DESIGN AND PERFORMANCE EVALUATION OF SOLAR POWERED WATER PUMPING SYSTEM: A CASE STUDY FOR MIRAB ABAYA

By

Tsegaye Paulos Dele

A Thesis Submitted to the Department of Mechanical Engineering School of Mechanical, Chemical and Materials Engineering,

Presented in Partial Fulfilment of the Requirement for the Degree of Master's in Thermal Engineering

Office of Graduate Studies

Adama Science and Technology University

December, 2021

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "**Design and Performance Evaluation of Solar Powered Water Pumping System: A Case Study for Mirab Abaya**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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APPROVAL OF ADVISOR

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Design And Performance Evaluation of Solar Powered Water Pumping System: A Case Study For Mirab Abaya**" prepared under my guidance by **Tsegaye Paulos** submitted in partial fulfilment of the requirements for the degree of Mater's of Science in Thermal Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Major Advisor	Signature	Date

APPROVAL OF BOARD OF EXAMINERS

I, the advisor of the thesis entitled "**Design and Performance Evaluation of Solar Powered Water Pumping System: A Case Study for Mirab Abaya**" and developed by **Tsegaye Paulos**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by **Tsegaye Paulos** have read and evaluated the thesis entitled "**Design And Performance Evaluation Of Solar Powered Water Pumping System: A Case Study For Mirab Abaya**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Thermal Engineering.

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ABSTRACT

Water is a basic need for the sustenance of every plant and advancing it through irrigation secure its sustainability. This thesis paper is concerned to design and performance evaluation of solar water pumping system without using battery storages. The following techniques were used; the analytical method for the system design, Numerical method by Homer pro software used to estimate the life cycle cost of the system and finally the experiment has been done for the performance evaluation of M-60W model PV panel in the Mirab Abaya, Birbir town. Technical, economic and environmental parameters were considered in the design procedures. Performance evaluation of solar water pumping system was studied using four expressions: yield factor (YF), Capacity factor, overall system efficiency and system performance index (SPI). A case study for the designing of solar water pumping system that implemented on a hectare farm land for Maize crop cultivation in Mirab Abaya, Ethiopia was studied. As a result shows a pump load is 1.12kW and after considering different effects, its PV panel sizing required 2.03kW electrical power. To convert and for the conditioning of power supply from the source, the latest 98% efficient, 1.6kW inverter was selected. By using the solar renewable power source, 2816.58 m^3*/total growing period of maize crop on 10,000* m^2 *farm land can be irrigated sufficiently with the average daily water volume 36.11* m^3*/day. As a result, the performance of the system, its yield factor is 4.22 (kWh/kWp/day), capacity factor 17.3%, overall system efficiency is 55.22% and system performance index is 0.0533* m^3*/day/Wp. The investment capital costs 3172$USAD, and the cost of energy is equal to 0.128$USAD /kWh and its simple Payback period is 5.44 years. Since there is zero emission from the system, environmental as well the economic factors are more feasible compared to the latest published paper of solar water pumping design with battery storage connected with cost of energy of 0.309$USAD/kWh and diesel generator pumps with cost of energy 0.790$USAD/kWh. The designed system capital cost and the cost of energy are effective when compared to a diesel generator and battery storages connected pumps. A comparison was made between the proposed solar powered water pumping system without battery storage and with other designs like solar water pumping system with battery storage, diesel generator pumps and hybrid systems in the literatures. The comparison indicated that the system cost of energy has low costing.*

Key Words: Photovoltaics, crop irrigation, Performance evaluation, solar water pumping, Energy

