Addis Ababa University

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School of Graduate Studies

School of Mechanical and Industrial Engineering

Design, Simulation and Analysis of Photovoltaic Water Pumping System for Irrigation of a Potato Farm at Gerenbo

By:-

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A thesis submitted to the School of Graduate Studies of Addis Ababa institute of Technology in partial fulfillment of the Masters of Science in Mechanical Engineering (Thermal Engineering Stream)

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Addis Ababa University

Addis Ababa, Ethiopia

Oct, 2016

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Declaration

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This is to certify that the thesis prepared by Abdulbasit Nasir, entitled: Design, Simulation and Analysis of Photovoltaic Water Pumping System For Irrigation of a Potato Farm At Gerenbo and submitted in partial fulfillment of the requirements for the degree of Master of Science (Thermal Engineering) complies with the regulation of the university and meet the accepted standards with respect to originality and quality.

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Acknowledgements

I would like to express my deepest gratitude to my advisor Dr. Ing. Edessa Dribsa for his continuous support, encouragement, invaluable comments and excellent supervision that helped me from the selection of this research topic to the time-consuming proofreading of the thesis, Dr. Ing. Edessa put in a great deal of effort to shape my work. His excellent research attitude and broad knowledge about the field of study always inspired and encouraged me. Without him, it would not have been achievable.

I would also like to thank my friends, and specially Mr. Mohammed Abrasha, for his support in giving me important research papers, journals, valuable software and in sharing of his ideas. I also want to appreciate all of my instructors/colleague in the school of Mechanical and Industrial Engineering, Addis Ababa Institute of Technology for their continuous encouragement.

Finally, I deeply and sincerely thank my family for the unending confidence, constant support and endless love.

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List of Abbreviations and symbols

AC Alternate current

AWG American Wire Guage

CF Cash flow

CRF Capital recovery factor

CWR Crop Water Requirement

DC Direct current

DWPs Diesel water pumping system

EF Emission factor

FAO Food and Agriculture Organization

GPM Gallon per Minute

ICC Initial capital cost

IWR Irrigation water requirements

LCC Life cycle cost

LPM Liter per Minute

LR Leaching requirements

MoA Ministry of Agriculture

MPP Maximum power point

NMA National Metrology Agency

NOCT Nominal operating cell temperature

NPV Net present value

NPSH Net Positive Suction Head

PBP Payback period

PC Pump Controller

PV Photovoltaic

PVC Polyvinyl Chloride

PVWPs Photovoltaic water pumping system

PW Present worth

SCB Solar-powered Centrifugal Pressure-booster

STC Standard testing condition

TDH Total dynamic head

TAC Total annualized cost ($)

Cc Capital cost

CF Annual fuel costs ($)

CO&M Annual operation and maintenance cost ($)

CO_2 carbon di oxide

CR Replacement costs ($)

η_e scheme efficiency

Ec Energy cost

ET0 Reference evapotranspiration (mm/day)

ETC Evapotranspiration in cultural conditions (mm/day)

GS Global solar radiation (W/m2)

H_f Friction Head

H_s Static Head

i Discount rate (%)

I_{SC} Short Circuit Current

KC Cultural coefficient

KWh Kilowatt hour

Mc Maintenance cost

N Years of the investment (year)

P Mean daily percentage of annual day time

Peff Effective precipitation (mm)

P_{max} favorable working Pressure

Pp	Photovoltaic array power peak (kWp)
PR	Performance ratio
Q	Pumping rate
Rc	Replacement cost
Sc	Salvage cost
t	Time (hour)
T	Transmissivity (m2/day)
T0	Reference temperature (25°C)
Ta	Ambient temperature (°C)
Tcell	Cell temperature (°C)
V	Volume (m^3)
V_{oc}	Open Circuit Voltage
αc	Photovoltaic modules temperature coefficient(%/°C)
ηmp	Efficiency of the motor-pump system (%)
ηirr	Efficiency of irrigation system (%)
$	United States Dollar
β	Tilt angle
α	Altitude angle
σ_{ys}	Yield Strength

Abstract

In locations where electricity is unavailable, other means are necessary to pump water for crop irrigation. Using diesel pump to deliver water to the place of use causes problems both in terms of productivity 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 considerable amount of CO_2 which cause global warming. A possible solution to these problems is use solar energy, which is environmentally friend and available for free. This paper presents design, simulation and analysis of photovoltaic water pumping system for irrigation of a potato farm located at a place named Gerenbo in Gurage zone. The system was designed, considering the site's topography and local metrological data. The PV system designing was made in such a way that, capable of irrigating a ha area potato farm with daily water requirement of $7m^3$ and total dynamic head of 21m.

To run simulations, different tools have been used. These includes CROPWAT to determine water requirements of the crop; MATlab to simulate I-V and P-V characteristics of the selected module, HOMER make economic and environmental analysis by comparing diesel water pumping system. Furthermore, after sizing all components and sub-systems, the entire system (from solar radiation to water production) was simulated using PVsyst software. Results showed that the amount of water pumped is greater than user's water need.

The economic aspects of PV water pumping systems have been investigated. Indicators of the initial investment cost (IIC) and life cycle cost (LCC) were used to compare with diesel powered water pumping system. All of the cost comparisons show that PV water pumping system is more cost effective than diesel water pumping system. The environmental advantages of using PV water pumping systems are analyzed in terms of CO_2 emissions reduction. Replacement of diesel powered water pumping system results in annual reduction of CO_2 emissions by 1500kg.

Keywords: Photovoltaic, water pumping system, system simulation, diesel engine, storages medium, irrigation, economic analysis, reduction in CO_2 emissions

CHAPTER ONE

1. Introduction

When considering development of the country, energy is one of the key points. Solar water pumps are most often applied when utility power is not readily available. In Ethiopia, about 73.44 % of population lives without access of electricity [World Bank 2015]. The site selected for this work is also rural area without access of electricity found in Southern Nations, Nationalities and Peoples' Region, the specific area is Gerenbo kebele.

Gerenbo has a high potential of growing potato, but lack of water at proper time affect the productivity of farmers. Diesel pumps have many drawbacks such as high running and maintenance costs, unreliable supply of fuel, and poor availability of spare parts. The use of diesel not only looked in term of cost but also in term of environmental perspective whereby the CO_2 emissions released have negative impact on environment and life of people. Therefore, it is important to look for and try other sources of renewable energy.

Solar photovoltaic water pumping has been recognized as suitable for grid-isolated rural locations in developing countries where there are high levels of solar radiation. The recognizable challenge [19], however, is the high initial cost of solar water pumping systems; while it demands virtually no maintenance, and requires no fuel.

PV power is more reliable energy source for almost all parts of Ethiopia. This is due to the fact that Ethiopia has an abundant supply of solar energy throughout the year (figure 1-1), especially, in irrigation periods i.e. from October to May [1].

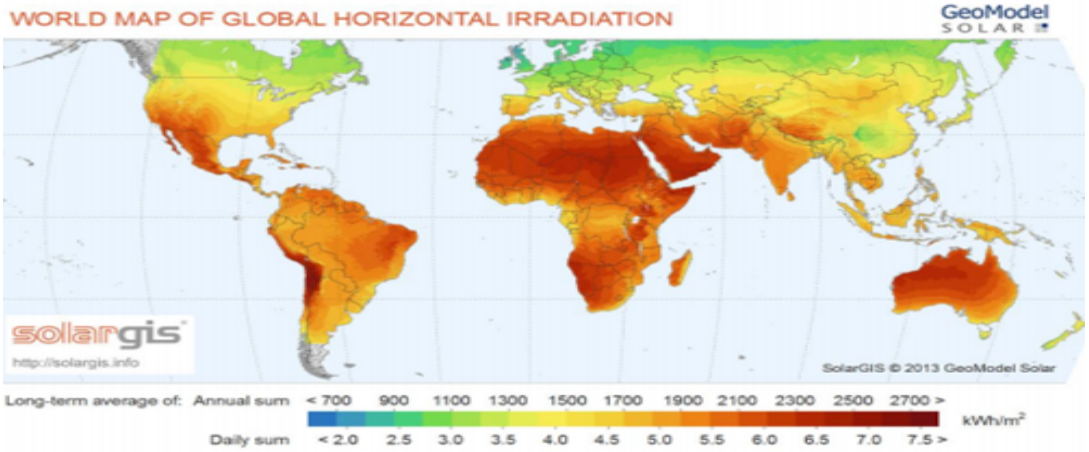


Figure 1-1: World map of Global Horizontal Irradiation

Gerenbo is in Enemor Woreda found in Gurage Zone. The site is located 30 km from Welkite and 150 km from Addis Ababa in south west direction (Figure 1-2). Gerenbo is geographically situated at 8°17′N 37°47′E with an elevation of 1930 meters above mean sea level.

Winque is a tributary of the Gibe River located in south west Ethiopia Gurage zone. It flows year round with sufficient capacity. Haram, Gotam, and Wabe are Feeder Rivers with major size. Other minor tributaries also contribute considerable size of water. The river flows west through Gerenbo, then it meets with Gibe River.

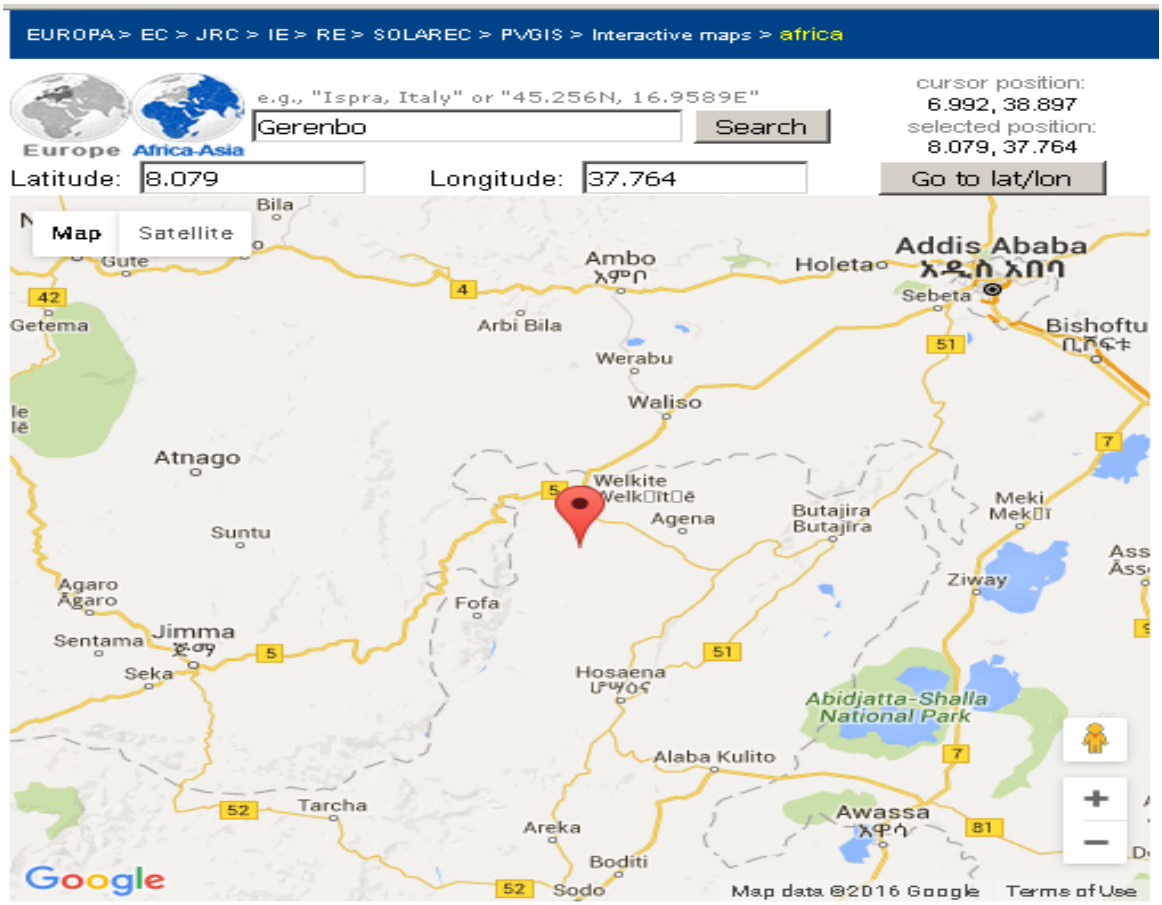


Figure 1-2: Site location

1.1. Statement of the Problem

In Ethiopia, most irrigation farms use diesel driven generators. Diesel pumps have many drawbacks such as high running and maintenance cost, unreliable supply of fuel, and poor availability of spare parts. The selected site for this research is directly facing with these

problems. Finding the best solution for this problem is very important to increase profitability of the farmers. Using renewable energy is a feasible option to fulfill the energy need without affecting the environment. The objective of this thesis is to design an efficient and cost effective photovoltaic water pumping system for irrigation of a potato farm, considering the specific area of Gerenbo to solve draw backs of diesel water pump and increase profitability of the farmers.

1.2. Purpose

The purpose of this thesis is to present the benefits of replacing diesel water pumping system by photovoltaic water pumping system in irrigation of a potato farm. The benefits are demonstrated both in terms of economic and environmental perspectives to show how much earning and how much reduction in CO_2 emissions is achievable when PVWP technologies are used to replace DWP technology.

1.3. Objective of the Thesis

1.3.1. General Objective

The overall objective of this thesis is; to design an efficient and cost effective photovoltaic water pumping system for irrigation of a potato farm at Gerenbo. Then compare the result with diesel powered water pumping system by making an economic and environmental analysis to show system feasibility.

1.3.2. Specific Objectives

Corresponding to the raised research questions, the specific objectives include:

- Collect primary data from site visit and interviews
- refer secondary data from published literatures and websites;
- determine crop water requirements and other design data;
- design photovoltaic water pumping system based on those design data;
- system simulation by using computer soft-wares;
- Analyze output data and interpret the results;
- make economic and environmental evaluations:

1.4. Delimitations

In this thesis, I will intended to design an efficient and cost effective photovoltaic water pumping system with the objective of irrigating one hector potato farm using Winque River, based on Gerenbo geographic and regional design data and present the benefits of replacing DWPs by PV water pumping system.

The geographical limitation to Gerenbo is done for practical reasons in order to visit the field and to meet the respective teams for interviews and discussions, besides Potato is very popular crop in this area. Metrological data of the area is also suitable for photovoltaic water pumping system.

1.5. Methodology

This section presents the methodology used to achieve objective of the thesis

1.5.1. Data Collection

The following data of the site were collected from Ethiopian Meteorology Agency for six years, (from 2010-2015), and used as input for the calculation of crop evapotranspiration (ETo).

- ✓ Maximum-minimum temperature
- ✓ Relative humidity
- ✓ Wind speed
- ✓ Sunshine hours.
- ✓ Rain fall

Other primary data like: - local topography of the site, soil type, amount of crop production, and fuel consumption are collected from site visit. Previous related works and websites are used to revise background information about the study.

1.5.2. Determination of Design Data

1.5.2.1. Crop Water Requirements

The crop water requirements (CWR) of potato were calculated using Theoretical method (Blaney Criddle) and Computer Software (Cropwat). Published documents from Ministry of Agriculture also used. Relevant crop coefficients (Kc) were used to calculate CWR from ETo. These coefficients present the relationship between references (ETo) and crop evapotranspiration (ET crop) or ET crop = Kc×ETo. Value of Kc varies with crops stage of growth, growing season and

the prevailing weather conditions. The Kc values were taken from FAO (1998). ET crop or CWR can be determined in mm per day as mean over 10-day periods. The effective rainfall was calculated with Cropwat by using USDA Soil Conservation Method.

1.5.2.2. Assessment of Solar Energy

Cropwat, RETscreen and theoretical methods are used to estimate the available solar energy hitting on the PV array. The optimization of the orientation angles, especially the tilt angle, has been carried out to optimize the solar energy gathered during the irrigation season.

1.5.3. System Design and Simulation

The design of a PVWP system is conducted under the worst operation condition. Typically, for standalone PV irrigation systems the worst condition is represented by the month marked out by the largest ratio between water requirement and daily available solar radiation. Water storage and System layout is modeled with the help of Catia. Matlab and PVsyst are used to show I-V and P-V characteristic curves of solar array. At last the overall system was simulated using PVsyst software.

1.5.4. Economic and Environmental Assessments

The economic aspects of the system have been investigated using initial capital cost (ICC) and life cycle cost (LCC) were used to compare with diesel powered water pumping system, and net present value (NPV) and payback period (PBP) were used to evaluate the capacity of producing benefits. The environmental advantages of using PVWP systems are analyzed in terms of CO_2 emissions reduction. PVsyst and HOMER are the main tools for conducting the economic analysis, and Homer specifically analyze environmental advantages of PVWPs. The methodology adopted in this thesis is summarized in figure 1-3.

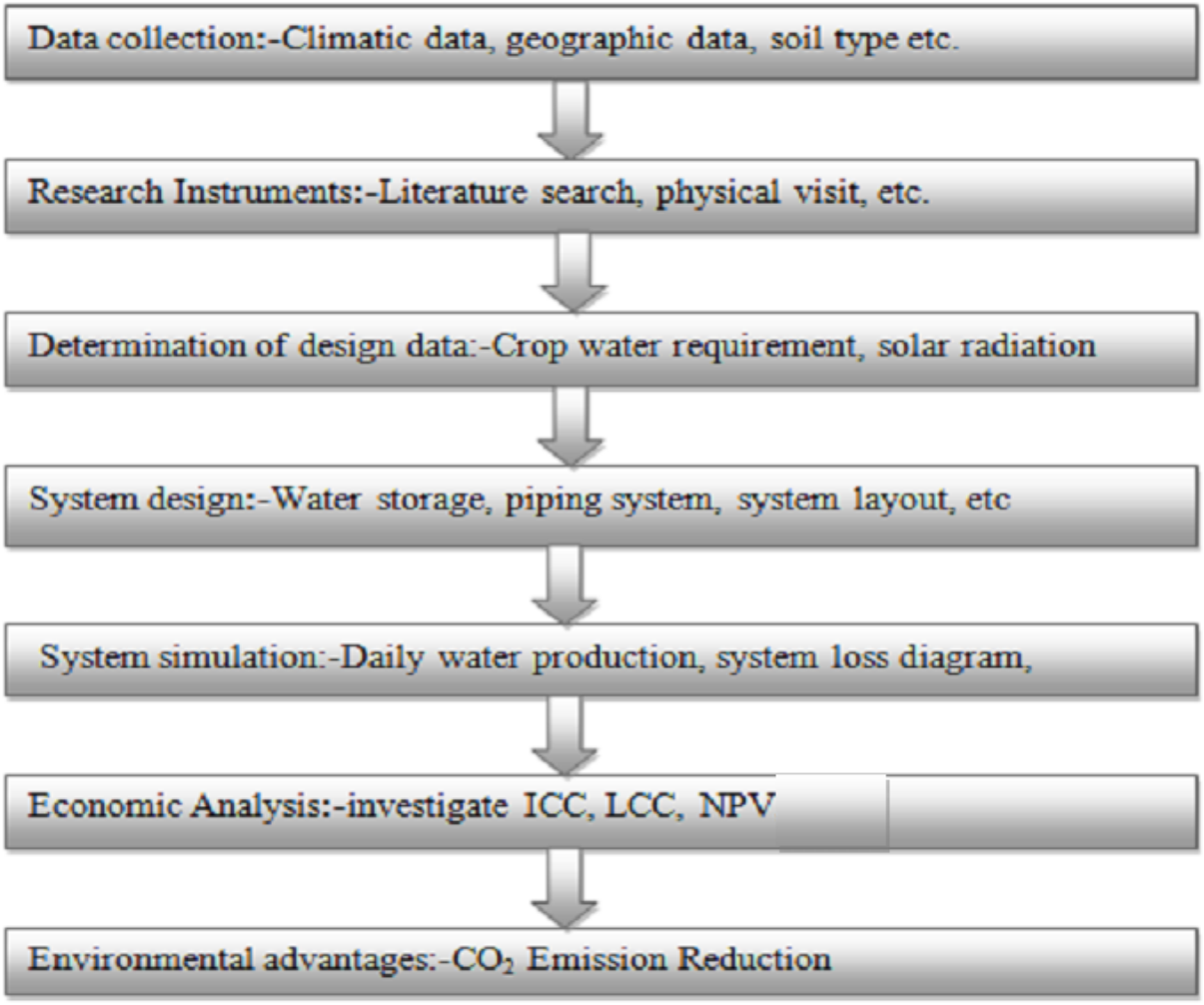


Figure 1-3: summary of methodology

1.6. Outline of the Report

This thesis provides background information about crop irrigation experienced in Ethiopia and design and analysis of PV water pumping system. The thesis consists of the six chapters: Chapter one introduce the thesis background, knowledge gaps and challenges, Purposes, objectives, delimitations, applied methodologies, and thesis outline. Chapter two review photovoltaic water pumping system design and presents the results achieved from related research in the field of photovoltaic irrigation. Advantage of adopting the technology is also presented. Chapter three the detailed description, design and sizing of all components of PVWPs and irrigation system to fulfill water needs are provided. Chapter four system simulation Pvsyst is used to simulate the designed system to check whether it pump the required water or not. The simulation result is discussed in chapter four. Chapter five describes assumptions made to carry out economic analysis of PVWPs technologies and DWPs The considerations for assessing CO_2 emissions are also illustrated in this chapter. Chapter six conclusions of the thesis have been taken by summing up all the findings and summarize them in Chapter six. Recommendation for Future work presents the discussions arisen from the studies conducted and future directions of this research. Also the thesis will include a references and appendixes at the end of the report.

CHAPTER TWO

2. Literature Review

2.1. Introduction

Water pumping is one of the simplest and most appropriate uses for photovoltaic. From crop irrigation to stock watering to domestic uses, photovoltaic-powered pumping systems meet a broad range of water needs. Most of these systems have the added advantage of storing water for use when the sun is not shining, eliminating the need for batteries, enhancing simplicity and reducing overall system costs. Many people considering installing a solar water pumping system are put off by the expense. Viewing the expense over a period of 10 years, however, gives a better idea of the actual cost. By comparing installation costs (including labor), fuel costs, and maintenance costs over 10 years, you may find that solar is an economical choice. A solar-powered pumping system generally costs more initially than diesel powered generator but again requires far less maintenance and labor [4].

2.2. Advantages of Photovoltaic Technology

Electricity produced by solar cells is clean and silent. Because they do not use fuel other than sunshine. PV systems do not release any harmful air or water pollution in to the environment, deplete natural resources, or endanger animal or human health.

Solar energy is a locally available renewable resource. It does not need to be imported from other regions of the country or across the world. This reduces environmental impacts associated with transportation and also reduces our dependence on imported oil. And, unlike fuels that are mined and harvested, when we use solar energy to produce electricity we do not deplete or alter the resource. Table 2-1 summaries advantages and disadvantages of photovoltaic and diesel water pumping system.

Table 2-1: Comparison of PV water pumping system and diesel water pumping system

System Type	Advantages	Disadvantages
PV Powered System	✓ Low maintenance ✓ Unattended operation ✓ Reliable long life ✓ No fuel and no fumes ✓ Easy to install, relocate, move or expand ✓ Low recurrent costs ✓ System is modular and closely matched to need ✓ No noise ✓ Produce best during sunny weather, when water is needed more	✓ Relatively high initial cost ✓ Low output in cloudy weather
Diesel Powered System	✓ Moderate capital costs ✓ Easy to install ✓ Can be portable ✓ Extensive experience available	✓ Needs maintenance and replacement ✓ Site visits necessary ✓ Noise, fume, dirt problems ✓ Fuel often expensive and supply intermittent

2.3. Photovoltaic Technology in Ethiopia

Photovoltaic technology has a short history in Ethiopia, but currently the government gives great attention for this technology. Solar photovoltaic are being promoted to replace fuel base lighting and off-grid electrical needs. Ethiopia is thought to have about 5 MW of off-grid solar. All most all current solar power is used for telecommunications. Other uses include village well pumps, health care and school lighting. A current government initiative plant to bring solar power to 150,000 households by 2015, the phase included 1 MW of panels [14]. The first large installation of solar was a village grid of 10 kW in 1985 expanded to 30 kW in 1989. A solar panel assembly

plant opened in Addis Ababa in early 2013 capable of making 20 MW of panel per year [15]. These show that government gives great attention for photovoltaic technology.

2.4. Photovoltaic Water Pumping System Design

A good photovoltaic pumping system is the one properly designed and sized to fit the job requirements [25]. Solar PV pumping requires more strictness as system components are really expensive and efforts need to be done to bring system set up cost to a minimum.

During the design phase, system designers need to decide on whether the system is to be on-grid or off-grid, with storage or without it and whether storage is in batteries or in water tanks. They need to decide on the type of pump being used and whether the application requires a submersible or a surface pump, using AC or DC power. These all are factors that affect the system performance and feasibility of the proposed solution.

2.4.1. Irrigation Scheduling

Irrigation scheduling is the procedure used to determine the time and depth of water application for each irrigation event. The time of water application is normally based on fixed depletion of stored soil water. Potato irrigation scheduling for maximum profit requires that the timing and amount of water application be determined and applied to minimize soil water fluctuations throughout the growing season.

Successful irrigation management requires regular quantitative monitoring of soil water and knowledge of field crop water use, soil water holding capacity, and crop-rooting depth. Excess irrigation usually results from applying too much water at a given irrigation rather than from irrigating too frequently. This is particularly true for furrow irrigation, where application depth is difficult to control. These situations lead to plant water stress when soil water falls below acceptable limits two to three days before irrigation, and subsequent irrigation applications are in excess of soil water storage capacity. Maximum irrigation interval for potato farm is calculated as follow [Stark 1996].

$$Max.irrigation\ interval = \frac{H_W \times D_r \times D_A}{ET_c} + 1\ day \quad \text{..... 2.1}$$

H_w=soil water holding capacity in $\frac{mm}{m}$

D_r=root zone depth (m)

D_A=allowable depletion,

ET_C=peak daily evapotranspiration (mm/day)

2.4.2. Pump Selection

There are two main types of pump commonly used for PV water pumping application: positive displacement and centrifugal [19]. Positive displacement types are used in low-volume pumps and cost-effective. Centrifugal pumps have relatively high efficiency and are capable of pumping a high volume of water and also there are two major types of pump based on their position in the system layout, (surface and submersible), the selection process depends on the type of water source, the flow requirements, and the site conditions [13]. Surface pumps are less costly than submersible pumps, and offered at larger variety. Pumps can push very long distances. The total dynamic head and flow rates are the primary factors that determine power requirements. In principle, submersible pumps are used in wells deeper than 7 meters and surface are used for shallow wells. The water source for the planed work is river, and suction depth is less than 2 meters, a centrifugal surface pump will be used.

Water pumps are driven by various types of motors. AC induction motors are cheaper and widely available worldwide. The system, however, needs an inverter to convert DC output power from PV to AC power, which is usually expensive, and it is also less efficient than DC motor-pump systems [19]. In general, DC motors are preferred because they are highly efficient and can be directly coupled with a PV module or array. Brushed types are less expensive and more common although brushes need to be replaced periodically (typically every two years) [19]. There is also an aforementioned brushless type.

SCB series pressure pumps are multi-stage centrifugal designed primarily for boosting pressure from surface water. SCB series pressure pumps specifically designed for standalone water delivery in remote locations are very high quality, maintenance free, pollution-free, corrosion-free, self-lubricating and quiet. There is no better way to provide water for remote homes, villages, small farms as well as many other needs beyond grid power [2]. They operate on 100 to 1500 watts of DC power with 12 through 180volt. They can be powered by batteries or directly from solar panels.

Brushless DC motors have many advantages over brushed DC motors [2]. A few of these are:

- Better speed versus torque characteristics;
- High dynamic response;
- High efficiency;
- Long operating life;
- Noiseless operation;
- Higher speed ranges:

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors.

2.4.2.1. Net Positive Suction Head (NPSH)

NPSH required is the minimum pressure head at the entrance to the pump, such that cavitation does not occur in the pump. The value depends on the type of the pump, its design, and size. NPSHr also varies with flow rate at which the pump operates. Generally, increases with increasing flow rate in a given pump. This is because higher velocities occur within the pump, leading to lower pressures. NPSHr is usually higher for larger pumps, meaning that cavitation can be more of a problem in larger pump sizes.

Available NPSH; (NPSHa) is equal to the atmospheric pressure minus all losses in the suction piping (upstream side of the pump), vapor pressure, and velocity head in the suction pipe, and static lift.

