calculated and compared with the minimum size for diesel engine which is 2.5 kW [61]. If the rating power ( $P_d$ ) is less than the minimum power, the power of 2.5kW is taken account. All the calculation have been made following the approached used by [61]. The rating power is given by the following relationship:

$$P_d = \frac{P_h}{4}$$

Equation 17

Given the size of the diesel engine and the capital cost per installed kW ( $C_d$ ), the total cost of pumping system ( $C_t$ ) can be determined.

$$C_t = P_d * C_d \quad \text{Equation 18}$$

During economic assessment of diesel powered pump, many assumptions have been made. It was assumed that the pump operates 8 hours; the pump efficiency is 60%; and pump is replaced every 7 years. The same discount rate as for PVWPs has been assumed to be 10%. It was also assumed the maintenance cost for diesel pump to \$125 per year.

Different factors such as total number of annual running hours ( $T_d$ ), power rating ( $P_d$ ), the cost of one liter diesel fuel ( $C_f$ /liter) and the average fuel consumption  $f_d$  (liters/kW) of engine per hour are used to determine the annual fuel consumption  $AFC_d$  as given by:

$$AFC_D = T_d * C_f * P_d * f_d \quad \text{Equation 19}$$

The number of running hours ( $T_d$ ) is obtained from the following equation:

$$T_d = 2 * H_{e,tot}/P_d \quad \text{Equation 20}$$

Where  $H_{e,tot}$  is the total annual hydraulic energy requirement in kilowatt-hour obtained by summing up the daily required hydraulic energy.



# 6 RESULTS AND DISCUSSIONS

The section presents the results for the site characteristics and simulation results of PVWPs designed with both storage tank and battery to meet water requirements for coffee and cassava. Moreover it includes the results for PVWPs directly connected to irrigation and irrigation system to satisfy water needs. The LCCs, PBP and NPVs of all PV water pumping systems and DWPs are also presented. Finally evaluation of CO<sub>2</sub> emissions when DWPs is used is included in this section.

## 6.1 Meteorological data

To design a PVWPs, it is required to know the climate characteristics of the region under consideration. In PVsyst, the region of Kampala (Uganda) with latitude 0.3°N, longitude 32.6°E and altitude of 1146m has been taken into account due to the lack of climatic data for Rwanda. Using PVsyst, meteorological characteristics of Kampala were obtained and are presented in Figure 4. One of the most important characteristic is availability of solar resource to be converted into usable power for pumping. To obtain higher efficiency of the system, the solar irradiation hitting the collectors has to be maximized by minimizing the losses. This is achieved by positioning the PV panels with the proper tilt angle to which the PV modules is facing the south and it was calculated using equation 1. The efficiency of solar modules is affected by the temperature of PV modules and it increases with lower temperature.

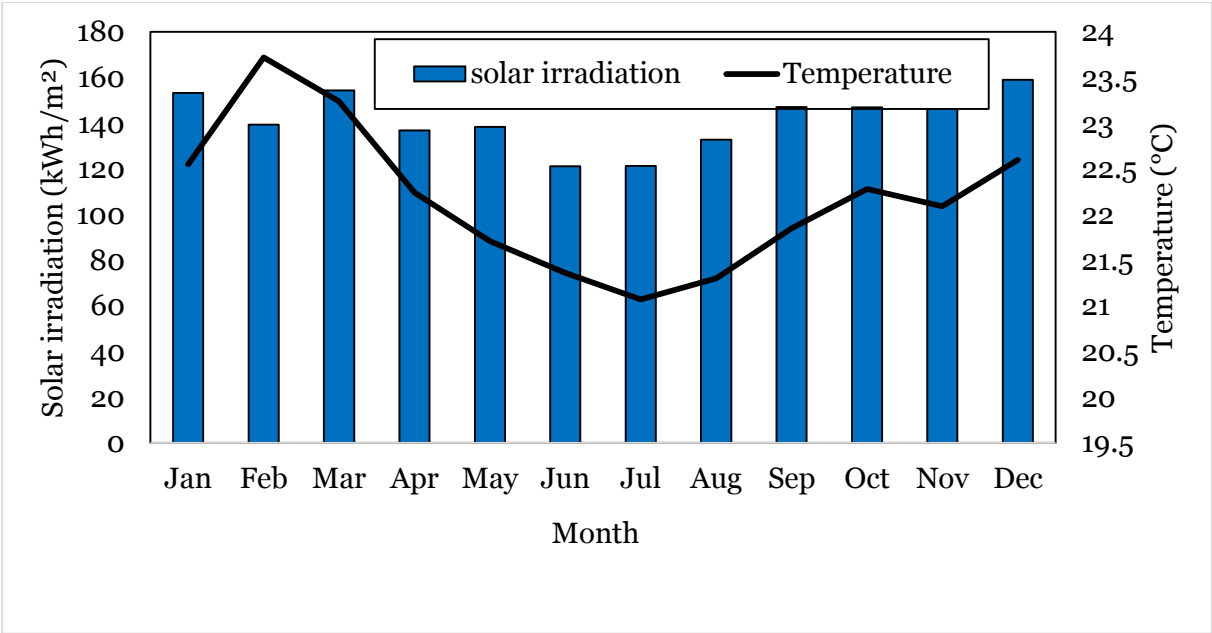


Figure 4. Meteorological characteristics of the region under study.

## 6.2 Crop water requirements

The Figure 5 below shows the monthly water requirements for both coffee and cassava. The water consumption was obtained using CROPWAT software. The water needs differ depend on season and type of crop being irrigated. Other factors such as such temperature, humidity, soil type, wind velocity, growth stage, shade and sun also determine the water requirements. During sunny period, the temperature increases whereas soil humidity decreases and hence a huge amount of water is required to compensate the water evaporated and water for irrigation of crop. As shown in Figure5, the irrigation of coffee plantation is performed almost the whole year while that for cassava needs to be done only for 7months per year. Furthermore for the same months of irrigation, coffee plantation presents higher amount of water consumption compared to the amount consumed by cassava.

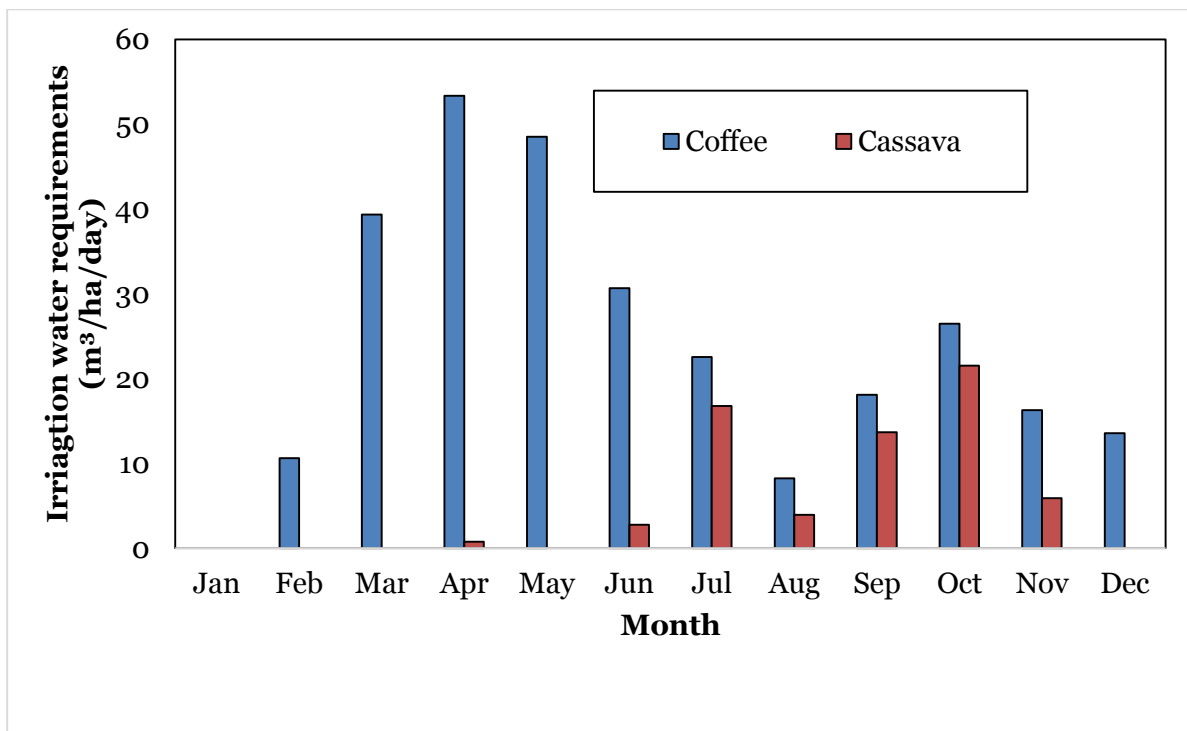


Figure 5. Water requirements for coffee and cassava.

## 6.3 Irrigation system design

The method of irrigation adopted was drip irrigation system due to its higher efficiency when taking into account water and energy savings compared to other methods of irrigation. The method was applied to both systems designed for irrigating coffee and cassava plantations. The two crops are cultivated on two different fields with the same size of 5 hectares each. The parameters of drip irrigation system were calculated in MS Excel sheet using equations 6, 7, 8, 9 and 10. The characteristics of drip irrigation system to water both coffee and cassava are summarized in a Table 2. It was required to divide each field into sub-sections with a discharge equals to the amount of the main feeder divided by total number of sub-mains decided. To ensure that the entire field is irrigated, each cropped land has been divided into three equally

sections with one sub-main pipe placed in the middle of each section. This was done assuming a square shape of the field and then using square root method, the width was also obtained to be 224m. Using equation 10, the discharge rate in each section has been determined to be 11l/sec and 0.1l/sec for irrigation system of coffee and cassava respectively. Due to the fact that sub-mains pipes placed in middle of each sub-section are not capable of spreading the water all around the rest of parts, additional pipes named laterals were attached to them. The length of laterals of 75m was calculated dividing the width of sub-section by 3. Assuming the spacing between two laterals pipes equals to 2m, the total number was obtained from equation 5 and it is 335 pipes. In turn, the total number of lateral pipes designed for each sub-section are not enough to make a uniform distribution of water. To achieve uniformity of water around the sub-part, the total number of 47170 emitters was calculated using equation 6. Those have to operate considering a mean value of spacing range to be 0.53m and a mean pressure value of 0.615bar. Finally the design has considered the friction head loss encountered in pipes. The head loss was added to the total dynamic head and hence increasing the power requirement for pump. Alternatively when the system uses water storage tank, the desired gravity should be higher enough to meet pressure need.

Table 2. Characteristics of drip irrigation system.

