# TITLE: FEASIBILITY STUDY AND DESIGN OF EFFICIENT AND COST EFFECTIVE PV POWERED WATER PUMP: CASE STUDY IN TUNDA CELL, RWANDA.

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MASTERS OF IN ELECTRICAL POWER SYSTEM

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# DECLARATION.

I, the undersigned, declare that this Feasibility Study and Design of Efficient and Cost Effective PV Powered Water Pump: Case Study in Tunda Cell, Rwanda is my original work, and has not been presented for a degree in University of Rwanda or any other Masters. All sources of materials that will be used for the thesis work will have been fully acknowledged.

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## Abstract

In recent days, people working in the agricultural field are facing a lot of problems in cultivating their crops due to the lack of sufficient rain that can help them for obtaining the good productions. The solution to such a problem can be provided by using a solar photovoltaic water pump which was designed because solar energy is environment friendly and available for free.

As objective research is feasibility study and design of efficient and cost-effective PV powered water pump for irrigation, The design of the solar PV powered water pumping system in Tunda cell based on the data of solar radiation, average monthly temperature, and other weather condition, It is designed to satisfy the total power demand of the hydraulic pump using solar PV modules to irrigate. The system components are a solar PV module, PMDC motor-driven PV water pump, and battery.

The system is configuration made to produce 12800 m3 water which is the maximum daily water demand for irrigating 160 hectares of the lands near the lake Cyohoho. The hydraulic power of the pump calculated considering the total dynamic head, volume of water required, density of water, and acceleration due to the gravity and maximum sun hour per day. Based on this initial power demand, the number of PV modules, and the battery is determined.

The comparison analysis made by using HOMER energy software, the total cost PV system is $8,499,742.00 while diesel fuel generator pumping system is $11,905,510, even by comparing levelized cost of energy, for a PV system is $0.2524 per kWh while for diesel fuel system is $0.3534, without including pump set, water storage tank, installation and pipes cost. Also, solar PV systems are friendly to the environment because their pollution is free to compare to diesel generator water pumping system produces different gases such as 1,415,643kg/year of carbon dioxide, 7,506 kg/year CO,3538kg/year SO2 to the living environment.

Even the comparison of initial investment, total life, maintenance and operation costs and the pollution production, the best considerable is PV powered water pump instead of diesel fuel generator

***Key words****; photovoltaic water pump, solar radiation, cost, water tank storage, Battery storage, PMDC motor driven by PV water pump system.*

## List of symbols and abbreviations

PRSP: Poverty Reduction Strategy Paper

MINAGRI:Ministry of Agriculture and Resources

PV: Photovoltaic.

Fig: Figure.

DC: Direct current.

TDH: Total Dynamic Head

$I_{mp}$: Current at maximum power point

$V_{mp}$: Voltage at maximum power point

Voc: Open circuit voltage

Isc: Short circuit current

$P_{max}$: Maximum power

PV: Photovoltaic

GHI:Global Horizontal Irradiance

HOMER: Hybrid Optimization Model for Electric Renewables

$CO_2$: Carbon dioxide

CO: Carbon monoxide

$SO_2$: Sulfur dioxide

LCOE: Levelized cost of Electricity

NPC: Net Present Cost

SPIS: Solar Photovoltaic Irrigation System

LCC: Life Cycle Cost

MPPT: Maximum Power Point Tracking

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# CHAPTER1.

# INTRODUCTION

## 1.1.Background

Rwanda relies heavily on agriculture for its income, employment opportunities, and the economic well-being of its people. Achieving food security and increased rural incomes will depend very much on increased productivity in the agriculture sector. In the Vision 2020 context, the Government prepared a Poverty Reduction Strategy (PRSP) whose core objective is improving the people's living conditions. The targets of PRSP are to reduce to 25% the percentage of the population living below the poverty threshold (compared to 60% in 2002) by 2015 and increasing the per capita income to US$ 1240 from US$ 230 (as of 2004) by 2020. This performance will largely come from agricultural development and processing, and the creation of additional jobs in the sector[1].

Rwanda has abundant untapped water resources in form of natural lakes, rivers, groundwater, marshlands, and runoff. The Government of Rwanda has considered that it needs to develop irrigated agriculture to offer a way out of poverty, to accomplish food security and mitigate climate change-induced drought and has charged the Ministry of Agriculture and Animal Resources(MINAGRI) to spearhead irrigation development particularly in the drought-prone areas of Eastern Rwanda where site selection is located[1].

In Rwanda, especially the Eastern province, Bugesera district, agriculture is facing the problem of poor production due to the lack of sufficient rain in that region. As Tunda, is the one cells the comprises Bugesera district located near lake CYOHOHA as shown in figure 8[2] Farmers live in this region try to solve this problem of poor productions by using their manual power in irrigation as shown in Figure 1[3], but only for small vegetables like tomatoes, beverages and, etc.

Figure 1 former using his manual power in irrigation in Tunda cell[3].

As the manual irrigation used in Tunda cell as shown in figure 1 have the following disadvantages:

1.It is differing from using PV power water pump because of the solar pumps are a public choice using higher effort for a small area, loss of time, and because of the mall the area of the pumps the production will be insufficient while there is spending time

2.Machines cannot be used in this method because, during the spray of insecticides or fertilizers, the earthen wall of the basin is destroyed.

4.Emppleyees are variable[4].

While PV pump system contributes the following advantages:

1.Photo -voltaic cell can be suitable, either in place location and faraway of the site

2.PV pump is cheaper in the running period.

3.PV pump is comfortable to carry and move to a new place[3].

4. For supporting or continuing operation of the photovoltaic pump, require less capital

5.In the period of hotness and more solar irradiance, the farmer can get sufficient water used in their crops for improving their productions.

Thus, this study focuses on the study in the feasibility of using solar-based pumps for pumping water for irrigation at Tunda cell, which is one of the cells located Kamabuye in the district of Bugesera. In Tunda cell some of the farms live near a lake, thus, a solar-powered irrigation system may be applicable for improving the productivity of the farmers.

## 1.2.Statement of the Problem

In Rwanda, most of the people living in rural areas are farmers. In the eastern province, Bugesera district, lack of sufficient rain is the biggest cause of low production from their cultivation. Most of the people living in that region have the opportunity to use grid electricity but only for lighting but have the capacity of water pump for irrigation.

Some farmers try to pump water by using a motor which consumes diesel and petrol which are very costly and others using their effort for a small agricultural area. The best solution for increasing production and to avoid drawbacks of diesel, using PV powered pump will be cost effective and environmentally friendly.

## 1.3. Objectives

### 1.3.1. Major Objective

The study focuses on feasibility study and design of efficient and cost-effective PV powered water pump for rural Rwanda in Tunda cell.

### 1.3.2. The Specific Objectives

- Collect climatic data and solar radiation of site.
- Design a PV water pump that is cost-effective, rugged, and simple for operation.
- Evaluate the performance of the PV water pump in terms of its output, cost, and efficiency using HOMER software
- Draw relevant conclusions and recommendations for further local manufacturing of such devices.

## 1.4. Scope of the study

The study includes

- Gathering climatic data and solar radiation of the site,
- Design a PV water pump that is cost-effective, rugged, and simple in operation,
- Evaluation of the performance of the PV water pump in terms of its output, cost, and efficiency, and

- Draw relevant conclusions and recommendations for further local manufacturing of such devices

### 1.5. Research Methodology

The methodology of the research includes:

- Data collection: solar insolation data of the site is collected for designing the Pump.
- Design: based on the need and available solar radiation, a PV pump is designed for one group of farmers.
- Performance Analysis: The designed PV pump is being modeled and evaluated using appropriate software for its pumping capacity, cost and efficiency.

The following methods have been followed in the execution of the research.

- Data of average monthly sun hour and UV index were collected from Meteo Rwanda website while average monthly temperature and average solar radiation.
- Water requirements were estimated for the total area of the land to be irrigated based on the volume of land to be irrigated and the types of crops the farmers used to cultivate.
- Total dynamic head was collected with measurement.
- The design part is done to determine the size of the PV based on the known theory of PV.
- The performance analysis is done using available software.

### 1.6. Relevance of the study

A solar-powered irrigation system can provide significant environmental and socio-economic benefits, both at the farm level and at the national level.

The photovoltaic-powered water pump can contribute important environmental and socio-economic profits, both at the plantation level and at the national level.

- ➢ SPIS provides significant socio-economic profits at the level of farm and national.
- Finding and cost of photovoltaic modules (solar array) proceed to drop, making photovoltaic powered irrigation system cheaply applicable and competitive with other sources of energy.
- It does not require fuel; this reduces the cost in the system compared to other sources of energy

- In the period of the running system of irrigation, the cost of Photovoltaic powered water pump is reduced.
- It is possible to increase productivity from agriculture due to the addition of cultivating in drought season.
- When the system of irrigation using photovoltaic panels is applicable, the problem of poor production will be solved. This causes foods to be secured.

➢ SPIS conducts the following significant environmental subsidies both at the farm level and national level.

- The solar-powered irrigation system is friendly to the environment.
- Possibility of ameliorating the quality of water between straining and fertilization and irrigation system

# CHAPTER2.

# LITRATURE REVIEW

## 2.1. Introduction

This chapter presents the theories and researches done in this particular area. It provides information on the background theory of PV and the pump components and the researches done on the area.