NOMENCLATURE

PV	Photovoltaics
SWPS	Solar Water Pumping System
GIS	Geographic Information System
NSRD	National Solar Radiation Database
ENMA	Ethiopia National Meteorological Agency
MAWAO	Mirab Abaya Agricultural Office
USAD	United State of America Dollar [$]
YF	Yield Factor [kWh/kWp/day]
CF	Capacity Factor [%]
SPI	System Performance Index [$m^3/Wp/day$]
TDH	Total Dynamic Head [m]
DC	Direct Current [A]
AC	Alternate Current [A]
Ho	Daily Extraterrestrial solar radiation outside the atmosphere [W/m^2]
I_d	Diffuse radiation on a horizontal surface [W/m^2]
I_b	Beam radiation on a horizontal surface [W/m^2]
T_{avg}	Average Temperature [℃]
I_{sc}	The Solar Constant the Irradiance under Standard Conditions [W/m^2]
T_{STC}	The Cell Temperature under Standard Test Conditions [℃]
Ppv	Panel Nominal Peak Power [Wp]
P_i	The illumination PV panel power at standard test conditions [W/m^2]
ST	The Local Solar Time [Hr]
Q	The Flow Rate Per Hour [m^3/hr]

Greek Symbols

ω Hour Angle [º]

β Tilt Angle [º]

ϕ The Latitude Angle [º]

δ The Angle of Inclination [º]

θz Zenith Angle [º]

α Altitude Angle [º]

γ Surface Azimuth Angle [º]

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CHAPTER ONE

1. INTRODUCTION

1.1 Background

Water is a basic necessity for the sustenance of every life. Making it available, most especially during the dry season, both for domestic and agricultural purposes require an extra effort. To supply the demand, people are using different driving machines and recently Solar powered watering pumping systems are becoming very popular throughout the world. A photovoltaic system, often known as a solar power system, is a power system that uses photovoltaics to provide usable solar power for any purpose. It is made up of several components, including solar panels that absorb and convert sunlight into electricity, a solar inverter that converts the output from direct to alternating current, as well as mounting, wiring, and other electrical accessories [1, 3]. It may also feature an integrated battery solution and use a solar tracking system to improve the system's overall performance since storage device prices are predicted to fall. Because of its positive impact on the power sector, the system has become very promising and popular, and this research work focuses on its impact on the agricultural sector for irrigation with the design and performance analysis of a solar-powered water pumping system in the case study area of Mirab Abaya.

The rise in agricultural productivity leads to an increase in farmer's income and decrease of poverty However, several factors jeopardize the development of agriculture [11]. These constraints are generally related to water scarcity, climate change, land degradation, and pests [12]. Agriculture is predicted to be affected by the effects of climate change, particularly for smallholders with a low ability of adaptation [13]. Climate change is expected to affect water resources in different ways, including changes in the amount and pattern of precipitation and droughts. These changes in precipitation can highly affect agricultural production in all regions of the world. Changes in precipitation patterns are also likely to reduce surface water quantity and groundwater recharge rates [14].

For this purpose, irrigation can be seen as an alternative. It could improve land productivity, enhance the resilience of farms, stabilize and increase farmers' incomes, reinforce food security and nutritional diversity, and create jobs [15]. In fact, the development of irrigation faces many constraints. Among them, the cost of energy is one of the most recurrent and important. The cost of energy is very high, especially for smallholder farmers who are using pumps in irrigation. As a result, energy costs have a particular impact on agricultural production costs. The energy sources used to power pumps are mainly diesel and grid. However, the cost related to these energy sources is very high and is not always accessible to farmers, and they negatively impact the environment. These conventional energies are non-renewable and are combined with climate change risks due to global warming emissions [17]. Indeed, the world's population demand for energy is increasing due to the high population growth. As a result, the use of energy from fossil fuels is increasing, leading to a scarcity of fossil fuel resources, increased pollution caused by greenhouse gas generation, and permanent variations in fuel prices now a days.

Hence, this research primarily focused on a direct linked solar water pumping system without batteries, as well as factors of improving overall system efficiency. The presence of batteries in a solar water pumping system has several drawbacks, including a reduction in the system's total lifetime due to the battery's short life span in comparison to the other system components, an increase in system cost, a reduction in overall system efficiency, and an increase in system maintenance costs due to the batteries' high maintenance requirements. Because of these factors, keeping water in tanks is a better alternative than storing electric energy in batteries [3]. The overall solar water pumping system consists of PV modules, inverters, protection systems, cables, water pumps, and a monitoring system.