<b>Parameter</b>	<b>Coffee</b>	<b>Cassava</b>
Surface area (m <sup>2</sup> )	5000	5000
Width, W <sub>c</sub> (m)	224	224
Number of sub-mains, N <sub>s</sub>	3	3
Length of lateral, L <sub>l</sub> (m)	75	75
Spacing between laterals, D <sub>l</sub> (m)	2	2
Number of laterals, N <sub>l</sub> (m)	335	335
Spacing between emitters, D <sub>e</sub> (m)	0,53	0,53
Number of emitters, N <sub>e</sub>	47170	47170
Flow rate main, Q <sub>m</sub> (l/s)	11	0,101851852
Number of laterals on one main, N <sub>ls</sub>	112	112
Flow rate laterals, Q <sub>l</sub> (m <sup>3</sup> /s)	0,099380799	0,000910991

## 6.4 Selected Loss of Load (LOL)

During design and simulation of PVWPs equipped with tank and battery storage, a best loss of load were determined. In PVsyst, the LOL were obtained considering the best and worst case and by varying the LOL from 1% to 10 % to get both power of PV modules and its corresponding power of pump. The worst case and best case were decided based on Rwanda groundwater level shown in Appendix 1. The best case took into consideration the low level of 1m height while the worst took the maximum level of 380m. The best LOL at which the PVWPs should be designed has been determined by the intersection between PV power of the best and PV power of the worst case. Alternatively LOL was selected based on intersection between the power pump of the worst case and power of the best case. As shown in Figure 6 of LOL for PVWPs to water coffee and Figure 7 of LOL for PVWPs to irrigate cassava, the best LOL were

found to be 6% and 5% for PVWPs to irrigate coffee and cassava respectively. Power of PV modules and power of pump become higher for high level of water whereas power of PV modules and power pump get decreased for low level of water. This due to the fact for higher level much power is needed to meet both head and pressure of pump while in case of lower height only pressure has to be achieved.

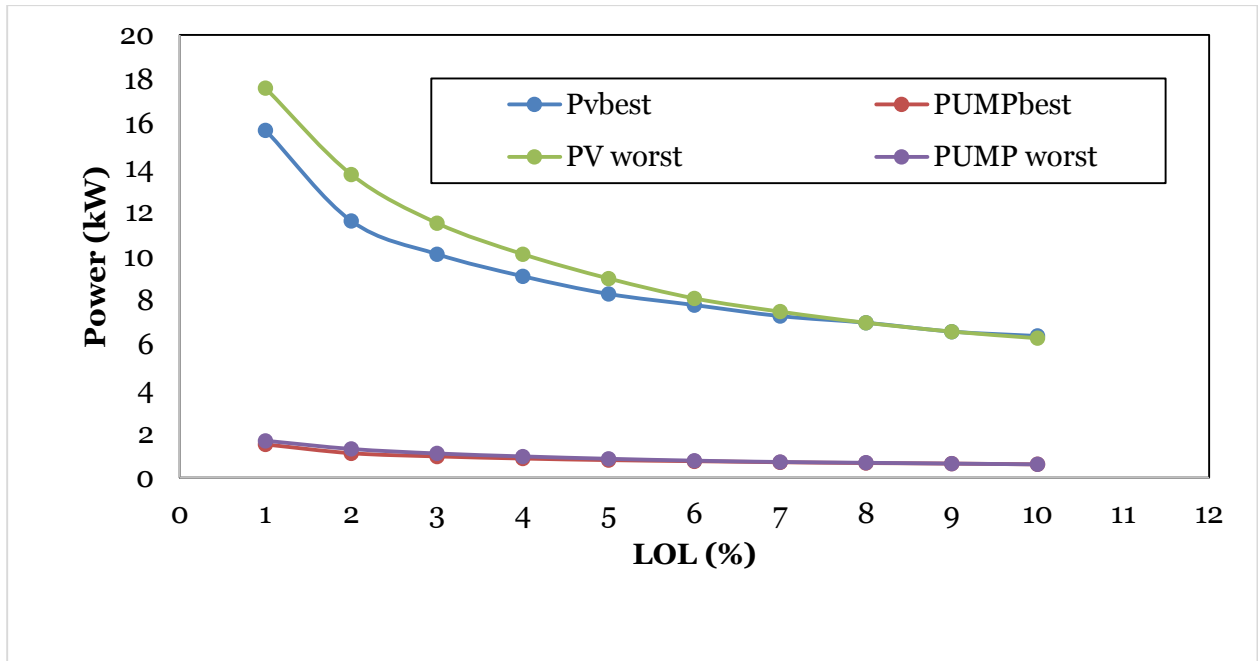


Figure 6. Required LOL to design PV water pumping system for coffee irrigation.

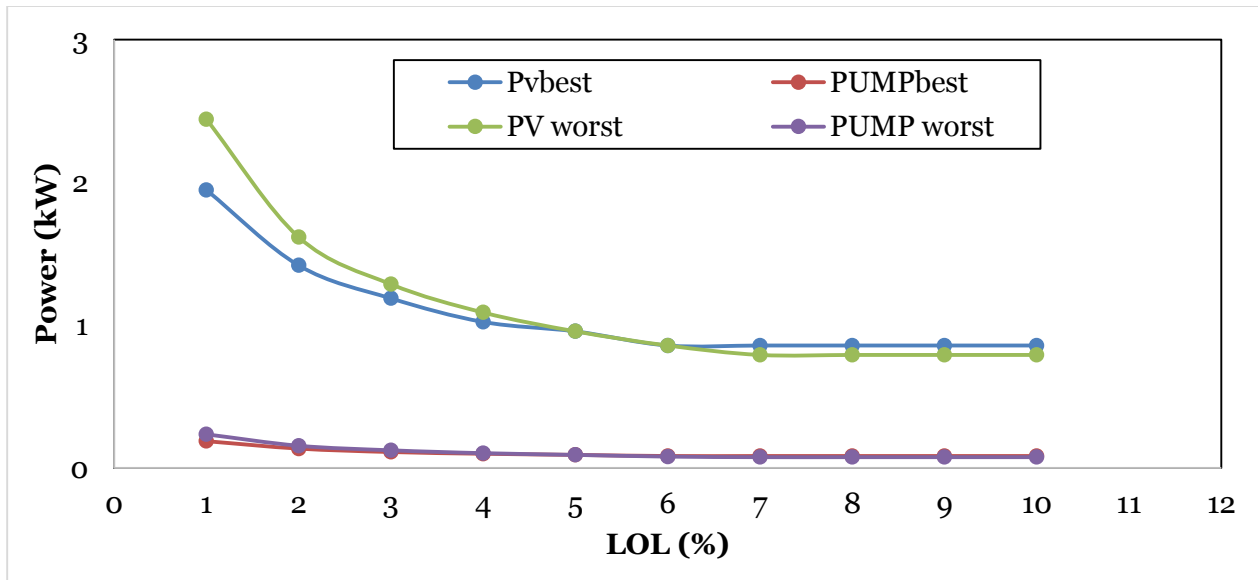


Figure 7. Required LOL to design PV water pumping system for cassava irrigation.

## 6.5 Evaluation of systems energy production and systems energy for PVWPs equipped with tank and battery storages

The energy produced by solar photovoltaic is directly proportional to solar irradiation available. The amount of solar energy production varies depends on how solar panel is mounted to capture solar irradiations onto its surface area. Moreover energy requirement for pump is a result of solar irradiations hitting the solar panel. Solar panel can be mounted either on fixed tilt angle or on system which tracks the sun. The results of solar irradiation obtained using tilted and tracking system are presented in Figure 8. Energy produced by those solar panel is to satisfy irrigation of coffee and cassava using PVWPs equipped with tank and battery storages. To get optimum energy production, tilt angle have to be properly determined and this takes into account the latitude of the area under investigation. Using equation 1, the optimum tilt angle was obtained to be  $7^\circ$  while a tracking tilted was used for other case. Both tilted system and tracking system were applied to two alternatives of PVWPs, with tank storage and battery storages. The PVWPs were designed to meet water needs for both coffee and cassava and all of them utilized the same type of pump, Lorentz (PS20-HR-04-MPPT). However the number of pumps are different depend on flowrate needed. For coffee which needs a huger amount of water during its irrigation compared to cassava, several pumps are required. The pumps are installed in series and in parallel to both meet head and flowrate. In PVWPs with tank, two pumps were coupled in series and six pumps in parallel for coffee while two pumps in series and two pumps in parallel were used for cassava. The type of solar modules utilized for PVWPs equipped with both tank and battery storages were Aide. The table 3 summarizes the capacities of PV modules and pumps for the two alternatives. As shown in Figure 9 and Figure 10, solar panel mounted on tracking system get more irradiations and hence results in energy surplus of about 20% more than the energy exceeded when a fixed tilt is used. Based on that, tracking tilted could be preferred as a best option to use due to its higher performance. However in terms of economic perspective, the system cost too much compared to the solar panel mounted on fixed tilt [62]. Furthermore in all two PVWPs considered, battery storage showed to have higher performance than tank storage due to its huge amount of energy excess.

Table 3. Summary of power produced by PV modules and power need by pump for PVWPs equipped with tank and battery to irrigate both cassava and coffee.

<b>PVWPs equipped with storages</b>	<b>PV power (kW<sub>p</sub>)</b>	<b>Pump power (kW)</b>
PVWPs equipped with tank to irrigate cassava	5,2	0,96
PVWPs equipped with tank to irrigate coffee	19	1,92
PVWPs equipped with battery to irrigate cassava	4,5	0,32
PVWPs equipped with battery to irrigate coffee	16	2,1

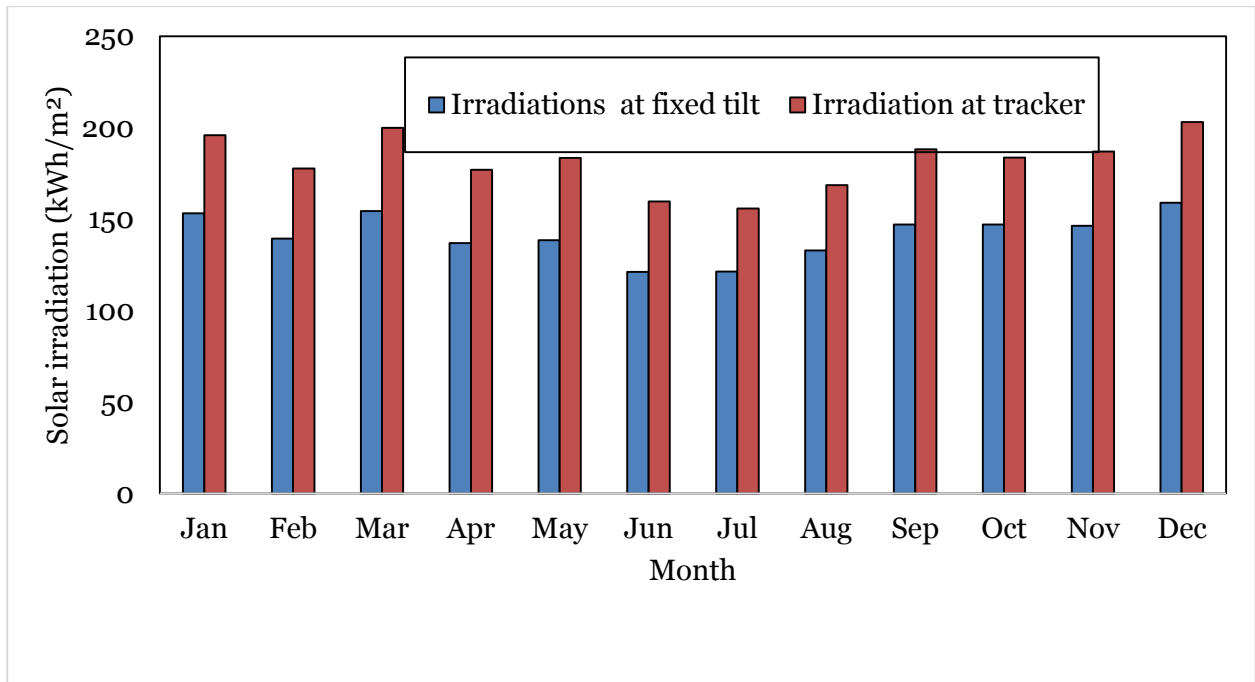


Figure 8. Solar irradiations for a PVWPs equipped with tank and battery storages to satisfy water need for coffee plantation when a solar panel is mounted on fixed tilt angle and tracking array, respectively.