When there is suction at the pump inlet (the pump is operating, but not yet primed), the only force available to raise the water is that of the atmospheric pressure. But, the suction is not perfect (pressure does not reduce to absolute zero in the pump) and there are some losses in the suction piping.

$$NPSH_a = h_{atm} - h_{vapor} - h_f - h_{lift} - \frac{V^2}{2g} \quad \text{2.2}$$

h_{atm}=Atmospheric pressure

h_{vapor}=Vapor pressure

h_f=Friction loss in the suction piping

V=Velocity loss

h_{lift}=Static suction lift

2.5. Sizing of PV System

Some of the terms used in solar energy applications are:

- Irradiance (W/m^2): The rate at which radiant energy is incident on a surface per unit area of surface.
- Irradiation or radiant (J/m^2): The incident energy per unit area on a surface, found by the integration of irradiance over a specified time, usually an hour or a day.
- Insolation is a term applied specifically to solar energy irradiation.

2.5.1. Radiation Geometry

The geometric relationships between a plane of any particular orientation relative to the earth at any time and the incoming beam solar radiation, that is, the position of the sun relative to that plane, can be described in terms of several angles.

2.5.1.1. Latitude (ϕ):

The latitude of a location is the angle made by the radial line, joining the given location to the center of the earth, with its projection on the equatorial plane. The latitude indicates how far north (or south) the location is from the equator. The latitude is positive for the northern hemisphere and negative for southern hemisphere; $90^0 \leq \phi \leq -90^0$.

2.5.1.2. Solar Time (ST):

Clock time is described based on longitudes and is dependent on the standard meridian for each country (region). The earth makes a complete rotation on its axis once in 24 hours, thereby moving across 360° longitude. The sun, therefore, takes 4 minutes to traverse 1^O of longitude or 15°per hour.

2.5.1.3. Longitudes or Meridians:

Longitudes are semi-great circles passing through the poles of the earth. Locations east of Greenwich are denoted by degrees. East, while the locations west are denoted by degrees west.

2.5.1.4. Declination Angle (δ):

The plane that includes the earth's equator is called the equatorial plane. If a line is drawn between the center of the earth and the sun, the angle between this line and the earth's equatorial plane is called the Declination angle (δ). As the earth rotates about the sun, it spins about an axis which points to the North Star and inclined at 23.45^O to the orbital plane.

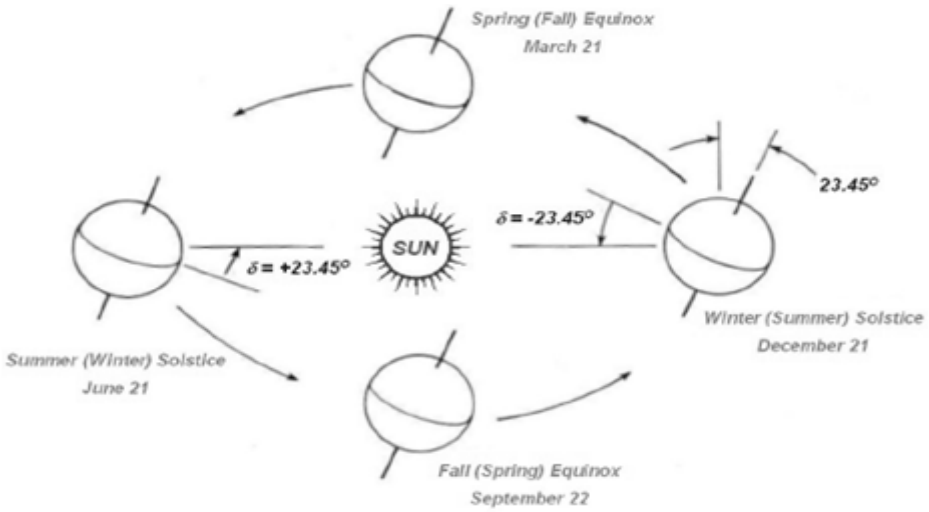


Figure 2-1: Northern/southern hemisphere earth-sun relationship

Declination Angle (δ) of the sun varies daily and is calculated from the following relation:

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + N)\right] \quad \text{2.3}$$

Sunrise and Sunset Hour Angle (ωs):

It is the hour angle at the time of sunrise (or sunset). It is the hour angle when the altitude angle is zero. The relationship for the sunrise and sunset hour angles and day-length could be obtained from the relation of zenith angle θz, which gives the angle between the sun's rays and the normal to the horizontal surface.

Since 15^O = 1 hour, the number of daylight (sunshine) hours Ns is given by:

$$N_s = \frac{2}{15}\cos^{-1}(-\tan\phi \tan\delta) \quad \text{2.4}$$

$$N_s = \frac{2}{15}\cos^{-1}(-\tan 8.17^0 \times \tan -23^0) = 11.53\text{hr}$$

2.5.1.5. *Mean Day of the Month*

The recommended average days for each month (N) by months are given in Table 2-2.

Table 2-2: Recommended Average days for months and values of N by months (Duffie and Beckman, 1991)

Month	N for i^{th} day of month	For the average day of the month		
		Date	Day of year N	Declination
January	i	17	17	-20.9
February	31+i	16	47	-13.0
March	59+i	16	75	-2.4
April	90+i	15	105	9.4
May	120+i	15	135	18.8
June	151+i	11	162	23.1
July	181+i	17	198	21.2
August	212+i	16	228	13.5
September	243+i	15	258	2.2
October	273+i	15	288	-9.6
November	304+i	14	318	-18.9
December	334+i	10	334	-23.0

2.5.1.6. *Hour Angle (ω):*

To describe the earth's rotation about its polar axis, the concept of the hour angle (ω) is used. The hour angle is the angular distance between the meridian of the observer and the meridian whose plane contains the sun. The hour angle is zero at solar noon (when the sun reaches its highest point in the sky). The hour angle increases by 15^O every hour. Hour angle ω and solar time ST in hour is related as:

$$\omega = (ST - 12) \times 15^0 \quad \text{..... 2.5}$$

2.5.1.7. *Zenith (θz):*

It is the angle between sun's ray and perpendicular line to the horizontal plane,

For horizontal surface:

$$\cos\theta z = \cos\phi \times \cos\delta \times \cos\omega + \sin\delta \times \sin\phi \quad \text{..... 2.6}$$

The relationship for the angle of incidence of surfaces sloped due north or due south can be derived from the fact that surfaces with slope β to the north or south have the same angular relationship to beam radiation as a horizontal surface at an artificial latitude of $(\phi - \beta)$

$$\cos\theta = \cos\delta \times \cos\omega \times \cos(\phi - \beta) + \sin\delta \times \sin(\phi - \beta) \quad \text{2.7}$$

The amount of solar radiation reaching the earth surface is also highly depends on air mass. Air mass is the ratio of the distance that solar radiation travels through the earth's atmosphere to the distance it would travel if the sun were directly overhead.

Radiation coming from directly overhead, therefore, is said to pass through an air mass of 1.0 at sea level. Solar irradiance coming from a zenith angle of 60 degree would pass through approximately twice the perpendicular path length and hence an air mass of 2.0.

Large value of air mass indicates that solar radiation travel greater distance in atmosphere.

$$Air\ mass = \frac{AB}{AC} = sec\ \theta_z \quad \text{2.8}$$

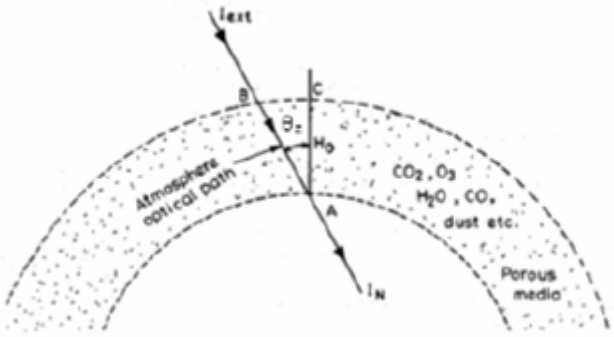


Figure 2-2: Directions of sun's ray with respect to Atmosphere

2.5.2. Components of Photovoltaic System

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. A solar cell is a unit that delivers only a certain amount of electrical power. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells have to be connected together to form a solar panel, also called a PV module. PV modules are the heart of the system and are usually called the power generators. For large-scale generation of solar electricity the solar panels are connected together into a PV array. Mounting structure and connecting wires are other components of PV system.

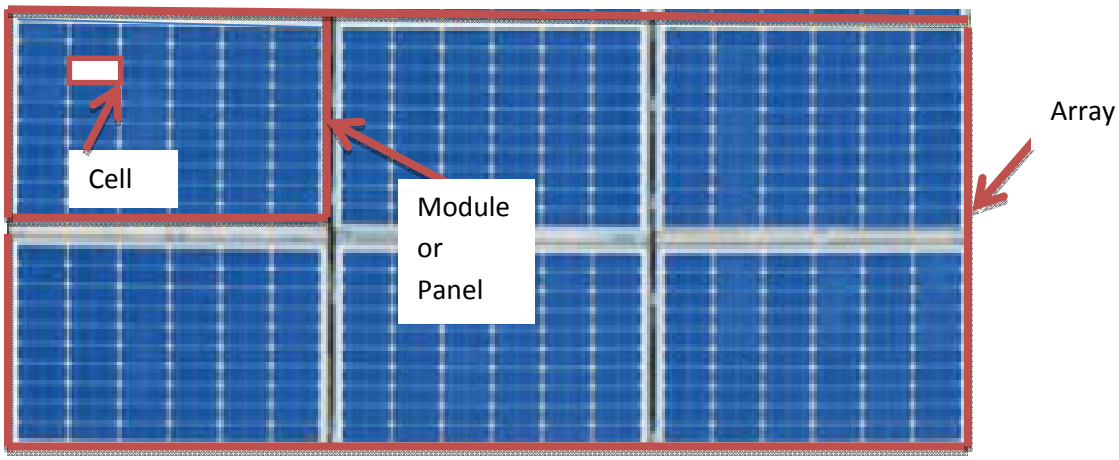


Figure 2-3: Components of a PV System

2.5.3. PV Module Selection

The solar cell is the basic unit of a PV system. An individual solar cell produces direct current and power typically between 1 and 2 W. In case of crystalline silicon solar cells with a typical area of 10 × 10 cm^2an output power is typically around 1.5 W_p, with $V_{oc} \approx$ 0.6 V and $I_{sc} \approx$ 3.5 A. For actual usage, the solar cells are interconnected in series/parallel combinations to form a PV module.

The photovoltaic panel is the energy collector that receives solar radiations and converts them to electrical energy. This conversion process loses as much as 80% of the energy thus leaving us with an efficiency of 20% at best cases. PV panels produce DC electricity; they are interconnected together in series and parallel to achieve the desired voltage and current.

2.5.3.1. Module I-V Characteristics

Electrical parameters are determined at standard test conditions, i.e. 1000 W/m^2solar irradiance, 25°C cell temperature and AM=1.5 solar radiation. Rated specifications are determined from the maximum power point (MPP) of the illuminated I-V characteristic. In order to guarantee performance specifications of modules, modules are sealed for protection against corrosion, moisture, pollution and weathering.

The PV module is a nonlinear device and can be described by its I-V characteristic. Assuming identical PV cells, the I-V characteristic of the PV model is obtained, depending of course on the global irradiance and temperature. The operation point of the system (PV array coupled with the motor-pump assembly) changes whenever any of these parameters changes.

There are several mathematical models which describe the I-V characteristic that can be distinguished by the calculation procedure, the number of intervening parameters and the accuracy of results [5].

Equation (2.9) describes the I-V characteristics of a solar cell:

$$I = I_L - I_O\,[\exp\left(\frac{qV}{KTA}\right) - 1] \quad \text{.....2.9}$$

Where I_L is the photocurrent, I_0 is the reverse saturation current, T the cell temperature, K the Boltzmann's constant, q the charge of an electron and A the p-n junction ideality factor can vary from 1 to 2.5[5].

The cell reverse saturation current I_0 varies with temperature according to the following equation:

$$I_O = I_r\,[\frac{T}{T_r]^3}\exp\,[\frac{qE_G}{KA}\,\left(\frac{1}{T_r} - \frac{1}{T}\right)] \quad \text{..... 2.10}$$

Where Tr is the cell reference temperature, Ir is the reverse saturation current at Tr, E_G is the band gap of the semiconductor used in the cell. The bang gap decreases with temperature and its temperature dependence is well modeled by:

$$E_G = E_g(o) - \frac{\alpha T^2}{T+\beta}\,q \quad \text{..... 2.11}$$

Where α and β are constants specific to each semi-conductor [24]. The photocurrent I_L depends on solar radiation and cell temperature as follows:

$$I_L = [I_{sc} + K_i\,(T - T_r)]\,\frac{S}{100} \quad \text{..... 2.12}$$

Where Isc is the cells short-circuit current at reference temperature and radiation, Ki is the short circuit current temperature coefficient and S is the solar radiation.

Analysis of specific site solar irradiance should be performed in the design process, in order to make a realistic estimate for how much power will be available from a photovoltaic array installed in a particular geographic location.

The amount of sun your solar cells are exposed to (and hence how much energy they will generate) depends upon [20]:

- The orientation and tilt of your installation (which will be optimized by your installer);
- Whether there are shadows cast over your cells (due to trees, buildings etc);
- The number of daylight hours (governed by where you live);

- The intensity of the sunlight (governed by where you live);
- The number of hours of full sun Vs cloudy days (governed by where you live):

The power that the manufacturer declares the PV array can produce under standard test conditions, which are a constant 1000W of solar irradiation per square meter in the plane of the array, at an array temperature of 25° C.

The global formula to estimate the electricity generated from a photovoltaic system is:

$$E = A \times r \times H \times PR \quad \text{..... 2.13}$$

E = Energy (kWh)

A = Total solar panel Area (m²)

r = solar panel yield (%)

H = Annual average solar radiation on tilted panels (shadings not included)

PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9)

r: is the yield of the solar panel given by the ratio : electrical power (in kWp) of one solar panel divided by the area of one panel.

2.6. Pumping Control Mechanism

The controller plays a vital role in the system performance due to match the power produced by the panels with that required by the pump. It also plays a critical role in protecting the system by turning it off when the voltage is at inappropriate level, meaning too low or too high compared to the operating voltage range of the pump. This voltage protection role helps extend the lifetime of the pump and reduce maintenance requirements.

The purpose of the controller is to operate the high efficiency, high reliability DC motor and maximize the total daily water output while providing protection for the pump as well as providing an interface with other related pumping system equipment.

2.6.1. Automatic Control for Full-Tank Shutoff

The pump's operation can be controlled by the use of a float switch in the storage tank, acting automatically when a defined water level is reached in the tank [5].

Water pumped will be greater than our daily requirements on any full sunny day. This is typically not an issue when float switches are incorporated into storage systems, which will stop the pumping when the tank is full then reset when the level drops. It's similar to the float in a

toilet tank but is wired to the pump controller. This conserves water source, prevents overflow, and eliminates unnecessary pump wear.

Float switch cable requirements:-

1. Two wires are needed.
2. Minimum wire size #18 AWG (1mm²). This is good for a distance as far as 600m.
3. The cable must be suitable for its environment.
4. If it must run a long distance, use twisted-pair shielded cable to reduce the chance of damage from lightning-induced surge.

2.7. System Simulation

System simulation is a set of techniques that use computers to imitate the operation of various real world tasks or processes through simulation. Computers are used to generate numeric models for the purpose of describing or displaying complex interaction among multiple variables within a system using different simulating tools. In this thesis PVsyst is used to simulate photovoltaic water pumping system.

2.7.1. System Simulating Tool

PVsyst has been developed at group of Energy Institute of the science of the Environment University of Geneva, Switzerland. By Dr. Andre Mermoud

PVsyst V6.43 is a PC software package for the study, sizing and data analysis of complete PV systems. It is one of the most widely used tools in solar projects. It deals with grid-connected, stand-alone**,** pumping and DC-grid (public transportation) PV systems, and includes extensive meteorology and PV systems components databases, as well as general solar energy tools.

This software is geared to the needs of architects, engineers, researchers. It is also very helpful for educational training. PVsyst is a provider of software to model PV system performance. PVsyst is used by system designers and financial institutions around the world to accurately analyzed different configurations with in a PV system evaluate the result and identify the best approach for efficiency and cost. Pvsyst is used to simulate the designed system to check whether it satisfies the required water or not. Some of basic inputs are presented in this section.

Full-featured study and analysis of a project.

- ✓ Excellent training program equip you with skills and better opportunity for the future;
- ✓ Accurate system yield computed using detailed daily and hourly simulations;
- ✓ Different simulation variants can be performed and compared;
- ✓ Horizon shadings, and 3D tool for near shadings effects study;
- ✓ Detailed losses analysis;
- ✓ Economic evolution performed with real component prices:

2.8. Economic and Environmental Analysis

2.8.1. Economic Analysis

For every project, there is need to perform economic evaluation to make sure that it is feasible or not. During economic analysis, PVWP system is compared with diesel water pumping. The comparison is conducted in terms of initial capital costs (ICC), life cycle cost (LCC) and the corresponding profitability, which is evaluated using the net present values (NPV) and the payback period (PBP) as indicators.

The profitability of PV water pumping system has been studied using the indicators such as the net present value (NPV) and the payback period (PBP). NPV and PBP methods are calculated with the following theoretical equations:

$$NPV(I) = -ICC + \sum_{t=1}^{N} \frac{CF}{(1+i)^t} \quad \text{2.14}$$

$$PBP = \frac{\text{cost of the investment}}{annual\ net\ cash\ flow} \quad \text{2.15}$$

Where, *CF* is the cash flow registered from year *1* to year *N* given by the annual difference between incomes and expenses, '*i*' is the discount rate.

2.8.2. Environmental Analysis of the System

Environmental advantages of the system analyzed using CO_2 emission reduction. The annual CO_2 emissions avoided in kilograms using PV modules as power source instead of the traditional diesel powered pumps are estimated using Homer software:

2.8.2.1. *Environmental Impacts of Solar Energy*

Solar energy environmental considerations include:

- land disturbance/land use impacts;
- potential impacts to specially designated areas;
- impacts to soil, water and air resources;
- impacts to vegetation, wildlife, wildlife habitat, and sensitive species;
- visual, cultural, paleontological, socioeconomic, and environmental justice impacts, and
- Potential impacts from hazardous materials.

2.9. Research Questions

The main research questions, rise when literature review are listed and they addressed in these thesis

- Is solar energy suitable to replace diesel as main source of power for pump?
- What factors affect the efficiency of solar water pumping system?
- How the system affects the environment?
- What is the optimum tilt angle of solar panel which can collect the maximum solar energy?
- How does crop water requirements variation during the irrigation season affect the system design?
- Is photovoltaic water pumping system economically and environmentally feasible for irrigating a potato farm?

CHAPTER THREE

3. Design of the Photovoltaic water Pumping System

3.1. Introduction

A good solar pumping system is the one properly designed and sized to fit the job requirements. Solar PV pumping requires more strictness as system components are really expensive and efforts need to be done to bring system set up cost to a minimum.

3.2. Water Source

The configuration of the water system will be defined primarily by the type of water source used, as well as by the local topography and the location of the delivery point.

The water source for the planned system is Winque River. The river flows year round with sufficient flow to supply the planned system, and the water quality is suitable for irrigation. However, adequate screening must be provided for the pump intake in order to protect the pump from failures.

3.3. Crop Water Requirement

The first step in designing PV water pumping system is to determine the overall water requirement for irrigation. The water requirement of crops varies with the type of crop, time and depends on the season and growth of crops. The type of soil and the climatic parameters are other factors that need to be considered. In this research, the crop is potato; the type of soil is categorized under loam and taking the site's metrological data.

3.3.1. Reference Crop Evapotranspiration

The first step to determine the irrigation water requirements is calculate the reference evapotranspiration ETo that represents the water loss due to the evaporation and plant transpiration from a reference surface (FAO, 1998). Grass has been taken as the reference crop.

3.3.2. Determination of Irrigation Water Requirement: -Using theoretical Method

A theoretical method (e.g. the Blaney-Criddle method) to calculate the reference crop evapotranspiration ETo has to be used. The Blaney-Criddle method is simple, using measured data on temperature only. It should be noted, however, this method is not very accurate; it provides a rough estimate or "order of magnitude" only. Especially under "extreme" climatic

conditions the Blaney-Criddle method is inaccurate: in windy, dry, sunny areas, the ETo is underestimated (up to some 60 percent), while in calm, humid, clouded areas, the ETo is overestimated (up to some 40 percent).

The Blaney-Criddle formula

$$ET_o = p(0.46T_{mean} + 8) \quad \text{..... 3.1}$$

ETo = Reference crop evapotranspiration (mm/day) as an average for a period of 1 month

T_{mean} = mean daily temperature (°C), = 18^0c (table 3-2)

p = mean daily percentage of annual daytime hours (Appendix-B)

$$ET_o = 0.28(0.46 \times 18 + 8) = 4.56mm/day$$

The evapotranspiration in cultural conditions ET_C, is calculated from ET_0 taking into consideration a specific cultural coefficient K_C dependent on the type of crop and growing phase. When considering potato, K_C varies from 0.3 to 0.93 depending on the growing phase of the crop as shown below [Agrimet crop coefficients].

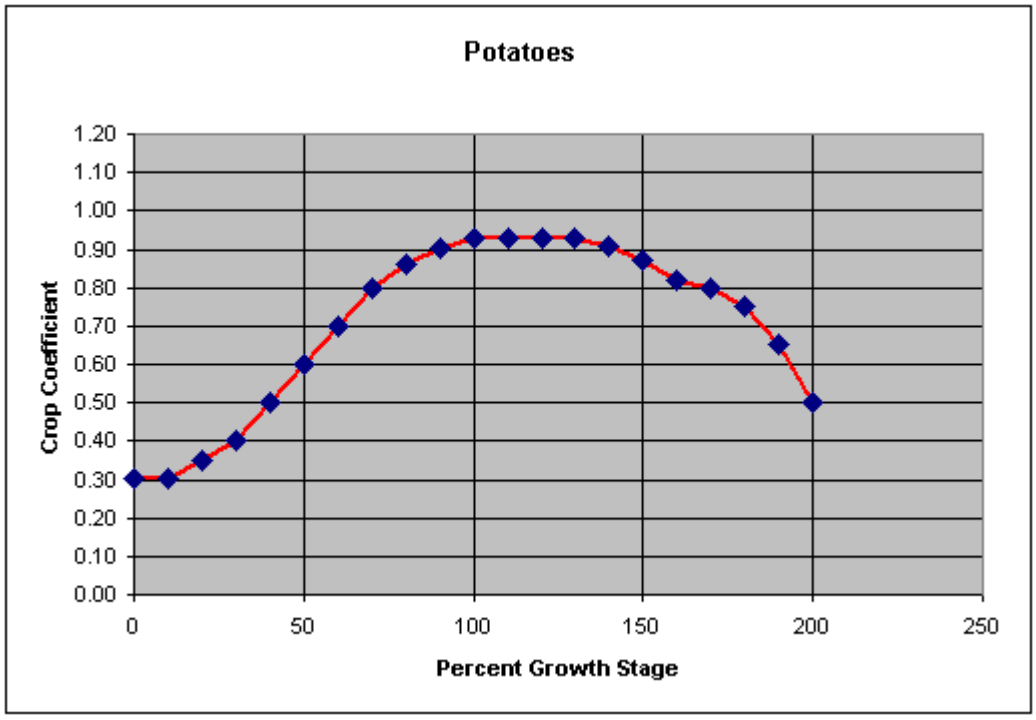


Figure 3-1: Crop cultural coefficient (k_c)

Every crop has its own duration of growth stage. Table 3-1 shows that approximate day of growth stage for potato.

Table 3-1: Duration of growth stages for potato in day.

Crop type	Total (day)	Stages			
		Initial	Crop development	Mid seasonal	Late seasonal
Potato	105	25	30	30	20
	145	30	35	50	30

$$ET_c = K_c ET_o \quad \text{..... 3.2}$$

$$ET_c = 0.93 \times \frac{4.56mm}{day} = 4.24mm/day$$

The irrigation water requirements *IWR* (m^3/ha day) are given by Blaney-Criddle formula:

$$IWR = \frac{10(ET_c - P_{eff})}{(1-LR)\eta_{irr}} \quad \text{..... 3.3}$$

P_{eff} = effective rain fall for the worst month is 1.6mm/day (figure 3-2)

LR = the leaching requirements, defined as the amount of water needed in order to remove residual salts from the root zone equal to 0.18

η_{irr} efficiency of the irrigation system set 50-60% when assuming to use a furrow irrigation system [6], 55% is used for this purpose. Substitute all numerical values in to equation 3.3 gives

$$IWR = \frac{10(4.24-1.6)}{(1-0.18)\times 0.55} = 5.6 \frac{m^3}{ha \times day}$$

3.3.3. Determination of Irrigation Water Requirement: -Using Computer software

The assessment of irrigation water requirement can be alternatively performed with the software CROPWAT. It is a decision support system developed by the Land and Water Development Division of FAO for planning and management of irrigation. CROPWAT is meant as a practical tool to carry out standard calculations for reference evapotranspiration, crop water requirements and crop irrigation requirements, and more specifically the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rain fed conditions or deficit irrigation.

Calculations of the crop water requirements and irrigation requirements are carried out with inputs of local climatic, crop, soil and geographical data.

Table 3-2: Monthly local climatic and geographic data.

Monthly ETo Penman-Monteith - C:\ProgramData\CROPWAT\data\climate\Eto1.PEM

Country: Ethiopia Station: Wolkite

Altitude: 1930 m. Latitude: 8.17 °N Longitude: 37.47 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	8.0	26.5	40	268	8.1	19.7	5.33
February	8.5	27.0	39	259	8.0	20.7	5.57
March	10.5	27.5	51	242	8.1	21.8	5.38
April	12.0	27.0	67	242	7.8	21.5	4.82
May	11.5	26.5	77	216	7.8	21.0	4.30
June	12.0	24.5	76	207	5.0	16.4	3.55
July	12.0	23.0	76	181	2.2	12.4	2.89
August	12.0	23.0	76	164	2.5	13.1	2.93
September	11.5	25.0	74	173	5.0	17.0	3.64
October	9.0	25.5	72	207	8.0	20.9	4.23
November	9.5	25.5	59	251	8.0	19.7	4.55
December	8.0	25.5	47	268	8.1	19.2	4.91
Average	10.4	25.5	63	223	6.5	18.6	4.34

Out put

The recorded data shows that, the amount of rainfall is decreased radically from October (Figure 3-2), therefore October first is taken as starting date of irrigation.