1.2 Problem statement

Agriculture is the backbone and main source of Ethiopian economy and people’s daily lifestyle is depend on it either directly or indirectly. Most part of Ethiopia, many farmers are cultivating the crops in the season of rainfall and some are using the pumping technologies and continues in dry season through irrigation. But many of them are unable to use either diesel or gasoline water pump for irrigation even if the water resource is available due to lack of awareness, lack of money, and lack of training. They rely only on the seasonal rainfall for their crop production. The higher costing and environmental concerns of generator pumps, namely; daily fueling, labor, maintenance, and emission effect are the main drawbacks of diesel water pumps. Therefore, to solve the related and above mentioned problems, the researcher deals with the solar water pumping system, which advances the irrigation trend in the case of Mirab Abaya area.

1.3 Objectives

1.3.1 General objective

The general objective of this study is to design and evaluate a solar-powered water pumping system that has been built for mini-irrigation for maize cropping in Mirab Abaya.

1.3.2 Specific objectives

- ✓ Determining the solar potential in the Mirab Abaya
- ✓ Determining water demand
- ✓ Evaluation of the performance of solar water pumping system(SWPS) analytically
- ✓ Experimental evaluation of the performance of PV panel outputs on the Location
- ✓ Numerical evaluation of life cycle cost (LCC) of the system by using Homer pro software

1.4 Hypotheses

Hypothesis 1: The site has close access to an excess supply of surface water from Lake Abaya, therefore the total dynamic head is low, that lowering the overall cost of the system (pumping power, suction head).

Hypothesis 2: The project is applicable in most places of Ethiopia, as long as the weather conditions are same.

1.5 Significance

Solar energy is clean and promising, given the autonomy and abundance of the solar resource in Mirab Abaya area with global horizontal radiation varying between 4.78 and 6.46kWh/m^2 which is comparable to the best sunshine regions of the world. Since the project deals with the most promising ways and it is believed to play a great role in enhancing food security and job opportunity creation, especially, in rural remote area communities via transforming their farming culture through renewable energy fueled irrigation-based to boost any agricultural productivity.

The following are some of the main benefits of SWPS implementation: -

- Its power source is renewable energy that's clean, and free
- Very low operating cost, like, cleaning of the panels
- The maximum providence of water output when it is needed the most, i.e. in sunny and drier conditions

1.6 Scope

This research was confined to designing and analysing of the solar powered water pumping system (SWPS) performance with the available solar potential of the Mirab Abaya area. To identify the system viability according to environmental, economic, and technical feasibility, the evaluation performance of the whole system has been done in analytical method, Life Cycle Cost Analysis (LCCA) of the system analysed in the Homer pro software and the performance of PV panel tested for ten days within each twenty minutes. For the design, a one hectare sized farm assumed for maize crop cultivation, irrigated from Lake Abaya water source under the perspectives of agricultural bases.

1.7 Limitations

- In the area, only small-scale farmers were considered, and water source is Abaya Lake.
- The performance evaluation has been done for the PV panel only.

1.8 Description of study area

Mirab Abaya is Woreda, which is divided into 24 Kebeles, one urban and 23 rural, and is located in the Southern Nations, Nationalities and Peoples Region, Gamo-Gofa Zone, 594 km far from Adama. There are three major agro-ecologies in the country: Dega (highland), Woina dega (mid-altitude), and Kolla (lowland) (low land). The kolla agro-ecology is represented by 16 Kebeles, the dega agro-ecology by six, and the woina dega agro-ecology by two. In the dega and woina Dega agro-ecologies, the average annual rainfall is 580mm. The average annual rainfall in the kola ranges from 1,000 to 1,100 mm. Birbir is the political center of the Woreda and lies about 230 km away from the regional capital. The Woreda is bounded in the north by Wolayita Zone (Humbo Woreda and Boreda Woreda) and in the south by Arbaminch Zuria Woreda and Lake Abaya. In the east, it is bounded by Lake Abaya and in the west by Chencha Woreda. More than 90% of the population of the Woreda depends on agriculture. The total area is 107,971 ha, out of which 40,200 ha are covered by water, 4,262 ha are woodland and 2,462 ha is non-arable land. Water supply schemes are found in only 23 of the Woreda's 24 Kebeles.