## 2.2. Theoretical background on PV pumping system.

### 2.2.1. Photovoltaic water pump

The installation work of the solar pump was done and the pump got installed in the 1970s. From these years, the improvement of the system was carried out to increase its performance. The first-generation photovoltaic pumping systems consisted of centrifugal pumps driven by DC motors or AC motors in presence of an inverter, long-term reliability, and hydraulic efficiency a range of 25 percent to 35 percent.

The second-generation Photovoltaic pumping systems are replaced by positive displacement pumps, diaphragm pumps, and progressive cavity pumps for low discharge, generally characterized by lower PV input power requirements, higher hydraulic efficiencies, and lower capital costs[5], [6]

A solar-powered water pumping system is made up of three basic components namely solar energy supply, power control, and dynamic system.

Block diagram shown in Figure 3, indicates the System of photovoltaic powered water pump

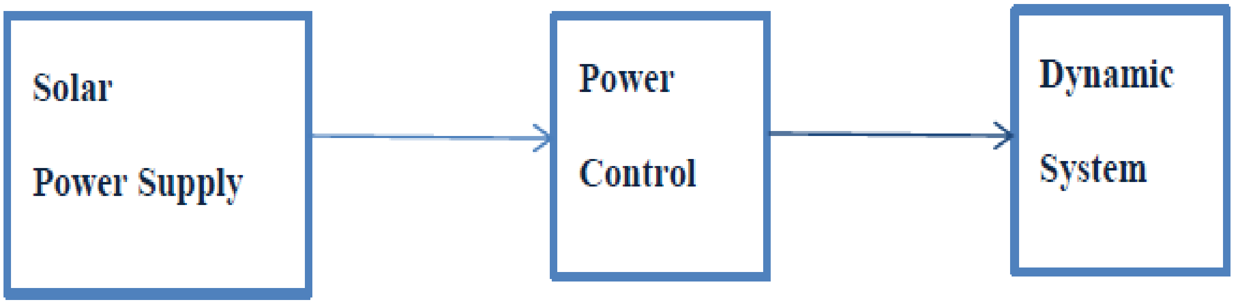

Figure 2 Block diagram of solar-powered water pump system

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- **Solar power supply**

The Solar power supply consists of a PV array and is a power generating section that consists of any number of photovoltaic modules and panels. The solar panel consists of solar cells which are semiconductor devices that convert sunlight to electrical energy. These solar cells together form a module. Photovoltaic modules include photovoltaic cell circuits that are enclosed and "sealed in an environmentally protective laminate". The solar panel includes one or more PV modules assembled as a pre-wired, field-installable unit.

When sunlight imposes on a solar cell, the positive charge carriers (the holes) and the negative charge carriers (electrons) appear in pairs. If those pairs can reach the electric field before they recombine (meaning to reunite and, hence, to neutralize themselves), they are ultimately separated, with the electrons moving toward the front wall (the n-type layer), where they collect on metallic contact fingers mounted above the surface and then return, by way of the external circuit, to the full-face metal-coated back wall of the cell, where they ultimately recombine with the holes.

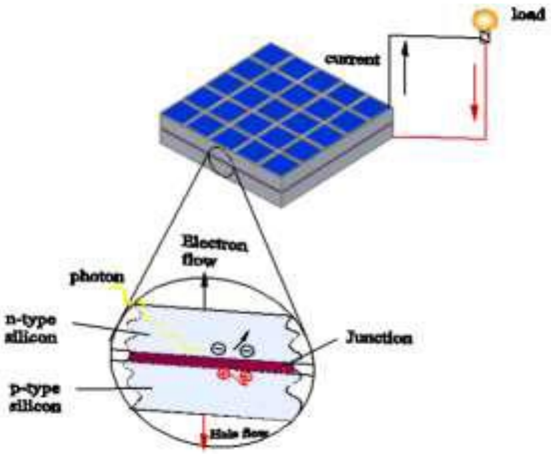


Figure 3 Basic operation of PV system[7].

To generate the desired power for running the motor, the panels have to be connected in series and parallel to form the PV array which can produce enough voltage and current The flexibility of the modular PV system allow designers to create solar power systems that can meet a wide variety of electrical needs, no matter how long or small[8].

- **Power Control**

The power control system consists of a charge controller, energy storage unit, inverter, and so on. In the case of a PV water pump with a battery storage system charge controller is used to charge the batteries from the solar panel system. This charge controller is also used as MPPT in both PV water pump systems with and without battery. Inverters are used to convert DC either from DC to DC converter or solar panel to AC when induction motors are used for water[8].

- **Dynamic System**

A dynamic system of PV water pump system consists of a motor and pump. The motor receives electrical energy from a solar panel through a power control system and transforms it into kinetic energy form while the pump converts this kinetic energy into hydraulic energy of water. In PV water pumping system three types of the pump are mostly used; submersible, centrifugal and positive displacement pumps.

### 2.2.1.1. Photovoltaic (PV) panels

A solar panel consists of many solar cells connected in series that converts the sunlight into electrical energy as shown in figure 4, the PV module has the capacity of producing large power depends on the number of solar cells connected where only one cell can produce around 3 Watts at the strong intensity of sunlight. The semiconductor layers of solar cells can be a thick film or crystalline, the crystalline solar cells are made of silicon and able to produce electrical power at a high conversion efficiency of around 15% while the solar cell made of thin-film and can contain different materials, its conversion efficiency is about 8% to 11%. The silicon solar cells are more durable than thin-film solar cells but their disadvantage is that is heavy and expensive, the solar panels have to be connected in series and parallel to raise the capacity of the system for making it, able to produce enough power output for running water pump[9]

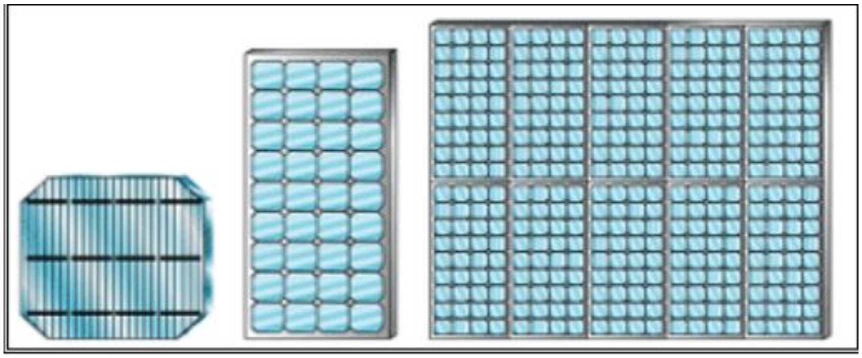


Figure 4 Solar panel[10]

Solar modules are mostly used in remote areas, where the grid connection is poor or absent and is more applicable in agricultural operations, solar modules play a vital role in generating electrical energy useful for powering domestic and motor pumps in irrigation systems.

### 2.2.1.2. Solar panel electrical characteristics

Solar panels are rated based on their output parameters, which is depending on the intensity of solar radiation falling on the surface of the panel and the working temperature of the PV module, the different factors can affect the output parameters of the solar panel (power, current, and voltage), for example when there is a large reduction in irradiance, it results in a fast decrease of current and slow decrease of voltage[9]

#### 2.2.1.3. Photoelectric effect

The photovoltaic system extracts electrical energy from sunlight through a photoelectric effect and this done when incoming solar radiation interacts with a conductive surface, such as a silicon cell or metal film, and electrons in the material become excited and jump from one conductive layer to the other as shown in Figure 5 below[9]

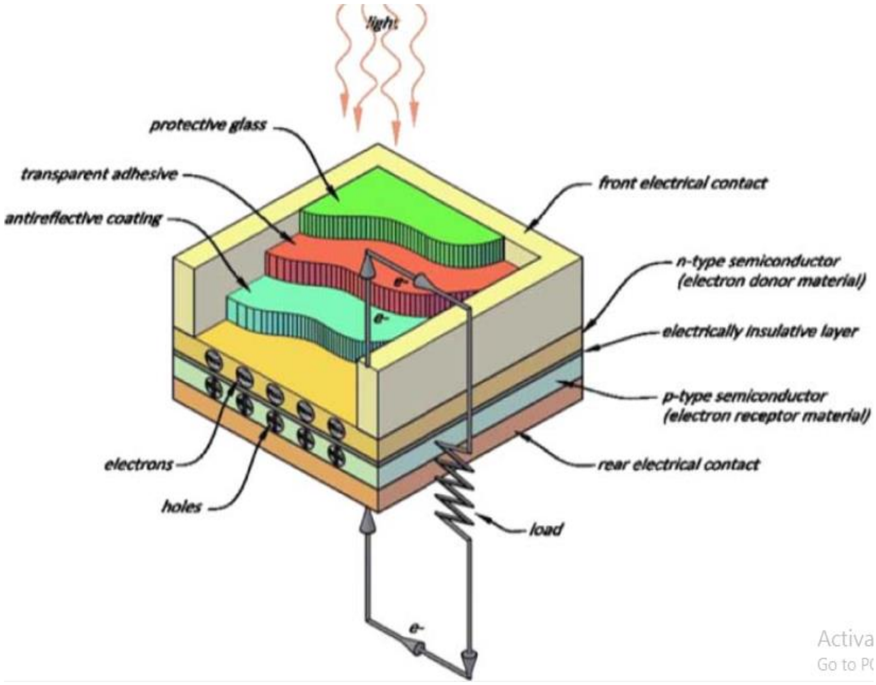


Figure 5 The photoelectric effect and subsequent electron motion[11]

Solar cells produce electricity that can be used for different purposes such as powering water pumps.