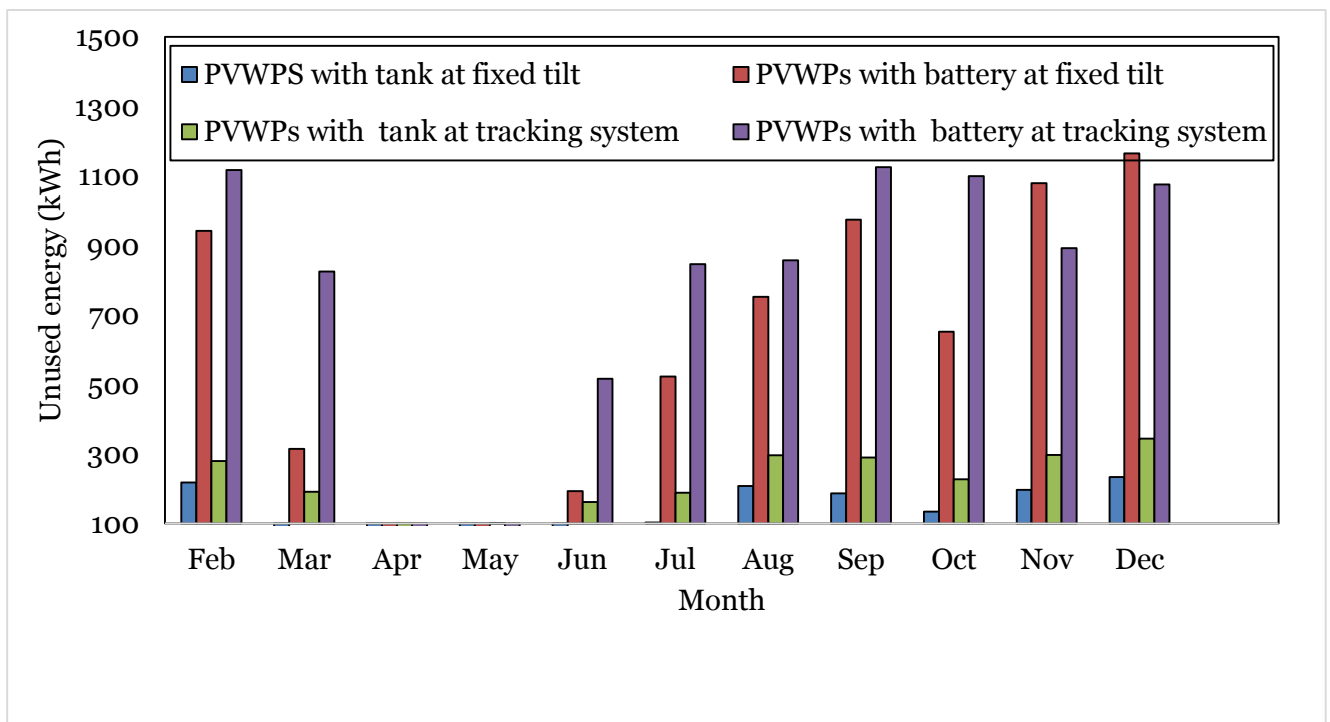


Figure 9. Unused energy of tank and battery for PVWPs designed to meet electricity requirements for coffee plantation when solar panel is mounted on both fixed tilted angle and tracking system array.

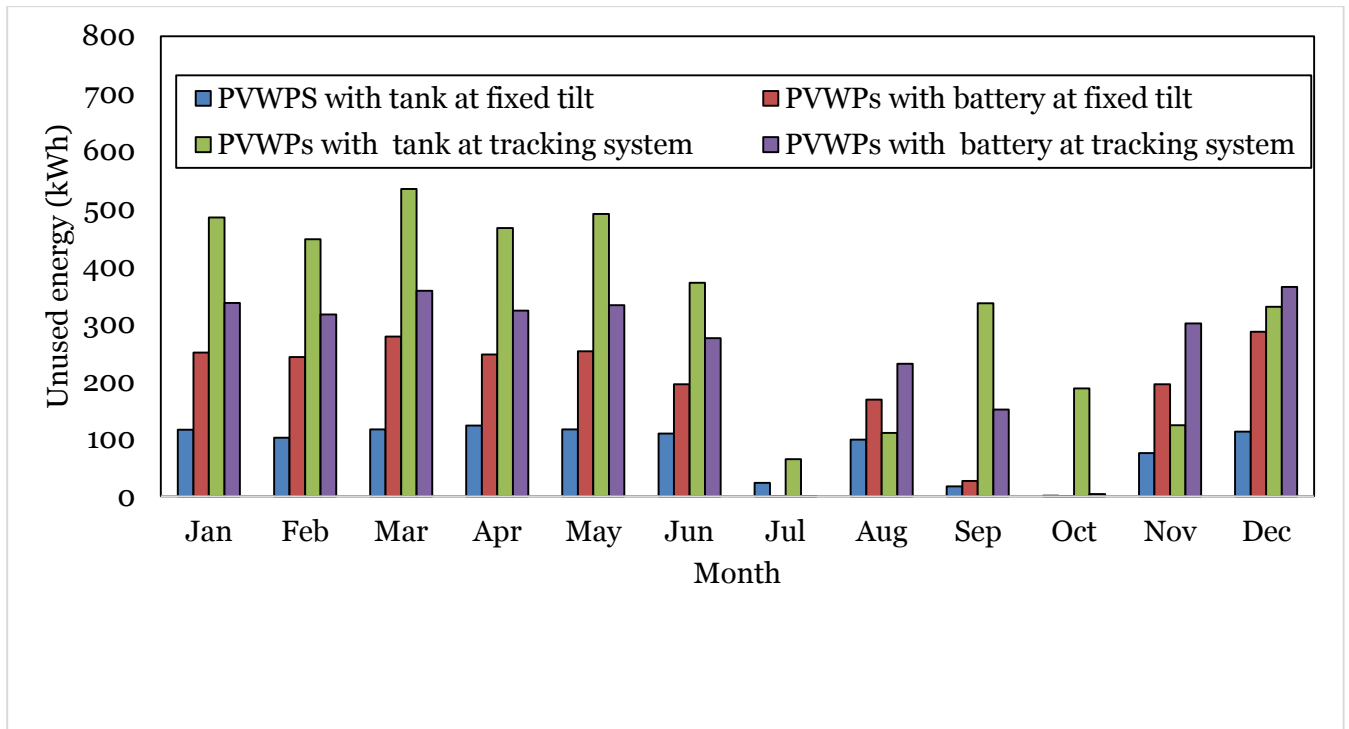


Figure 10. Unused energy of tank and battery for PVWPs designed to meet requirements of cassava plantation when solar panel is mounted on both tilted angle and tracking system.

## 6.6 Analysis of energy production for PVWPs directly connected to irrigation system

The power peak of PVWPs directly connected to irrigation was determined at design month. As shown in Figures 11 and 12, the design month was determined by the ratios between monthly water requirements and monthly solar irradiations obtained from PV syst software and then the highest ratio was taken into account. The tilt angle of solar panel were changed from 0 to 50 degrees in order to see monthly solar irradiation which determines the highest ratio. The design month for a PVWPs to meet water need for coffee plantation is April while the one to satisfy water requirement for cassava was obtained to be July. The power peak depends on many parameters and it was calculated using equation 4 and 5. Those parameters includes; monthly irrigation water requirement (IWR), total dynamic head (TDH), matching factor ( $f_m$ ), PV module temperature coefficient ( $\alpha_c$ ), ambient temperature ( $T_a$ ), reference temperature ( $T_o$ ), nominal operating cell temperature (NOCT). The results of Figures 13 and 14 were obtained after doing sensitivity analysis. The sensitivity analysis was performed by changing the above mentioned parameters from -30% with an increment of 10% up to 30%. The variations started taking into account reference cases as shown in Table 4 and Table 5.

Table 4. Reference case for coffee.

IWR <sub>p</sub>	53,3
TDH	60
f <sub>m</sub>	0,9
α <sub>c</sub>	0,0045
T <sub>a</sub>	25
NOCT	48
G	1000
T <sub>cell</sub>	60
η <sub>p</sub>	0,6
E <sub>sm</sub>	5

Table 5. Reference case for cassava.

IWR <sub>p</sub>	21,5
TDH	60
f <sub>m</sub>	0,9
α <sub>c</sub>	0,0045
T <sub>a</sub>	25
NOCT	48
G	1000
T <sub>cell</sub>	60
η <sub>p</sub>	0,6
E <sub>sm</sub>	6,5

The results obtained showed that varying IWR and TDH doesn't have impact on power peak requirement of PVWPs. Changing  $\alpha_c$ ,  $T_a$  and NOCT in range defined, leads to the increases of peak power while the peak power get decreased when varying the parameters such as  $f_m$  and  $E_{sm}$ . The results are shown in figures 13 and 14.



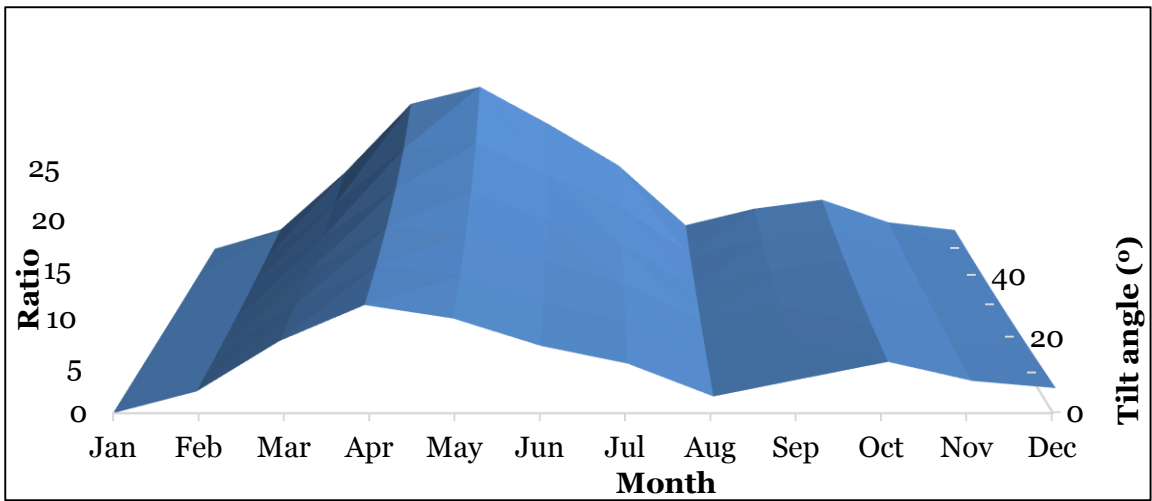


Figure 11. Design month for coffee irrigation.