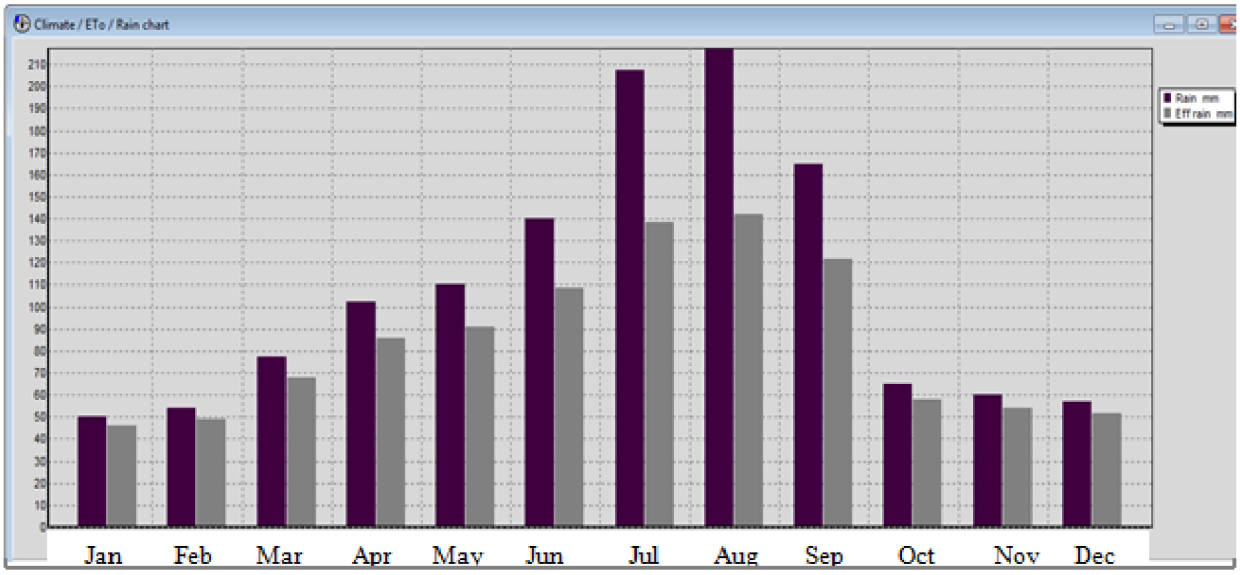


Figure 3-2: Month wise average rainfall data of the site

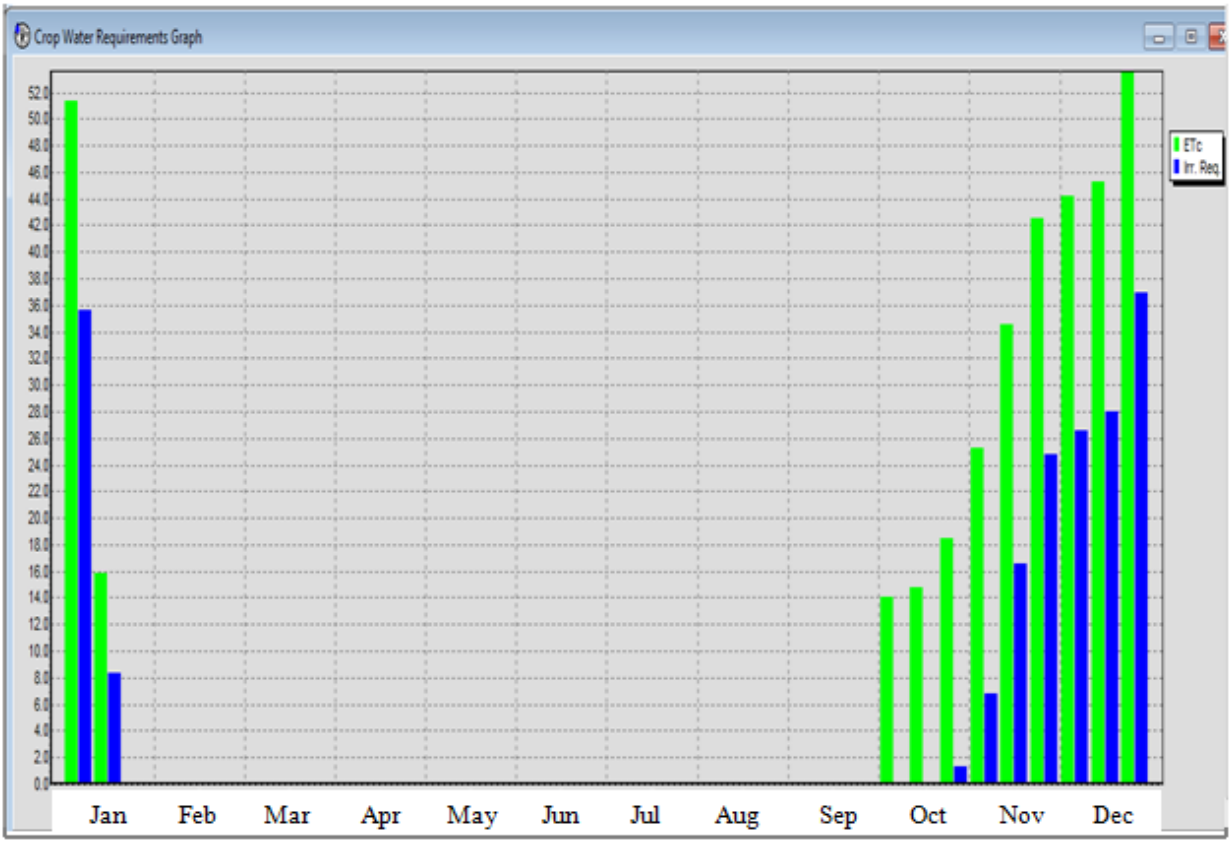
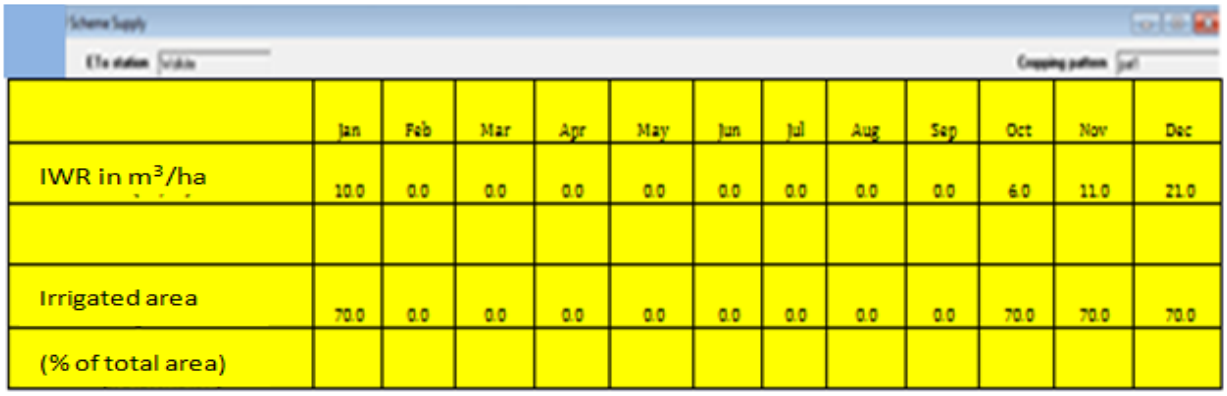


Figure 3-3: Simulated irrigation water requirement (for one irrigation season)

$$IWR = ETc - Peff \quad \ldots\ldots\ldots\

Table 3-3: Monthly water requirement of potato



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IWR in m^3/ha	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	11.0	21.0
Irrigated area	70.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	70.0	70.0	70.0
(% of total area)												

The simulated result shows that, the maximum water requirement is in December i.e.

$IWR = 21 \frac{m^3}{ha}$

Approximate water requirements of irrigating a potato farm is 21,000 liters per hector.

3.3.4. Irrigation Scheduling

Irrigation scheduling is the procedure used to determine the time and depth of water application for each irrigation event. Maximum irrigation interval for potato farm is calculated as eqn. 2.1.

$$Maximum\ Irrigation\ Interval = \frac{80\frac{mm}{m} \times 0.45m \times 0.35}{5.27mm/day)} + 1\ day = 3.39$$

H_w=soil water holding capacity in $\frac{mm}{m}$ (Table 3-4)

D_r=root zone depth (m)

D_A=allowable depletion, Potato can be irrigated at 35% depletion of available soil moisture without losing any significant yield [Stark 1996].

ET_C=peak daily evapotranspiration (mm/day)

3.3.4.1. *Soil Water Holding Capacity*

Soil serves as the reservoir for plant nutrient and water needs. Soil has a finite capacity to hold water against gravity.

Table 3-4: Water holding capacity of agricultural soils [27]

	Water holding capacity (mm/m)	
Soil type	Average	Range
Sand	80	50-110
Loamy sand	80	60-120
Sandy loam	130	110-150
Loam	150	110-180
Silt loam	150	110-190
Silt	170	120-200
Silty clay loam	150	120-180
Silty clay	150	110-190
clay	150	100-200

Average Soil water holding capacity for loam = 80mm/m (Table 3-4)

Water holding capacity for loamy sand is 80mm/m

Average root zone depth for potato = 0.45m [Agrimet]

Allowable depletion = 35%

Peak daily ETo = 5.27 mm/day

Maximum irrigation interval will be approximated to three days.

$$IWR\ for\ one\ hetor = 21{,}000\frac{l}{3\ day} = 7{,}000l/day$$

Determination of daily Irrigation water requirement for a hector potato farm using Cropwat is $7m^3$ that is greater than $5.6m^3$ it is calculated using theoretical method. This method is not very accurate; it provides a rough estimate or "order of magnitude" only but Cropwat is the most accurate way determining the crop water requirement. Therefore, the system is designed based on $7m^3$ daily water requirement.

3.4. Water Storage Design

Water storage is very practical when the system is properly sized. During sunny days, the system provides enough water for the daily requirements, since solar energy is free; this water can be stored in storage that should be sized to ensure sufficient capacity depending on climatic conditions and water consumption [25].

The capacity of the water storage should be sufficient for two up to ten days' worth of water storage in the event of extended cloudy weather or maintenance issues that prevent the pump from operating.

3.4.1. Water Evaporation and Other Losses

The amount of evaporated water from an open tank depends on the temperature, humidity and velocity of the air above the surface.

Now, calculate the approximate evaporated water at 25^0c the saturation humidity ratio is 0.02kg/kg. With an air temperature of 25^0c and 65% relative humidity, the humidity ratio of the air is 0.06 Mollier diagram (Appendix J-1). For a 4m×12.225m open tank and 1m/s air velocity above the surface of the tank, evaporation can be calculated as follow [28].

$$E_w = \Theta A(Xs - X) \quad \text{..... 3.6}$$

E_w = amount evaporated water (kg/hr)

Θ = (25+19v)=evaporation coefficient(kg/m^2hr)

v= velocity of air above open tank (m/s)

A = water surface area (m^2)

Xs= humidity ratio in saturated air at the same temperature as the water surface (kg H_2O in kg dry air)

X=humidity ratio in the air (kg H_2O in kg dry air)

Substitute all numerical values in to equation 3.6 gives

$$E_w = \big(25 + 19(1)\big)\big((4m)(12.225m)\big)\left(\frac{0.02kg}{kg} - \frac{0.016kg}{kg}\right) = 9kg/hr$$

Considering 10 sun hr and six day of storage length gives 540 liter of water be evaporated. Lining of storage tank also decrease volume of stored water.

The minimum storage capacity for six day worth is calculated using the water requirement derived in Section 3.3 with 2 m^3 additional water.

$$Water\ storage\ volume\ =$$

$$\frac{7m^3}{day} \times\ 6\ day\ +\ additional\ 2m^3\ water\ for\ evaporation\ and\ other\ losses = 44m^3$$

The storage should be provided with plastic/lining, to minimize water wastage

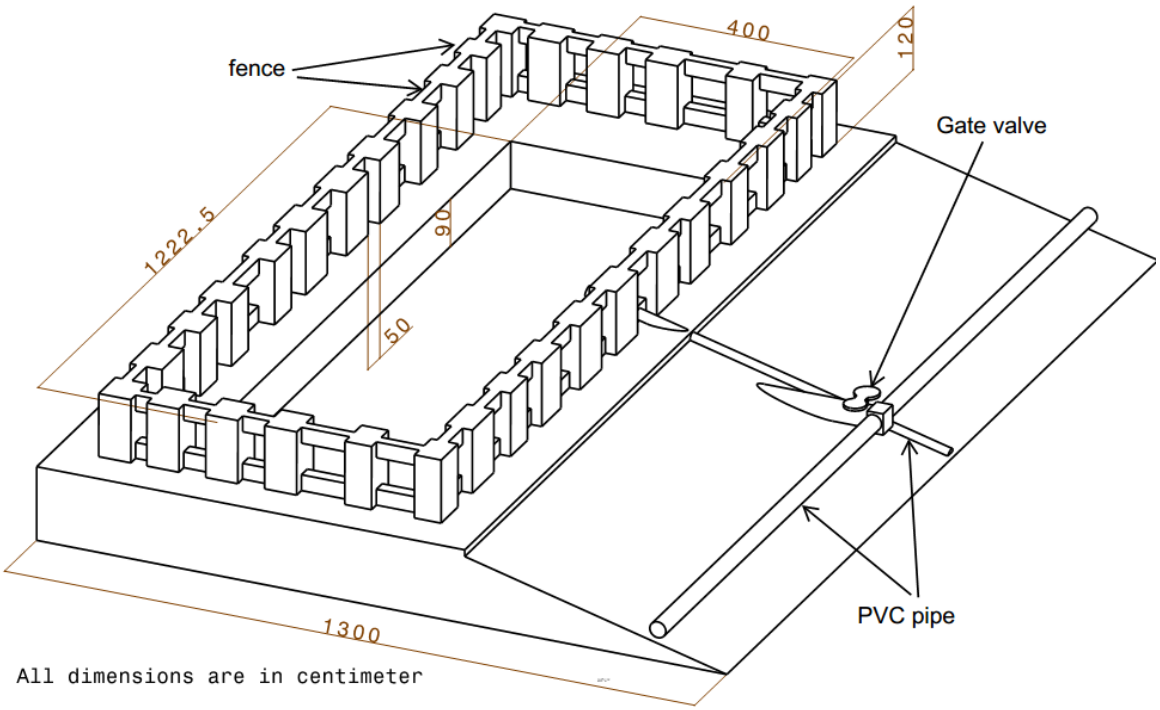


Figure 3-4: Designed water storage

3.5. Piping System Design

3.5.1. Design Flow Rate of the System

The pump's design flow rate is based on the operation's estimated daily water needs divided by the number of peak sun hours per day, as shown below.

Average sun hour per day=6.5 (Table 3-2)

$$Design\ flow\ rate = \frac{7{,}000\ l}{6.5\ peak\ sun\ hr \times 60\ min/hr} = 17.95\ \text{L/min} \approx 18\text{L/min} \ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

3.5.2. Selection and Sizing of Piping Materials

There are three major concerns regarding the selection of piping materials. The chosen pipe must meet the mechanical requirements of the system, have sufficient corrosion resistance to prevent corrosion build up and be cost effective. According to the McGraw-Hill Piping Handbook, the most desirable piping material for water pumping applications is Polyvinyl Chloride (PVC) piping due to its favorable working pressure rating and excellent chemical resistance, PVC

schedule 40 piping material has a yield strength of σys=57,571,223.3N/m^2 and a roughness factor of εPVC=0.0015±0.0009mm. Schedule 40 PVC is cheaper and has a large inside diameter than schedule 80. It will be used for all pipes All the piping for the system will be 3/4in (19.05 mm), with a nominal wall thickness of t= 2.87mm, an outer diameter of do= 26.67mm and an inner diameter of di = 20.5mm [appendix D-2]. In order to ensure that the pipes in the system will not burst it is necessary to compute the maximum allowable pressure for the pipe. The maximum allowable pressure rating for the piping material is determined from the hoop stress experienced when the material is stressed at its yield strength. For thin-walled pressure vessels where the ratio of the wall thickness to the outer diameter is less than or equal to 10% Barlow's formula provides an accurate representation of the maximum allowable pressure in the pipe. Barlow's formula, which is given by:-

$$\sigma_{ys} = \frac{pd_o}{2t} \Rightarrow p_{max} = \frac{2\sigma_{ys}t}{d_o} \quad \text{.....3.8}$$

For Schedule 40 pipe the ratio t/do=0.10, and by applying Equation 3.8 it is determined that p_{max}=*12341615.5N/m^2*.

3.5.3. System Layout Design

The next step is design layout of the irrigation system. We will need to identify all necessary distances and elevations for the intake point, pump, PV panels, and water tank as shown in Figure 3-5 and the detail drawing are figure 3-6, and 3-8). Based on the site-specific data, the site has good south-facing exposure and well suited for solar power. Flow from the tank to the field will be by gravity. Based on the given elevations, the natural layout of the site provides an adequate elevation difference between the tank and the field. In addition, the pump, controller and PV panels can all be located in close proximity to one other in order to minimize electric power losses. Figure 3-5, is a profile of the proposed layout showing all the related information needed to design the pump and PV panels.

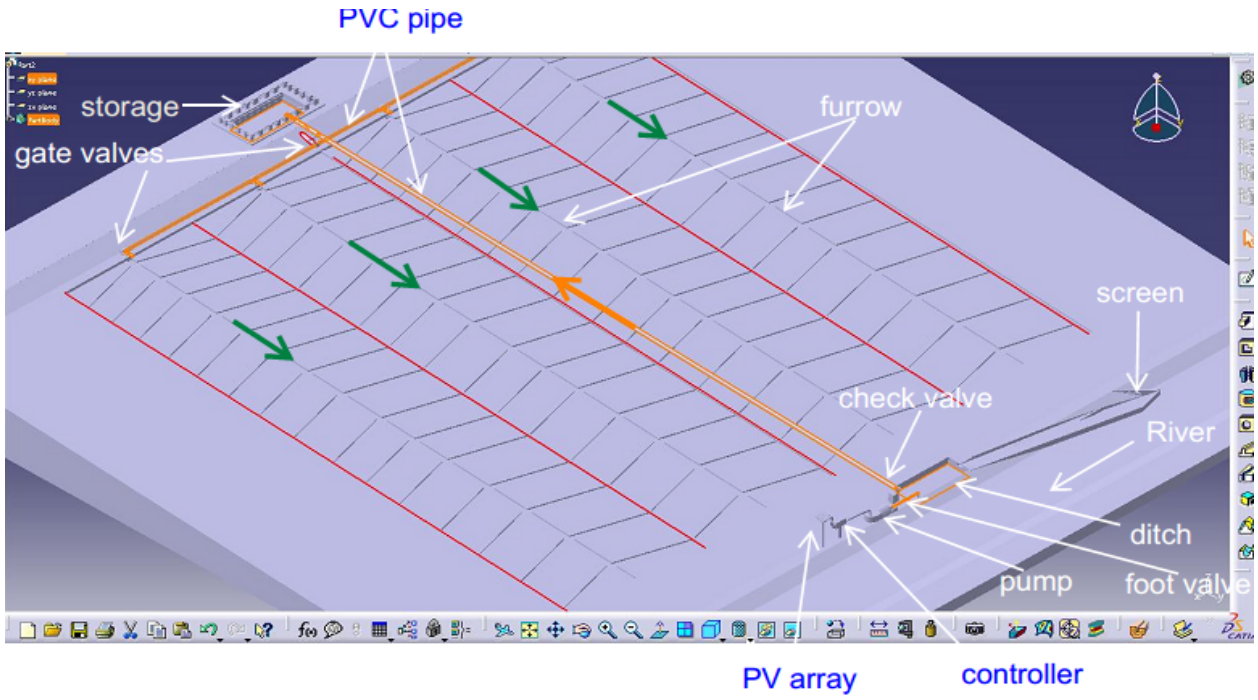


Figure 3-5: Layout of the system

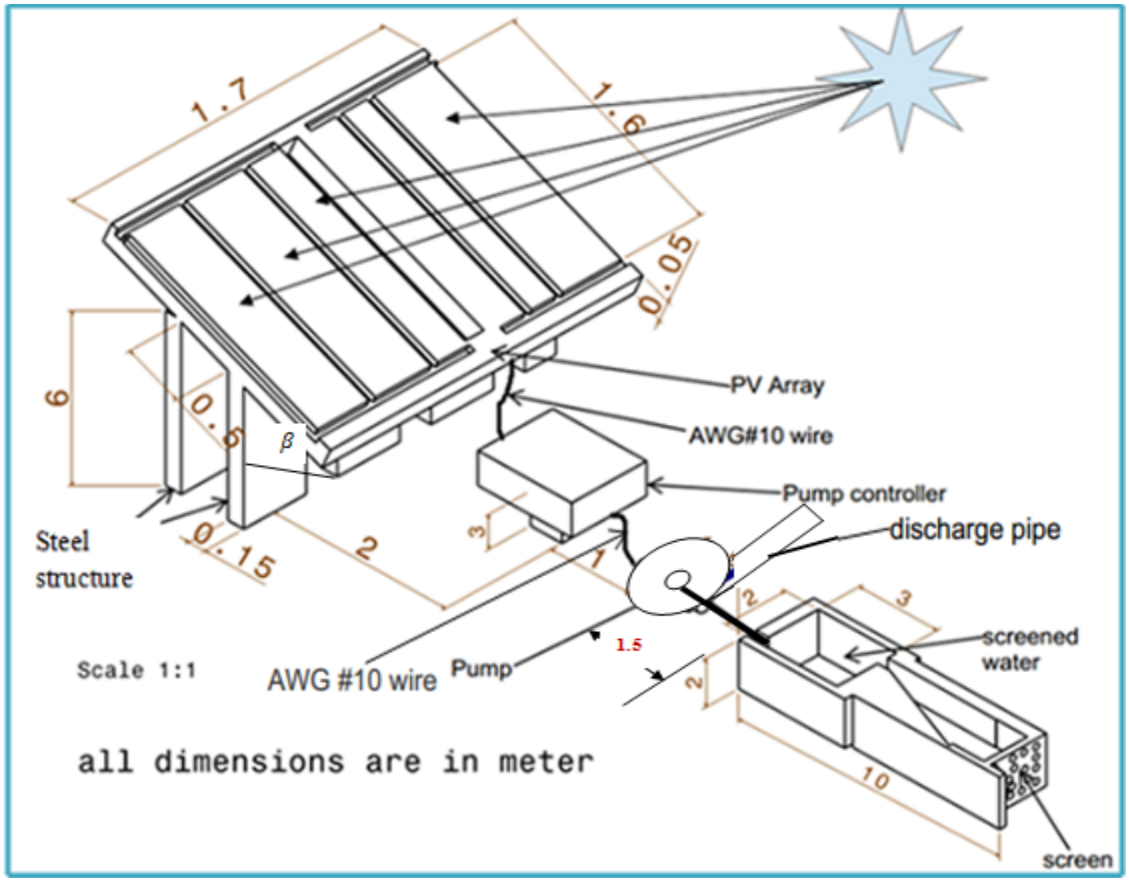


Figure 3-6: Detail layout of the designed system

3.5.4. Performance Characteristics of the Piping System

A system-head curve is a graphical representation of the relationship between flow and hydraulic losses in a given piping system. Since hydraulic losses are functions of rate of flow, size and length of pipe, and size, number and type of fittings, each system has its own characteristic curve and specific values. The system curve is commonly independent of the pump characteristics.

3.5.4.1. Static Head (Hs) of the System

Static head is the vertical distance between the water surface at the intake point (the river's water surface) and the water surface at the delivery point.

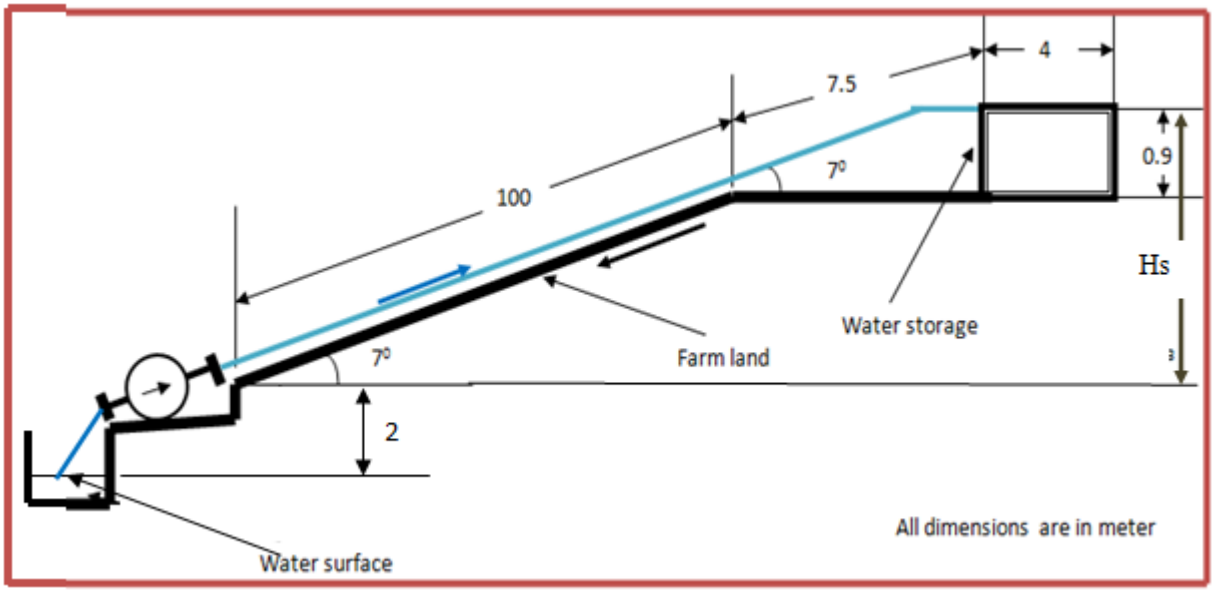


Figure 3-7: Static head of the system

Using sine Low to determine static head of the system (equation 3.9)

$$\frac{sin90^0}{107.5m} = \frac{sin7^0}{Hs} \quad \text{..... 3.9}$$

Hs= $sin7^0 \times 107.5m = 13m$, where approximate inclination of the farm land is 7^0

Therefore, $Static\ head\ = 2m + 13m\ = 15m$

3.5.5. Head Loss Due To Friction

In fluid flow, friction loss is the loss of pressure or "head" that occurs in pipe due to the effect of the fluid's viscosity near the surface of the pipe. Since all liquids have weight, they also have momentum. This means the liquid will always try to continue moving in the same direction. When the liquid change its direction (such as an elbow), fittings (such as valves) its momentum caries the flow to the outer edge of the fitting, the effective area of the fitting is reduced. The velocity of the liquid increase and the head loss due to friction increases.

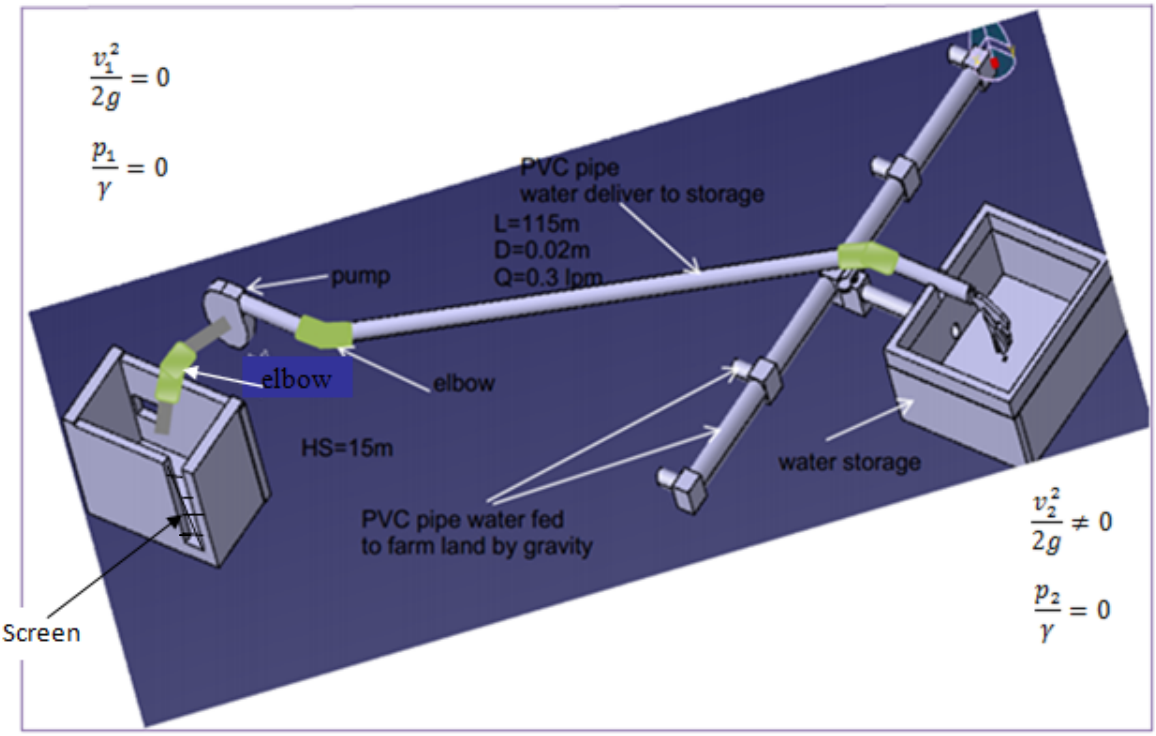


Figure3-8: System piping network

Since the system have three elbows and two valves (foot valve and check valve), other valves (gate valves) that are found between water storage and field are not considered because the flow is fed by gravity. The general equation to calculate system head loss due to friction is:-

$h_f = h_{pipe} + 3 * h_{elbow} + h_{fv} + h_{cv} + h_{screen} + velocity\ losses$ 3.10

Consider design flow rate of the system, i.e. 18 Liters per minute

$Q = 0.0003\ m^3/s$

Average velocity,

$V = \frac{Q}{A}$ 3.11

$$V = \frac{4*0.0003m^3/s}{\pi(0.02m)^2} = 1m/s$$

Table 3-5: Common pipe materials

material	Roughness (m)
Steel	0.0003
PVC	0.0000015
copper	0.0000015

For PVC, $\varepsilon \approx 1.5(10)^{-6}$ m, relative roughness is:

$$\frac{\varepsilon}{D} = r = \frac{1.5(10)^{-6}m}{0.02m} = 7.46(10)^{-5}$$

Reynolds number, for 10^0c water:

$$R_e = \frac{VD}{v} = \frac{(1m/s*0.02m)}{0.5(10)^{-5}m^2/s} = 13{,}230$$

3.5.5.1. *The Darcy Friction Factor*

The Darcy friction factor in turbulent flow is determined from the Moody diagram (Appendix-E) or by solving it from the Blasius,, Swamee-Jain or Haaland equations [23].