### 2.2.2. Solar radiation, solar irradiance and solar insolation

To design a solar-powered water pump system, quantification of the availability of solar energy will be needed. It is, therefore, significant to be intimated with definitions and distinctions between solar radiation, solar irradiance, and solar insolation

- **Solar radiation** is the power produced by the sun and reaches to earth. It is measured in $kW/m^2$.
- The measure of the power density of sunlight received at the location on the earth and is measured in watt per meter square is called **solar irradiance**[12]
- Lastly, **solar insolation** is the amount of solar irradiance measured over a given period. It is typically quantified in peak sun hours, which are the equivalent number of hours per day when solar irradiance averages1 $kW/m^2$[9]

Figure7 shown below indicates how peak sun hours are founded for any special day. The total sum of solar irradiance is divided by 1 kW/m2, which equals the total number of peak sun hours for that day.

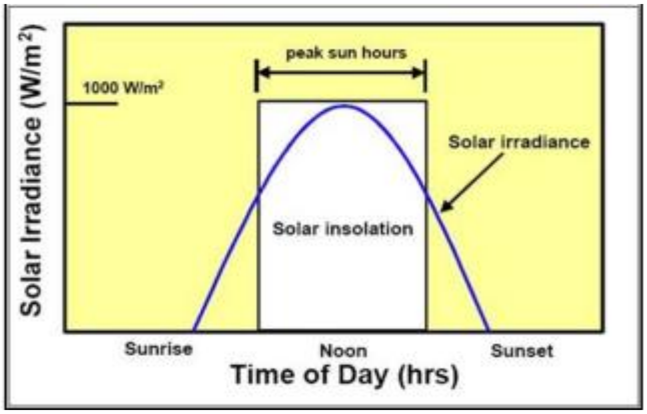


Figure 6 Solar irradiance and peak sun hours[11]

### 2.2.3. Solar powered pumps

The pumping system consists DC motor which uses the input DC power from the PV module to turn the pump shaft, the AC motors are also used but on a small scale because they require additional components and complex control systems.

The pumping system using AC motor has the losses during the energy conversion from DC to AC by an inverter, the system with DC motor produces more amount of energy the one with AC motor and it requires the less control system, this makes it the most applicable solar-powered pumps[9]. Solar-powered pumps can be coupled with different types of pumps, either positive displacement pumps or centrifugal pumps, positive displacement pumps are typically used when the total dynamic head(TDH) is high and the rate of flow required is low. However, centrifugal pumps are typically used for low TDH and high flow rates[13], [14]

To design a PV powered pump, the following information is required:

- Specification of availability of solar power to the site selected.
- Quantity of water required during the time needed, either for using, or storing.
- The vertical distance of water to be pumped and friction losses for the pump
- Possibility of obtaining water in quality and quantity
- The system's proposed design and hydraulic criteria[9]

### 2.2.4. Performance parameters of a solar pump

2.2.4. Performance parameters of a solar pump

The performance of PV water pump mainly depends on the water flow rate which is influenced by weather conditions at the location, especially solar irradiance and air temperature variations. The performance of solar pump depends on the water requirement, size of the water storage tank, head (m) by which water has to be lifted, water to be pumped ($m^3$), PV array virtual energy (kWh), Energy at the pump (kWh), solar energy (kWh) which is not used, the efficiency of a pump (%), and system efficiency (%) and diurnal variation in pump pressure due to change in irradiance and pressure compensation[15]

The formula shown below will be used in the performance of the solar pump.

1.With respect to the quantity of water required, hydraulic energy required per day to supply that amount of water should be calculated as follows in equation 1[15]

$$E_h = \rho * g * V * TDH \qquad (1)$$

Where Eh is hydraulic energy required to supply water demand, it is expressed in the system unit of (kWh/ day), ρ is a density of water, g is the acceleration due to gravity expressed in $m/s^2$, V is the volume of water required and THD which is the summation of vertical distance of water to be pumped and friction losses.

2. Power of a photovoltaic array(Ppv), this required power is calculated as shown in equation 2 below

$p_{pV}=E_h/\ (\mathrm{I_T} * \eta_{\mathrm{mp}} * \mathrm{F})$ (2)

Where Eh: Hydraulic energy required to supply water demand, $\mathrm{I_T}$: Average daily solar isolation in kWh/day, F: array mismatch and $\eta$mp which is daily motor pump efficiency..

3.Motor pump efficiency($\eta_{\mathrm{mp}}$) is calculated as follow in equation 3

$$\eta_{mp} = \frac{Hydraulic\ energy\ output}{Input\ energy} \quad (3)$$

4.Efficiency of the solar array($\eta_{\mathrm{pv}}$) is calculated as shown in equation 4

$$\eta_{\mathrm{PV}}=\frac{\mathrm{P}_{p\mathrm{V(w)}}}{\mathrm{I}_T\left(\frac{\mathrm{W}}{m^2}\right)*A_C(\mathrm{m}^2)} \quad (4)$$

Where Ac is a total area of solar panel

5. Lastly, the total efficiency of the photovoltaic water pump system is the product of motor pump efficiency and solar array efficiency shown in equation 5 below

$$\eta_{\mathrm{total}}= \eta_{\mathrm{pv}} * \eta_{\mathrm{mp}} \quad (5)$$

### 2.3 Literature review

A report done by Abu-Aligah states that in remote areas where the national grid is absent, the supply of water and irrigation can be achieved by photovoltaic pumping system, it is easy to be installed, and it requires low operating cost, low maintenance activities, and long life[16]

Odeh et al.[17] carried out the analysis in terms of the economy by comparing diesel and photovoltaic water pumping systems, in his analysis, he took the size range between 2.8 – 15 kWp. NPC, annuity Livelized COE, and operation cost were calculated. The results showed that the systems of pumping which is less economical are diesel pumping systems for equivalent hydraulic energy below 2,100,000 m4 /year, where solar water pumping systems become less economical than diesel pumping systems for larger applications.

Curtis[18] conducted an economic feasibility study of solar photovoltaic irrigation for forage production in the Great Basin Nevada, western Utah. He reported that the solar PV irrigation system was a cost-effective alternative for forage production in the area.

In summary, all above researchers who study the feasibility study of a PV pumping system, their reports show that photovoltaic pumping system was proven as the best method to be used in supplying drinking water and irrigation where it requires low maintenance activities, long lifespan, low operating cost, and easy installation works. They are most successful in locations with the best irradiance, it provides many advantages to the environment as well as population compared to the use of diesel engine driven pumps where diesel pumps need fuel and lubricants which pollute wells, soil and groundwater differ from photovoltaic pumps that are an environmentally sound and resource-conserving technology. Their report also concludes that diesel pumping systems are more economical than diesel pumping systems and solar PV irrigation system was cost-effective.

### 2.3.1. Performance analysis

The analysis was done by Atlam and Kolhe[4] on the operation of straight solar panels powered permanent magnet direct current motor inspirer for the selection of motor pump, in their result show that performance of the system depends on the incident solar radiation, operating cell temperature, direct current motor and propeller road parameters.

Research done by Bhave [19]in India where he studied on the possibility of replacing diesel pumps technic to Photovoltaic pump in the system of pumping water for the low and medium head, where the pumped water be used for drinking and irrigation, his result shows that solar panel water pump system is more preferable as he compared the costs required for every system.

Alawaji et al.[20] discussed components, basic operation, and performance of water pumping and desalination in the remote areas of Saudi Arabia. The study reported that utilization of PV energy for water pumping and desalination is reliable and cost-effective.

### 2.3.2. Optimal sizing of PV pumping system

Wagdy et al.[21] suggested a 'switched-mode' solar-powered pumping system. At 100% or maximum storage battery charging, the system directly joins the pump to the PV array; this pump and PV array coupling aims to maximize the utilization of available sunlight energy to minimize the cost of the size of the solar array, storage battery, and water tank respectively. The authors realized that the optimum solution is one that should minimize the size of solar array size as the array cost is the major item and found that increasing battery storage without increasing array size does not mostly affect the system performance.

Yahia et al.[22] optimized the sizing model to minimize the capacity sizes of different components of a standalone photovoltaic water pumping system using a water tank and analyzed a pumping system, which is constructed to supply drinking water and perform irrigation located in Ghardaia, Algeria. The authors simulated the PV water pumping system by using a designed program and demonstrate the interactions between system configurations and system power. The optimal configurations of the pumping system are determined for different desired system reliability requirements (LPSP) and the life cycle cost (LCC).

Zvonimir and Margeta[23] did a simulation of a PV irrigation water pumping system using a mathematical hybrid simulation optimization model for optimal sizing and the optimization method used is dynamic programming. The constraints are subjected to the simulation model, by referring to the following elements relevant to PV pumping system: boreholes, local climate, soil, crops, and irrigation system. The model was tested on two locations in Croatia. This model takes into account all characteristic values and their relations in the integrated system. Finally, the electrical output power generated by the PV after optimization is completely smaller than that obtained by the usual method.

Hamidat and Benyoucef[24] suggested two mathematical models for PV pumping sizing. These prototypes bond the operating electrical power to the water flow rate of the pump versus the total head. Two pumping subsystems of different technologies and manufacturers are studied. The first pump is the centrifugal pump which consists of a three-phase AC engine and a centrifugal pump. The second is the positive displacement pump which consists of a DC engine and a positive displacement pump. The outcomes indicate that the displacement pump has a healthier performance (higher efficiency, the higher average volume of water pumped, and low energy losses) in comparison to a centrifugal pump.