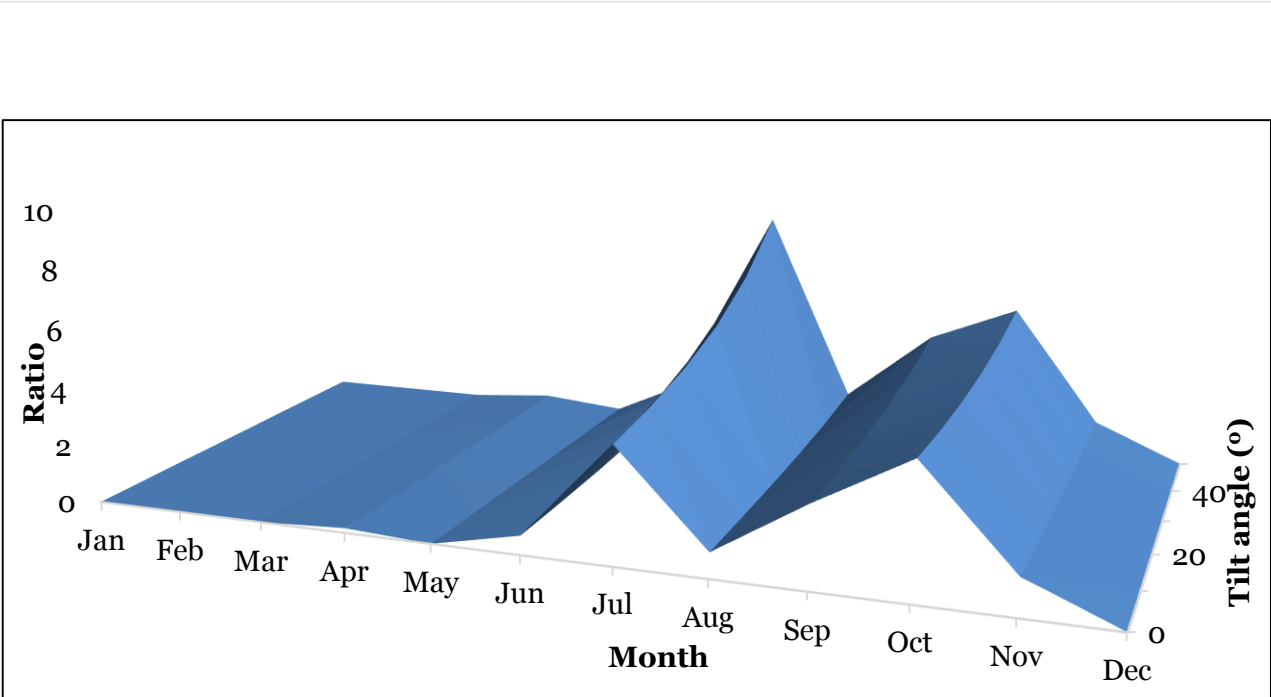


Figure 12. Design month for cassava.

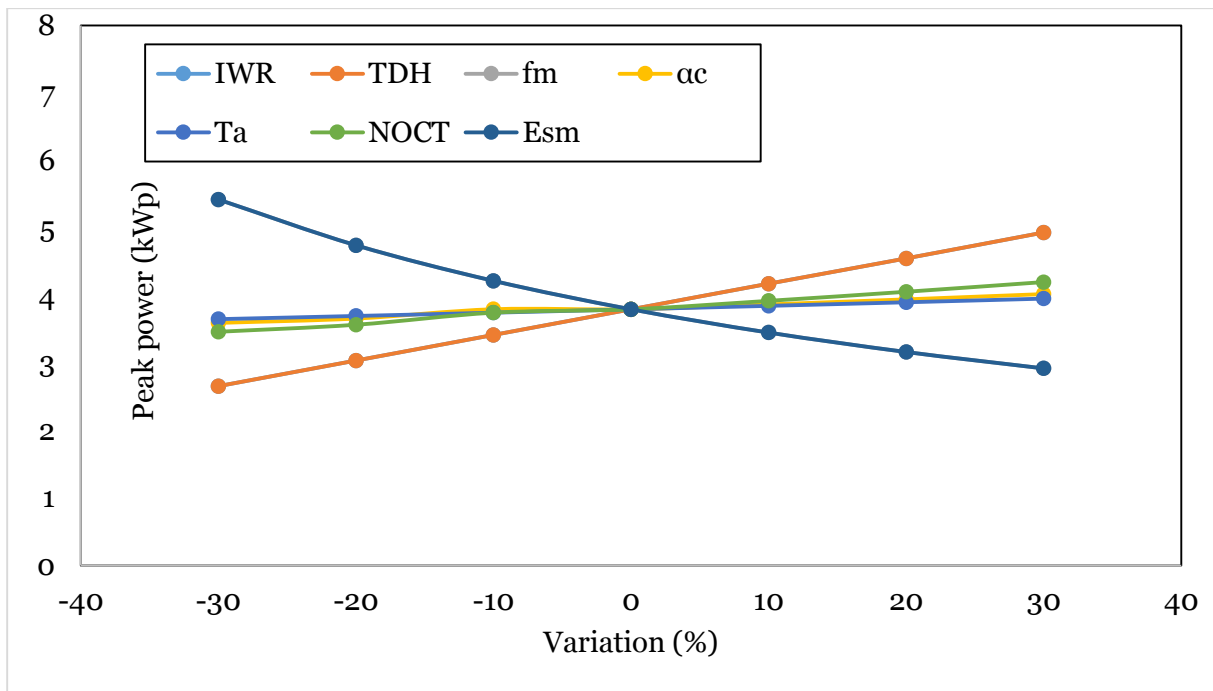


Figure 13. Power peak requirement for PVWPs directly connected to irrigation of coffee land obtained by varying different parameters by 10 % from -30% to 30%.

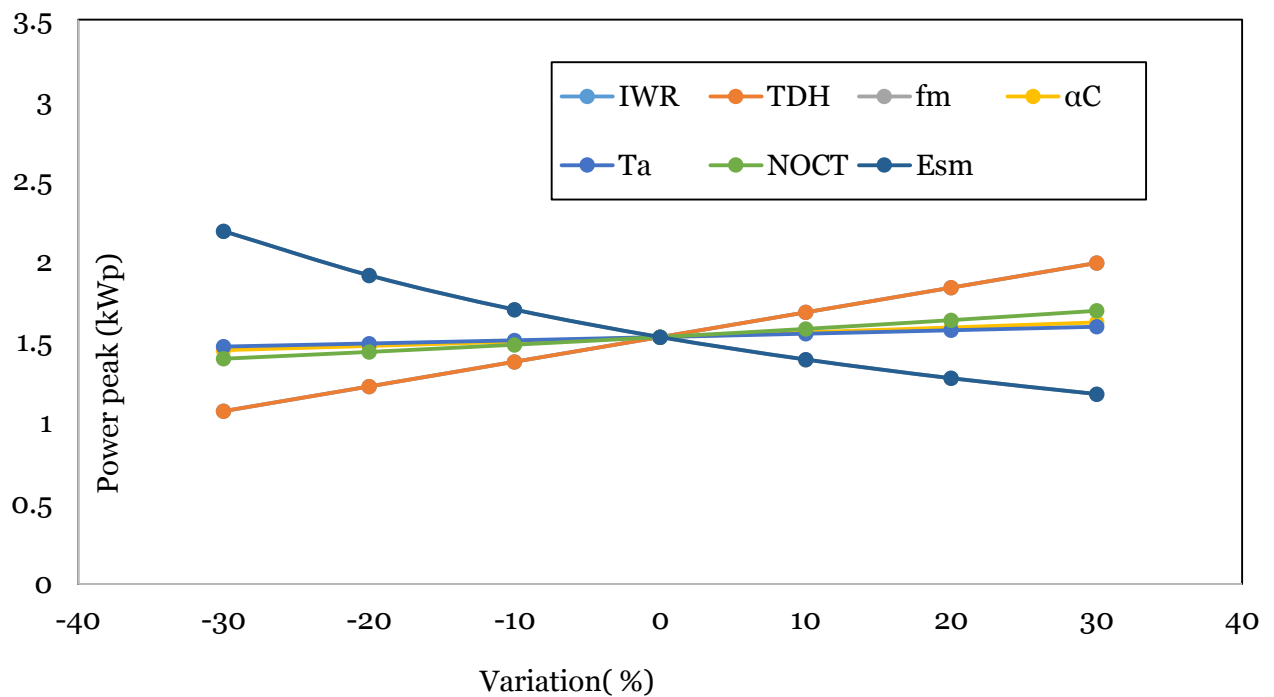


Figure 14. Power peak requirement for a PVWPs directly connected to irrigation of cassava land obtained by varying different parameters by 10% from -30% to 30%.

The total electricity production from PV system is not 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 water into tank or in form of chemical energy into battery. Alternatively electricity surplus is obtained for a PVWPs directly connected to irrigation without storages medium. In addition the difference in water consumption of crops during their irrigation and the period in which irrigation is being made, are other two major important factors affecting electricity production and electricity surplus. Electricity exceeded for a PVWPs is directly proportional to the water requirements to irrigate a specific crop and it becomes higher for crop which needs much water. A significant increases in electricity surplus is obtained when there is no irrigation required. Even though some months do not need electricity for pumping water but solar panel keeps producing it from the available sun energy resource. Figure 15 presents monthly electricity surplus from three alternatives of PVWPs to meet irrigation of coffee and cassava. A summary of total annual electricity produced is also presented in Table 6. Due to higher storing efficiency, the PVWPs incorporating battery storage produces a huge amount of electricity excess compared to the rests of PVWPs used. The reason behind the difference in electricity surplus is that electricity produced from PVWPs directly connected to irrigation is used only when water is needed and during no irrigation period, the electricity is lost as there is no way to conserve it. On other hand low electricity surplus in PVWPs with tank as storage is due to loss of water either by evaporation in summer or water is freezing in tank during cold period.

Table 6. Total annual electricity surplus for PVWPs technologies.