The Blasius equation is the most simple equation for solving the Darcy friction factor. Because the Blasius equation has no term for pipe roughness, it is valid only to smooth pipes. However, the Blasius equation is sometimes used in rough pipes because of its simplicity. The Blasius equation is valid up to the Reynolds number 10^5 [22]. The Blasius equation is:

$$f = \frac{0.316}{R_e^{0.25}} \quad \text{.... 3.12}$$

Where:-

f Darcy friction factor

R_e the Reynolds number.

$$f = \frac{0.316}{13{,}230^{0.25}} = 0.029$$

Swamee and Jain have developed the following equation to the Darcy friction factor

$$f = 0.25[\log\left(\frac{r}{3.7} + \frac{5.74}{R_e^{0.9}}\right)]^{-2} \quad \text{.... 3.13}$$

In which, r is relative roughness

In the Swamee Jain equation the Darcy friction factor is solved directly without iteration

$$f = 0.25[\log\left(\frac{7.46(10)^{-5}}{3.7} + \frac{5.74}{13{,}230^{0.9}}\right)]^{-2} = 0.028$$

Haaland has deduced the equation

$$\frac{1}{f} = -1.8\log\left[\left(\frac{r}{3.7}\right)^{1.11} + \frac{6.9}{R_e}\right] \quad \text{3.14}$$

$$\frac{1}{\sqrt{f}} = -1.8\log\left[\left(\frac{7.46(10)^{-5}}{3.7}\right)^{1.11} + \frac{6.9}{13{,}230}\right], f = 0.028$$

In the Haaland equation there is no need to iterate the Darcy friction factor. The accuracy of the Darcy friction factor solved from this equation is claimed to be within about 2 %, if the Reynolds number is greater than 3000 [23].

From the moody diagram, f=0.03 (Appendix-E)

From the Blasius equation, f=0.029

From the Swamee-Jain equation, f=0.028

From the Haaland equation, f=0.028

Now, calculating all possible system loses, taking the approximate darcy friction factor f=0.03

$$h_{pipe} = f\frac{L}{D}\frac{V^2}{2g} \quad \text{3.15}$$

Equation 3.31 is called Darcy Weisbach equation.

$$h_{pipe} = 0.03\frac{115m}{0.02m}\frac{(\frac{1m}{s})^2}{(2*\frac{9.8\ m}{s^2})} = 5m$$

From Appendix-I for long radius 45-deg flanged elbow, the Kr value is 0.2

Loss coefficient for pipe components ($h_L = K_L\frac{V^2}{2g}$)

$$h_{elbow} = K_L\frac{V^2}{2g} \quad \text{3.16}$$

There are 3 elbows in the system layout

$$h_{elbow} = 0.2\frac{(\frac{1m}{s})^2}{2*9.81m/s^2} * 3 = 0.03m$$

Foot valve, the foot valve is a check valve installed at the water intake. It is required in any case where the pump is located higher than the low water level in the source. A high quality spring loaded type is recommended to avoid loss of prime. A check valve allows water to flow one way and not the other. Be sure to install it the right way.

$$h_{fv} = K_L\frac{V^2}{2g} \quad \text{3.17}$$

For a piston foot valve Kr value is 15

$$h_{fv} = 15\frac{(1m/s)^2}{2*9.81m/s^2} = 0.665m$$

Check Valve at the pump outlet, a check valve at the pump outlet is required if there is more than a 10 m/30 ft lift above the pump, or in any pressurizing system [2]. This allows the pump to start easier. It also prevents back flow when changing filter cartridges.

$$h_{cv} = K_L\frac{V^2}{2g} \quad \text{3.18}$$

For a disk type check valve Kr value is 10

$$h_{cv} = 10\frac{(1m/s)^2}{2*9.81m/s^2} = 0.51m$$

$$Velosity\ loss = \frac{V^2}{2g} \quad \text{3.19}$$

$$Velosity\ loss = \frac{(1m/s)^2}{2*9.81m/s^2} = 0.051m$$

For the screen, assume a 0.15m loss, the total friction loss is:

$h_f = 5 + 0.03 + 0.665 + 0.51 + 0.051 + 0.15 = 6.015\text{m} \approx 6\text{m}$

Other alternative methods also give the same value of system head loss due to friction.

The same fashion is applied for the rest flow rates and tabulated the result in Table 3-6

3.5.5.2. Total Dynamic Head (TDH) of the Piping System

To determine TDH of the piping system, use the following equation:

$$TDH = Static\ head + friction\ losses \quad \text{3.20}$$

$$TDH = 15m + 0m + 6m = 21m$$

The following table shows the calculated total dynamic head and friction head losses as a function of flow rate.

Table 3-6: Head losses as a function of flow rate

Q /(l/m)	Static head (m)	Friction losses (m)	TDH (m)
0	15	0.15	15.15
4	15	0.21	15.21
8	15	1.18	16.18
12	15	3.35	18.35
16	15	4.00	19.00
18	15	6.00	21.00
22	15	9.00	24.00
26	15	12.00	27.00

Hydraulic losses are functions of rate of flow, size and length of pipe, and size, number and type of fittings, each system has its own characteristic curve and specific values (figure 3-9).

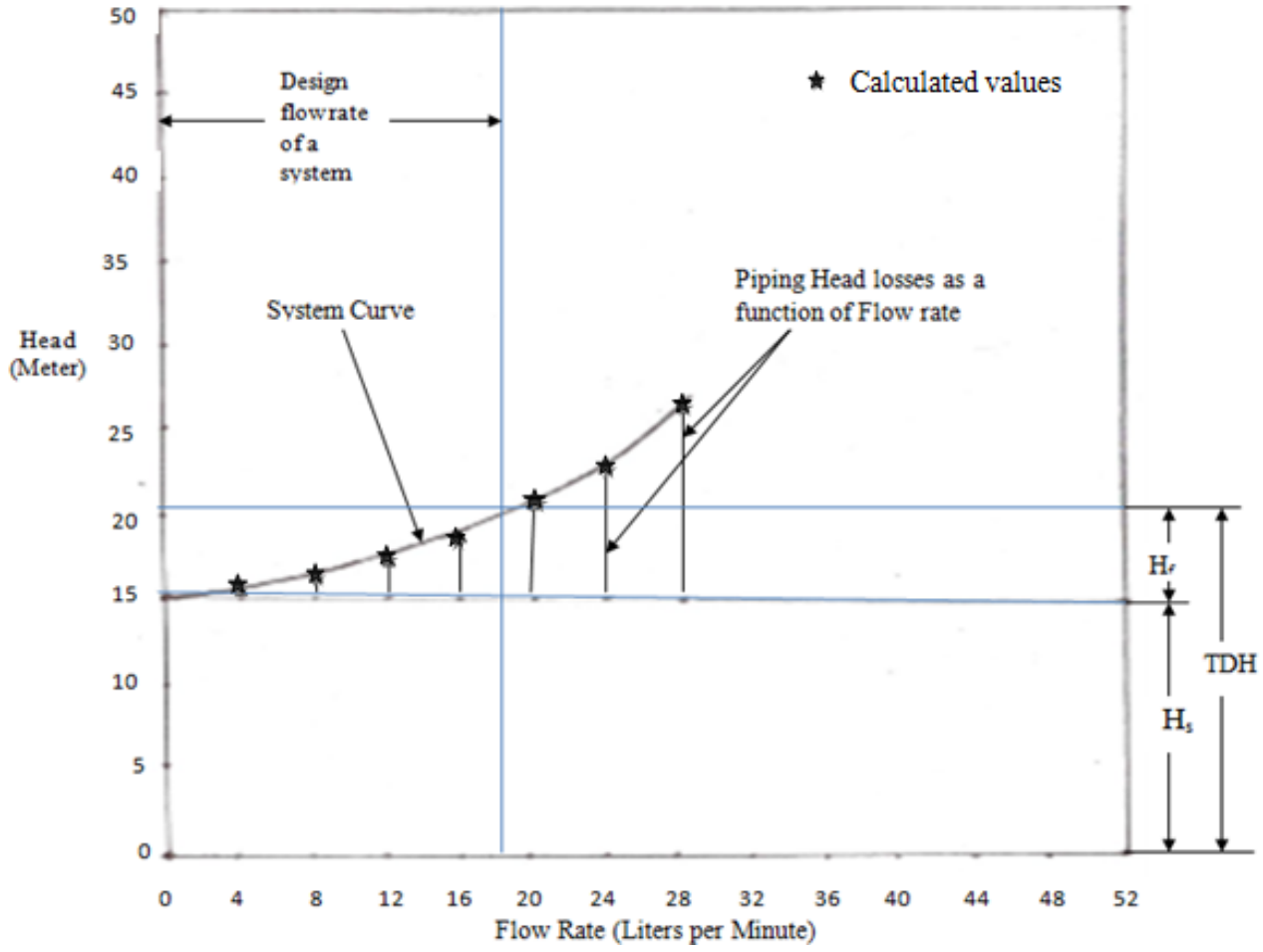


Figure 3-9: Performance characteristics of the Piping system

3.6. Pump Selection

There are two main types of pump commonly used for PV water pumping application. These are positive displacement and centrifugal. Positive displacement types are used in low-volume pumps and cost-effective. Centrifugal pumps have relatively high efficiency and are capable of pumping a high volume of water. From the time when determining irrigation water requirement, the volume is relatively high.

3.6.1. Candidate Pumps for the System

1. Sun pump: - model: SCB10-150-120BL, pump technology: centrifugal, motor type: DC motor brushless, layout: surface. Nominal running conditions: voltage 75V, power 236W, flow rate 2.31m^3/h, efficiency 47.0%, head 21m
2. Dankoff: - model:-centrifugal 7140-24PV, Pump technology: centrifugal, motor type: Dc motor, Nominal running conditions: voltage 24, power 345, flow rate 6.3 m^3/h, efficiency 44.8%, head 18m
3. Shurflo: - model: RV Extreme smart sensor 5.7, pump technology: membrane diaphrame, motor type: DC motor, permanent magnet, lay out surface, Nominal running conditions: voltage 36V, power 123W, efficiency 25%, flow rate 3m^3/h, Head 28.5m

The pump chosen here for its nominal operating condition and cost is candidate number one i.e. SCB 10-150-120BL surface solar pump. It is a pressure booster type centrifugal pump equipped with DC brush less motor and designed for use in standalone water delivery systems, specifically for water delivery in remote locations. Flow rates up to (42LPM) with a total dynamic heads of 28.9*m* (Appendix-G). The rated maximum power consumption is 236W. It operates with voltage (75 V DC).

3.6.2. Performance Characteristics of SCB 10-150-120BL Pump

The fluid quantities involved in all hydraulic machines are the flow-rate (Q) and the head (H), whereas the mechanical quantities associated with the machine itself are the power (P), speed (N), size (D) and efficiency (η). Although they are of equal importance, the emphasis placed on certain of these quantities is different for different pumps. The output of a pump running at a given speed is the flow rate delivered by it and the head developed. Thus, a plot of head and flow rate at a given speed forms the fundamental performance characteristics of a pump. A power input is required which involves efficiency of energy transfer. Thus, it is useful to plot also the power P and the efficiency η against Q.

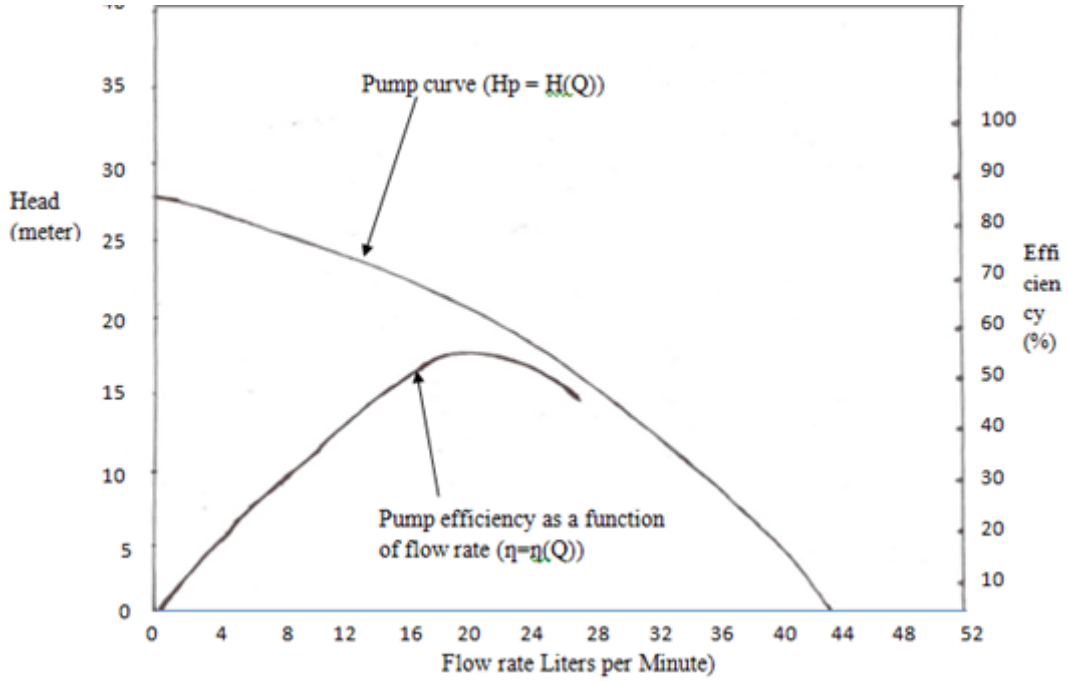


Figure 3-10: Performance characteristics curve of the selected pump

3.6.3. Working Point

Working point is the TDH-flow pair corresponding to the pump function, taking into account the head-losses in the pipe system. When the pump operates, a particular working point is reached, corresponding to the balance between flow and TDH.

To determine this working point in advance, a graph representing the characteristic curve of the pipe system is drawn. This graph is obtained by calculating the head-losses for different theoretical flows in the system (figure 3-9). The intersection point of this curve with the characteristic curve of the pump (figure 3-10) gives the working point of the pump in the pipe system (Figure 3-11). Accordingly, pump flow rate at working point (Qw) =19l/min, pump head at working point (Hw)=21m, and pump efficiency at working point (ηw)=54%.

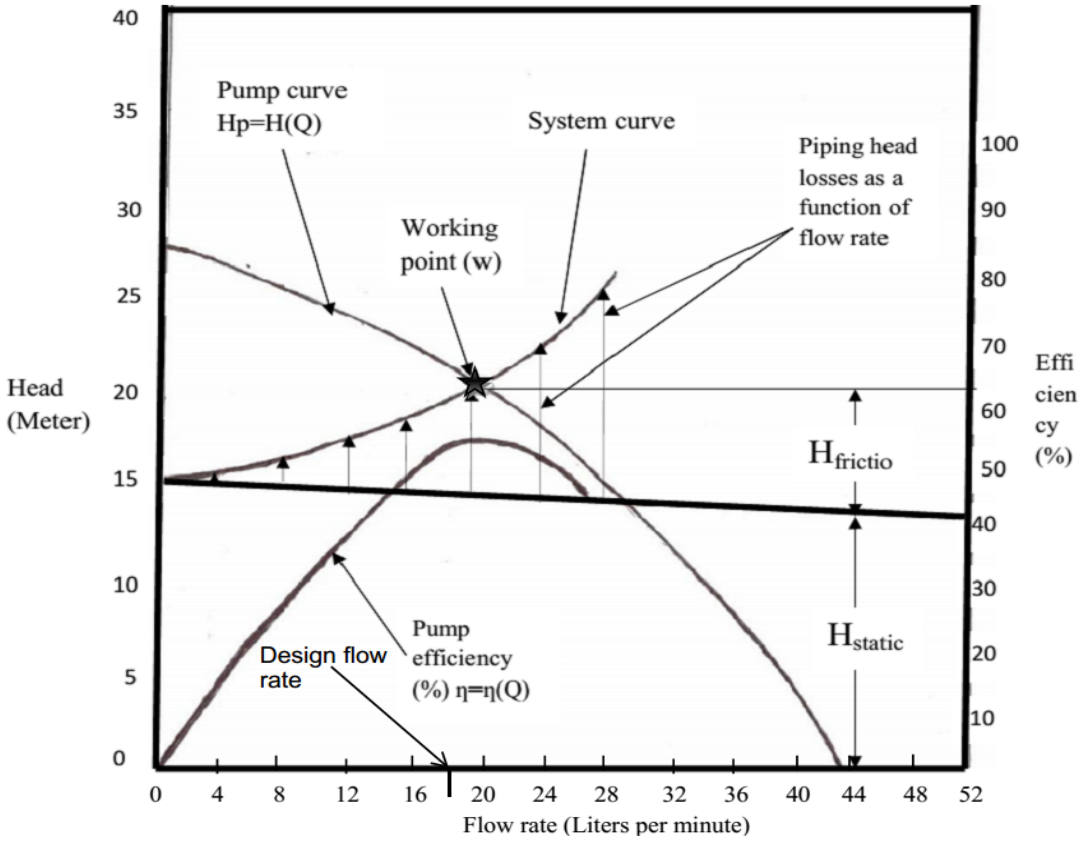


Figure 3-11: System working point

Figure 3-11 shows, the pump flow rate at working point is 19 liters per minute, this value is very close to the design flow rate i.e. 18 liters per minute. This indicates, the selected pump is working in its best operating condition.

3.6.4. Checking for Cavitation

Vapor bubbles will form when the pressure is a pump drops bellows the vapor pressure. If the pressure increases to above the vapor pressure downstream, the bubbles will collapse. This phenomenon is called “cavitation”. Cavitation often occurs in pumps, hydroelectric turbines, pipe valves, and ship propellers

Potential problems are:-

- Physical damage to impellers due to pitting;
- Noise and vibration;
- Reduce efficiency in pumps;
- Reduce flow rate and head in pumps:

3.6.4.1. Net Positive Suction Head (NPSH)

NPSH required is the minimum pressure head at the entrance to the pump, such that cavitation does not occur in the pump. In this case, the required net positive suction head at the entrance to the pump is 2m.

Available NPSH; (NPSHa) is equal to the atmospheric pressure minus all losses in the suction piping (upstream side of the pump), vapor pressure, and velocity head in the suction pipe, and static lift. According to equation 2.1:

$NPSH_a = 8.185m - 0.25m - 0.978m - 2m - 0.051m = 4.90m$

Atmospheric pressure, at 1930 m above mean sea level, h_{atm}=8.185m (Appendix J-2)

Vapor pressure, for water at 20^0c, h_{vapor}=0.25m

Friction loss in the suction piping, h_f=0.978m

Velocity loss, 0.051m

Static suction lift, the center of surface pump is 2m above the water surface

3.6.4.2. Requirement to Avoid Cavitation

- If NPSHr<NPSHa, there would be no cavitation
- If NPSHr=NPSHa, cavitation is impending
- As the available NPSH drops below the required value, cavitation will become stronger, the efficiency will drop, and the flow rate will decrease
- At some point, the pump would “break suction” and the flow rate would go to zero (even with the pump still operating)

The result shows that, available net positive suction head is greater than required net positive suction head. Therefore, cavitation is not a problem in the designed system.

3.6.5. Power Requirement at the Working Point

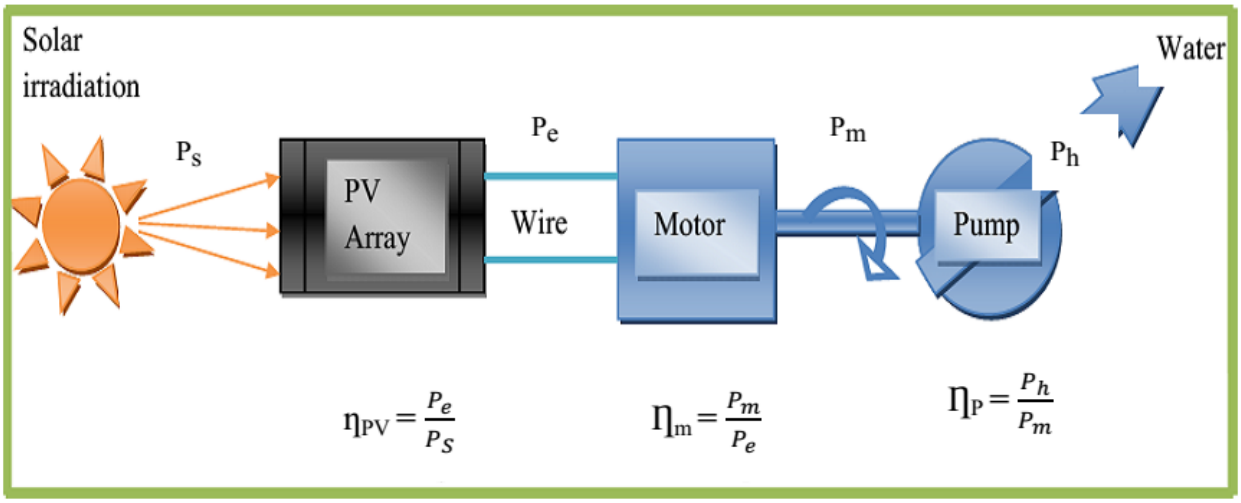


Figure 3-12: Block diagram representation of solar to water system

Where:$P_h = Hydraulic\ power$

$P_m = Mechanical\ power$

$P_e = Electrical\ power$

$\eta_p = pump\ efficiency$

$\eta_m = motor\ efficiency$

The formula calculating the wire-to-water energy efficiency of any solar pumping system:

$$\eta_{syst} = \frac{H_s\,(m) \times Q\left(\frac{L}{min}\right) \times 16}{P_e(W)} \quad \text{..... 3.21}$$

System efficiency at working point= $\frac{21m \times 19l/min \times 16}{229W} = 28\%$

$P_h = \rho g Q_w H_w$

Where:$P_h = Hydraulic\ power\ in\ kWh/day$

$\rho = density\ of\ water = 1000\,\frac{kg}{m^3}$

$g = gravity\ of\ earth = 9.81\,\frac{m}{s^2}$

$Q_w = pump\ flow\ rate\ at\ working\ point\ (m^3/s)$

$H_w = Pump\ head\ at\ working\ point\ (m^3/day)$

For 6.5 sun hour day, $P_h = 1000 \times 9.81 \times 21 \times \frac{7}{3.6\times10^6} = \frac{0.4005KWh}{day} = 65W$

$\eta_{Pw} = \frac{P_h}{P_M}$,

Where, η_{pw} = pump efficiency at working point

$P_M = \frac{P_h}{\eta_{pw}} = \frac{65W}{0.54} = 120W$

Pump efficiency at working point is 54%

System efficiency = pump efficiency × motor efficiency=0.28

From this relationship motor efficiency at working point is: $\eta_{mw} = \frac{0.28}{0.54} = 0.52 = 52\%$

$but, \eta_{Mw} = \frac{P_m}{P_e}$,

Where, η_{mw} is motor efficiency at working point

$P_e = \frac{P_m}{\eta_{mw}} = \frac{120W}{0.52} = 230W$

Sizing of PV array is done based on 230W electrical power

$System\ efficiency = \frac{P_m}{P_e} \times \frac{P_h}{P_m} = \frac{P_h}{P_e} = \frac{65}{230} \times 100\% = 28.26\%$

For any other vertical lifts and flow rates can be calculate using equation 3.21, the result is the same as stated under appendix G. Based on a calculated design flow rate of 18 lpm (rounded 19.7lpm) and a TDH of 21mm (rounded up to 21.1m), in the manufacturer specification, a minimum input of 229 motor Watts and solar array watt of 286 power is required, this is the same as the above calculated value.

3.7. Sizing of PV system

Sizing of photovoltaic system is based on the worst operating condition. From Table 3-9 it was cleared that for December the ratio of water requirement to solar radiations was largest and according to Table 2-2, for the average day of the month the recommended date is 10^{th} day.

Therefore, December 10 i.e. N=344 is chosen for PV sizing, and the declination angle can be calculated using equation 2.3

$\delta = 23.45 \sin[\frac{360}{365}(284 + 344)] = -23$, as shown in Table 2-2.

Hour angle ω and solar time ST in hour is related as equation 2.5:

Considering 1:30 PM for the selected site:

$\omega = (13{:}30 - 12) \times 15^0 = 22.5^0$

For horizontal surface, zenith (θz) can be calculated using equation 2.6

$\cos \theta z = \cos \phi \times \cos -23^0 \times \cos 22.5^0 + \sin -23^0 \times \sin \phi$

Where, the latitude ϕ of the site is 8.17^0

$\theta z = 38.57^0$

The relationship for the angle of incidence of surfaces sloped due north or due south can be derived from the fact that surfaces with slope β to the north or south have the same angular relationship to beam radiation as a horizontal surface at an artificial latitude of $(\phi - \beta)$

$\cos \theta = \cos \delta \times \cos \omega \times \cos (\phi - \beta) + \sin \delta \times \sin (\phi - \beta)$ 3.22

$\cos \theta = \cos (-23) \times \cos 22.5 \times \cos (8.17 - 8.17) + \sin (-23) \times \sin (8.17 - 8.17)$

$\theta = 31.74^0$

3.7.2. Estimation of Solar Radiation

The solar radiation passing through the atmosphere and reaching the earth's surface is classified into two components:

- **Beam radiation Ib**: is the solar radiation propagating along the line joining the receiving surface and the sun. It is also referred to as direct radiation.
- **Diffuse radiation Id**: is the solar radiation scattered by aerosols, dust and molecules. It does not have a unique direction.

The total radiation I: is the sum of the beam and diffuse radiation and is sometimes referred to as the global radiation

3.7.2.1. Estimation of Clear Sky Radiation on Horizontal Surface

Hottel, et. al. (1976) presented a simple model for the estimation of the transmittance of beam radiation in clear sky conditions. The input needed are the altitude of the location A in km above

mean sea level, day number of the year N and the zenith angle (θz). Combined with the Liu and Jordan's model for the transmittance of diffuse radiation through clear skies, the clear sky beam and diffuse radiation can be easily computed.

The clear sky beam radiation on a horizontal surface is:

$I_{b=}I_n\tau_b\cos\theta_z$ ..... 3.23(a)

Where: $I_n = I_{sc}[1.0 + 0.033\cos\left(\frac{360\,N}{365}\right))$

$= 1367 w/m^2[1.0 + 0.033\cos\left(\frac{360\,(344)}{365}\right) = 1409\ w/m^2$

$\tau_b = a_0 + a_1 e^{(-k/\cos\theta_z)}$ ..... 3.23(b)

$a_o = a_o^* r_o, a_1 = a_1^* r_1, k = k^* r_k$

Where,

$a_o^* = 0.4237 - 0.00821(6 - A)^2$

$a_1^* = 0.5055 + 0.00595(6.5 - A)^2$

$k^* = 0.2711 + 0.01858(2.5 - A)^2$

$r_o = 0.95, r_1 = 0.91, r_k = 1.02,$

A is altitude of the location in km above mean sea level

$a_o^* = 0.4237 - 0.00821(6 - 1.93)^2 = 0.2877$

$a_1^* = 0.5055 + 0.00595(6.5 - 1.93)^2 = 0.63$

$k^* = 0.2711 + 0.01858(2.5 - 1.93)^2 = 0.277$

Therefore,

$a_o = a_o^* r_o = 0.2877 \times 0.95 = 0.2733$

$a_1 = a_1^* r_1 = 0.63 \times 0.91 = 0.5733$

$k = k^* r_k = 0.277 \times 1.02 = 0.28254$

Substitute the values into equation 3.23(b) gives:

$\tau_b = 0.2733 + 0.5733 e^{(-0.28254/\cos 38.57^0)} = 0.58873$

Then using equation 3.23(a) to calculate beam radiation

$I_b = 1409 w/m^2 \times 0.58873 \times \cos 38.57^0 = 648.55 w/m^2$

The transmittance of diffuse radiation through clear skies can be estimated from the beam radiation transmittance based on the study of Liu and Jordan:

$\tau_d = 0.271 - 0.2939\tau_b = 0.271 - 0.2939 \times 0.58873 = 0.07$

The clear sky diffuse radiation is:

$$I_d = I_n \tau_d \cos\theta_z \quad \text{..... 3.24}$$

$$I_d = 1409 \times 0.07 \times \cos 38.57^0 = 77.11 \text{w/m}^2$$

Therefore, the total clear sky radiation on a horizontal surface could then be estimated as:

$$I_T = I_b + I_d \quad \text{.....3.25}$$

$$I_T = 648.55 + 77.11 = 725.66 \text{ w/m}^2$$

3.7.2.2. Estimation of Solar Radiation on Inclined Surface

The following formula was given by Liu and Jordan (1962), for evaluating the total radiation on a surface of arbitrary orientation from knowledge of beam and diffuses radiation on horizontal surface.

$$I_T = I_b R_b + I_d R_d + r R_r (I_b + I_d) \quad \text{..... 3.26}$$

Where:

r = reflectivity of the ground = 0.2.

Rb, Rd and Rr are known as conversion factors for beam, diffuse and reflected components respectively.