### 2.3.3. Performance improvement of PV water pumping systems

The performance improvement of the PV water pump is highly increasing. The efficiency of the PV module is affected by solar radiation, the irradiance, the working temperature of the panel, and the cleanliness in addition to some other factors that don't have a significant effect on the efficiency. PV Panel Orientation and Tracking has a great impact to ameliorate the performance of solar water pumping systems. The solar panel works at a maximum point when the sunlight is perpendicular to the panel surface, for reaching, the use of one or two tracking mechanisms.

Mahesh Kumar carried out Modelling and Simulation of Solar Photovoltaic DC water pumping system Using MPPT. The simulation result has shown great improvement on the efficiency of the PV water pump system, using of Perturb and observe algorithm[25].

### 2.3.4. Economic and environmental aspects

Nowadays the PV pump is more economic than the diesel water pumping system Odeh et al.[17] analyze the possibility of the system of pumping water, either using solar water pumping or diesel water pumping using existent data real data and three-year operational experience of eight installations. Estimation of the required form, sizing of the tank, and choice of wells with low pumping head are talked about to reduce unit cost. The research indicates that mismatch between water required and supply form has a major effect on the economic possibility of solar pumping systems and thus required to be examined seriously. Zenab Naseem and Sadia Imran carried out accessing the viability of solar water pumps economically, socially, and environmentally. The result shows in all analysis solar energy is a viable alternative to diesel[26]

# CHAPTER3.

# DESIGN OF PV WATER PUMP SYSTEM

## 3.1. Site Description

Tunda is one of 72 Cells comprising of 15 Sectors (in Kamabuye sector) in the district of Bugesera in the Eastern province that is shown on the Map of Bugesera district.

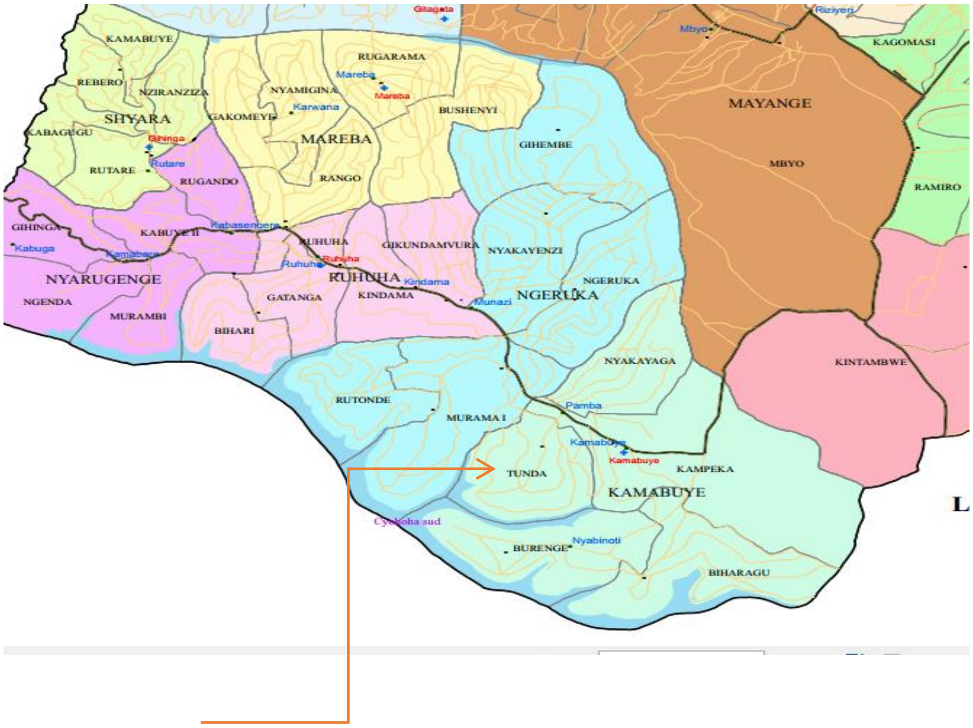


Figure 7 Bugesera Administrative Map[2]

By comparing the climatic of Bugesera region with other ones, its weather is dried accompanied by deferring between 20 and 30 0C. The temperature average range is between 26 and 29 0C.In the past, the district has turned into a desert zone. However with increased government effort, the district had been afforested, this cause natural resources be protected. This has resulted in improved climatic conditions. Currently,Bugesera district has two dry periods and two rainy periods same as Tunda cell as shown in table 1[27].

Table 1 Bugesera’s climatic seasons(Same as Tunda cell)[27].

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

### 3.1.1. Climatic data

Climatic data are collected using email of  Amos UWIZEYE who is an employee in Mateo Rwanda because of the problem COVID-19 and others are collected from Homer software. Where data shown in table 2,table 3,and table 4 are obtained via email  and data shown in table 5 and figure 8 are collected from Homer software.

Table 2 Kamabuye monthly average temperature data

| Month | Max | Average | Minimum |
|---|---|---|---|
| January | 28 | 21 | 15 |
| February | 27 | 21 | 15 |
| March | 26 | 20 | 15 |
| April | 23 | 19 | 15 |
| May | 23 | 18 | 14 |
| June | 25 | 19 | 14 |
| July | 27 | 20 | 15 |
| August | 27 | 21 | 16 |
| September | 27 | 22 | 17 |
| October | 27 | 24 | 22 |
| November | 26 | 23 | 20 |
| December | 27 | 23 | 20 |

Figure 8 Kamabuye average monthly temperature graph  same as Tunda from homer

Table 3 Average sun hour, Sun days and UV Index in 2018

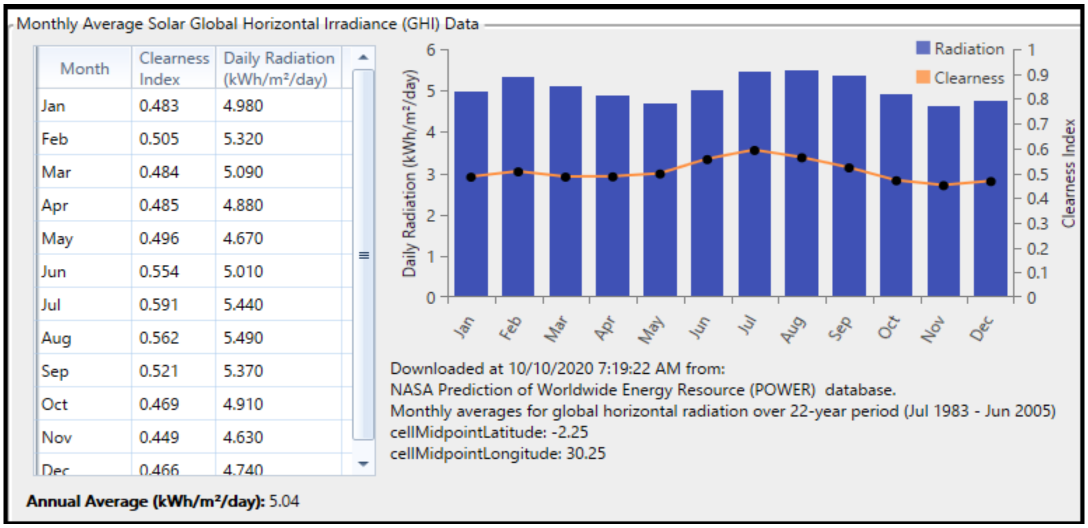
| Month | Sun hour | Sun day | UV Index |
|---|---|---|---|
| January | 322.5 | 15 | 6 |
| February | 275.5 | 3 | 6 |
| March | 274.5 | 0 | 5 |
| April | 241 | 1 | 5 |
| May | 278 | 3 | 5 |
| June | 286 | 20 | 6 |
| July | 307 | 28 | 6 |
| August | 310.5 | 12 | 6 |
| September | 308 | 4 | 6 |
| October | 199 | 3 | 5 |
| November | 174 | 0 | 5 |
| December | 271.5 | 7 | 5 |

Sun day which 0 it is the time of sun is not shining (Autonomy day).

Table 4 Monthly average solar radiation(W/$m^2$) in Mayange sector same as Tunda cell

| Month | 2018 |
|---|---|
| January | 183.23 |
| February | 253.32 |
| March | 212.8 |
| April | 267.91 |
| May | 579.66 |
| June | 375.7 |
| July | 289.1 |
| August | 300.48 |
| September | 299.49 |
| October | 313.58 |
| November | 409.22 |
| December | 446.57 |

Table 5 Average monthly Solar Global Horizontal Irradiance(GHI) in kamabuye sector same as Tunda cell from homer


Monthly Average Solar Global Horizontal Irradiance (GHI) Data

| Month | Clearness Index | Daily Radiation (kWh/m²/day) |
|---|---|---|
| Jan | 0.483 | 4.980 |
| Feb | 0.505 | 5.320 |
| Mar | 0.484 | 5.090 |
| Apr | 0.485 | 4.880 |
| May | 0.496 | 4.670 |
| Jun | 0.554 | 5.010 |
| Jul | 0.591 | 5.440 |
| Aug | 0.562 | 5.490 |
| Sep | 0.521 | 5.370 |
| Oct | 0.469 | 4.910 |
| Nov | 0.449 | 4.630 |
| Dec | 0.466 | 4.740 |

**Annual Average (kWh/m²/day):** 5.04

Downloaded at 10/10/2020 7:19:22 AM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly averages for global horizontal radiation over 22-year period (Jul 1983 - Jun 2005)
cellMidpointLatitude: -2.25
cellMidpointLongitude: 30.25

Solar radiation and average daily sun hour will be used in PV array sizing and daily water demand, flow rate, and total dynamic head are used in the design of pump and motor.