<b>PVWPs Technologies</b>	<b>Total annual electricity surplus (kWh)</b>
PVWPs equipped with tank to irrigate cassava	1013
PVWPs equipped with tank to irrigate coffee	1 672,9
PVWPs equipped with battery to irrigate cassava	2 141,8
PVWPs equipped with battery to irrigate coffee	7466
PVWP directly connected to irrigate cassava	2 197,7
PVWP directly connected to irrigate coffee	4 104,8

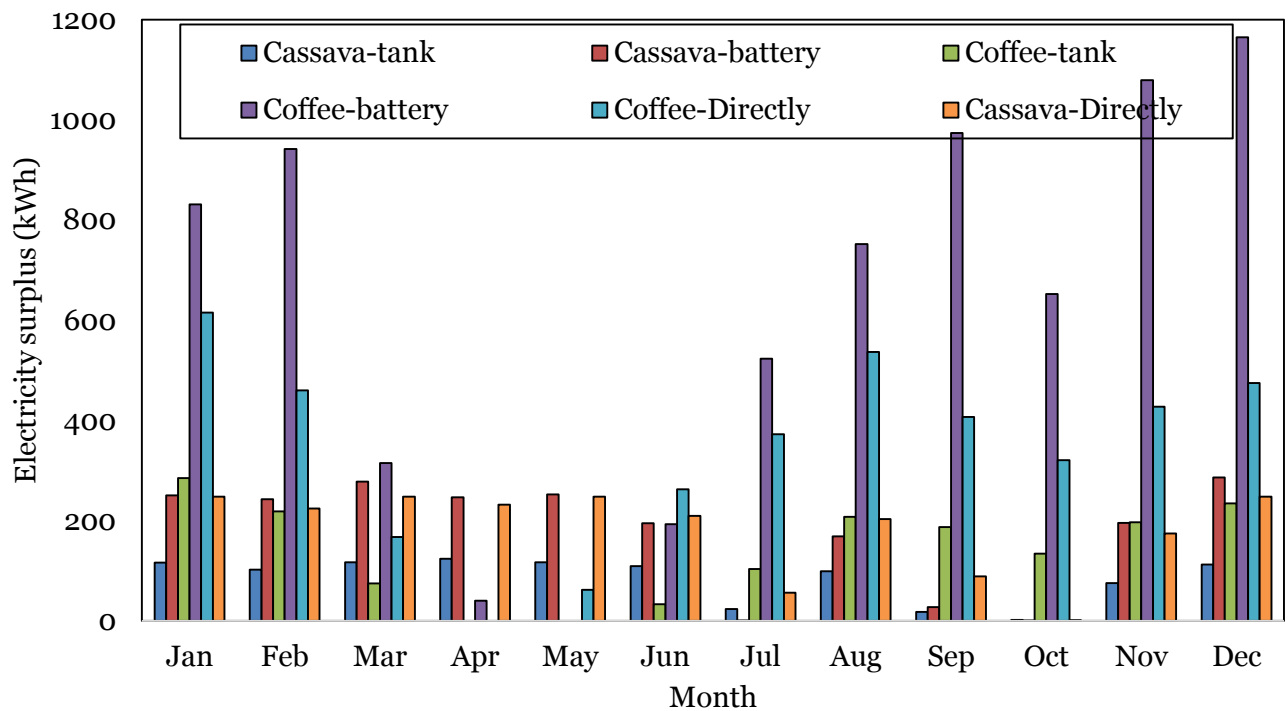


Figure 15. Monthly electricity surplus obtained during irrigation of coffee land and cassava land using PVWPs with tank, battery storages and PVWPs directly connected to irrigation system.

## 6.7 System profitability

The profitability of a project is quantified in term of amount of money saved per certain time of period. The profitability of water pumping systems used in irrigation system differs depends on source and technology utilized to provide power requirement of pump to deliver the appropriate amount of water. Moreover savings are due to the method used to store energy before being delivered to the irrigation area. The market price of crop and increases of yield also affect the profitability as discussed in the next section about sensitivity analysis of varying productivity. The NPV is a method which best calculate the annual savings and profit of the project during its entire lifetime period. The NPVs for PVWPs directly connected to irrigation, with tank storage, with battery storage and a DWPs to water crops have been calculated with use of Equation 15 and by considering the lifetime of 20 years. The calculations of NPVs were also carried taking into account the yield produced with use of irrigation to be 5 times more than the productivity harvested without application of irrigation [3]. The amount of productivity harvested per year was 35 tonnes for coffee and cassava. The results in Figures 16 shows NPVs for four alternatives stated to fulfill irrigation of coffee plantation and cassava plantation. For every project lunched, the first year presents losses as the investment is done in the same period. The PVWP technologies to fulfill water requirements of cassava have low NPVs compared to the water pumping technologies to irrigate coffee plantation. The low NPVs

are due to the market price of cassava which is very low in comparison to that of coffee and the higher the price on market, the more there is money earned. Furthermore higher profitability of PVWP technologies to satisfy water needs of coffee comes from an annual electricity surplus of about 30% more than electricity surplus from cassava and which is sold at 0.22\$/kWh. Initially, higher cost of battery storage results in higher initial investment costs of PVWPs equipped with battery thereby making the system to be the least profitable at the first year. However within time, PVWPs generates much money because of a huge amount of electricity surplus during its operation. In all cases, DWPs is the least to save money and even becomes negative for irrigation of cassava plantation. Initially DWPs can be a best option due to its lowest investment costs. However within the system lifetime, the operation and maintenance costs become much higher than the system using solar energy as a source of power. The PVWPs directly connected to irrigation can also be the best option as the costs are minimized due to the fact there is no storages medium used. However the problem for the system is to operate only when sun is available.

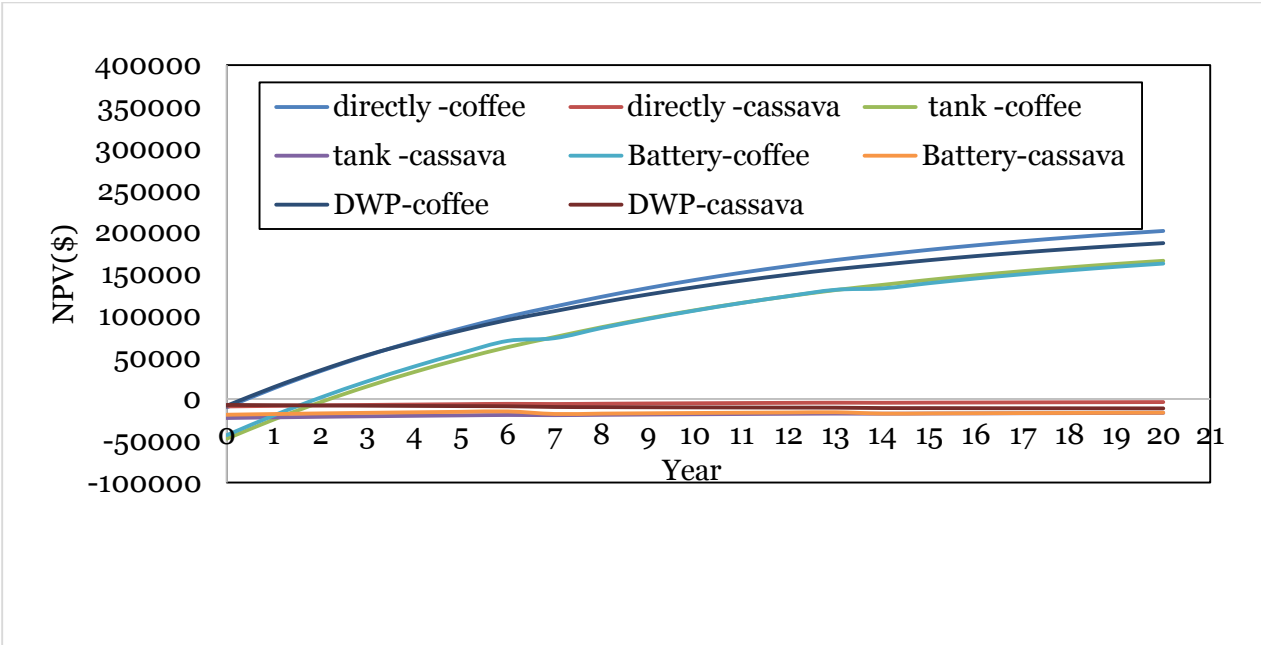


Figure 16. Comparison of NPVs for PVWPs with battery and tank, PVWPs directly connected to irrigation and DWPs to meet water requirements of coffee and cassava when production is increased by 5times.

The NPVs for PVWPs vary depend on yields harvested. In order to see how much is the variations in NPVs, a sensitive analysis were carried increasing the actually annual productivity of 7tonnes by 20% and 40% respectively. Technologies such as PVWPs incorporating tank storage, PVWPs with battery, PVWPs directly connected to irrigation and DWPs have been considered. Moreover using all technologies, the NPVs were calculated taking into account irrigation of both coffee and cassava plantations. The Figures 17 and 18 present the NPVs obtained when increasing productivity by 20% and 40%. The NPVs generated from a technology when the production is increased by 40% became higher than the NPVs obtained when a technology is used for the yield topped up to 20%. Coffee and cassava are sold on market at the prices of \$1.4/kg and \$0.02/kg respectively [50, 51]. This implies that an

increases of yield by 20% results in annual income of \$3920 for a technology designed to irrigate coffee whereas the one designed for cassava irrigation produces and income of \$56 per year. The impact of increases in production when irrigation is applied is mostly seen in the results of Figure 17 whereby except the PVWPs directly connected to irrigation of coffee, the rest of PVWP technologies present losses.

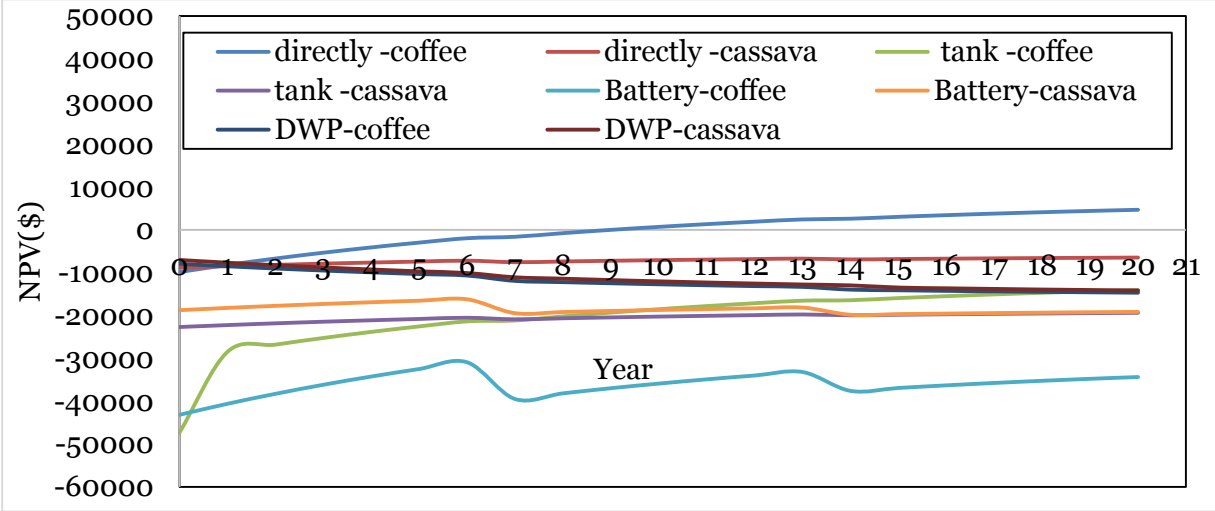


Figure 17. NPVs for PVWPs with storages medium, DWPs and PVWPs directly connected to irrigation system when the actual production of both coffee and cassava is increased by 20%.