The expressions for these are as follows:

Rb: is defined as the ratio of flux of beam radiation incident on an inclined surface to that on a horizontal surface. The flux of beam radiation incident on a horizontal surface (Ib) is given by:

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\cos 31.74^0}{\cos 38.57^0} = 1.08$$

Rd : is the ratio of the flux of diffuse radiation falling on the tilted surface to that on the horizontal surface. This conversion factor depends on the distribution of diffuse radiation over the sky and on the portion of sky seen by the surface.

$$R_d = \frac{1+\cos\beta}{2} = \frac{1+\cos 8.17^0}{2} = 0.995$$

Rr: The reflected component comes mainly from the ground and other surrounding objects.

$$R_r = \left(\frac{1-\cos\beta}{2}\right) = \left(\frac{1-\cos 8.17^0}{2}\right) = 5 \times 10^{-3}$$

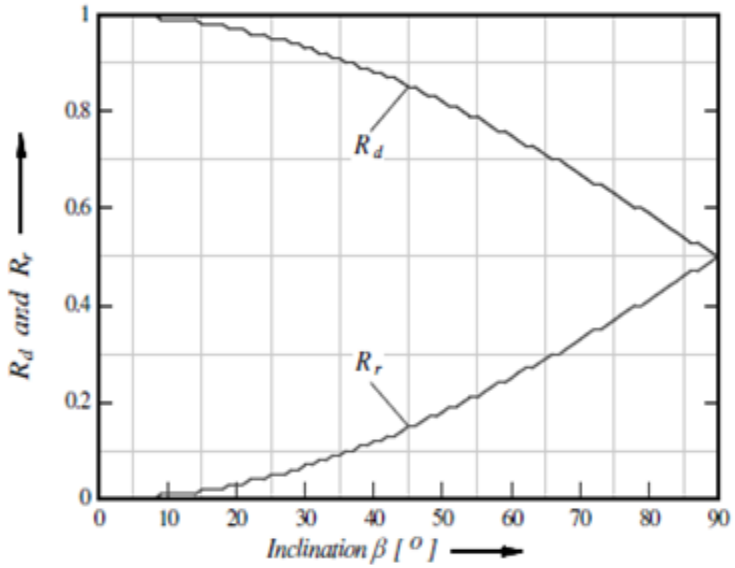


Figure 3-13: Variation of Rd and Rr with inclination

In this case ($\beta = 8.17^0$), Rd=0.995 and Rr = 5×10^{-3}

This indicates that small slop planes receive little reflected radiation and more deflection radiation.

Using equation 3.26 to determine solar radiation on inclined surface:

$I_T = 725.66 \times 1.08 + 77.11 \times 0.995 + 0.2 \times 5 \times 10^{-3}(725.66 + 77.11)$

$I_T = 861.226\ w/m^2$

The above calculations are repeated for other hours, and the results are given in the Table3-7.

Table 3-7: Estimated hourly solar resource of the site for December 10.

Time	Beam (w/m^2)	Diffuse (w/m^2)	Global (w/m^2)	Hour angle $\omega(^0)$	Calculated rad. on inclined surface (w/m^2) at $\beta=8.17^0$
9 AM	545.39	67.15	612.54	-45	657.81
10 AM	602.32	74.55	676.87	-30	725.93
11 AM	702.09	78.05	780.14	-15	836.87
12 AM	736.30	79.32	815.62	0	874.98
1:30PM	725.66	77.11	802.77	22.5	861.22

The Estimation of solar resources can be alternatively performed with the software Cropwat. Both methodology indicates that, the site is blessed with good solar radiation levels, varying from a daily average of 3.92kWh/m^2 in the least irradiated month to 5.82kWh/m^2 in those months with best solar irradiance. Irradiance reaches highest levels during the months of October to May, peaking in March at 176.08kWh/m^2 per month. The monthly average solar radiation is shown in figure 3-14.

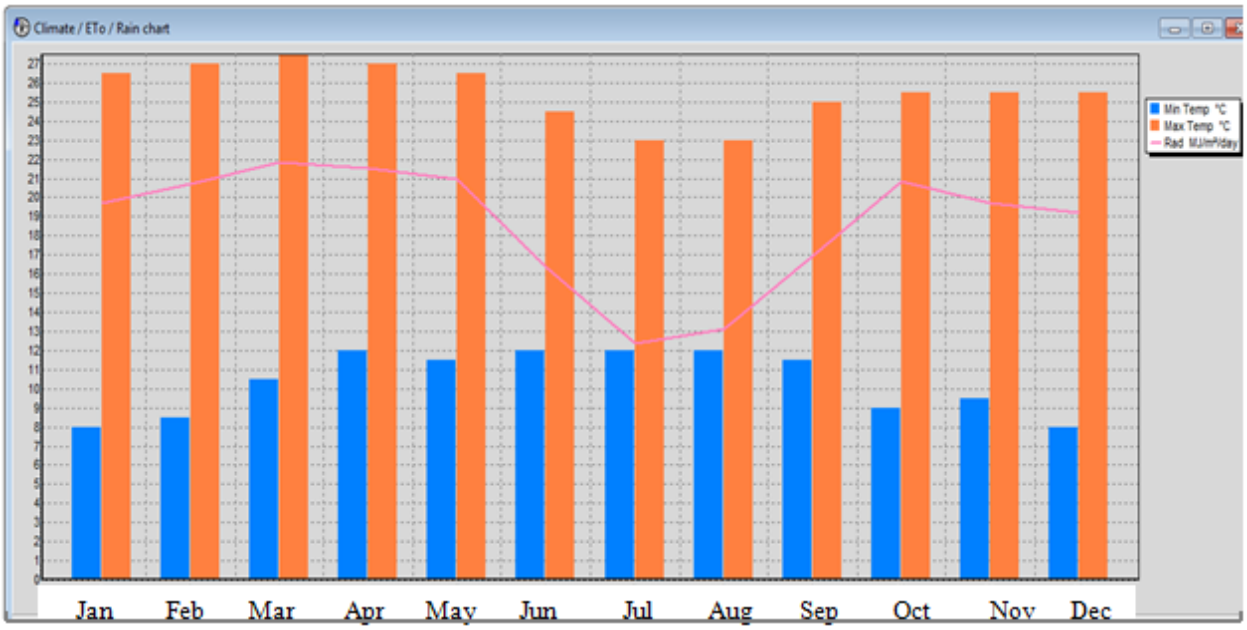


Figure 3-14: Simulated solar radiation of the site

The decision of which approach to use to determine the peak sun hours to base the system design on is up to the decision of the designer and should be based on good engineering judgment. There are several different ways to assess the number of peak sun hours to use when designing the system. The designer may select to use the peak sun hours for the month that generates the most as that month would most likely correlate with the month in which the operation's water need is greatest. Or the designer may select to use the peak sun hours for the month that generates the least number of peak sun hours for added insurance. For this work using the average of all months will be used, in which 6.5 peak sun hours per day (Table 3-2).

Table 3-8: Month wise Average Solar Radiation Data (kWh/m^2/day)

Month	Average solar Radiation kwh/(m^2 day)			
	On Horizontal Surface			On Inclined Surface (at $\beta = 8.17^0$)
	Cropwat (local metro. data)	RETscreen (NACA)	Average	
Jan	5.47	5.43	5.45	5.72
Feb	5.75	5.82	5.78	6.07
Mar	6.00	5.37	5.68	5.96
Apr	6.00	5.64	5.82	6.11
May	5.83	5.39	5.61	5.81
Jun	4.55	4.87	4.71	4.94
Jul	3.44	4.41	3.92	4.12
Aug	3.63	4.64	4.13	4.33
Sep	4.72	5.21	4.96	5.21
Oct	5.8	5.39	5.60	5.87
Nov	5.47	5.40	5.43	5.70
Dec	5.33	5.41	5.37	5.64
Average	5.166	5.248	5.20	5.46

3.7.3. Ratio of Water Requirement to Solar Radiation (Wr/Sr)

The calculation is made on considering the worst operation condition that is less amount of rain fall is available at this season (figure 3-2), as a result the designed system satisfies the rest irrigation season. From Table 3-9 it was cleared that for December the ratio of water requirement to solar radiations was largest therefore daily solar radiation of 5.33kWh/m^2 and water requirement of 91.5 mm/dec were considered for optimum PV array sizing.

Table 3-9: Ratio of Water Requirement to Solar Radiation (for first irrigation season)

month	Irrigation requirement (irr_r) mm/dec	Solar radiations available (s_r) (kwh/m^2/day)	Ratio of water requirement to solar radiations (Irr_r/s_r)
Oct	1.3	5.87	0.221
Nov	48.2	5.70	8.46
Dec	91.5	5.64	16.22
Jan	44	5.72	7.69

3.7.4. Module Selection

The PV panels selected for this system must be able to provide the minimum energy requirement to run the pump. As determined in Section 3.6.5., the minimum power needed is 223 Watts. However, the panels must also have additional capacity to account for any potential reduction in power due high heat, dust, age, etc. Many PV manufacturers recommend increasing the minimum peak power value by 25% to account for these environmental factors. Therefore, the PV panels will be sized to provide a minimum output of 279 Watts.

3.7.5. Candidate Modules for the System

1. Generic: - model: 190 Wp 54 cells, nominal power 190.0 Wp technology: Si poly ISc 7.820A, Impp 7.250A, Voc 32.80v, Vmpp 26.2v, temperature coefficient=0.05 %/^{o}c, module efficiency 12.92%
2. BP Solar: -model: BP7180 S, nominal power 180 Wp, technology crystalline silicon, ISc 5.3A, Impp 5A, Voc 44.2V, Vmp36V, temperature coefficient 0.05%/^{o}c, module efficiency 14.3%.
3. Mitsubishi: -model: PV-UD180mfs, nominal power: 180 Wp, technology: Si poly, ISc 8.03A, Impp 7.45A, Voc 30.4V, Vmpp24.2V, temperature coefficient 0.03%/^{o}c, module efficiency 13.6%.

Candidate number two i.e. BP Solar BP 7180 S Saturn technology module, is selected for this purpose because of its best efficiency and better temperature coefficient. It provides reliable photovoltaic power operating DC loads directly or, in an inverter-equipped system. With 180 watts of nominal maximum power, the BP 7180 S is used in utility-grid supplemental systems

for residences, commercial buildings, and centralized power generation and in remote systems for applications including telecommunications, pumping and irrigation, remote villages and homes, and land-based aids to navigation [23].

Table 3-10: Electrical and mechanical characteristics of the selected PV module (23)

Electrical characteristics	**BP 7180 S**
Maximum power (P_{max})	180W
Power tolerances	-3%/+5%
Number of cell	72
Voltage at P_{max} (V_{mp})	36 V
Current at P_{max} (I_{mp})	5 A
Open-circuit voltage (V_{oc})	44.2 V
Short-circuit current (I_{sc})	5.3 A
Temperature coefficient of I_{sc}	0.065±0.015%/^{o}c
Temperature coefficient of V_{oc}	-160± 20 mV/^{o}c
Temperature coefficient of power	±0.05%/^{o}c
NOCT	47±2^{o}c
Series fuse rating	15A
Peak efficiency	14.3 %
Mechanical characteristics	
type	Polycrystalline silicon
Output terminal type	Multi contact connector type 3
Frame color	Clear
length	1.593 m
width	0.80 m
depth	0.05m
weight	15.9 kg
Installation method	Rack-mounted
80% power output warranty period 25 years	

3.7.5.1. Module I-V Characteristics

Figure 3-15 shows the plots of *I-V* characteristics at various solar radiations model BP 7180 S PV module. Data points superimposed on the plots are taken from the *I-V* curves published on the manufacturer's datasheet [23].

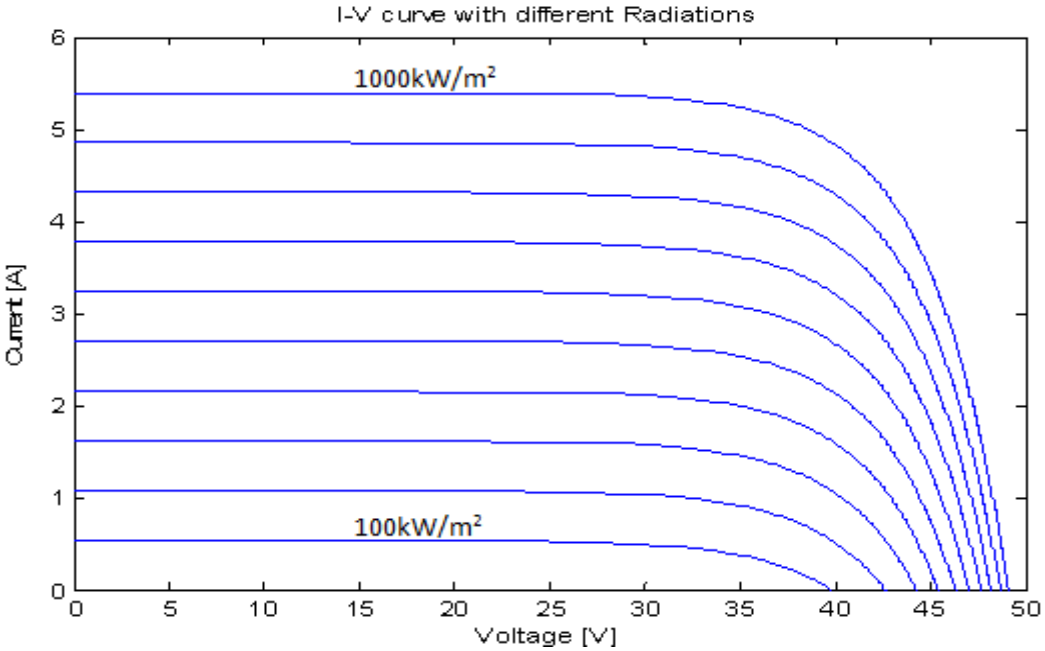


Figure 3-15: Current-voltage curve of the selected PV module for different solar radiations

I-V curve of module with different solar radiations shown in the above figure (from 100kW/m^2-1000kW/m^2 solar radiations) other electrical characteristics are taken from Table 3-10 MATLAB functions are presented in Appendix C-1.

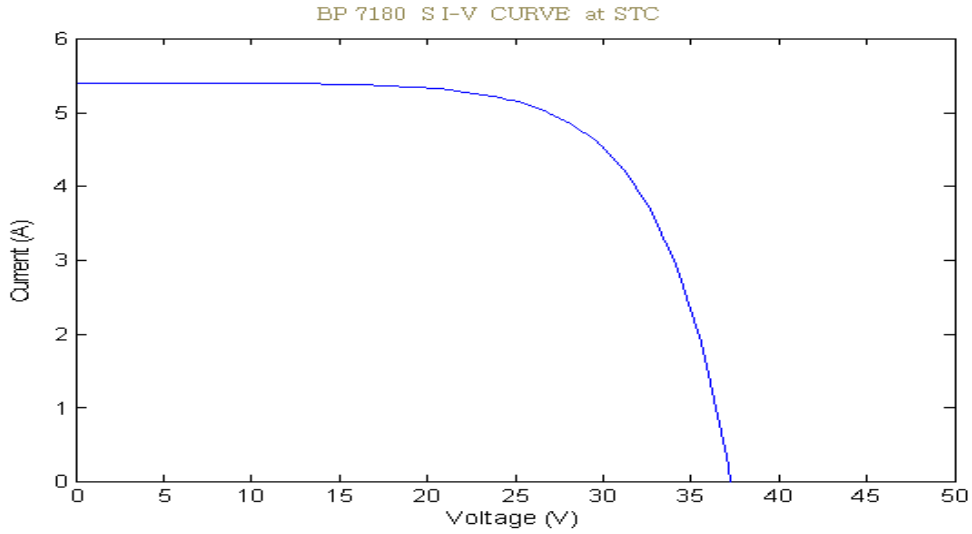


Figure 3-16: I-V curve of BP 7180 S module at STC using MATlab

3.7.5.2. I-V Curve and Maximum Power Point

Figure 3-18 shows the *I-V* curve of the BP 7180 S PV module simulated with the MATLAB model. A PV module can produce the power at a point, called an operating point, anywhere on the *I-V* curve. The coordinates of the operating point are the operating voltage and current. There is a unique point near the knee of the *I-V* curve, called a maximum power point (MPP), at which the module operates with the maximum efficiency and produces the maximum output power. It is possible to visualize the location of the by fitting the largest possible rectangle inside of the *I-V* curve, and its area equal to the output power which is a product of voltage and current.

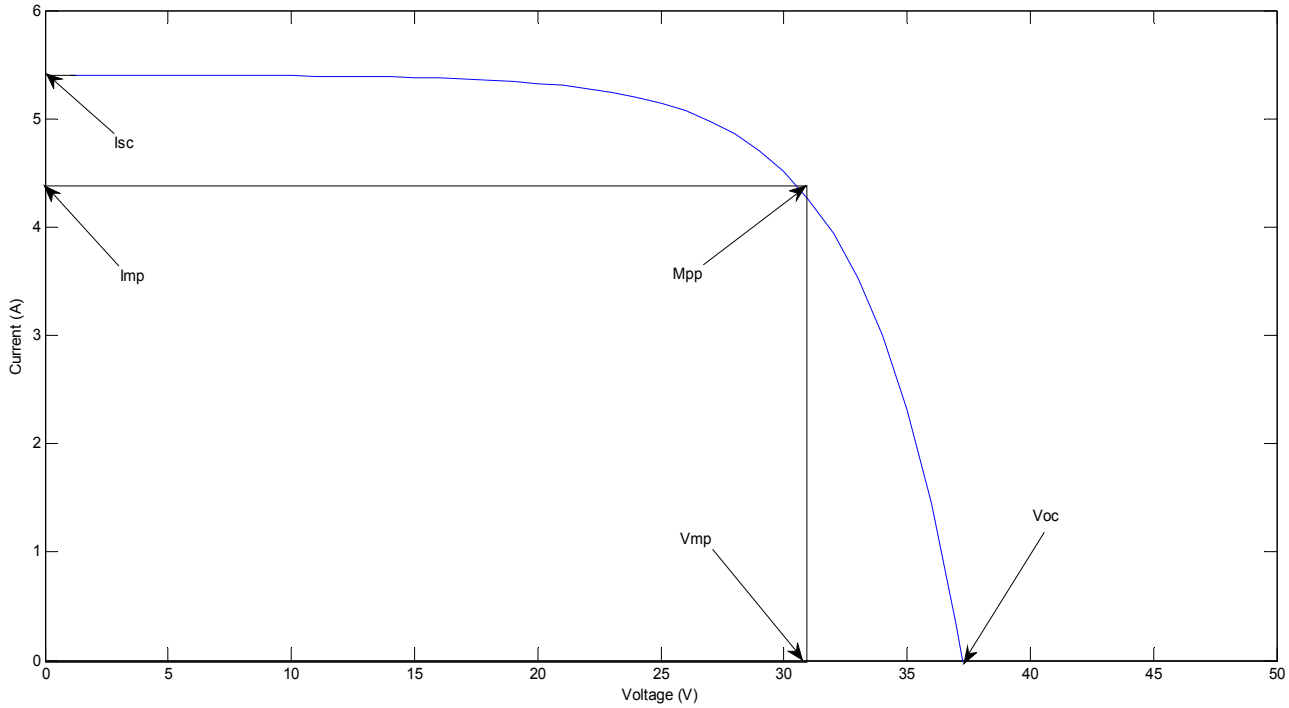


Figure 3-17: Simulated I-V curve of BP 7180 S PV module and its MPP.

The global formula to estimate the electricity generated from a photovoltaic system is:

$E = A \times r \times H \times PR$ 3.27

For this work the solar panel yield of a PV module of 180Wp with an area of 1.26 m² is 14.30%.

H = Annual average solar radiation on tilted panels

PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9,

r: is the yield of the solar panel given by the ratio : electrical power (in kWp) of one solar panel divided by the area of one panel.

Now substitute all the values in to equation 3.27 gives the actual energy output.

$$E = 1.26m^2 \times 0.16 \times \frac{6KWh}{m^2} \times 0.85 = 0.9575\ kWh$$

Taking the average site's sun hour=6.5h

$$E = 0.1473kW = 147W$$

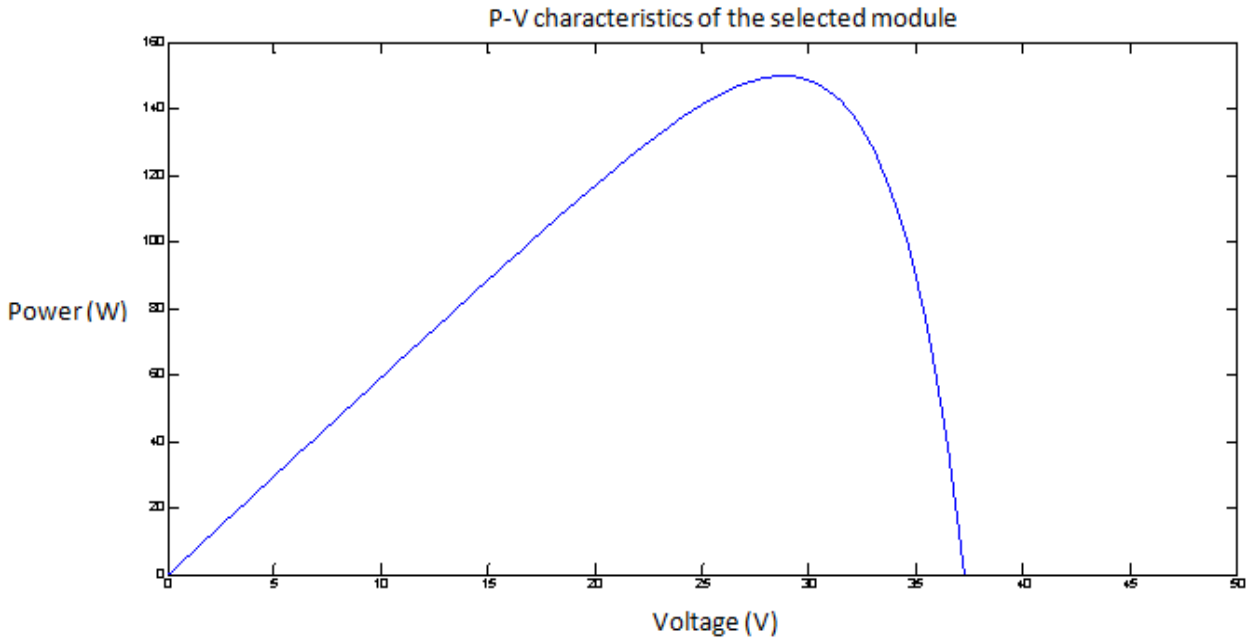


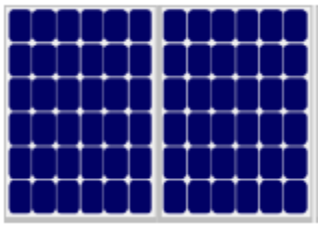
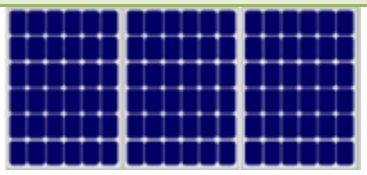
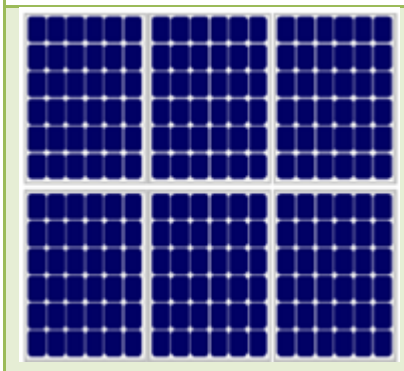
Figure 3-18: Power-Voltage characteristics of module

3.7.6. Array Layout

The final stage is deciding on the solar array connections and how to make the interconnections in order to achieve the desired voltage and current.

Connecting the panels in series adds up the voltages of the panels while keeping the current fixed. While parallel connections add up the current while keeping the voltage fixed.

Table 3-11: Module connections in parallel and series

Panel connection	connections	Voltage	current
	none	44.2	5.3
	Series	88.4	5.3
	Parallel	44.2	10.6
	Series	132.6	5.3
	Parallel and series	132.6	10.6

Two panels are required to meet the pump's power requirement. They will be wired in series to provide the necessary voltage for the pump.

3.7.6.1. Electrical Connection of Modules

Solar panels have a negative (-) and a positive terminal (+) similar to the terminals on a battery. PV panels are wired in series by connecting the negative terminal of one panel to the positive terminal of the next panel as shown in Figure 3-19. When panels are wired in series, the panel voltages are added.

If the panel has the characteristics shown in Table 3-10, the resultant voltage output for panels shown in Table 3-11 is:- $44.2 + 44.2 = 88.4v$. The current output would be the same as for an individual panel or 5.3 A.

The manufacturer declares that two BP 7180 S PV array can produce under standard test condition is 360W, that is a constant 1000W of solar irradiation per square meter in the plane of the array, at an array temperature of 25° C. and AM=1.5.This power output is cannot be found in the real condition. The actual power output of PV panel (using equation 3-27) is 294W; each panel can produce 147W as calculated in section 3.10.3.

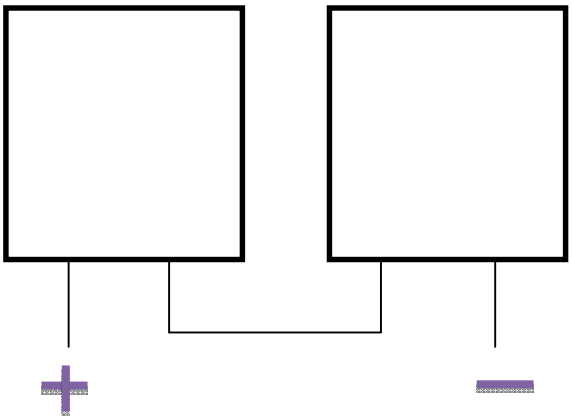


Figure 3-19: Solar panels wiring in series

3.7.7. PV Array Mounting

The main purpose of mounting structure is to hold the modules in a required position without stress. Metallic structures are normally used to hold the panels; these structures are designed to withstand high winds and stormy weather. The structure itself needs to be properly coated and protected against environmental factors such as rain, humidity, and other conditions. Since site conditions permit (i.e. the depth of embedment is not limited by shallow bedrock) and the site is located in less than the recommended design wind speed tolerance i.e. 85 mph.

3.7.7.1. Tilt Angle and Orientation

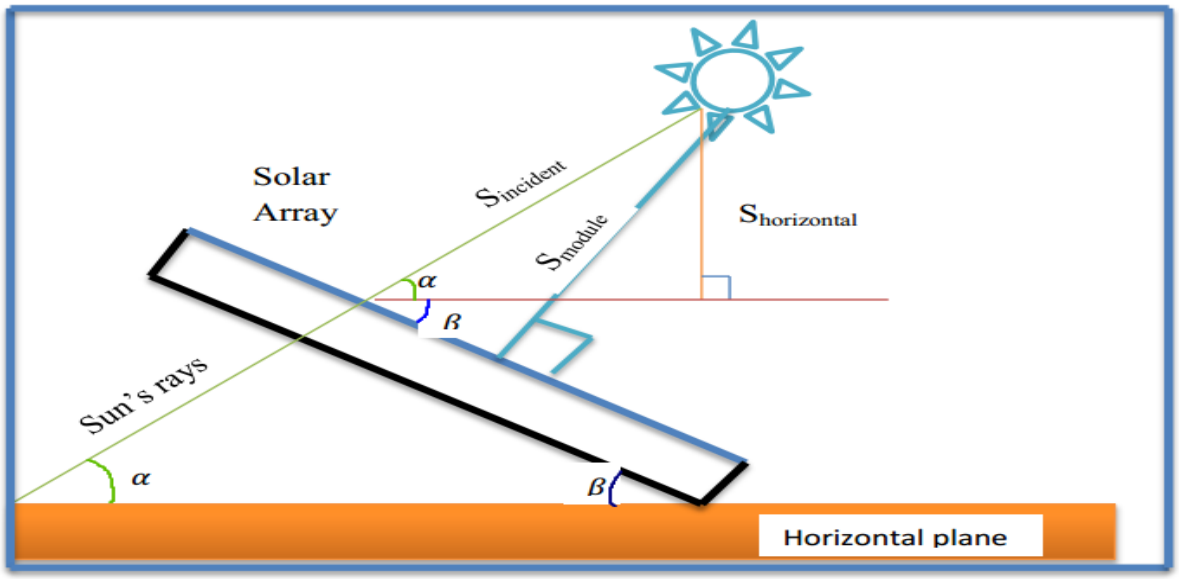


Figure 3-20 Orientation of PV Array

The orientation of the module with respect to the direction of the sun determines the intensity of the sunlight falling on the module surface. Two main parameters are defined to describe this. The first is tilt angle (β), which is the angle between the plane of the module and the horizontal. The second parameter is the azimuth angle, which is the angle between the plane of the module and due south (or sometimes due north depending on the definition used).