### 3.2. Design of PV water pump system components.

The following are the basic necessary parameters to design a PV water pump system.

- Estimate water demand
- Solar power availability level at the selected site
- Motor pump size
- PV array size

#### 3.2.1. Maximum amount of water needed per day

The quantity of water required should be determined for the region of interest at the beginning of designing photovoltaic powered water pump

Due to variation of the amount of water needed for irrigation in Tunda cell, Sizing of pump has been carried out where it will be used in the period of insufficient of rainfall and drought where sufficient water will be required. So water from the pump will be used for irrigation.

Water estimated for one hectare per day(1ha/day) is equal to 80000l/day used for irrigation. From the site visit.it is found that the total hectare that can be irrigated is approximately equal to 160ha, thus total water required equal to 12,800,000 liters/day and the plants will be grown are shown in Table 6.

Table 6 Types of plants to be irrigated and the water demand

| Types of plant | Water demand/day(l) |
|---|---|
| Small vegetable(Baverages,tomatoes) | 4,300,000 |
| Beans, potatoes | 8,500,000 |

The possibility of storing water should be at least enough for a minimum of 2 days of water absorbency. Thus,

- Then total water required will be equal to 12,800,000l/dayx2day=25,600,000litters
- For 160ha, the volume of water required will be equal to 12,800m3.
- The storage tank has to store a minimum of 25,600m3without a battery.

### 3.3. Design of PV powered PMDC pumping motor.

In PMDC is directly supplied by PV without converting it into ac power, to achieve higher efficiency and lower investment costs

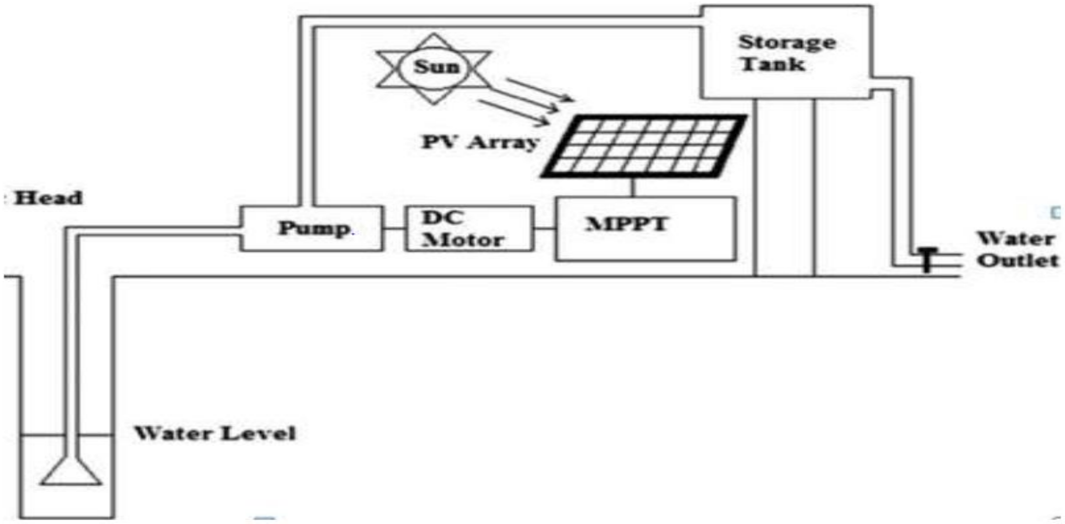


Figure 9 Direct-coupled PV water pump system layout[15]

### 3.3.1. Designing of rate of flow for pump

The rate of flow for the pump is equal to the ratio of the quantity of water required per day and the average daily sun hour

$$\text{Rate of flow(Q)} = \frac{\text{Water required per day}}{\text{Average daily sun hour}} \tag{7}$$

Table 3 shows average daily sun hour and this is equal to 5hour=300 min
Daily water demand equal to 80000 liters
Flow rate(Q)= 12800000litters/5*60 min
Q=42,666.6liters/min
Q=42667l/min

### 3.3.2. Total dynamic head (TDH) for the pump

Total dynamic head(THD) is calculated by adding vertical distance that water is pumped and friction losses. Thus,

THD= vertical distance that water is pumped+ frictional losses. Where

The vertical distance that water is pumped is the sum of elevation, standing water level, and draw down[28]and Friction losses=1/2 % of total vertical distance of water to be pumped[8]

Approximation of data obtained from the site is 80 m of elevation,30 m of standing water level, and 2m of drawdown.

The vertical distance of water to be pumped= (80+30+2) m=112m

Thus, Friction loss=0.5%* 112m=56m.Then,

TDH=112m+56m=168m

### 3.3.3. Design of pump and motor

The motor pump which can be used in PV water pump systems is designed by seeing probable variation in solar panel power which depends on weathers condition at the site. The sizing of the motor pump system is carried out by considering the rate of flow required and total dynamic head:

Where Rate of flow(Q)=42667l/min=11263.9824gallons/min ~11264gallons/min

And Total dynamic head(THD)=168m

Minimum pipe size could be determined for proper working by assuring that velocity is equal to 1.524 m/s in a pipe[7]

Diameter of pipe (D)=$\sqrt{0.082 * Q}$ [8]

D=30.39inch

1 inch=0.0254m

30.39 inch=0.771m

Pump capacity is equal to hydraulic energy(Eh) divided by average sun hour

Where Hydraulic energy is given as follow

$$E_h = \rho * g * V * TDH \qquad (8)$$

Where ρ is density of water=1000kg/m3

V is a volume of water required12800000l/day=12800m3/day

g is gravity of the earth=9.8m/s2

TDH=168m

Eh=1000kg/m3*12800m3*9.8m/s2*168m= (21073920000 kgm2/s2)/day

=21,073,920,000J/day

1W=1J/s, 1J=1W*s

1W*s=1hour/3600

Then, Eh=(21,073,920,000Watt*1hour/3600)/day

=5,853,866.66Watt-hour/day

The pump capacity= (5,853,866.66 Watt-hour/day)/5hour=1,170,773.33W=1,170.773kW

Pump which will be used in irrigation has the following parameters

- Motor with: Power feed=3.1 kW.

- volume of 150liters/min,277g/min.
- Total head of 27m, 90feet, 3600rpm.
- a serial number of 160401862.
- Net weight of 28.7kg.
- Type of SEV-80X-EAI-3.

To irrigate 160 hectares, and the pump capacity to produce the required energy,378 will be used concerning the pump capacity (1,170.773773 kW) and selected motor capacity will be used (3.1 kW).

### 3.3.4. PV Array design

Solar photovoltaic consists of many numbers of photovoltaic modules that are sized based on the amount of energy needed. The sizing of the PV array varies according to location, solar radiation, temperature, and other atmospheric factors. Considering of hydraulic energy(Eh) required for lifting water, daily average radiation (kWh/m2 day) on the photovoltaic array and daily subsystem efficiency makes the system precise and reliable.

$$\text{Solor array power} = \frac{\text{hydrauric energy (Eh)in kWh per day}}{\text{average daily solar isolation}\times\text{F}\times\text{E}} \tag{9}$$

Where F is Array mismatch factor on average of 0.85, E is average daily subsystem efficiency with a typical range of 0.25-0.4.

Then in this PV array design, 0.3 was taken as average daily subsystem efficiency,0.85 was taken as mismatch factor, and table 5 show the average daily solar isolation which is 5.04 kWh/m2

Solar array power =(5,853.86666kWatt-hour/day)/5.04 kWh/m2*0.85*0.3=4554.8kW.

The PV panels is selected and it is shown in Table 7, its power is 290 W and the solar array power required to irrigate 160 hectares is 4554.8kW, Thus, the total PV panels will be used are 15707 which are connected in series and parallel.

Table 7 Parameter of Canadian solar All Black CS6K-290MS290W MONO solar panel selected From Homer

| | |
|---|---|
| STC power rating | 290W |
| PTC power rating | 266.1 W[1] |
| STC power per unit of area | 16.5W/ft(177.2W/$m^2$) |
| Number of cells | 60 |
| Nominal voltage | Not applicable |
| Vmp | 32.1 |
| Imp | 9.05 |
| Voc | 39.3V |
| Isc | 9.67A |
| Peak efficiency | 17.72% |
| Max. system voltage | 1000V |
| NOCT | $45^0$C |
| Power tolerance | 0%/+2% |
| Temperature coefficient of power | -0.39%/K |
| Series fuse rating | 15A |
| Temperature coefficient of voltage | -0.118V/K |
| Temperature coefficient(Isc) | 0.05%/K |

### 3.5. Design of Storage Battery

Battery storage will be required to supply the water pump with power when solar radiation is unavailable, particularly during cloudy days.

Table 8 Parameter of selected battery from Homer.

| | |
|---|---|
| Type | Iron Edison LFP 700 Ah |
| Nominal voltage(V) | 48 |
| Nominal capacity (Ah) | 700 |
| Roundtrip efficiency (%) | 95 |
| Maximum charge current (A) | 200 |
| Maximum discharge current(A) | 200 |

For the designed battery, the motor capacity, the PV panel size, and days of autonomy are used as input data.