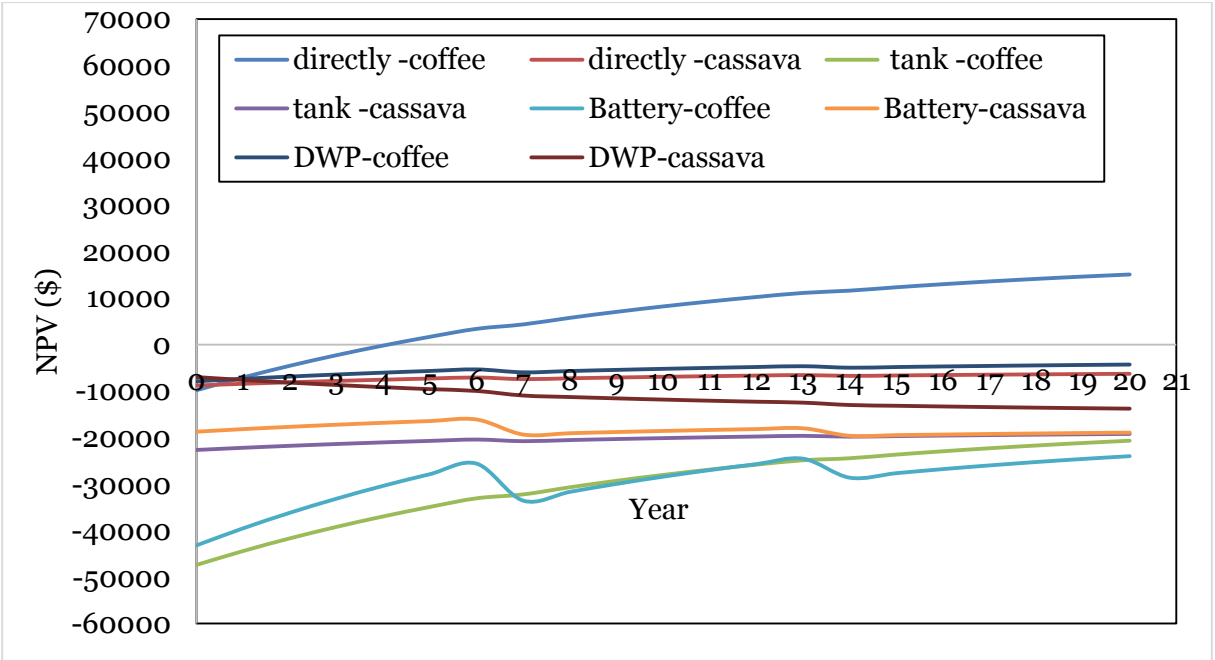


Figure 18. NPVs for PVWPs with storages medium, DWPs and PVWPs directly connected to irrigation system when the actual production of both coffee and cassava is increased by 40%.

The life cycle costs analysis has been computed using MS Excel and including all the costs occurring in 20 years of PVWPs with tank storage, battery storage, and PVWPs directly connected to the irrigation system, and DWP for irrigation of both coffee and cassava. The costs included in this analysis were initial investment costs, operating & maintenance costs and other recurring costs. The costs of replacing some components such as pump motor and battery with lifetime of 7 years each had also been considered. Using Equation 14, the total life cycle costs in 20 years for each system was then calculated by summing up all yearly costs and compared as shown in Figure 19. The cost of water storage tank is directly proportional to its capacity and it is 0.2\$/liter. The life cycle costs for PVWPs with tank storage designed to irrigate coffee plantation got higher LCCs due to the fact that a huge amount of water is needed and therefore a big tank is required to hold sufficient water for later use. The source of power has a significant impact on life cycle costs analysis of any system designed to pump water. Apart for sun which is a source of power available for free of charge, diesel is bought on higher price. About 82% of the total LCCs for DWP are costs of diesel fuel and this makes the system to cost much in long run of the project unless initial investment costs and other costs occurred during its operation are very low. The life cycle costs for PVWPs designed with tank and battery storages depend on how much water required for specific type of crop. With less water consumption of cassava plantation, the LCCs of systems designed for cassava irrigation become lower than those for a system designed for coffee plantation. Those costs are much low for PVWPs directly connected to irrigation due to the fact that the costs of storages capacities are not included. However those systems incorporate new components such as control valves and pressure regulators which were not used for systems equipped with storages medium but their prices are very low compared to storage capacities. The results for LCCs are shown in Figure19.

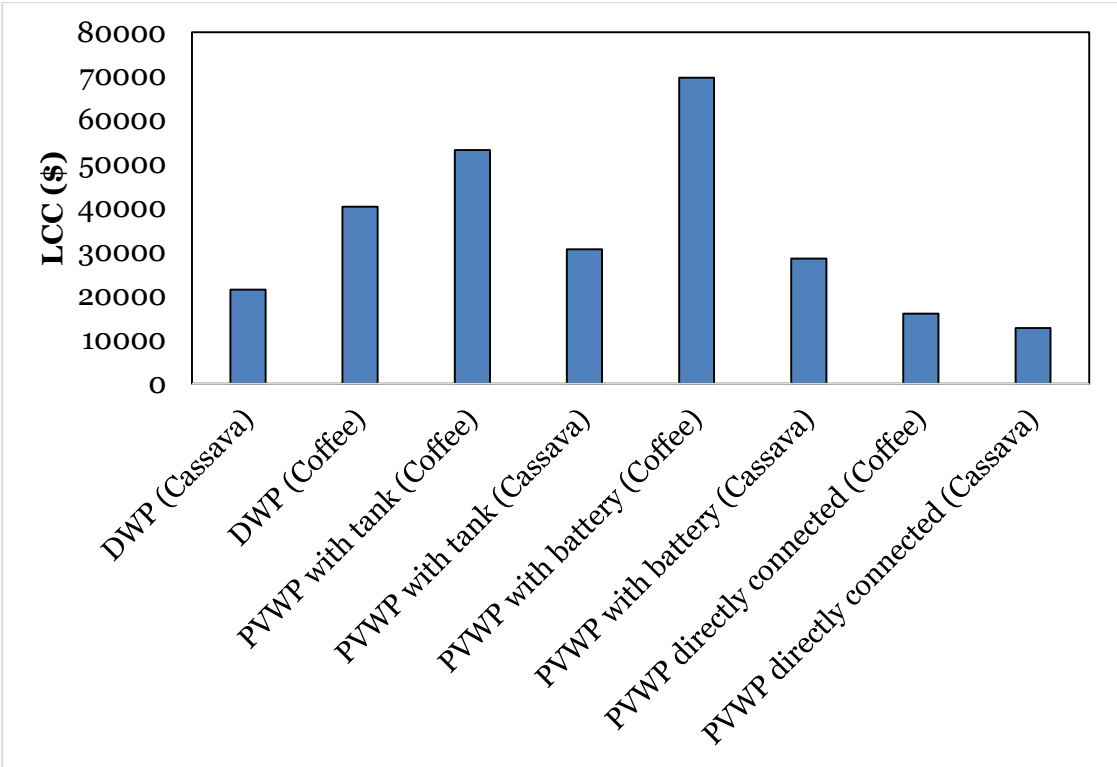


Figure 19. Comparison of LCCs for all the systems.

The time period after then a project will be financed itself, is an important factor which needs to be taken into account. The payback periods (PBPs) for all three PVWPs alternatives in addition to DWPs have been calculated in MS Excel using Equation 17. The results of Figure 20 show the impact of LCCs and NPVs on PBPs considering a case where annual productivity without irrigation is increased by 40%. NPVs taken into account are a sum up of all annual NPVs in a lifetime period of 20years. Increases of production results in additional money saved every year as the yield is sold on market at certain price. The PBP depends on both LCCs occurred during lifetime of the project and its annual incomes. In other word the more there is money saved, the more the payback period of the project becomes shorter. In contrary the PBP takes longer in case the LCCs are higher. Although water pumping technologies to water coffee plantation cost much because of big size of systems required but annual incomes from a huge amount of electricity surplus and higher price of coffee encompass all costs and make the technologies to be paid back in a very short time. The PBP becomes much shorter for a PVWPs without any storage medium because the costs of storages medium are not included in LCCs.

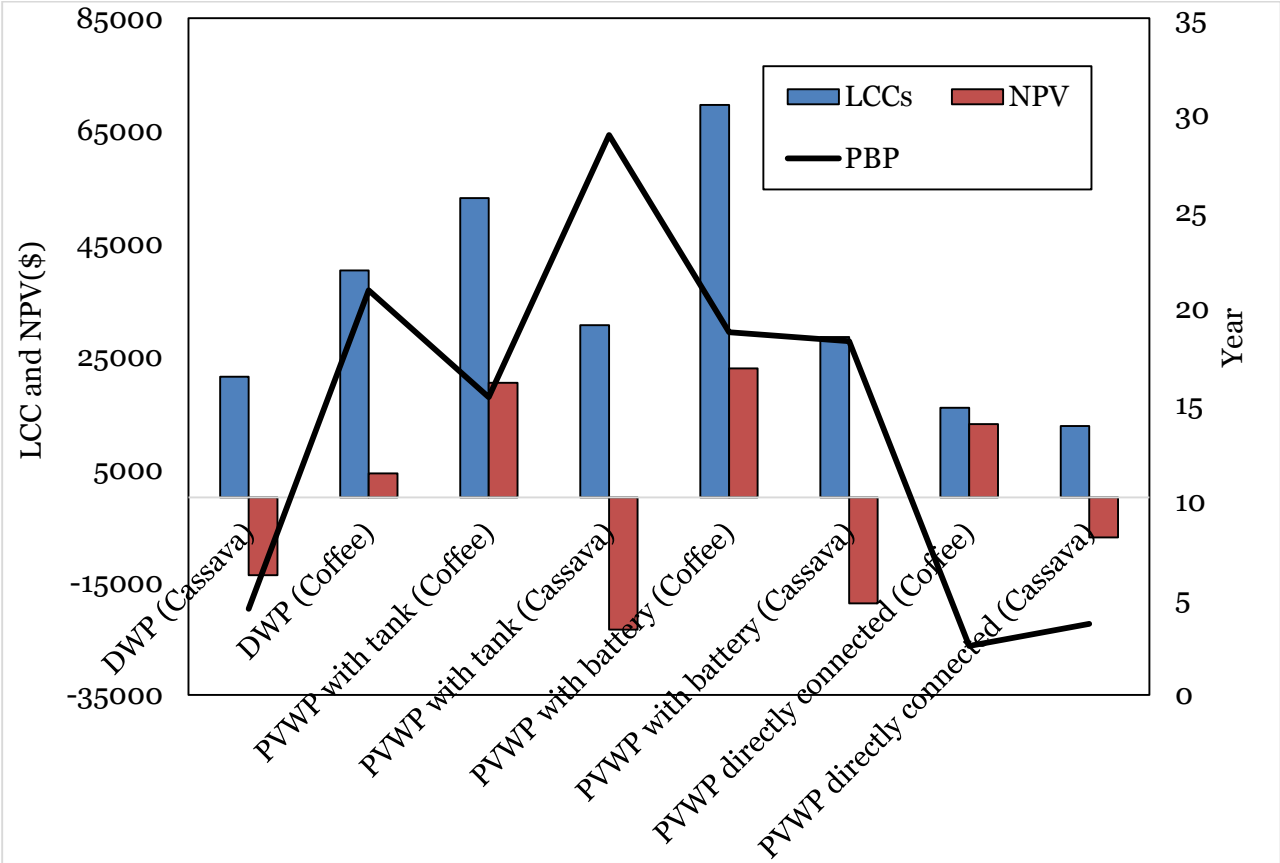


Figure 20. Impact of LCCs and NPVs on Payback period for different systems when actually productivity is increased by 40%.