Figure 1.1: Geographical location of Mirab Abaya

1.8.1 Geographic coordinates of the selected site

- Latitude: 6.17° N
- Longitude: 37.47° E
- Sunset: 03:35
- Sunrise: 15:41
- Elevation above sea level: 1221m

1.9 Organization of the paper

This thesis is organized into six chapters. The first chapter presents the introduction of the study including its background, statement of the problem, the purpose of the study, the general and specific objectives, significances, scope, and limitations of the study. The second chapter presents detailed literature reviews including one paragraph of conclusion for the reviews. Chapter three discusses the methodology and materials for the thesis work. The fourth chapter deals with solar potential estimation, estimation of water requirement, pump selection, PV panel sizing, inverter sizing, and other details about the system designs. The fifth chapter is all about the results and a discussion of the results. The last chapter; chapter six, is finalizing the thesis by the conclusion based on the results and recommendations for future work accordingly.

1.10 Summary

The first chapter of a thesis is discussed about the introduction concerning the background of the study, problem statement, main and specific objectives, hypotheses about the study, significances, scope, limitations, background of a case study location and finally, the organization of the paper has been discussed accordingly.

CHAPTER TWO

2. LITERATURE REVIEWS

2.1 Introduction

The Solar powered water pumping system is a set of scientific principles that uses solar radiation as a source of energy to pump water, with this energy being converted into electrical energy by solar panels and then used to drive electric motors connected to the pump set. According to recent world trends, it is mostly used for three purposes: village drinking water supply, livestock watering, and irrigation. Figure 2.1 shows a schematic of a solar pump for the village water supply. Although there will be a need to conserve water during periods of low insolation, the Village will have a continual water requirement.

Figure 2.1: Village water supply West Madison (Source:acellcsolar Solarirrigation)

2.2 Types of a solar water pumping system

There are two types of solar photovoltaic water pumping system that functions for different purposes; Battery based and direct-coupled solar water pumping system. A variety of factors must be considered in determining the optimum system for a particular application.

2.2.1 Battery based solar water pumping system

This system consists of a photovoltaic panels charge controller, batteries, pump controller, and DC water pump. The electric current produced by PV panels during daylight hours charges the batteries, and the batteries in turn supply power to the pump anytime water is needed. The use of batteries spreads the pumping over a longer period by providing a steady operating voltage to the DC motor of the pump. Thus, during the night and low light periods, the system can still deliver a constant source of water for livestock. The use of batteries has its drawbacks. First, batteries can reduce the efficiency of the overall system because the operating voltage is dictated by the batteries and not the PV panels. Depending on their temperature and how well the batteries are charged, the voltage supplied by the batteries can be one to four volts lower than the voltage produced by the panels during maximum sunlight conditions. This reduced efficiency can be minimized with the use of an appropriate pump controller that boosts the battery voltage supplied to the pump [1, 2]. In direct-coupled pumping systems, electricity from the PV modules is sent directly to the pump, which in turn pumps water through a pipe to where it is needed. This system is designed to pump water only during the day. The amount of water pumped is dependent on the amount of sunlight hitting the PV panels and the type of pump. Because the intensity of the sun and the angle at which it strikes the PV panel change throughout the day, the amount of water pumped by this system also changes throughout the day. For instance, during optimum sunlight periods (late morning to late afternoon on bright sunny days) the pump operates at or near 100 percent efficiency with maximum water flow. However, during the early morning and late afternoon, pump efficiency may drop by as much as 25 percent or more under these low-light conditions. During cloudy days, pump efficiency will drop off even more. To compensate for these variable flow rates, a good match between the pump and PV module is necessary to achieve efficient operation of the system.