### 3.5.1. Battery System Sizing

Battery sizing is determined to meet the load demand during the cloudy day where there is no sun. Battery storage is sized for two days of autonomy.

Total PV water pump 4554.8kW is with a working hour of 5 hours/day. Thus, the battery capacity is determined as follows:

Total load capacity=4554.8kW

Working hour=5 hour per day, for two days (2days)=10 hours which are total hour that battery provides power without being recharged by a photovoltaic array

Total battery energy=4554.8kWx10hours=45548 kWhs

$$Total\ energy\ consumption = Ah = \frac{Wh}{Vdc\ battery\ bank} \qquad (10)$$

Where Vdc battery bank =48 V

Then Ah= 45548000Wh/48V=948,916.66Ah

According to the specification of the battery selected, the total number of battery that will be 1355.

### 3.6. Cost estimation for PV powered water pump

Jeanine Uwibambe[29], show the estimation cost for monocrystalline PV modules range in 190W and 560W is $1000. Thus the selected PV modules' cost with 290W is $1000.

The total cost for a system of PV powered water is presented is in Table 9. below

Table 9 Estimation cost of PV powered water pump

| Types | Quantity | Cost/unit | Total cost |
|---|---|---|---|
| PV modules | 15707 | $1000 | $15707,000 |
| Battery | 1355 | $24,600.0 | $33,333,000 |
| Tank | 1 | $7500 | $7500 |
| Pumps and PVC pipes | 378 | $400 | $151200 |
| Installation | | | $48,070,700 |
| Labors | 150 | | $132,000 |
| Replacement, operation and maintenance cost | | | $7,000,000 |
| Total | | | $104,401,400 |

# CHAPTER 4.

# SIMULATION AND RESULT

The trial HOMER software was used in this study to simulate and analyze both terms of optimization and economic of optimization system.

For designing a PV-powered water pump by using HOMER, the required information is summarized in a subchapter of 4.1below.

## 4.1. Designed of PV powered water pump specification

The inputs data used for designing the PV powered water pump are as follow:

- ✓ Load demand of 1172kW, PV panel, and battery specifications are shown in Table 7and 8 respectively.
- ✓ PV panel with a capital cost of $1000, estimated replacement, operation, and maintenance cost of $500 and $10 respectively.
- ✓ Resources data inputs shown in Table 2 and 5
- ✓ The battery is Iron Edison LFP 700Ah of 48V,95% round trip efficiency,200Aof maximum discharge current, and 200 A of maximum charge current.

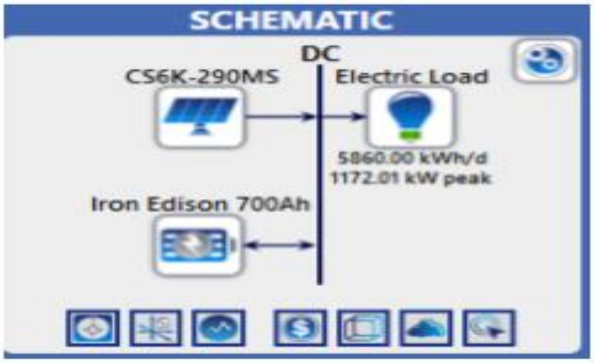
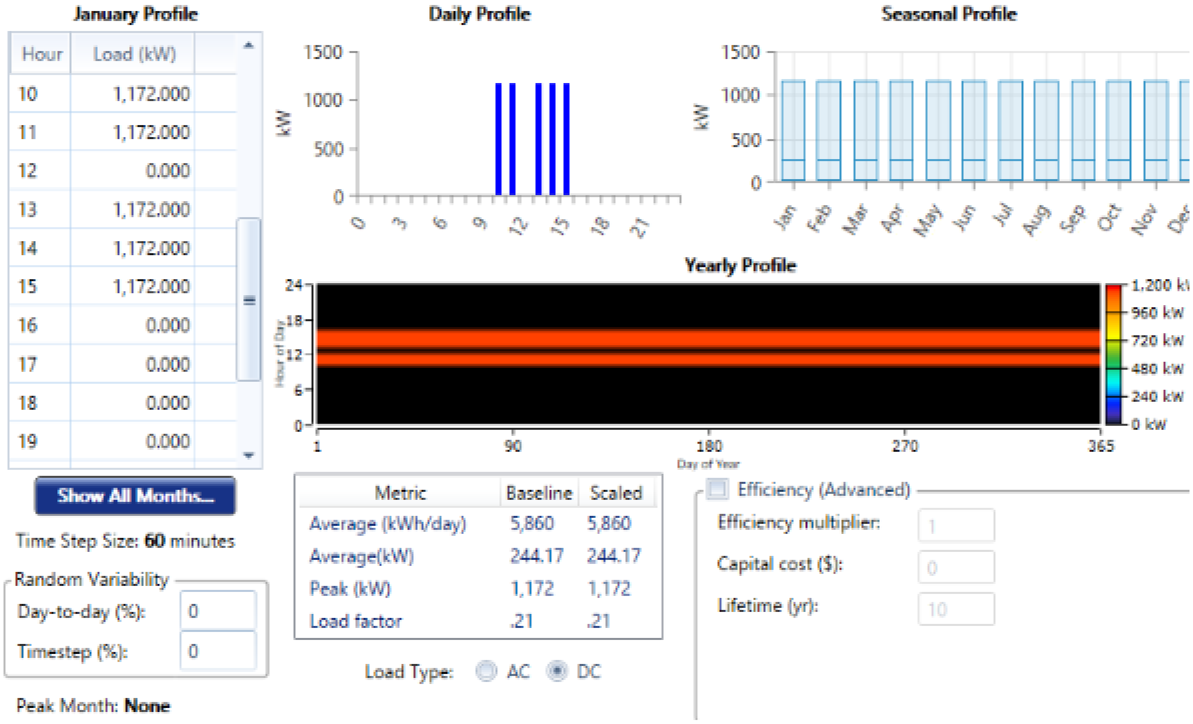


Figure 10 Input for modeling the PV powered water pump system

### 4.1.1. Load Input

Load input is PMDC motor-driven pump with 1172Kw that will operate from 10 to 12 AM and from 1 to 3 PM as shown in Figure 11 below.



| Hour | Load (kW) |
|---|---|
| 10 | 1,172.000 |
| 11 | 1,172.000 |
| 12 | 0.000 |
| 13 | 1,172.000 |
| 14 | 1,172.000 |
| 15 | 1,172.000 |
| 16 | 0.000 |
| 17 | 0.000 |
| 18 | 0.000 |
| 19 | 0.000 |

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 0

Timestep (%): 0

Peak Month: **None**

| Metric | Baseline | Scaled |
|---|---|---|
| Average (kWh/day) | 5,860 | 5,860 |
| Average(kW) | 244.17 | 244.17 |
| Peak (kW) | 1,172 | 1,172 |
| Load factor | .21 | .21 |

Load Type: ○ AC ● DC

☐ Efficiency (Advanced)

Efficiency multiplier: 1

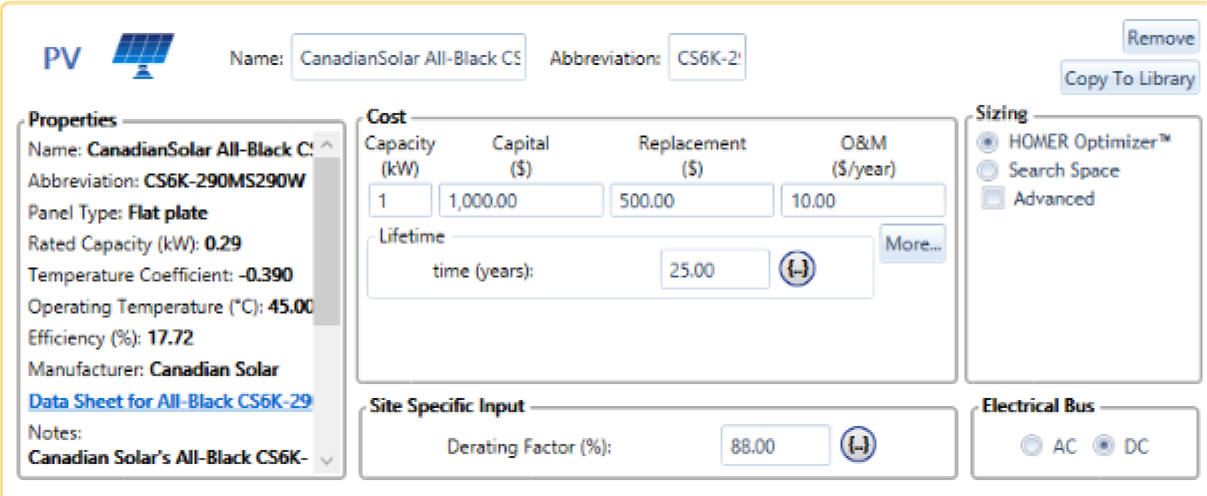
Capital cost ($): 0

Lifetime (yr): 10

Figure 11 Input for load of typical PV powered water pump

### 4.1.2. Photovoltaic panel input

Canadian solar ALL Black CS6K-290MS 290 W solar panel is selected and connected specification and it cost are mentioned in Table 7 and subchapter 4.1 respectively, and its total capacity of 4554.8 kW to supply PMDC motor-driven pump in irrigation. All those specifications will be optimized by HOMER. So, those specifications are displayed in figure 12 below.