### 6.8 Assessment of systems CO<sub>2</sub> emissions

To avoid global warming, it is necessary to compare the amount of CO<sub>2</sub> emitted for two energy sources thereby quantifying its reduction. The CO<sub>2</sub> emitted when DWPs is used to deliver water was determined taking into consideration the specific emissions per liter of diesel consumption [46]. The CO<sub>2</sub> emissions released and their corresponding reductions when DWPs is fully replaced by PVWPs were calculated and summarized in Figure 21. In all cases considered, the total amount of 6.6 tonnes of CO<sub>2</sub> emissions are saved per year when PVWPs is used in place of DWPs. According to [63], the annual CO<sub>2</sub> emissions released in Rwanda was estimated to be 594\*10<sup>3</sup> tonnes. The amount of CO<sub>2</sub> emissions saved using PVWPs can contribute to an annual reduction for about 0.001% of total annual CO<sub>2</sub> emitted and even more when many farmers get familiar with use of solar technology in irrigation.

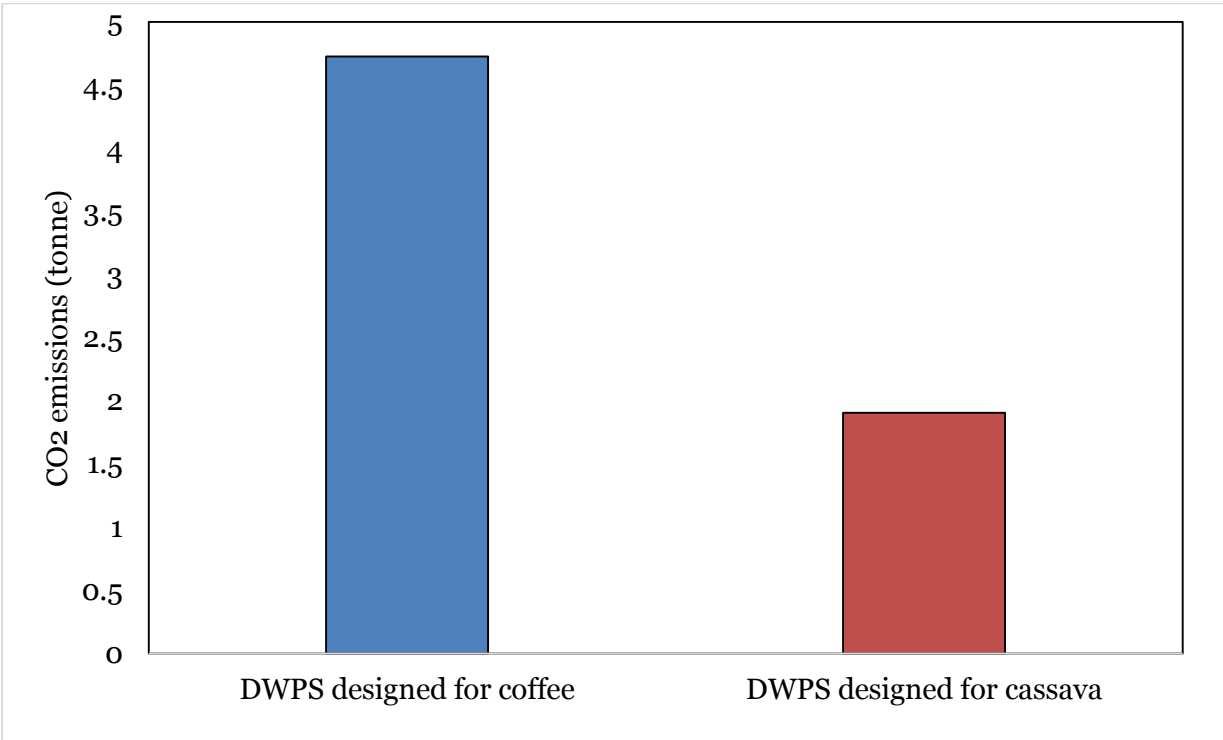


Figure 21. CO<sub>2</sub> emissions when DWP is used to irrigate both coffee and cassava.

## 7 CONCLUSIONS

This thesis was focused on design and optimization of a cost effective of PVWPs considering different alternatives such as: PVWPs with storage tank, battery storage and PVWPs directly connected to irrigation system without storage medium. The PVWPs were designed to fulfil the irrigation water requirements of coffee and cassava cultivated on two different location and marked out by an irrigated area of 5 hectares each. The irrigation method used to water the crops was drip irrigation due to its higher efficiency both in terms of water saving and energy consumption. MS Excel was used mainly for the design of PVWPs directly connected to irrigation, economic analysis, evaluation of CO<sub>2</sub> emission and reduction, design of drip irrigation system and calculations of different parameters. The water requirements for two crops were obtained from CROPWAT software. Other tool which was utilized is PVsyst to determine meteorological data of Kampala (Uganda), the region which was taken into consideration. After making sure that solar is available enough to provide energy requirements of pump, the same tool of PVsyst was also used to design and simulate a PVWPs with tank and battery storages. During design and simulation in PVsyst, solar irradiation and energy surplus for PVWPs equipped with both tank and battery storages were obtained and compared when solar panel is mounted on fixed tilt and tracking system. Electricity surplus produced from all the alternatives stated above were determined and discussed. In terms of economy LCCs, NPV, and PBP were analyzed comparing all the PVWPs with DWPs. Finally CO<sub>2</sub> emissions from DWPs and their corresponding reductions when DWPs is fully replaced by PVWPs were determined and discussed. In brief, the main findings are summarized here below:

- Two factors need to be properly investigated in order to optimize the energy from available sun resource. Those include the optimum tilt angle which is the angle determined by the latitude of the region under consideration and temperature of the PV modules which affects the performance of solar modules. Apart for tilt angle and temperature of PV modules, the power peak production of PVWPs directly connected to irrigation system is affected by different parameters and it changes depends on how much those parameters are varied.
- The energy produced and exceeded depends on how big is the size of the PVWPs. The size of PVWPs in turn is determined based on type of crop to be irrigated and its water requirements. The highest energy production and surplus was obtained for PVWPs designed to irrigate coffee plantation while it becomes lower for PVWPs designed for cassava plantation.
- Market price of crop to be irrigated, increases of productivity and electricity surplus from a PVWPs are the most three important factors which impact the profitability both in terms of money savings and time period after then a system can finance itself. In all systems designed for irrigation of coffee and cassava, DWPs showed to have lower profitability and becomes even negative for cassava irrigation.
- Even though PVWPs directly connected to irrigation system needs to operate only when sun is available, it has been selected to be the best configuration due to its low initial investment costs, high NPVs and short PBP.
- Fully replacement of DWPs by PVWPs results in CO<sub>2</sub> emissions reduction of about 6.6tonnes.

## **8 SUGGESTIONS FOR FURTHER WORK**

To have realistic design of PVWPs, hydraulic characteristics of the region under study need to be carefully investigated. Total dynamic head to which water should be pumped is an important input parameter and mostly affects the performance of the system in general. Moreover varying heads can result in changing size of both photovoltaic system and pumping system and hence affecting the profitability and CO<sub>2</sub> emissions analysis. Further work would be to determine the exact head required and redo the same work accordingly. In addition due to a huge amount of electricity surplus from PVWPs, future work will be to integrate the excess of electricity to the electrical grid nearby.

## REFERENCES

- [1]U.S.Department of Energy, 2014, the water energy nexus: challenges and opportunities
- [2]Food and Organization of the United Nations, 2014, the water-food- energy nexus
- [3]MAIMBO Mabanga Malesu, 2010, Rwanda Irrigation Master Plan, World Agroforestry Centre (ICRAF)
- [4]Andreas P.SAWA, Karen FRENKEN, 2001, Irrigation Development: a Multifaceted Process, Social, Economic, Engineering, Agronomic, Health and Environmental Issues to be considered in a Feasibility study, Irrigation Manual, Module 1.
- [5]T.Khatib, 2010, Design of Photovoltaic water pumping system at minimum cost for Palestine: A Review
- [6]M.Abu-Aligah, 2011, Design of Photovoltaic Water Pumping System and Compare it to Diesel Powered Pump, Jordan Journal of Mechanical and Industrial Engineering, volume 5, pp 273-280
- [7]Bardi, U., El Asmar, T. &Lavacchi, A., 2013, agriculture can be powered by renewable energy resources.
- [8] Overview of renewable energy and energy efficiency  
<http://africa-toolkit.recep.org/modules/Module1.pdf>, 2015-04-03
- [9]B.Kavitha, S.Karthikeyan, B.Iswarya, 2014, Design of solar PV water pumping system using BLDC drive using sensorless method.
- [10]Fabien Twagiramungu, 2006, Environmental Profile of Rwanda
- [11] National Institute of Statistics of Rwanda (NISR), 2013, Seasonal Agricultural Survey Report
- [12]IPAR Rwanda Report, 2009, Rwanda Agriculture Sector Situation Analysis
- [13]Brian Harding, 2009, Review of the Economic Impacts of Climate Change in Kenya, Rwanda and Burundi.
- [14]Nang Saw Yuzana Kyaing, 2011, Design considerations of PV water pumping and rural electrification in lower Myannar  
[https://www.gafspfund.org/sites/gafspfund.org/files/Documents/Rwanda\\_StrategicPlan.pdf](https://www.gafspfund.org/sites/gafspfund.org/files/Documents/Rwanda_StrategicPlan.pdf), agriculture sector, 2015-05-17
- [15]<http://www.1001worldmap.com/map-of-rwanda/>