The optimum array orientation will depend on the latitude of the site, prevailing weather conditions and the loads to meet. It is generally accepted that, for low latitudes, the maximum annual output is obtained when the array tilt angle is roughly equal to the latitude angle and the array face due south (in the northern hemisphere).

The tilt angle was selected in accordance with the latitude of the location. Latitude of the site is 8° 17' N, therefore solar PV array was tilted at this angle.

3.8. Pumping Control Mechanism

The controller plays a vital role in the system performance due to match the power produced by the panels with that required by the pump.

The Sun Pumps PCC-BLS-M2 series controllers were designed specifically for Sun Pumps sensor less brushless three phase DC pumps. When properly installed and configured, the unique

features incorporated into this stand-alone system will automatically control and protect the pump system permitting many years of dependable.

3.8.1. Automatic Control for Full-Tank Shutoff

The pump's operation can be controlled by the use of a float switch in the storage tank, acting automatically when a defined water level is reached in the tank [5].

Water pumped will be greater than our daily requirements on any full sunny day. This is typically not an issue when float switches are incorporated into storage systems, which will stop the pumping when the tank is full then reset when the level drops. It's similar to the float in a toilet tank but is wired to the pump controller. This conserves water source, prevents overflow, and eliminates unnecessary pump wear.

SPDT float switch can be used to control a pump in tank filling or tank emptying operations. Contacts in the float switch at 12 degrees above or below horizontal. A pipe clamp secures the cable to something in the tank. The length of cable from the clamp to float determines the difference between turn-on and turn-off level. Maximum current is 5 amps. For larger pumps, use this float switch to turn a relay on and off and let relay contacts control the pump. Item no. 75-111 Float Switch controllers allow the use of small signal cable to a remote float switch, even if the tank is a long distance away.

Float switch cable requirements

1. Two wires are needed.
2. Minimum wire size #18 AWG (1mm²). This is good for a distance as far as 600m.
3. The cable must be suitable for its environment.
4. If it must run a long distance, use twisted-pair shielded cable to reduce the chance of damage from lightning-induced surge.

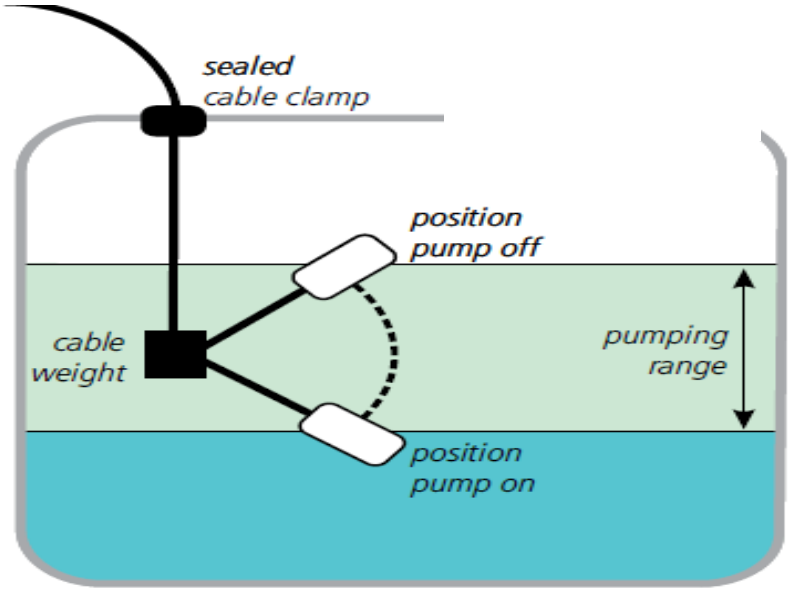


Figure 3-21: Typical pumping range [7]

3.9. Other Considerations

Energy efficiency factors must be carefully considered while designing photovoltaic water pumping system if you want to get the best out of your efforts.

3.9.1. Cable Thickness

While the size and length of the cables is a matter of system design and installation. Thus cable length and size needs careful attention right at the planning stage. Likewise, there would be wiring all round and careful attention must be paid to know the impact on overall system efficiency. Selecting the correct size and type of wire when connecting the pump to the controller or solar panels increases the performance and reliability of the system. PV-direct systems, AWG #10 wire to maximum distance of 10 m, 4.77 mm^2 is selected for this work.

3.9.2. Power Loss in Transmission Wires

The solar array produces power that is driven by a DC voltage at a relatively high current. Because the array is located at a distance from the load some voltage drop is experienced due to resistance in the transmission wires. The power dissipated by a resistor is given by the relation,

$$p_{loss} = I^2R \quad \text{3.28}$$

Where: I is the current through the resistor

R is the resistance.

$V = IR$ 3.29

In general, the resistance of a cylindrical conductor increases with length and decreases as the diameter of the conductor increases. The resistance of a length of wire depends on these two properties and also on the material that the wire is made of. In this application Medium hard-drawn solid copper wire will be used to transmit power from the solar array to the pump.

The length of wire required completing a circuit between the solar array and the pump is 15 m. The transmission wire for the pump is size AWG #12which has a resistance of 5.6 ohms per Kilo meter of wire length (Appendix-F). The total resistance of the transmission wire is $0.084\Omega$and the power loss through the wire by Equation 3.28 is $2.45W$ corresponding to a voltage drop of $0.4536V$ or 0.52% of voltage drop, it is acceptable.

3.9.3. Shading

Ideally solar panels should be located such that there will never be shadows on them because shading of any part will reduce its output, but this reduction will vary in magnitude depending on the electrical configuration of the array. Clearly, the output of any cell or module which is shaded will be reduced according to the reduction of light intensity falling on it. However, if this shaded cell or module is electrically connected to other cells and modules which are un-shaded, their performance may also be reduced.

3.9.4. Distance of the Panel from the Ground Level

It avoids hot spots, which is a major factor that affects the efficiency. Therefore the distance of panel from the ground should be at optimum distance.

3.10. Operation Guidelines

- The pump should be switched off when not in operation;
- Priming the Pump, Priming a pump means filling its intake and suction line completely with water. This must be done if the pump is mounted higher than the water source. A removable plug or a valve must be installed at the highest point is in the suction plumbing. Prime the pump and intake line by pouring water into the opening until it is completely full. Your foot valve prevents loss of prime by not allowing water to flow back into the water source;
- The pump should be properly mounted and fixed on the base-plate to withstand vibrations and avoid unwanted noise that could also reduce the lifetime of the pump;
- Pump should be covered adequately for weather protection. In a pump pit with adequate air venting system;
- Surface pumps are not water proof and need to be kept away from water and protected from environmental conditions to prolong their lifetime and reduce maintenance requirements;
- The pump should not be switched on and off too often. There should be at least 15 seconds between a switch off and a switch on;
- Sharp bends should be avoided in the pipe lines to avoid unnecessary pressure drops;
- The cover of the main junction box should not be left open;
- No loose wire should be un-insulated;
- Distance between the pump and the PV panels should be kept to a minimum to reduce voltage drop in the cables;
- In most cases, it can be assumed that 3-5% of performance will be lost if the system is only cleaned annually, with up to half of that loss being experienced within a few weeks of cleaning:
- The amount of maintenance required by solar pumping systems depends on the type and complexity of the system. While PV panels generally require very low maintenance (they must stay clean), pumps, batteries and other components require periodic routine maintenance. Most failures of solar pumping systems are caused by pump problems. Sand and silt pulled in by the pump are the primary cause of failure. Filtering out silt or sand at the pump intake with fine mesh screen will prolong the life of the pump.

CHAPTER FOUR

4. System Simulation

4.1. Introduction

System simulation is used to show the eventual real effects of alternative conditions and courses of action. Simulation is also used when the real system cannot be engaged, because it may not be accessible, or it may be dangerous or unacceptable to engage, or it is being designed but not yet built, or it may simply not exist. After designing and sizing all components and sub system, the entire system is simulated with the help of PVsyst.

4.2. Input parameter for PVsyst

4.2.1. Geographical and Metrological Data

The meteorological data are the starting point of the evaluation of a project. But, also the main source of uncertainty.

PVsyst holds a limited metrology internal data base of about 300 sites in the world, but gives an easy access to several public sources directly available from the Web. Data of other providers like national meteorological offices may also be imported using a flexible importing tool. A geographical site is defined by: Its name, country, and world region,

Its geographical co-ordinates: latitude, longitude, altitude (which uniquely define the (x ,y ,z) coordinates of a given point of the earth), and the time zone, for Ethiopia, the time corresponds to GM T+3, (figure 4-1) the sun paths corresponding to the site is found in Appendix K-1.

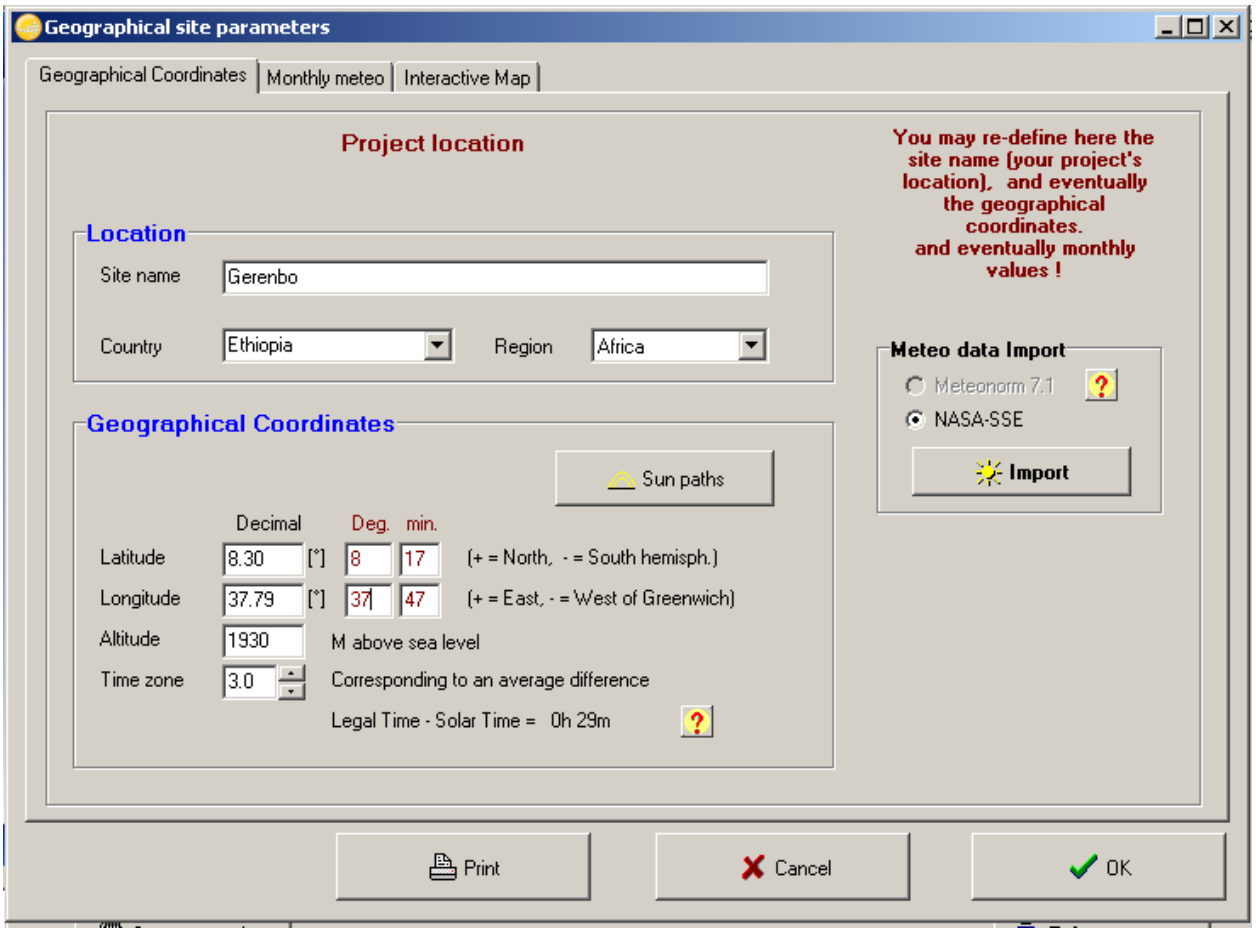


Figure 4-1: Project location

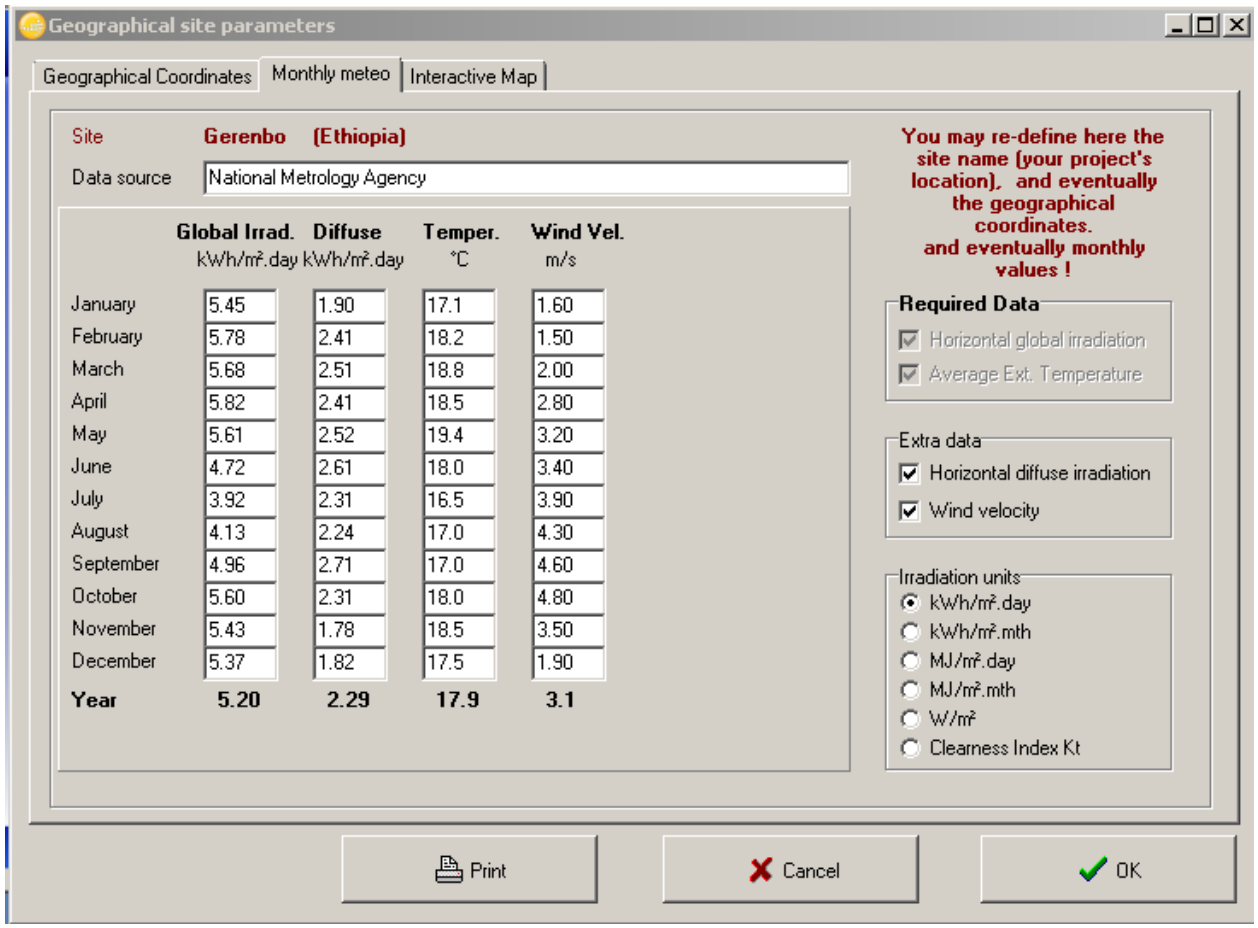
Monthly meteorological data, to be used in the simulation, the minimum meteorological data should include: (Table 4-1)

- the monthly Global horizontal irradiation;
- Monthly averages of the ambient temperature.

The file may also include the optional data:

- Monthly Diffuse horizontal irradiation
- Monthly average of wind velocity.

Table 4-1: Climatic data for Gerenbo used in PVsyst software.



4.2.2. Plane Orientation

The orientation of the module with respect to the direction of the sun determines the intensity of the sunlight falling on the module surface. Two main parameters are defined to describe this. The first is tilt angle and the second parameter is the azimuth angle.

The optimum array orientation will depend on the latitude of the site, prevailing weather conditions and the loads to meet. Figure 4-2: shows defined system speciation in order to gain the highest output from the system.

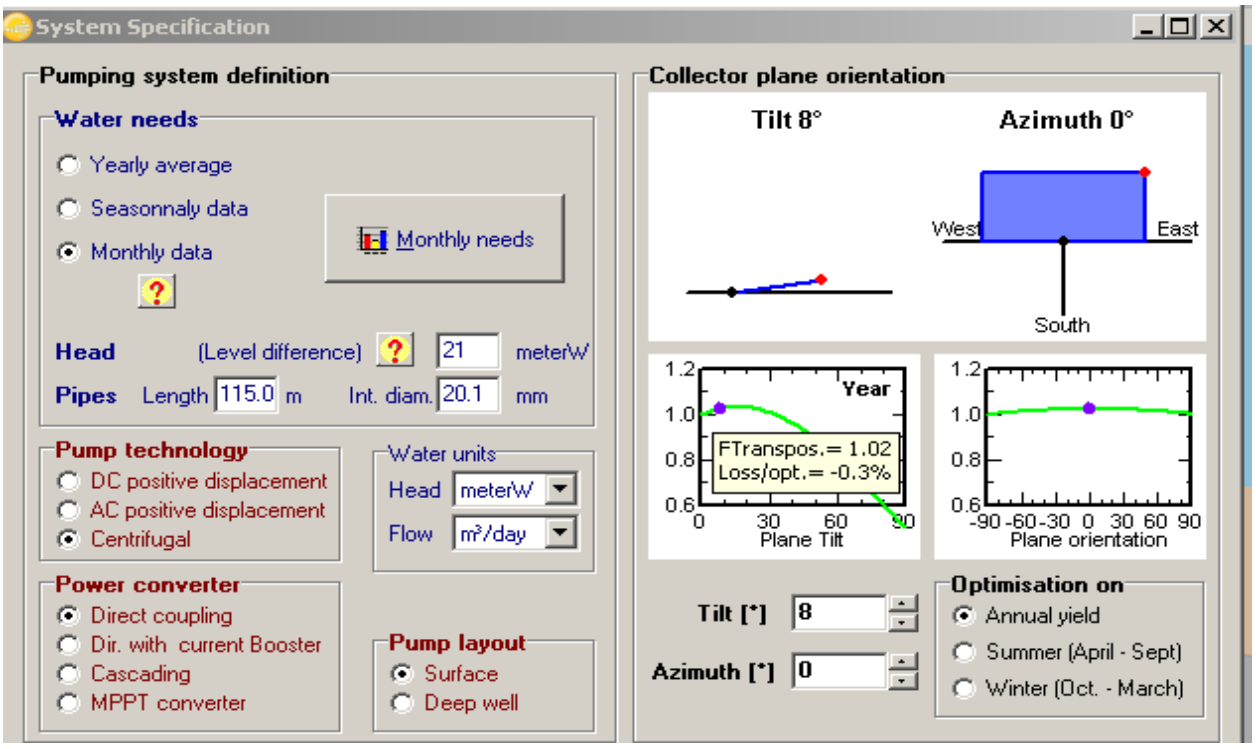


Figure 4-2: PV system orientation

Plane tilted by 8^0 and oriented 0^0 due south gives maximum annual yield.

4.2.3. Daily Water Requirement

Daily irrigation water need is determined under section 3.3; the daily water requirement is $7m^3$.

Table 4-2: Daily irrigation water requirement

PVSYST V6.40		25/05/16	

Pumping PV System: Detailed Simulation parameters

Project : **Pumping PV Project at Gerenbo**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Lake or River to Storage**	
System Requirements	Basic Head	15.0 meterW	
Pump	Model / Manufacturer	SCB 10-150-120BL / sun pump	
PV Array	Model / Manufacturer	Mono 180Wp 72 cells / Ecosol PV tech	
	Nb. of modules	2 in series	Array Power 360 Wp
System Configuration	Control Strategy	**Direct coupling**	

Water needs: monthly values

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
7.00	7.00	7.00	7.00	7.00	0.00	0.00	0.00	0.00	7.00	7.00	7.00	4.66	m³/day

4.3. Hourly, Daily and Monthly values

Now the simulation process operates on monthly, daily, or hourly basis. After choosing meteo file having the opportunity of visualizing them as "Graphs" and "Tables". Both may be in Hourly, Daily or monthly values.

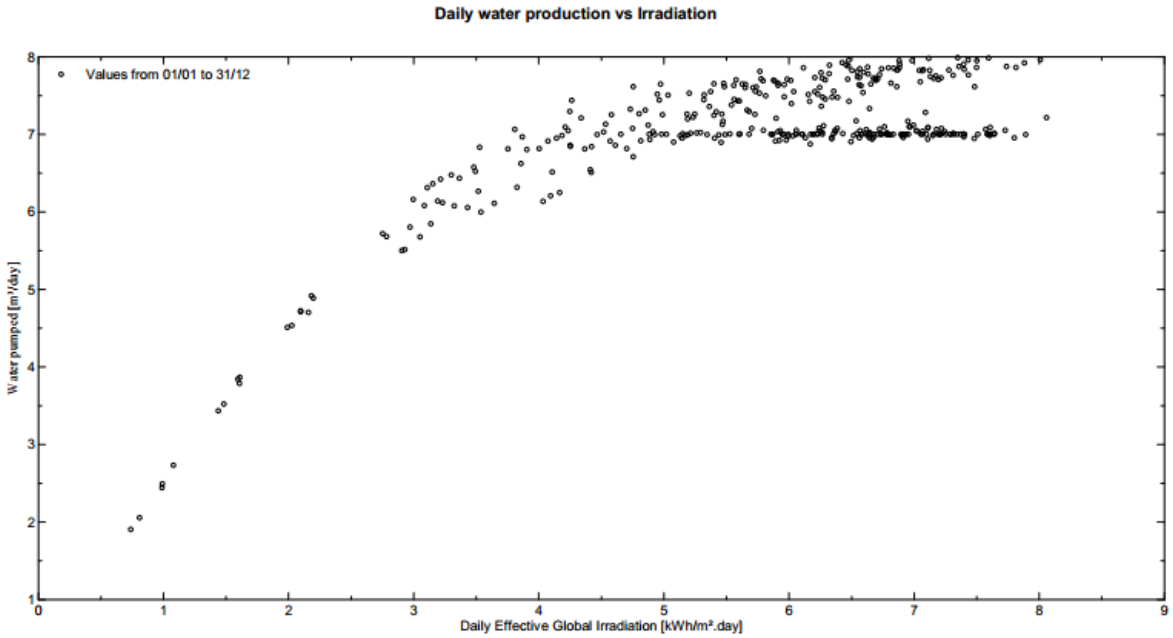


Figure 4-3: Daily water production versus available irradiation

Table 4-3: Average daily pumped water

	Incid. kWh/m².day	PV avail. kWh/day	PV needs kWh/day	PV Excess kWh/day	Pumped W. m³/day
Jan.	5.9	3.0	2.7	0.3	7.0
Feb.	6.1	3.1	2.7	0.4	7.0
Mar.	5.8	3.0	2.7	0.3	7.0
Apr.	5.7	2.9	2.7	0.2	7.0
May	5.4	2.7	2.7	0.1	6.9
June	4.5	2.3	2.7	0.0	5.9
July	3.8	1.9	2.7	0.0	5.0
Aug.	4.0	2.1	2.7	0.0	5.3
Sep.	5.0	2.5	2.7	0.0	6.6
Oct.	6.0	3.1	2.7	0.0	8.0
Nov.	5.9	3.0	2.7	0.3	7.0
Dec.	5.9	3.0	2.7	0.2	7.2
Year	5.3	2.7	2.7	0.2	6.7

We can stop pumping of water at Ethiopian summer (June-September) and can be used the designed system for other purposes.

Daily and Hourly water productions are presented in Appendixes K-2 and K-3 respectively.

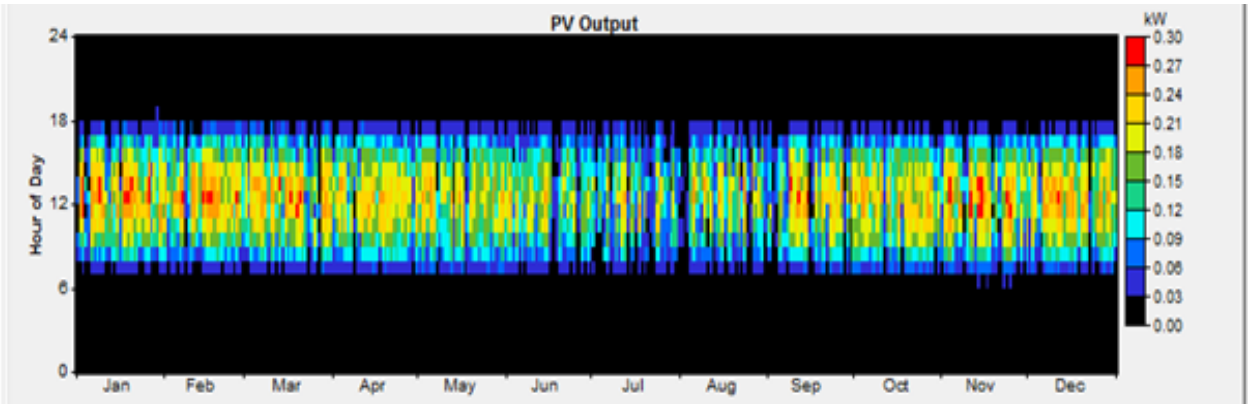


Figure 4-4: Monthly average PV output

Monthly average output energy from PV is a smaller amount starting from Jun up to September and also there is no need of irrigation water at this time.

4.3.1. Annual System Loss Diagram

System loss diagram (Figure 4-5) presents all major and minor losses starting from solar radiation to water production. The loss diagram provides a quick and insight look on the quality of a PV system design, by identifying the main sources of losses. The loss diagram is available for the whole year or for each month in order to evaluate seasonal effects of particular losses.

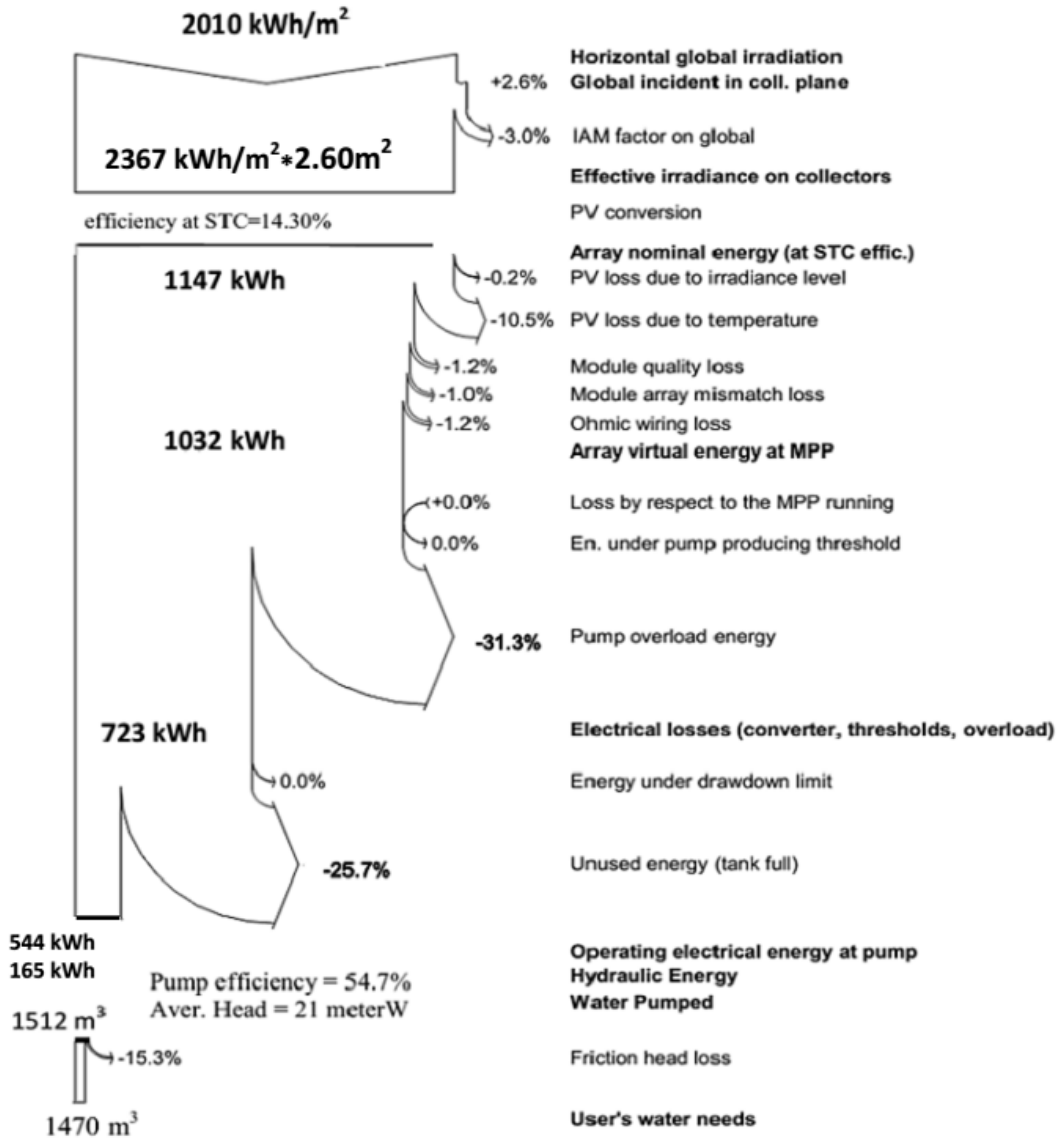


Figure 4-5: System Loss diagram

Figure 4 represents the overall system loss diagram for the system. The horizontal global irradiation is 2010 kWh/m^2. The effective irradiation on the collector plane is 2376 kWh/m^2. Then the PV cell converts solar energy into electrical energy. After PV conversion, array nominal energy is 1147 kWh. The efficiency of PV array is 14.30% at Standard Test Condition (STC). Array virtual energy obtained is 1032kWh. After the electrical loss, the available energy at the output is 723kWh. The used operating electrical energy at pump is 544kWh and the hydraulic energy is 165 kWh. Amount of annual pumped water, is 1512m^3. It is greater than user's water need. Therefore, the designed system satisfies irrigating a hector potato farm.