Name: CanadianSolar All-Black C

Abbreviation: CS6K-2

**Properties**

Name: **CanadianSolar All-Black C**

Abbreviation: **CS6K-290MS290W**

Panel Type: **Flat plate**

Rated Capacity (kW): **0.29**

Temperature Coefficient: **-0.390**

Operating Temperature (°C): **45.00**

Efficiency (%): **17.72**

Manufacturer: **Canadian Solar**

Data Sheet for All-Black CS6K-29

Notes:

**Canadian Solar's All-Black CS6K-**

**Cost**

| Capacity (kW) | Capital ($) | Replacement ($) | O&M ($/year) |
|---|---|---|---|
| 1 | 1,000.00 | 500.00 | 10.00 |

Lifetime

time (years): 25.00

**Sizing**

● HOMER Optimizer™

○ Search Space

☐ Advanced

**Site Specific Input**

Derating Factor (%): 88.00

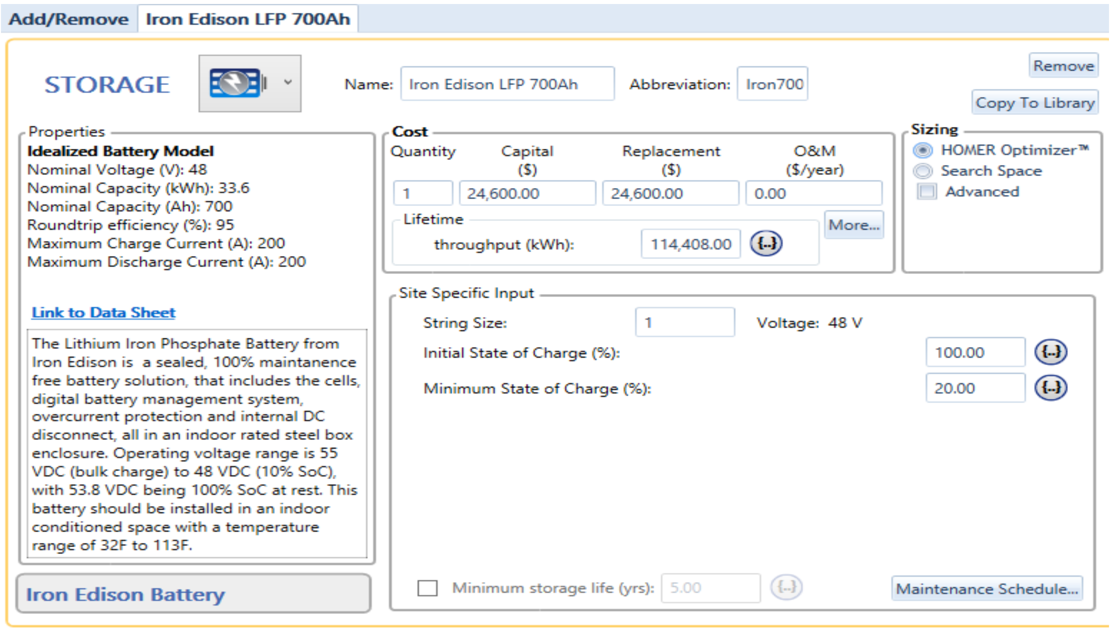
**Electrical Bus**

○ AC ● DC

Figure 12 Homer input window for PV system

### 4.1.3. Input of battery.

In this study, the type of battery of Iron Edison LFP 700Ah was selected with help system to be feasible, the specification of this type battery has a nominal voltage of 48V, the nominal current capacity of 700 Ah, roundtrip efficiency of 95, maximum charge current of 200 A, and maximum discharge current of 200A. Addition is its capital cost is $24,600.00, replacement cost of $24,600.00 with $0 for operation and maintenance (O&M).



Name: Iron Edison LFP 700Ah

Abbreviation: Iron700

Properties

**Idealized Battery Model**
Nominal Voltage (V): 48
Nominal Capacity (kWh): 33.6
Nominal Capacity (Ah): 700
Roundtrip efficiency (%): 95
Maximum Charge Current (A): 200
Maximum Discharge Current (A): 200

The Lithium Iron Phosphate Battery from Iron Edison is a sealed, 100% maintanence free battery solution, that includes the cells, digital battery management system, overcurrent protection and internal DC disconnect, all in an indoor rated steel box enclosure. Operating voltage range is 55 VDC (bulk charge) to 48 VDC (10% SoC), with 53.8 VDC being 100% SoC at rest. This battery should be installed in an indoor conditioned space with a temperature range of 32F to 113F.

**Cost**

| Quantity | Capital ($) | Replacement ($) | O&M ($/year) |
|---|---|---|---|
| 1 | 24,600.00 | 24,600.00 | 0.00 |

Lifetime
throughput (kWh): 114,408.00

**Sizing**
● HOMER Optimizer™
○ Search Space
☐ Advanced

Site Specific Input
String Size: 1
Voltage: 48 V
Initial State of Charge (%): 100.00
Minimum State of Charge (%): 20.00
☐ Minimum storage life (yrs): 5.00

Figure 13  Battery input window

## 4.2.RESULT

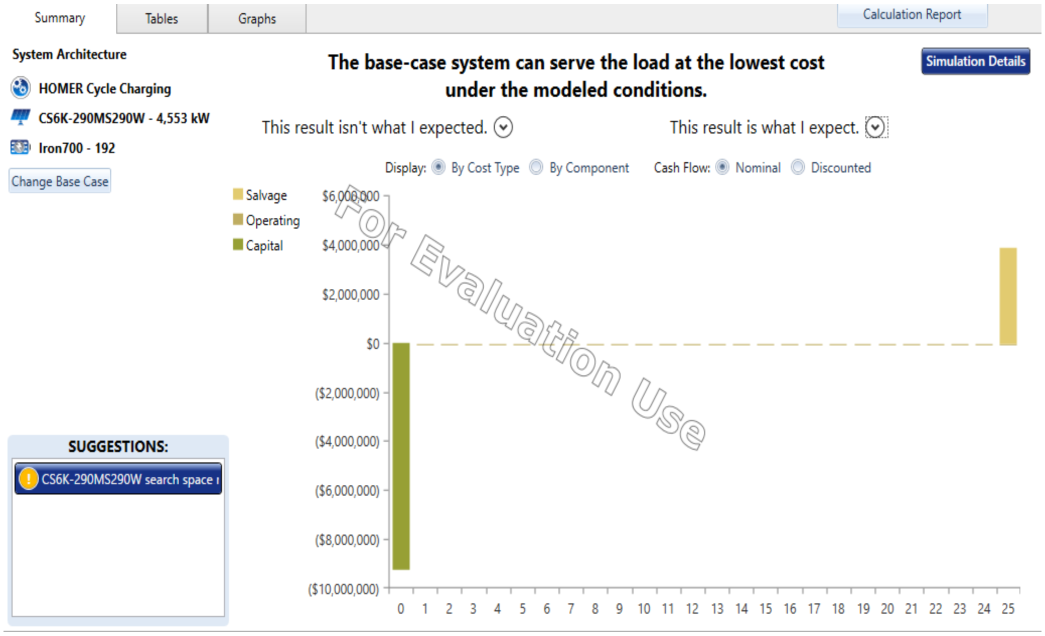
Results are categorized into two part which are:

1, Result for PV panel system

2, Result for diesel fuel generator

### 4.2.1. Result for PV panel

The bar chart in Figure 3, shows the optimum cost of the system in terms of salvage, operating, and capital cost.



**System Architecture**

**HOMER Cycle Charging**

**CS6K-290MS290W - 4,553 kW**

**Iron700 - 192**

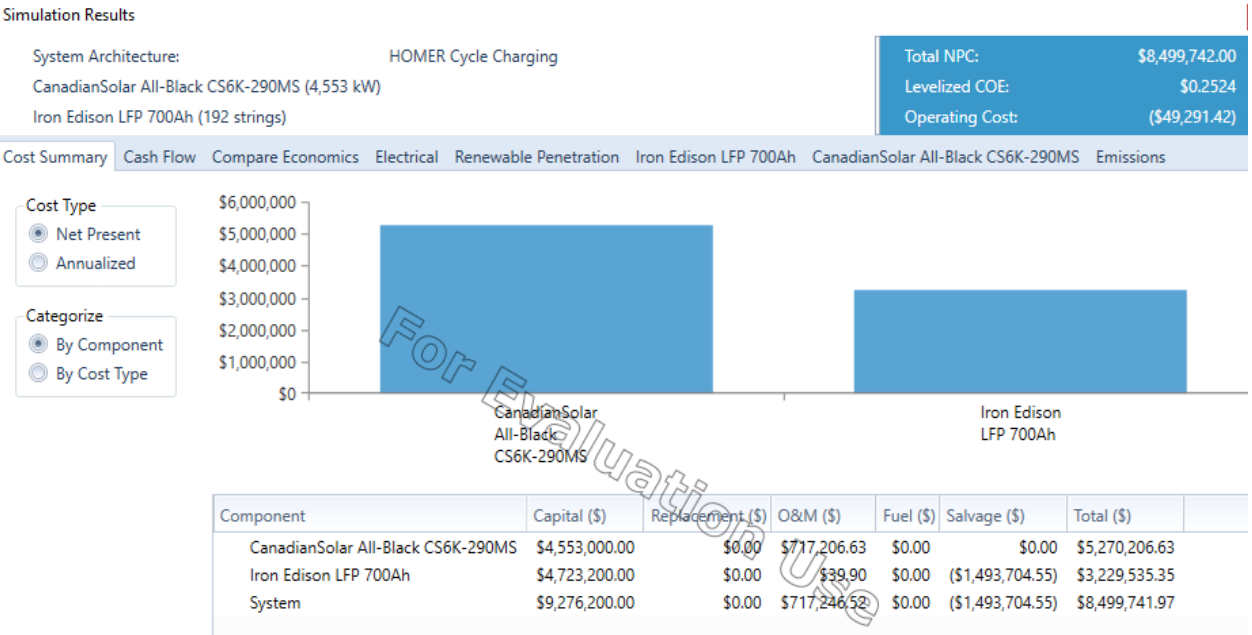
**The base-case system can serve the load at the lowest cost under the modeled conditions.**

This result isn't what I expected.