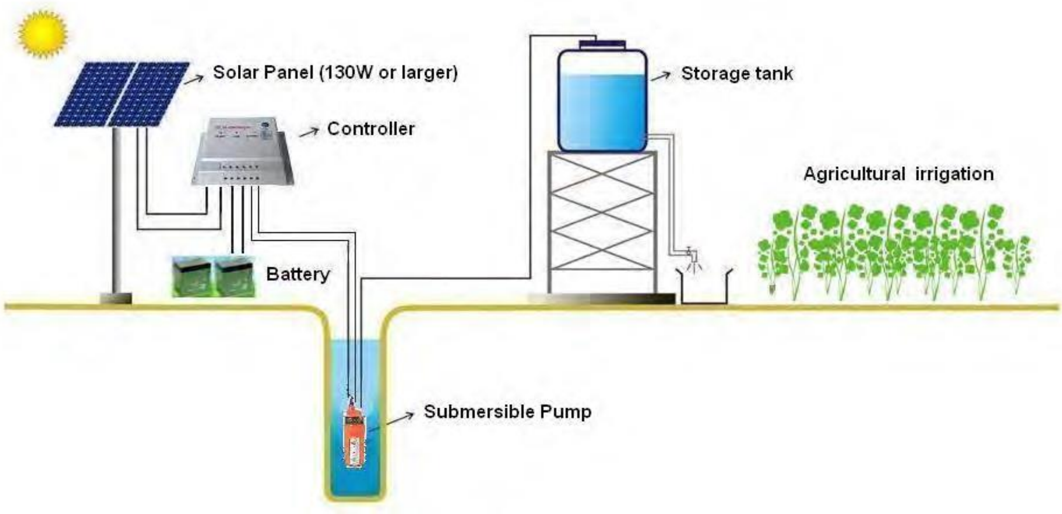

Figure 2.2: The battery-based submersible solar water pumping system [6]

2.2.2 Solar-Direct coupled water pumping system

In a solar direct pumping system, the electric power from the PV modules is sent directly to the pump which in turn pumps water through a pipe to where it's needed. This system is sized to store extra water on sunny days so it is available on cloudy days and at night. Water can be stored with the excess amount of water that is needed in a watering tank or a separate storage tank and then gravity fed to smaller watering tanks. Solar water pumps enable you to move water from its remote source to where you need it, without access to power lines.

Solar water pumps are different from regular AC-powered pumps in more ways than the simple fact that they use DC power instead of AC [4, 5, 6]. Most solar pumps are designed to be used in off-grid situations and are designed to be extremely efficient. By not experiencing losses when going from DC to AC and back to DC, it can maximize the pumping while minimizing the power in use. The most efficient way to use a solar pump is PV-direct, powering the pump directly off the solar panel, without using batteries. Rather than experiencing losses through storing power in batteries, the water itself is stored in a tank to be used when needed.