CHAPTER FIVE

5. Economic and Environmental Analysis of the System

5.1. Introduction

For every project, there is need to perform economic evaluation to make sure that it is feasible or not. In this section, the economic evaluation, PVWP system is compared with diesel water pumping. The comparison is conducted in terms of initial capital costs (ICC), life cycle cost (LCC) The project was not looked only in term of economic perspective but also in term of environmental perspective. An environmental advantage of PVWPs used in place of DWPs is evaluated using CO_2 emission reduction.

5.2. Economic Analysis

In order to determine the economic viability of the system, it is necessary to perform a detail cost analysis of the total system cost, and make estimate the yearly and monthly cost of the system based on it projected service lifetime. A summary of the cost of each individual system component and the total cost of all components is presented in Appendix-L.

5.2.1. 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 and inflation rates of certain items. The life cycle of the entire system is decided considering the component of system with longest replacement interval.

Major assumptions made in economic assessment for PVWPs are [29]:-

- The operating life of the PV panels was assumed to be 20 years.
- Life of solar pump was assumed to be 10 years;
- Maintenance cost of PV system assumed to be a 0.1% of total capital cost per year.
- Salvage value of PV system is 15% of total initial purchasing cost
- Availability of sunshine hours considered to be a 2374.125 hours in a year.
- Salvage value of diesel engine was assumed to be a 20 % of capital cost of engine.
- No parts of the system are stolen.
- The discount rate was assumed to be 10%

5.2.2. Economic Assessment for DWPs

During economic assessment of diesel powered pump, many assumptions have been made [29]. It was assumed that the pump operates 4 hours per day; the pump efficiency is 60%; and pump is replaced every 10 years. The same discount rate as for PVWPs has been assumed to be 10%. It was also assumed the maintenance cost for diesel pump is10% of capital cost per year and Salvage value of diesel engine was assumed to be a 20 % of capital cost of engine. Cost of 5.2 hp diesel engine with its component= $722.6 and it consumes 0.775 liter of diesel/kW.

Different factors such as total number of annual running hours (Td), power rating (Pd), the cost of one liter diesel fuel (Cf/liter) and the average fuel consumption fd (liters/kW) of engine per hour are used to determine the annual fuel consumption AFC_D as given by:

$$AFC_D = T_d \times C_f \times P_d \times f_d \quad \text{..... 5.1}$$

Total number of annual running hour is calculated as follows:

$$T_d = \frac{g_c \times I_s}{I_i} \times operation\ hour\ per\ day \quad \text{..... 5.2}$$

Where $g_c = duration\ of\ total\ crop\ grouth = 105 days$

$I_s = Irrigation\ season\ per\ year = 2\ irrigation\ seasons$

$I_i = Schedule\ of\ maximum\ irrigation\ interval = 3 days$

5.2.3. Life Cycle Cost Analysis (LCCA) of the System

Life cycle cost analysis is a process of evaluating the economic performance of a project over its entire life. LCCA balances initial monetary investment with the long-term expense of owning and operating the system. This is a method for assessing the total cost of facility ownership. The life cycle costs analysis has been computed using Homer and MS Excel; it takes into account all costs of acquiring, owning, and disposing of a system. In this research, implementing LCCA for the current system (diesel driven pump) and for the alternative that considered to replace it (PV pump system) gives the total cost of both - including all expenses incurred over the life period of the systems. 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 85% of the total LCCs for DWPs are costs of diesel fuel (figure 5-1) 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 cost of both alternatives listed in this project can be calculated using the formula:

$$LCC = CC + MC + EC + RC - SC \quad \text{5.3}$$

Where,

CC= Capital cost of a project includes the initial capital expense for equipment, the system design, engineering, and installation.

MC= Maintenance cost

EC= Energy cost of a system is the sum of the yearly fuel cost.

RC=Replacement cost is the sum of all repair and equipment replacement cost anticipated over the life of the system.

SC=Salvage value of a system is the estimated value that an asset will realize upon its sale at the end of its useful life.

To analyze the costs of both systems, the following factors need to be considered for an optimum conclusion.

Table 5-1: System cost comparison by life cycle cost analysis (equation 5.3)

Sr. No.	Costs ($)	PV system	Diesel Engine
1	Initial Investment Cost (IIC)	5923.75	722.60
2	Maintenance Cost (MC)	118.47	1445.20
3	Fuel/Energy Cost (EC)	None	15620.10
4	Replacement Cost (RC)	1030	722.60
	Total Cost	7072.22	18510.50
5	Salvage Cost (SC)	888.56	144.52
	Life Cycle Cost (LCC)	6183.65	18365.98

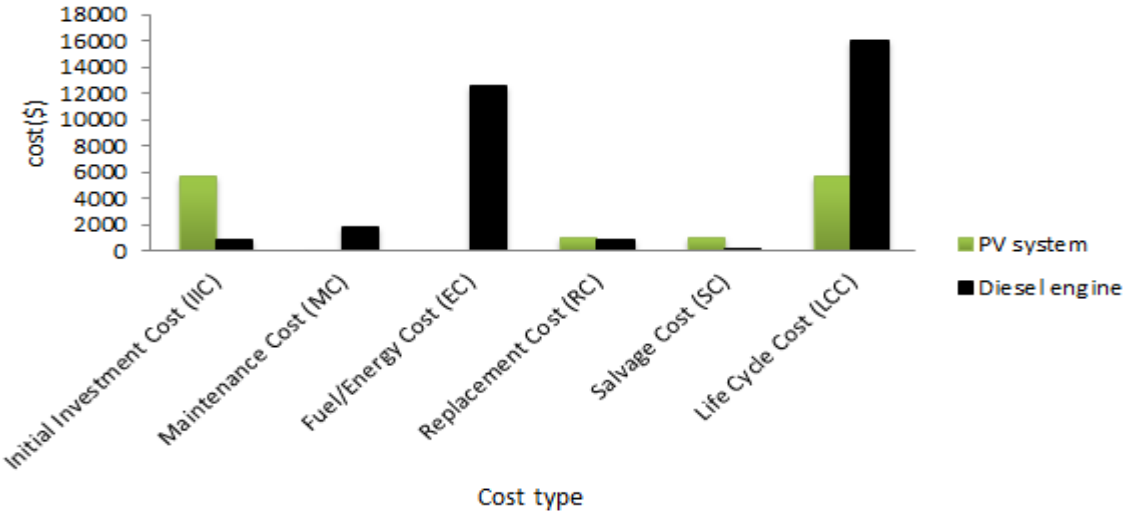


Figure 5-1: Comparisons of the present values of different costs over systems life cycle

As shown in Figure 5-1 above, the PV pumping system has higher initial cost than the diesel-powered pump but its recurrent cost proved declining over their current cost. However, in remote areas aspects such as lower operation & maintenance costs, the more reliability as well as the longer expected useful life of PV systems could economically justified the higher initial cost of PV systems. The comparison of the life cycle costs of the both systems also noted that the operation and maintenance cost and fuel cost are higher for the diesel system, and if it is considered that fuel prices are increasing, these numbers could keep going up. The bar chart in Figure 4 above shows that the fuel cost of the diesel system was really high compared with PV system costs within the system such as operation & maintenance cost, replacement as well as the capital cost. The Initial investment cost and Life cycle cost for both systems throughout the 20 years life cycle was shown in Fig 5-3 below.

Figure 5-2 presents the variation of LCCs for PVWP and DWP systems over 20 years Despite the lower operation and maintenance cost and no fuel costs, the high PV modules and the low diesel prices made the PVWP system unaffordable compared to the DWP system in first year. The PVWP system could still not compete with the DWP in the fifth year, but gaps became smaller. PVWP has started to be more competitive after the fifth year. Lately, the gap between the two alternatives was further increased. The LCC of the DWP system will be up to three times the LCC of the PVWP system.

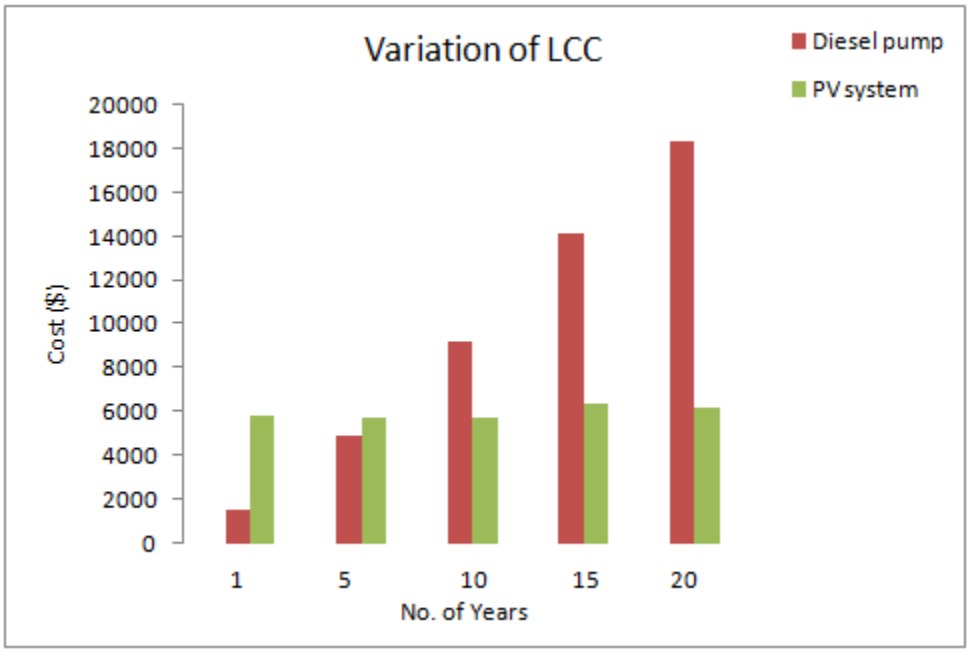
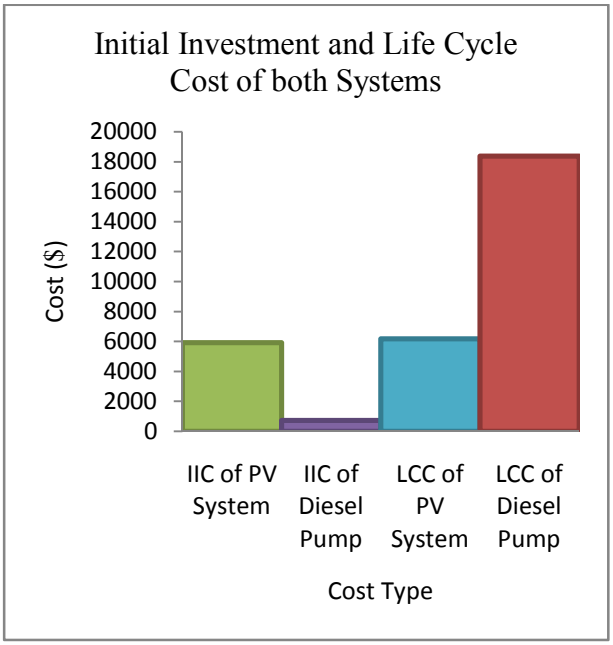


Figure 5-2: Variation of LCCs of PVWP and DWP system between year 1 and year 20

The life cycle costs analysis has been computed using Homer; it takes into account all costs of acquiring, owning, and disposing of a system. In this research, implementing LCCA for the current system (diesel driven pump) and for the alternative that considered to replace it (PV pump system) gives the total cost of both - including all expenses incurred over the life period of the systems figure 5-4. Future cash flows are discounted to the present.



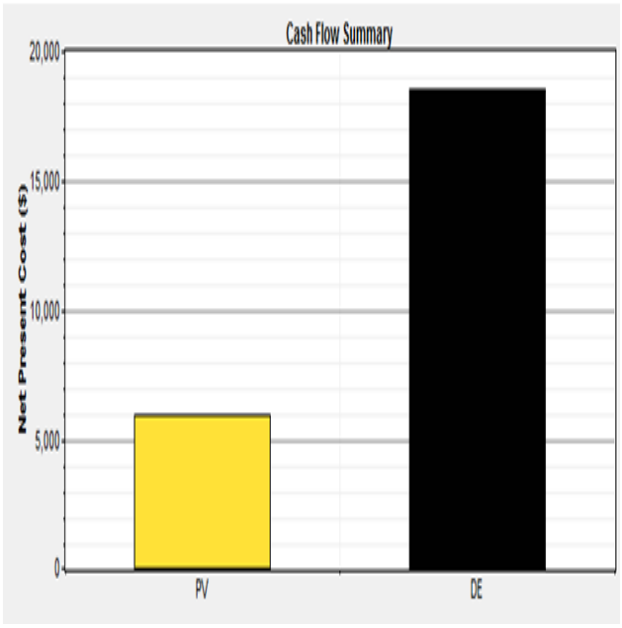


Figure 5-3: IIC and LCC for 20 years. Figure 5-4: LCC of PV and Diesel engine (Homer)

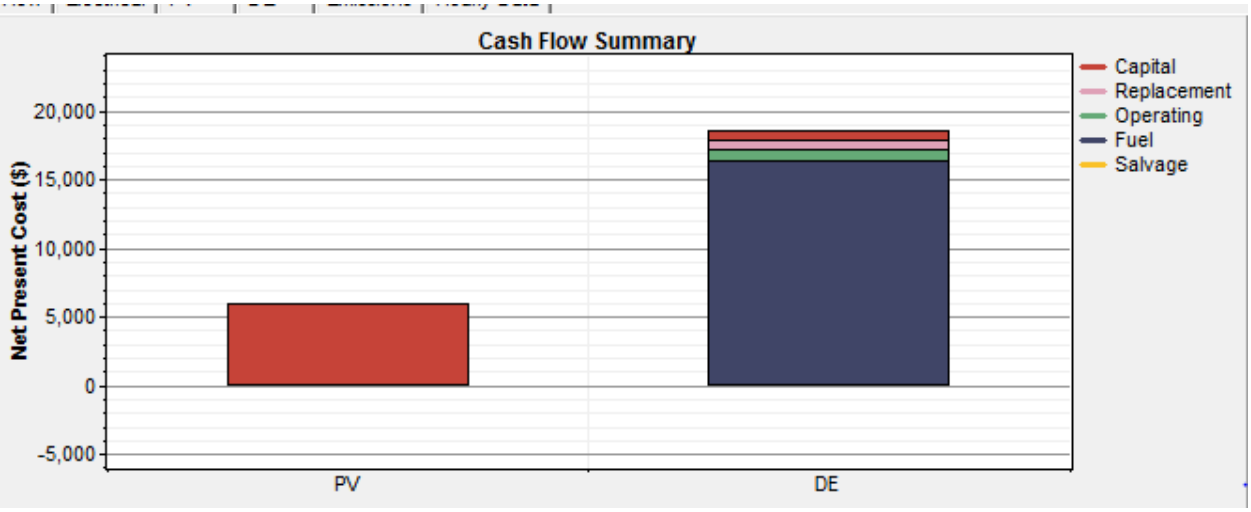


Figure 5-5: 20 year cost analysis of PVWP and DWP system.

The total estimated cost for the designed system $6183.65. Based on an estimated service lifetime of 20 years the estimated yearly cost of the system is $309.18 and the estimated monthly cost of the system is $25.76. Based on the projected system lifetime production the equivalent cost of water is $0.1187 per cubic meter. Photovoltaic water pumping system is more cost effective than diesel water pumping system, i.e. $0.3526 per cubic meter.

A detailed economic evaluation of the designed photovoltaic water pumping system can be performed using real component prices alternatively, with the help of PVsyst. But the result is almost the same as calculated above (Appendix-M).

5.3. Environmental Analysis

5.3.1. Assessment of Systems CO_2 Emission

The main cause of global warming is CO_2 emission released from different sources of energy. The amount of CO_2 emitted varies depends on energy produced and power technology used for conversion. Compared diesel powered system; the operation of PV technology is CO_2 emissions free. The calculation of CO_2 emissions was done considering of DWPs used to pump water for irrigation purpose. The CO_2 emission from DWPs was obtained per year and it is equivalent to 1,500 kg of CO_2 emissions.

The CO_2 emissions released and their corresponding reductions when DWPs is fully replaced by PVWPs were calculated and summarized in Table 5-2. According to Homer result, the total

amount of 1500 kg of CO_2 emissions is saved per year when PVWPs is used in place of DWPs. The annual CO_2 emissions released in Ethiopia was estimated to be 6006×10^3 tonnes [26]. The amount of CO_2 emissions saved using PVWPs can contribute to an annual reduction for about 2.5×10^{-5} % of total annual CO_2 emitted and even more when many farmers get familiar with use of solar technology in irrigation. In addition to CO_2 emission reduction, environment will not be impaired by any sound produced by the pump.

5.3.2. Emissions

HOMER present annual emissions of different pollutants from diesel engine.

Table 5-2: Different pollutants emitted from diesel engine

Pollutant	Emissions (kg/yr)	Emissions (kg/lifetime)
Carbon dioxide	1,500	30,000
Carbon monoxide	9.96	199.2
Unburned hydrocarbons	1.1	22
Particulate matter	0.751	15.02
Sulfur dioxide	8.1	162
Nitrogen oxides	88.9	1778

The table shows that, the amount of carbon dioxide emitted from diesel engine is very high and it is also the main cause of global warming.

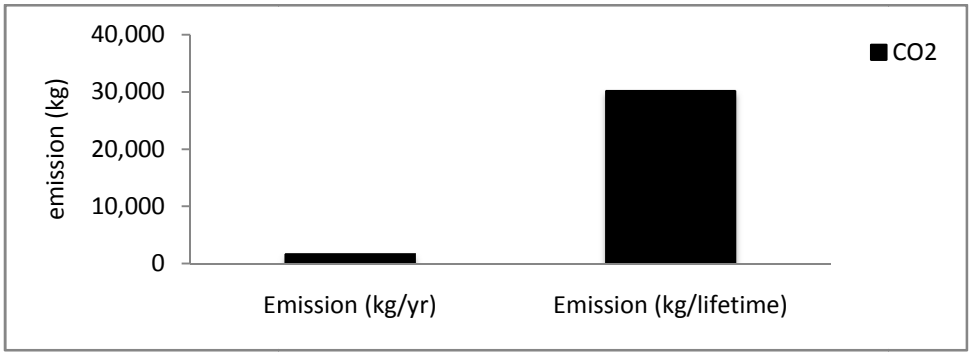


Figure 5-6: CO_2 emissions when DWP is used to irrigate potato

CHAPTER SIX

6. Conclusions and Recommendations

6.1. Conclusions

The study has accomplished its objectives. From the entire discussions good results could be achieved; based on the results of the investigation, the following conclusions were drawn:

- Assessment of crop water requirements and available solar resources are the two basic design data essential to design of PVWP system;
- The output of a solar pumping system is dependent on good system design derived from accurate site data. Therefore the designer should be investigate every design data and considering all major and minor losses;
- Solar PV power is more reliable for small scale irrigation for almost all parts of Ethiopia. This is due to the fact that solar energy is in phase with water demand to irrigate crops, Secondly; Ethiopia has an abundant supply of solar energy throughout the year. Especially in irrigation periods i.e. from October to May the horizontal daily solar radiation of the site is about 5.2 Kwh/m^2 which is very promising for solar PV utilization;
- The designed system of solar PV water pumping system was capable of irrigating a ha area of potato, within 6.5 hrs with a daily water requirement of 7m^3 and total dynamic head of 21m.
- The results of the study indicate that irrigating crops using PV systems is beneficial and suitable for long-term investments as compared to diesel powered engines, as life cycle cost of PV system considering life span of 20 years was found to be ` $6,183.65 while life cycle cost of diesel engine was ` $18,365.98;
- Based on the projected system lifetime production, the equivalent cost of water for PVWPs and DWPs is $0.1187/$m^3$ and $0.3526/$m^3$ for respectively;
- All of the cost comparisons show that PV water pumping system is more cost effective than diesel water pumping system;
- Application of PVWPs instead of DWPs, results in annual reduction of CO_2 emission by 1,500 kg:

6.2. Recommendation for Future Investigation

This paper presents design and simulation of photovoltaic water pumping system for irrigation of a potato farm in Gurage zone specifically at Gerenbo, and analyzed from technical, economic and environmental point of views. The study provides a good understanding and inspiration of using PVWP technology for irrigation centers. More works need to be carried out in order to achieved better working condition for the system. In particular, the following works will be set:

- Consider the effects of different potato species on the system design, economy and water resources;
- Design appropriate drip irrigation should be performed to save water demand and system cost;
- Study on overall benefits of providing maximum power point Tracking to maximize power production;
- Study the effects of PVWP system for irrigation on the local water balance to solve the controversial aspect related to the over exploitation of the water resources;
- Production of electricity from PVWPs is not only at irrigation seasons, future works will be use these energy to other purpose specially, at non-irrigating season;

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Appendixes

Appendix A: Calculated Seasonal CWR for Different Locations in Ethiopia

Crop	Growth period (day)	ETo (mm)	CWR (mm)	Peff (mm)	IWR (mm)	Location
Potato	130		607.90	227.52	380.38	Kulumsa
	130		369.30	260.00	150.40	Kofele
	130		435.00	181.80	264.00	Arsi robe
	130		362.00	114.10	249.70	Asasa
	130		389.90	137.30	250.70	Bokoji
	105	436.31	378.86	94.05	284.81	Ginich
	129	639.18	570.23	266.41	305.6	Ambo
	125	589.75	529.23	157.69	371.54	Holleta
	95		464.1	192.5	271.6	Tepi

Appendix B: Mean Daily Percentage (p) of Annual Daytime Hours for Different Latitudes.

Latitude	North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°		.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
55		.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
50		.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
45		.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
40		.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35		.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30		.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25		.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20		.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15		.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10		.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26

5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

Appendix C-1: MATLAB Function to Simulate the Current-Voltage Relationship of (BP 7180 S) Module.

```
% calculates module current under given voltage, irradiance and temperature
% Io = Module operating current (A),
% Vo = Module operating voltage (V),
% G = Irradiance (1G = 1000 W/m^2)
% TaC = Module temperature in deg C
% Written by AbdulbasitNasir 5/04/2016
% Revised 25/04/2016
%////////////////////////////////////////////////////////////////////////
%///
closeall;
clearall;
clc;
T=302;%cell temprature
Tr=298;% Reference temperature (25 degree Celcius)
S=[100 80 60 40 20];%is the solar radiation in W/cm2
ki=0.00023;%is the short circuit current temperature coefficient
Isc=5.3;%Isc (short circuit current per cell) at Tr
Ir=0.000021;%reverse saturation current at Tr
k=1.38065*10^(-23);% Boltzmann's constant
q=1.6022*10^(-19);% Electron charge
A=2.15; %the p-n junction ideality factor
Eg0=1.166; % Band gap energy; 1.12eV (Si), 1.42 (GaAs),1.5 (CdTe), 1.75
(amorphous S
alpha=0.473;
beta=636;%alpha and beta are constants specific to each conductor
Eg=Eg0-(alpha*T*T)/(T+beta)*q;% EG is the band gap of the semiconductor used
in the cell.
Np=1;
Ns=72;% # of series connected cells in the module (BP SX 3180W, 72 cells)
V0=(1:1:43.6);%Module operating voltage (V),
for i=1:5;% Perform 5 iterations
```

```
Iph=(Isc+ki*(T-Tr))*((S(i))/100);% Calculate photon generated current at a
given irradiance
Ir=Ir*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));% Calculate reverse
saturation current for given temperature
I0=Np*Iph-Np*Ir*(exp(q/(k*T*A)*V0./Ns)-1); %Module operating current (A),
P0 =V0.*I0;%module power output
end
figure(1)
plot(V0,I0);
axis([0 50 0 6]);
xlabel('Voltage (V)');
ylabel('Current (A)');
title ('BP 73180 S I-V curve and its MMP')
holdon;
figure(2)
plot(V0,P0);
axis([0 50 0 160]);
xlabel('Voltage (V)');
ylabel('Power (W)');
title ('P-V characteristics of selected module')
holdoff;
```

Appendix C-2: MATLAB Function for Different Solar Radiation

```
clearall;
closeall;
clc;
T=28+273;% cell temperature
Tr=298;%cell reference temperature
S=[100 90 80 70 60 50 40 30 20 10]; %solar radiation corresponde a 1000 800
etc W/m2
ki=0.00023;%is the short circuit current temperature coefficient
Isc=5.3;%short curcuit current
Ir=0.000021;%reverse saturation current at Tr
k=1.38*(10^-23);%Boltzmann's constant
q=1.6*(10^-19);%the charge of an electron
A=2.15;%the p-n junction ideality factor
Eg0=1.166;% Band gap energy; 1.12eV (Si), 1.42 (GaAs),1.5 (CdTe), 1.75
(amorphous S
```

```
alpha=0.473;
beta=636;%alpha and beta are constants specific to each conductor
Eg=Eg0-(alpha*T*T)/(T+beta)*q; % EG is the band gap of the semiconductor used
in the cell.
Np=1;
Ns=72;%# of series connected cells in the module (BP SX 3180W, 72 cells)
V=(0:0.005:23*Ns);
for i=1:10
Iph=(Isc+ki*(T-Tr))*(S(i)/100);
Irs=Ir*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));
I=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V./Ns)-1);
P=V.*I;
figure(1)
plot(V,I)
axis([0 50 0 6])
xlabel('Voltage [V]')
ylabel('Current [A]')
Title ('I-V curve with different Radiations')
holdon
end
```

Appendix D-1: Friction Head Loss for Schedule 40 PVC Pipe; (Head loss in feet per 100 feet of pipe C=150)

GPM	1/2	3/4	1	1-1/4	11/2	2	21/2	3	4	5	6
1	1.16	0.28	0.09	0.02	0.01						
2	4.19	1.03	0.31	0.08	0.04	0.01					
3	8.88	2.17	0.65	0.17	0.08	0.02	0.01				
4	15.13	3.70	1.11	0.29	0.13	0.04	0.02	0.01			
5	22.88	5.60	1.69	0.43	0.20	0.06	0.02	0.01			
6	32.07	7.85	2.36	0.61	0.28	0.08	0.04	0.01			
7		10.44	3.14	0.81	0.38	0.11	0.05	0.02			
8		13.37	4.02	1.04	0.48	0.14	0.06	0.02	0.01		
9		16.63	5.01	1.29	0.60	0.18	0.07	0.03	0.01		
10		20.21	6.08	1.57	0.73	0.21	0.09	0.03	0.01		
11			7.26	1.87	0.87	0.26	0.11	0.04	0.01		