This result is what I expect.

Display: ● By Cost Type ○ By Component   Cash Flow: ● Nominal ○ Discounted

Figure 14 : Simulation results based on cash flow summary in form of Bar chart



Simulation Results

System Architecture: HOMER Cycle Charging

CanadianSolar All-Black CS6K-290MS (4,553 kW)

Iron Edison LFP 700Ah (192 strings)

| | |
|---|---|
| Total NPC: | $8,499,742.00 |
| Levelized COE: | $0.2524 |
| Operating Cost: | ($49,291.42) |

Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

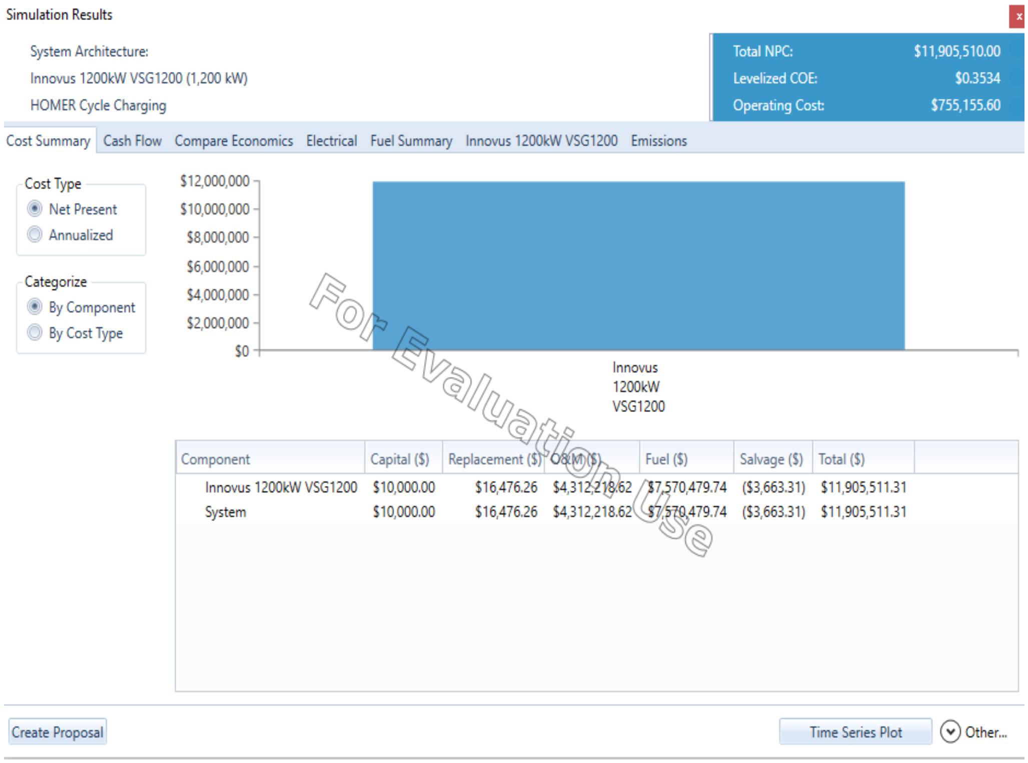
| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| CanadianSolar All-Black CS6K-290MS | $4,553,000.00 | $0.00 | $717,206.63 | $0.00 | $0.00 | $5,270,206.63 |
| Iron Edison LFP 700Ah | $4,723,200.00 | $0.00 | $39.90 | $0.00 | ($1,493,704.55) | $3,229,535.35 |
| System | $9,276,200.00 | $0.00 | $717,246.52 | $0.00 | ($1,493,704.55) | $8,499,741.97 |

Figure 15 Simulation result for PV system  in terms of NPC, Levelized COE, and operating cost with a classification of components.

From optimization shown in figure 15, indicates that the total power of the selected PV system is 4553kW and the total number of battery strings is 192. Homer software determines total Net Present Cost and Levelized Cost of Electricity and Operating cost which is $8,499,742.00,0.2524 per kWh and $49,281.42 per year respectively.

### 4.2.2. Result for Diesel fuel generator

The simulation was done by considering the load which is the same as for the PV panel. The result was shown in figure 16 below.



System Architecture:
Innovus 1200kW VSG1200 (1,200 kW)
HOMER Cycle Charging

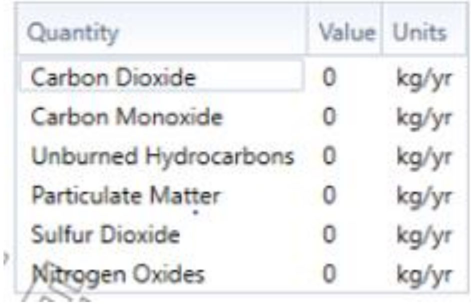
Total NPC: $11,905,510.00
Levelized COE: $0.3534
Operating Cost: $755,155.60

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Innovus 1200kW VSG1200 | $10,000.00 | $16,476.26 | $4,312,218.62 | $7,570,479.74 | ($3,663.31) | $11,905,511.31 |
| System | $10,000.00 | $16,476.26 | $4,312,218.62 | $7,570,479.74 | ($3,663.31) | $11,905,511.31 |

Figure 16 Simulation  result for the diesel fuel system in terms of total NPC,Levelized COE, and operating cost.

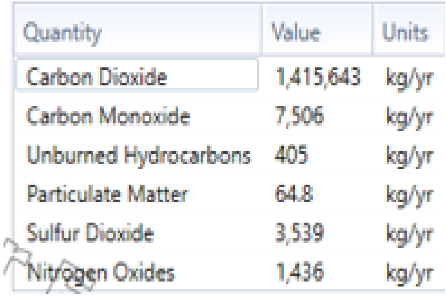
Optimization Homer indicates that the total power of a diesel generator with the same load as for PV panel is 1200kW. The total Net Present Cost(NPC), $11,905,510.00, Levelized COE and operation costs are $11,905,510, $0.3534 per kWh and $755,155.60 respectively.

From the window displayed as shown in Figure 16, there is a cost summary, compare economic electrical, fuel summary selected diesel generator and emission. By clicking on emission, display quantity, value, and unit of emission as shown in Figure 17 below.



| Quantity | Value | Units |
|---|---|---|
| Carbon Dioxide | 0 | kg/yr |
| Carbon Monoxide | 0 | kg/yr |
| Unburned Hydrocarbons | 0 | kg/yr |
| Particulate Matter | 0 | kg/yr |
| Sulfur Dioxide | 0 | kg/yr |
| Nitrogen Oxides | 0 | kg/yr |

A)PV panel



| Quantity | Value | Units |
|---|---|---|
| Carbon Dioxide | 1,415,643 | kg/yr |
| Carbon Monoxide | 7,506 | kg/yr |
| Unburned Hydrocarbons | 405 | kg/yr |
| Particulate Matter | 64.8 | kg/yr |
| Sulfur Dioxide | 3,539 | kg/yr |
| Nitrogen Oxides | 1,436 | kg/yr |

B)Diesel generator

Figure 17 Emission rate A,B

# CHAPTER 5.

# CONCLUSION AND RECOMMENDATION

## 5.1. Conclusion:

According to the title state, a feasibility study and design efficiency and cost-effectiveness in Tunda cell were carried out.

- The design of PV-powered water pump was designed based on data of solar radiation, average monthly temperature, and other weather conditions. It is designed to satisfy the total power demand of hydraulic pumps to use in irrigation using solar PV modules. This system uses a temporary electricity storage battery for the time of sun is not shining.
- The system has preferably used a PMDC motor-driven pump. The number of PV modules, batteries, and pumps needed for the system is sized accordingly to the input power demand.
- The feasibility analysis was conducted comparing the solar PV module system with the diesel fuel power generator. The comparison made by using costs of the system such us total initial investment, maintenance, and operation, and fuel cost, and environmental pollution concern

Thus, an analysis conducted comparing solar PV module system and diesel fuel power generator to pump water used in irrigation, show that solar PV module is more feasible than diesel fuel due to the higher cost of diesel fuel compared to the PV modules. Also due to emissions of CO2, SO2, and other emissions gases, produced by generators show that using fuel is not environmentally friendly.

## 5.2. Recommendation:

The government of Rwanda should help its population use renewable energy-based energy technology instead of using diesel-based technology, as this benefits the environment and the economy.

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