- [16]Ministry of Agriculture and Animal Resources, Republic of Rwanda, Strategic Plan for the Transformation of Agriculture in Rwanda-Phase II (PSTAI), 2009, Final report
- [17]Eline Boelee, Henry Madsen, 2006, Irrigation and Schistosomiasis in Africa: Ecological Aspects, Research Report 99
- [18][http://css.wsu.edu/wp-content/uploads/2012/09/L\\_James\\_Ch21.pdf](http://css.wsu.edu/wp-content/uploads/2012/09/L_James_Ch21.pdf), Farm Irrigation Systems and System Design Fundamentals, 2015-05-17
- [19][http://css.wsu.edu/wp-content/uploads/2012/09/L\\_James\\_Ch21.pdf](http://css.wsu.edu/wp-content/uploads/2012/09/L_James_Ch21.pdf), Farm Irrigation Systems and System Design Fundamentals, 2015-05-17
- [20]<http://www.jains.com/irrigation/popups%20and%20sprinklers/sprinklersystems.htm>
- [21]Reuben M.J.Kadigi, GirmayTesfay, Alfred Bizoza, Genet Zinabou, 2013, Irrigation and Water Use Efficiency in Sub-Saharan Africa, Working Paper No.63
- [22] NaanDanJain Brazil, 2009, Drip Irrigation for Coffee Plantations: Feasible and Profitable <http://www.naandanjain.com/uploads/catalogerfiles/coffee-2/Coffee-dripirrigation.pdf>, 2015-03-25.
- [23]<http://www.jains.com/irrigation/drip%20irrigation%20system.htm>
- [24][http://www.minagri.gov.rw/fileadmin/user\\_upload/documents/Tenders/Concept\\_note\\_and\\_Terms\\_of\\_Reference\\_for\\_Irrigation\\_expert\\_-\\_TA\\_Dfid\\_fund\\_CORRECT\\_Document.pdf](http://www.minagri.gov.rw/fileadmin/user_upload/documents/Tenders/Concept_note_and_Terms_of_Reference_for_Irrigation_expert_-_TA_Dfid_fund_CORRECT_Document.pdf), Irrigation and Mechanization, 2015-04-27
- [25]Derrel .L.Martin, 2011, Evaluation Energy use for pumping irrigation water
- [26]Tamara Jackson, 2009, an appraisal of the on-farm water and energy nexus in irrigated agriculture, a thesis submitted to Charles Sturt University for the degree of Doctor of Philosophy
- [27]Mahir DURSUN, Semih OZDEN, 2012, Application of Solar Powered Automatic Pumping in Turkey, International Journal of Computer and Electrical Engineering, vol4, No2, April, 2012
- [28]Luisa F. Cabeza (Spain), K.G.Terry Hollands (Canada), Arnulf Jäger-Waldau (Italy/Germany), Michio Kondo (Japan), Chalres Konseibo (Burkina Faso), Valentin Meleshko (Russia), Wesley Stein (Australia), Yutaka Tamaura (Japan), Honghua Xu (China), Roberto Zilles (Brasil), 2011, Direct Solar Energy, Chapter 3.
- [29] Mark Hankins, 2009, Rwanda's solar Market
- [30]Ulrich Elmer Hansen, 2014, Prospects for investment in large-scale, grid-connected solar power in Africa
- [31]Esdras Nshimyumuremyi, 2015, Solar Water Pumping System in Isolated Area to Electricity: The Case of Mibirizi Village (Rwanda)

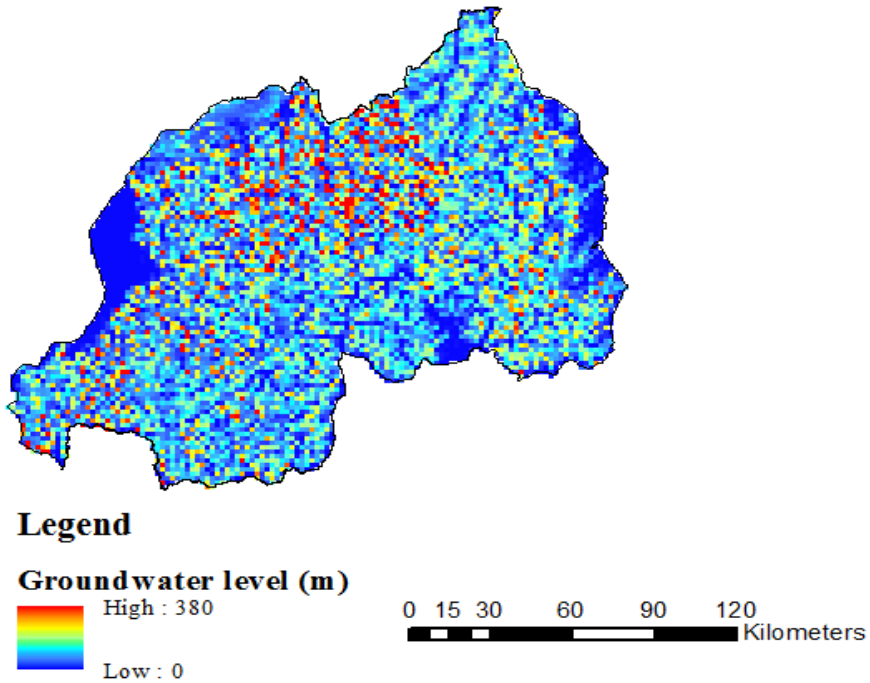
- [32] Gasore Geoffrey, Munyaneza Jean de Dieu, Ngendabanga Jean Pierre, Twibanire Aimable, 2015, Design of Automatic Irrigation System for Small Farmers in Rwanda.
- [33] Y. Fan, H. Li, G. Miguez-Macho, "Global patterns of groundwater table Depth", *Science*, vol. 339, p. 940–943, 2013
- [34] Christian Kwaku Amuzuvi, Emmanuel Effah, 2014, Design of a photovoltaic system as an alternative source of electrical energy for powering the lighting circuits for premises in Ghana, *Journal of Electrical and Electronic Engineering*, Vol.2, No.1, 2014, p9-16.
- [35] <http://software.informer.com/search/CROPWAT>
- [36] K.G.Mansaray, 2009, Optimum Design of Solar Photovoltaic Pumping System by Computer Simulation, *International Journal of Engineering Technology and Advanced Engineering*, Volume 4, Issue 9, September 2014.
- [37] M.Prins, 2001, *Irrigation Water Management: Irrigation Method*
- [38] Jean Niyongabo, 2004, Where Sustainable Agriculture means Agricultural Productivity? The case study of Gikongoro in Southern Rwanda
- [39] Robert Nyamvumba, 2014, Expression of interest for Scaling up Renewable Energy Program (SREP) Financing for Energy Projects in Rwanda
- [40] Oko COC and Ogoloma OB, 2011, Generation of Typical Meteorological Year for Port Hardcourt Zone. *Journal of Engineering Science and Technology*, 6(2):204-214
- [41] Nang Saw Yuzana Kyaing, 2011, Design considerations of PV water pumping and rural electrification in lower Myannar
- [42] Gain-Angee Migan, 2013, Study of the operating temperature of a PV module
- [43] Muhammad Ashraf, 2012, Design of Drip Irrigation System, pp
- [44] Seleshi Bakele Awulachew, Philippe Lemperiere, Taffa Tulu, 2009, Irrigation methods: Drip irrigations for smallholders
- [45] Technical manual for affordable micro-irrigation technology (AMIT), <http://www.siminet.org/images/pdfs/technical-manual.pdf>, 2015-04-01
- [46] Emil Nilson, Milos Jacksic, Diana Osta, Roje Torsian, Tobias Jahn, 2015, Solar-Driven Irrigation in Dhulghat, India; Project 3.7, Sustainable Energy Systems-Advanced studies.
- [47] [http://people.exeter.ac.uk/TWDavies/energy\\_conversion/Calculation%20of%20CO2%20emissions%20from%20fuels.htm](http://people.exeter.ac.uk/TWDavies/energy_conversion/Calculation%20of%20CO2%20emissions%20from%20fuels.htm), calculation of CO2 emissions, 2015-05-02
- [48] Pietro Elie Campana, 2013, PV water pumping systems for grassland and farmland conservation, Licentiate Theses, No 172
- [49] Dimitry Mindlin, 2013, Present Values, Investment Returns and Discount Rates, ASA, MAA, PhD, CDI Advisors LLC.

- [50]<http://www.theigc.org/wp-content/uploads/2015/02/Macciavello-and-Morjaria-2015-Project-Memo.pdf>, 2015-04-22.
- [51] <http://www.asareca.org/researchdir/FILES/NPPFULLCASSAVA.PDF>, 2015-04-22
- [52]<http://www.theeastafrican.co.ke/news/Rwanda-to-lower-power-tariff-for-industries/-/2558/2406242/-/fa5dhi/-/index.html>, Rwanda to lower power tariff for industries, 2015-04-22
- [53]J.I.Sodiki et al., 2014, Solar-Powered Groundwater Pumping Systems for Nigerian Water Sheds, Vol.4, No.2
- [54]Hamed ALLaham, A-K. Hamid, Ali Cheaitou, 2014, Technical and Econmic Analysis of Photovoltaic System Applied to UAE Data Centre
- [55]Arnulf-Waldau, 2013, PV Status Report
- [56]Matthew Bates, Bryan Pon, Anna Petersons, 2009, Irrigated Agriculture in Djibouti: An Economic and Physical Analysis of Irrigation Systems
- [57][https://www.google.se/?gfe\\_rd=cr&ei=yGw3VZP9DcqCZIGMgNgE&gws\\_rd=ssl#q=types+of+water+storage+tank,pdf&start=0](https://www.google.se/?gfe_rd=cr&ei=yGw3VZP9DcqCZIGMgNgE&gws_rd=ssl#q=types+of+water+storage+tank,pdf&start=0), Chapter VI, Water storage tanks, 2015-05-22
- [58][http://www.nswfarmers.org.au/\\_\\_data/assets/pdf\\_file/0007/35854/Energy-Irrigation-Diesel-versus-electric-pumps.pdf](http://www.nswfarmers.org.au/__data/assets/pdf_file/0007/35854/Energy-Irrigation-Diesel-versus-electric-pumps.pdf), Diesel versus electric pump, 2015-04-22
- [59] Antoni C.Jimenez, Tom Lawand, 2000, Renewable Energy for Rural School, book.
- [60][http://ocw.tudelft.nl/fileadmin/ocw/courses/SolarCells/res00029/CH9\\_Photovoltaic\\_systems.pdf](http://ocw.tudelft.nl/fileadmin/ocw/courses/SolarCells/res00029/CH9_Photovoltaic_systems.pdf), Miron Zeman, Photovoltaic Systems, chapter 9, Delt University of Technology, 2015-05-21
- [61]Michael G. Thomas, 1996, Water pumping: The solar alternative
- [62][https://www.nswfarmers.org.au/\\_\\_data/assets/pdf\\_file/0011/35858/Energy-Irrigation-Solar-PV-pumping-systems.pdf](https://www.nswfarmers.org.au/__data/assets/pdf_file/0011/35858/Energy-Irrigation-Solar-PV-pumping-systems.pdf), 2015-05-23
- [63][http://en.wikipedia.org/wiki/List\\_of\\_countries\\_by\\_carbon\\_dioxide\\_emissions](http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions), List of countries by 2010 CO2 emissions, 2015-05-02

# APPENDIX

## Appendix 1. Rwanda groundwater level

Without hydrological data provided, it is difficult to know the exact depth of water for a given region. However the groundwater map can give an indication on how to make assumptions. As it is seen in figure below, Rwandan groundwater seems to be situated on higher height below the surface and this could prevent the pump from meeting the water demand due to higher pressure head requirement.







**MÄLARDALEN UNIVERSITY**  
**SWEDEN**

Box 883, 721 23 Västerås **Tel:** 021-10 13 00  
Box 325, 631 05 Eskilstuna **Tel:** 016-15 36 00  
**Email:** [info@mdh.se](mailto:info@mdh.se) **Web:** [www.mdh.se](http://www.mdh.se)