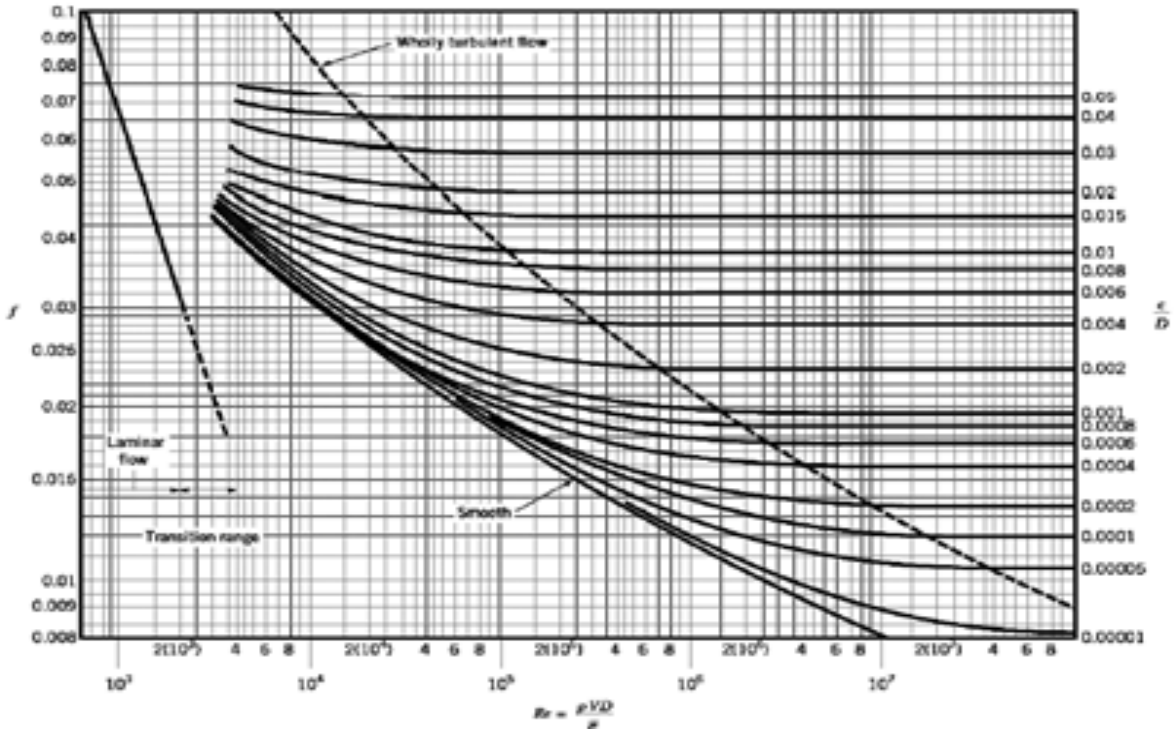
12	8.53	2.20	1.03	0.30	0.13	0.04	0.01		
14	11.34	2.92	1.37	0.40	0.17	0.06	0.02	0.01	
16	14.53	3.74	1.75	0.51	0.22	0.07	0.02	0.01	
18		4.65	2.17	0.64	0.27	0.09	0.02	0.01	
20		5.65	2.64	0.77	0.33	0.11	0.03	0.01	
22		6.75	3.15	0.92	0.39	0.13	0.04	0.01	
24		7.92	3.71	1.08	0.46	0.16	0.04	0.01	0.01
26		9.19	4.30	1.26	0.53	0.18	0.05	0.02	0.01

Appendix D-2: Schedule 40 PVC Pipe Dimensions and Pressure Rating

Nom. Pipe size (In)	O.D.	Average I.D.	Min. wall	Nominal Wt/Ft.	Maximum w.p.psi
1/8	0.405	0.249	0.068	0.051	810
¼	0.540	0.344	0.088	0.086	780
3/8	0.675	0.473	0.091	0.115	620
½	0.840	0.602	0.109	0.170	600
3/4	1.050	0.804	0.113	0.226	480
1	1.315	1.029	0.133	0.333	450
1-1/4	1.660	1.360	0.140	0.450	370
1-1/2	1.900	1.590	0.145	0.537	330
2	2.375	2.047	0.154	0.720	280
2-1/2	2.875	2.445	0.203	1.136	300
3	3.500	3.042	0.216	1.488	260
3-1/2	4.000	3.521	0.226	1.789	240
4	4.500	3.998	0.237	2.118	220
5	5.563	5.016	0.258	2.874	190
6	6.625	6.031	0.280	3.733	180
8	8.625	7.942	0.322	5.619	160
10	10.750	9.976	0.365	7.966	140
12	12.750	11.889	0.406	10.534	130

14	14.000	13.073	0.437	12.462	130
16	16.000	14.940	0.500	16.286	130
18	18.000	16.809	0.562	20.587	130
20	20.000	18.743	0.593	24.587	120
24	24.00	22.544	0.687	33.652	120

Appendix-E: Friction Factor as a Function of Reynolds Number and Relative Roughness for Round Pipes the Moody Chart



Appendix F: Stranded Wire Chart (AWG)

AWG	Stranding	Appxt. O.D. (mm)	Circular mill area	Square mm	Weight Kg/Km	DC resistance ohms/Km
36	7/44	.1524	28	0.0143	.126	1217.18
34	7/42	.1905	43.75	0.0223	.196	777.55
32	7/40	.2032	67.27	0.0343	.302	538.05
32	19/44	.2286	76.00	0.0388	.342	447.50
30	7/38	.3048	112.00	0.0571	.504	338.58
30	19/42	.3048	118.75	0.0606	.534	286.41

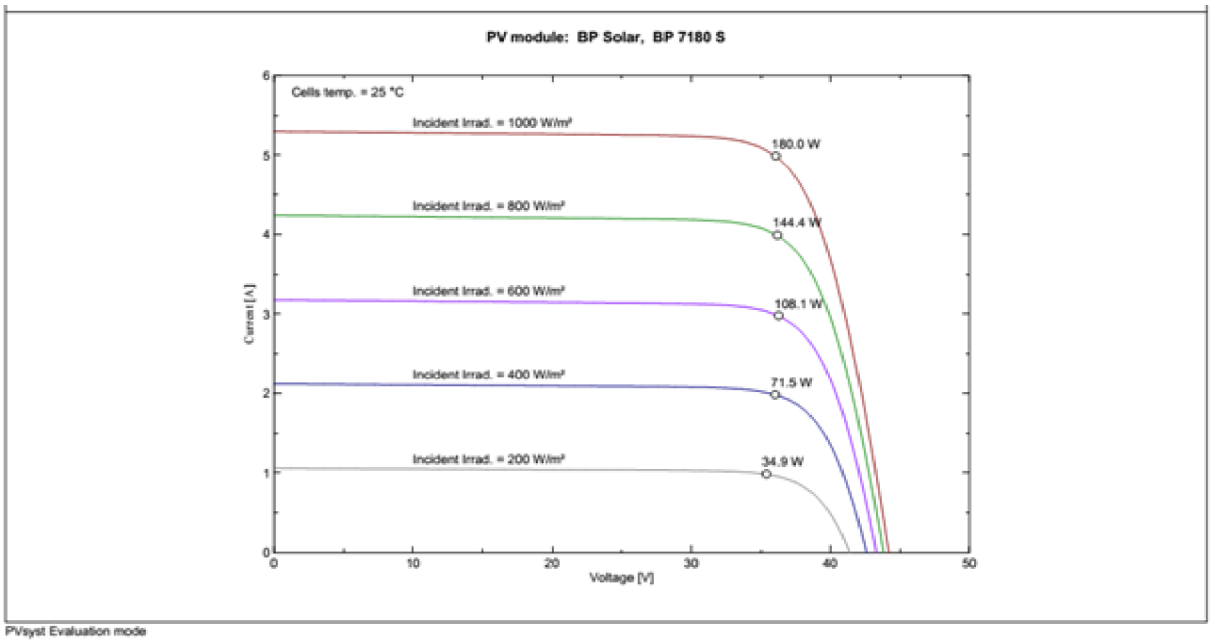
28	7/36	.3810	141.725	0.0723	.787	212.92
28	19/40	.4064	182.59	0.0931	.823	186.02
27	7/35	.4572	219.52	0.1120	.988	178.71
26	10/36	.5334	250.00	0.1275	1.126	136.09
26	19/38	.5080	304.00	0.1550	1.369	112.96
26	7/34	.4826	277.83	0.1417	1.251	122.37
24	7/32	.6096	448.00	0.2285	2.018	76.44
24	10/34	.5824	396.90	0.2024	1.787	85.60
24	19/36	.6096	475.00	0.2423	2.128	69.16
24	41/40	.5824	384.40	0.1960	1.726	83.96
22	7/30	.7620	700.00	0.3570	3.155	48.36
22	19/34	.7874	754.11	0.3846	3.393	45.05
22	26/36	.7620	650.00	0.3315	2.932	52.30
20	10/30	.2890	1000.00	0.5100	4.502	33.86
20	19/32	.9393	1216.00	0.6202	5.476	28.31
20	26/34	.9144	1031.94	0.5263	4.643	32.97
20	41/36	.9144	1025.00	0.5228	4.613	32.87
18	7/26	1.2192	1769.60	0.9022	7.176	19.23
18	16/30	1.1938	1600.00	0.8160	7.202	21.26
18	19/30	1.2446	1900.00	0.9690	8.557	17.91
18	41/34	1.1938	1627.29	0.8299	7.321	20.90
18	65/36	1.1938	1625.00	0.8288	7.307	20.96
16	7/24	1.5440	2828.00	1.4423	12.738	12.04
16	65/34	1.4986	2579.85	1.3157	11.622	13.19
16	26/30	1.4936	2600.00	1.3260	11.711	13.12
16	19/29	1.4732	2426.30	1.2374	10.938	14.01
16	105/36	1.4986	2625.00	1.3388	11.830	13.09
14	7/22	1.8542	4480.00	2.2848	20.179	7.58
14	19/27	1.8542	3830.40	1.9535	17.247	8.86
14	41/30	1.8542	4100.00	2.0910	18.452	8.30
14	105/34	1.8542	4167.50	2.1254	18.765	8.17
12	7/20	2.4384	7168.00	3.6557	32.277	4.76

12	19/25	2.3698	6087.60	3.1047	27.426	5.58
12	65/30	2.4130	6500.00	3.3150	29.256	5.74
12	165/34	2.4130	6548.90	3.3399	29.494	5.18
10	37/26	2.9210	9353.60	4.7703	42.128	3.64
10	49/27	2.9464	9878.40	5.0380	44.479	3.58
10	105/30	2.9464	10530.0	5.3703	47.262	3.22
8	49/25	3.7338	15699.6	8.0068	70.729	2.20
8	133/29	3.7338	16984.1	8.6619	76.518	2.00
8	658/36	3.7338	16625.0	8.4788	73.780	2.00

Appendix G: Pump Specification and System Efficiency (SCB 10-150-120BL)

PSI	TDH feet	TDH meters	Motor voltage	Motor Amps	US GPM	LPM	Motor watts	Solar array watts	System efficiency %
0	0	0.0	75	3.0	11.2	42.3	222	278	0
5	12	3.5	75	3.0	10.4	39.4	226	282	10
10	23	7.0	75	3.1	9.6	36.5	230	287	18
15	35	10.6	75	3.1	8.7	32.9	233	292	24
20	46	11.1	75	3.2	7.7	29.2	236	295	28
25	58	17.6	75	3.2	6.7	25.3	236	295	31
30	69	21.1	75	3.1	5.2	19.7	229	286	30
35	81	24.6	75	2.9	3.3	12.5	215	268	23
41	95	28.9	75	2.2	0.0	0.0	167	208	0

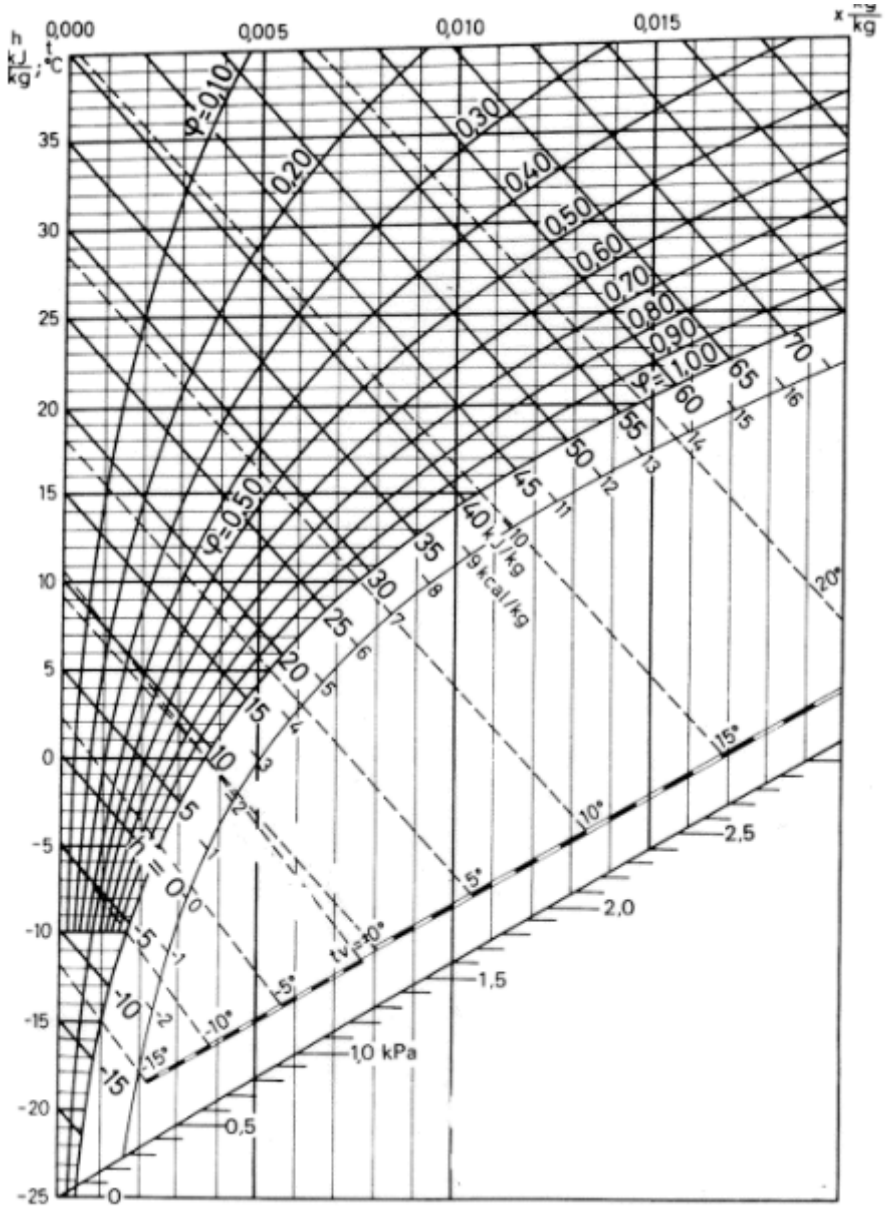
Appendix H: I-V curve of BP 7180 S Module at Standard Testing Condition (STC) Using PVsyst



Appendix I: K_L Values of Different Fittings

component	K_L	
elbows		
Regular 90^0, flanged	0.3	
Regular 900, threaded	1.5	
Long radius 90^0, flanged	0.2	
Long radius 90^0, threaded	0.7	
Long radius 45^0, flanged	0.2	
regular 90^0, flanged	0.4	
Valves		
Glob, fully open	10	
Gate fully open	0.15	
Check, disk	10	
Foot, piston	15	
Foot, disk	7	

Appendix J-1: Mollier Diagram



Appendix J-2: Atmospheric Pressure at Different Altitudes

Altitude Above Sea Level			Temperature		Barometric Pressure		Atmospheric Pressure		
Feet	Miles	Meters	F	C	In. Hg. Abs.	mm Hg. Abs.	PSIA	Kg / sq. cm	kPa A
0		0	59	15	29.92	760.0	14.696	1.0333	101.33
500		153	57	14	29.38	746.3	14.43	1.015	99.49
1000		305	55	13	28.86	733.0	14.16	0.956	97.63
1500		458	54	12	28.33	719.6	13.91	0.978	95.91
2000		610	52	11	27.82	706.6	13.66	0.960	94.19
2500		763	50	10	27.32	693.9	13.41	0.943	92.46
3000		915	48	9	26.82	681.2	13.17	0.926	90.81
3500		1068	47	8	26.33	668.8	12.93	0.909	89.15
4000		1220	45	7	25.84	656.3	12.69	0.892	87.49
4500		1373	43	6	25.37	644.4	12.46	0.876	85.91
5000	0.95	1526	41	5	24.90	632.5	12.23	0.86	84.33
6000	1.1	1831	38	3	23.99	609.3	11.78	0.828	81.22
7000	1.3	2136	34	1	23.10	586.7	11.34	0.797	78.19
8000	1.5	2441	31	-1	22.23	564.6	10.91	0.767	75.22
9000	1.7	2746	27	-3	21.39	543.3	10.5	0.738	72.40
10,000	1.9	3050	23	-5	20.58	522.7	10.1	0.71	69.64
15,000	2.8	4577	6	-14	16.89	429.0	8.29	0.583	57.16
20,000	3.8	6102	-12	-24	13.76	349.5	6.76	0.475	46.61
25,000	4.7	7628	-30	-34	11.12	282.4	5.46	0.384	37.65
30,000	5.7	9153	-48	-44	8.903	226.1	4.37	0.307	30.13
35,000	6.6	10,679	-66	-54	7.06	179.3	3.47	0.244	23.93
40,000	7.6	12,204	-70	-57	5.558	141.2	2.73	0.192	18.82
45,000	8.5	13,730	-70	-57	4.375	111.1	2.15	0.151	14.82
50,000	9.5	15,255	-70	-57	3.444	87.5	1.69	0.119	11.65
55,000	10.4	16,781	-70	-57	2.712	68.9	1.33	0.0935	9.17
60,000	11.4	18,306	-70	-57	2.135	54.2	1.05	0.0738	7.24
70,000	13.3	21,357	-67	-55	1.325	33.7	0.651	0.651	4.49
80,000	15.2	24,408	-62	-52	0.8273	21.0	0.406	0.406	2.80
90,000	17.1	27,459	-57	-59	0.520	13.2	0.255	0.255	1.76
100,000	18.9	30,510	-51	-46	0.329	8.36	0.162	0.162	1.12
150,000	28.4	45720				1.10	2.1×10^{-3}	1.4×10^{-3}	0.146
200,000	37.9	60960				0.17	3.27×10^{-3}	2.0×10^{-4}	2.2×10^{-2}
300,000	56.8	91440				8×10^{-4}	1.47×10^{-5}	1.06×10^{-4}	1.09×10^{-6}
500,000	94.7	152400				3.73×10^{-6}	7.22×10^{-8}	5.07×10^{-9}	4.98×10^{-7}
2,000,000	378.8	609600				3.6×10^{-9}	7.0×10^{-11}	4.9×10^{-12}	4.8×10^{10}

Appendix K-1: Solar Path at Gerenbo

PVSYST V6.40		19/05/16 06h26

Definition of a geographical site

Geographical Site **Gerenbo K.** Country **Ethiopia**

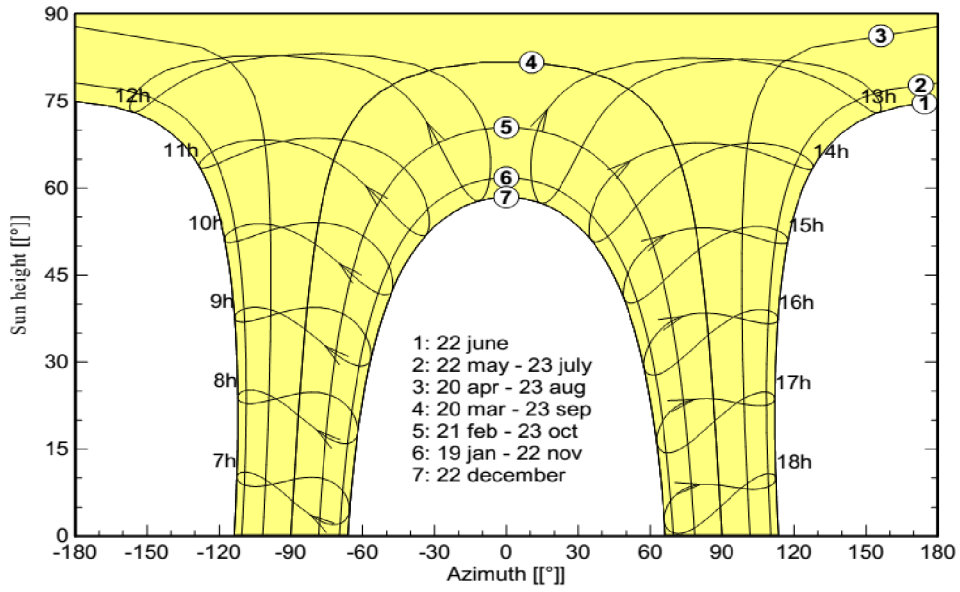
File Gerenbo k_MN71.SIT of 00/00/00 00h00

Situation Latitude 8.1°N Longitude 38.0°E
Time defined as Legal Time Time zone UT+3 Altitude 1930 m

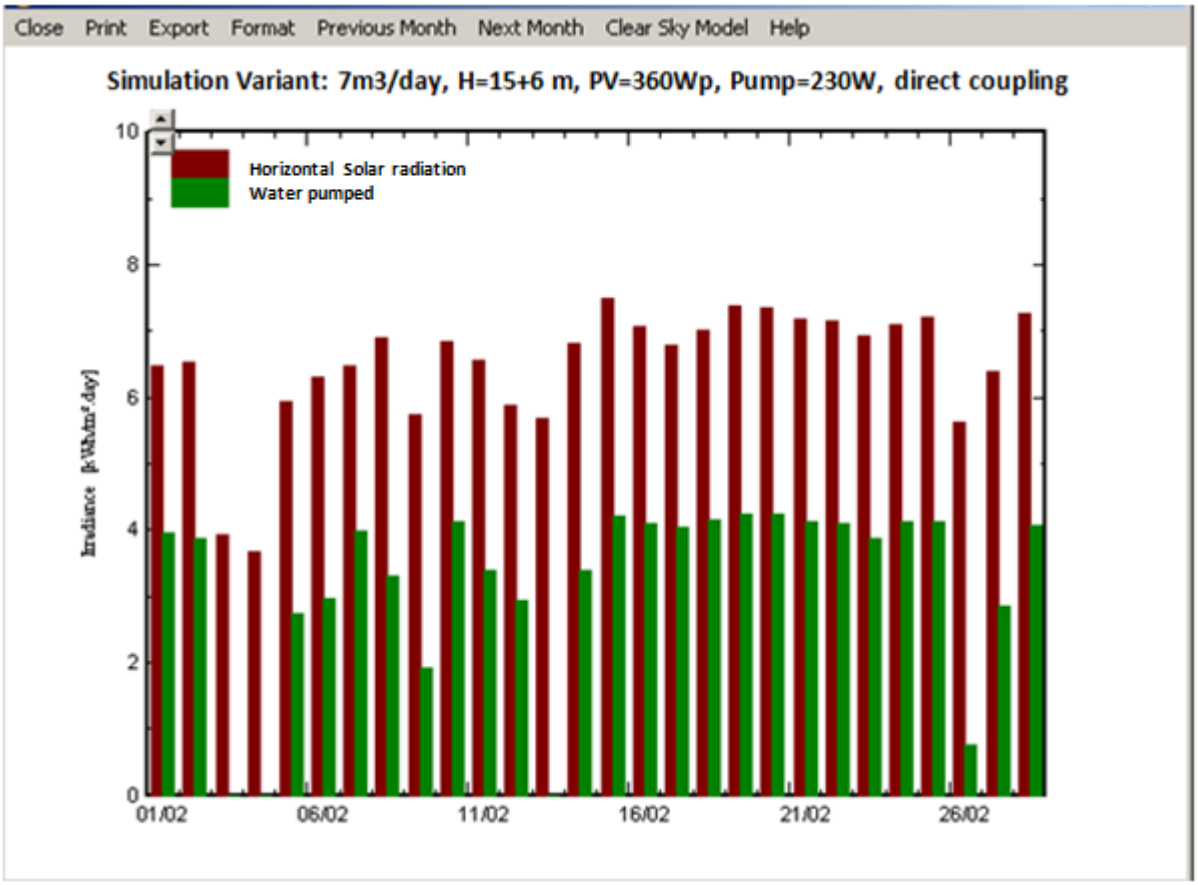
Monthly Meteo Values Source MeteoNorm 7.1 station (modified by user)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Hor. global	5.45	5.78	5.68	5.82	5.61	4.71	3.92	4.13	4.96	5.60	5.43	5.37	5.20	kWh/m².day
Hor. diffuse	1.90	2.41	2.51	2.41	2.52	2.61	2.31	2.24	2.71	2.31	1.78	1.82	2.29	kWh/m².day
Extraterrestrial	9.04	9.74	10.29	10.51	10.36	10.18	10.22	10.37	10.33	9.89	9.21	8.79	9.91	kWh/m².day
Clearness Index	0.603	0.594	0.552	0.554	0.541	0.463	0.384	0.398	0.480	0.566	0.590	0.611	0.525	
Amb. temper.	16.1	17.2	17.8	17.5	18.4	17.0	15.5	16.0	15.9	16.7	15.4	15.6	16.6	°C
Wind velocity	1.6	1.5	2.0	2.8	3.2	3.4	3.9	4.3	4.6	4.8	3.5	1.9	3.1	m/s

Solar paths at Gerenbo k, (Lat. 8.1°N, long. 38.0°E, alt. 1930 m) - Legal Time



Appendix K-2: Daily Water Output



Appendix K-3: Hourly Water Output

	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	10.6	14.4	14.3	11.3	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
February	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.1	17.4	18.1	18.9	16.8	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
March	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.9	19.7	20.4	20.3	18.1	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
April	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.9	19.7	19.5	19.3	15.6	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
May	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.8	15.1	15.1	15.0	10.6	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	7.6	7.5	8.2	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
July	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	3.8	3.7	3.5	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
August	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	4.5	9.1	8.6	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
September	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	10.6	11.6	10.7	7.1	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
October	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	14.4	18.8	18.0	17.6	13.2	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
November	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1	15.9	15.8	15.4	9.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
December	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	9.1	10.6	9.3	4.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Year	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	85.4	152.7	164.0	161.1	118.7	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix L: Component Cost

S. No.	Component name	Quantity	Total cost($)
1	PV module	2	900
2	Solar Pump	1SCB 10-150-120BL	1029.99
3	Pump controller	1 PCC-120-BLS-M2	632
4	PVC Pipe	Mfg#59507-3/4" 205m	98.85
5	Foot valve	1 No. SFV75: ¾"	10.59
6	Check valve	ITEM NO. 6VDT3	12.33
7	Main gate valve	1 (610F)	25
8	Other valves	4	25
9	Unions, elbows and joints		100
10	Storage preparation and Lining	1 lining + preparation	650
11	Screening and ditch preparation		233
12	Wire	AWG#12	40
13	Mounting Bracket		70
14	Floating switch	SPDT item no. 75-111	79
15	Shipping	PV and Pump component	1000
16	Installation and transportation	5% CC	282.10
17	Tax	15%	
	PV Total		5923.75
	Diesel pump and accessories		722.2

Appendix-M: Economic Evaluation of PVWPs (Using PVsyst)

PVsyst		23/05/16 07h26
Pumping PV System: Economic evaluation **Project: Pumping project at Gerenbo** **Simulation variant: 7m^3/day, H=15+6m, PV=360Wp, Pump: 230W**		
Main system parameters	system type	**Lake or River to Storage**
System Requirements	Basic Head	21 meterW water needs 7.0 m^3/day

Pump	model/manufacturer	SCB 10-150-120BL / Sun pump	
PV array	model/manufacturer	BP 7180 S / BP Solar	
	Nb. of modules 2 S		Array power 360 Wp
System Configuration	control strategy	**Direct coupling**	
Investment			
PV module (Pnom=180 Wp)	2 units	450 $/unit	900 $
Solar Pump	1 unit	1029.99 $/unit	1029.99 $
Pump controller			623 $
Mounting Bracket		35 $/module	70 $
Settings and Wirings			375.77 $
Engineering			800 $
Shipping			1000 $
Installation and transportation			282.1$
Gross investment (without taxes)			5080.86 $
Financing			
Gross investment (without taxes)			5080.86 $
Taxes on investment (VAT)	Rate 15.0 %		762.13 $
Gross investment (including VAT)			5842.98 $
Net investment (all taxes included)			**5842.98 $**
Maintenance			5.2 $/year
Provision for pump replacement	(lifetime 10 years)		51.5 $/year
Total yearly cost			348.85 $/year
Water and Energy cost			
Energy used for pumping			203 kWh/year
Excess energy (tank full			0.0 kWh/year
Cost of energy			0.00 $/kWh
Water pumped			1512 m^3/year
Cost of pumped water			**0.1105 $/$m^3$**