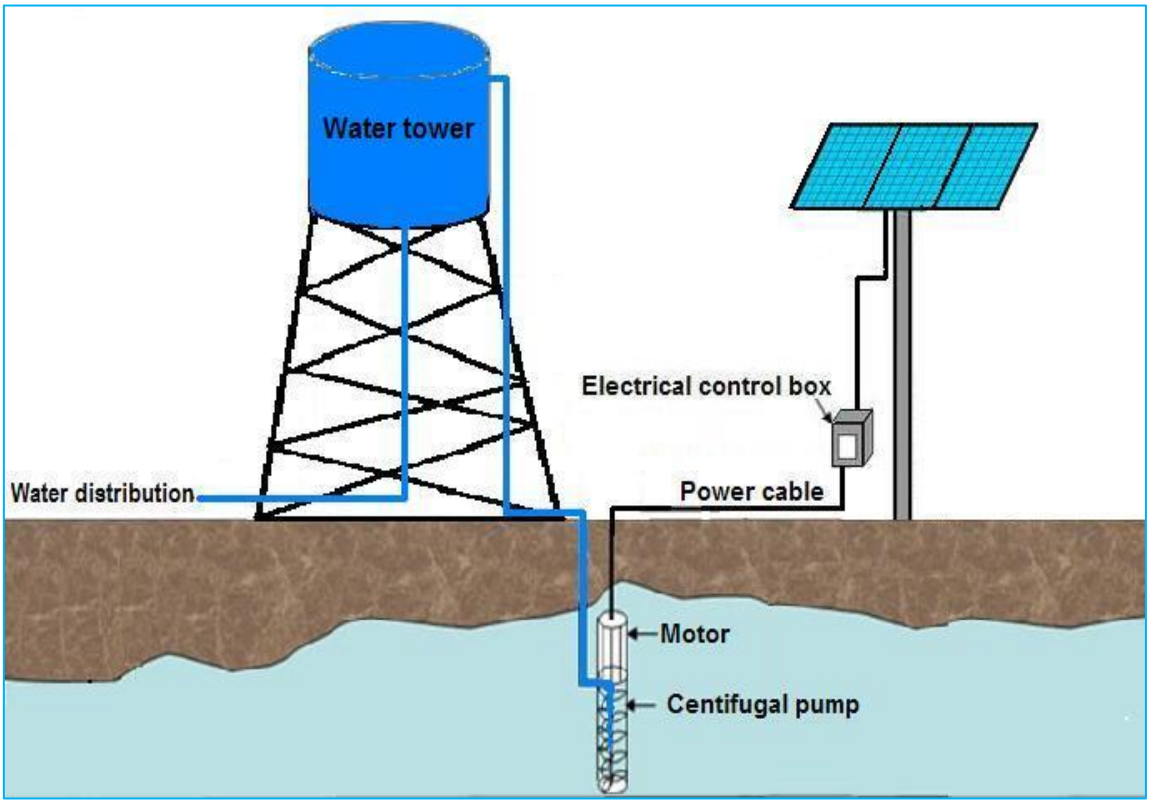

Figure 2.3: Block diagram of the solar water pumping system without battery storage [11]

2.3 Basic components of the solar water pumping system

There are two major components in the solar-driven pumping system, which are; Power supply components and water storage with its distribution systems. The power supply part includes a Solar array, controlling systems, and battery, and the second part is Solar pumps which are designed to be operated by solar energy, these pumps have electric motors which can be either AC or DC connected to a pump set [12]. However, Jeff and Bill described the three main parts of SWPS which are; the PV array, the Motor and pump subsystem, and the storage and distribution system that takes water to the point of use.

2.3.1 Power supply components

A. Solar Panel:- It's the main unit of the solar water pumping system built from the solar modules, to get the required voltage and current required by the solar pump, these modules should connect in either parallel or series connection. These modules are rated in different peak watt and tested at 1000 (W/m^2) radiation level and 25℃ temperatures. Solar modules are made up of the smallest elements known as solar cells, the combination of cells called modules, and the collection of modules called solar array; thus, the special layered semiconductors materials in the solar cells when exposed to light produce direct current (DC) electricity [10, 11]. On the base of the sunlight collection method, PV systems can be classified into two generals

- ✓ **Flat-plate systems**: - Flat-panel PV systems directly capture the sunlight or they use the diffused sunlight from the environment. They can be fixed or combined with sun-tracking systems.
- ✓ **Concentrator systems: -** The system collect a large amount of sunlight and concentrate and focus the sunlight to target PV panels using lenses and reflectors. These systems reduce the size and required several cells while the power output is increased. Moreover, by concentrating the solar light, the efficiency of the PV cell is increased [1, 9].

Types of solar panels in the market

Solar cells today are mostly made of silicon, a chemical element with semiconducting properties. In most types of solar cells, silicon is in a crystal form.

- Because 100% pure silicon crystal doesn't transfer electric current, it is "doped" with very small amounts of "impurities" usually phosphorus and boron that do readily carry an electric current within the silicon crystal lattice.

- The silicon doped with phosphorus is called N-type (for “negative” because it has a surplus of electrons).
- Silicon doped with boron is referred to as P-type (for “positive” because it has a deficit of electrons).
- When constructed with one N-type section next to one P-type in this manner, the solar cell is called single-junction, meaning it has only one p-n junction

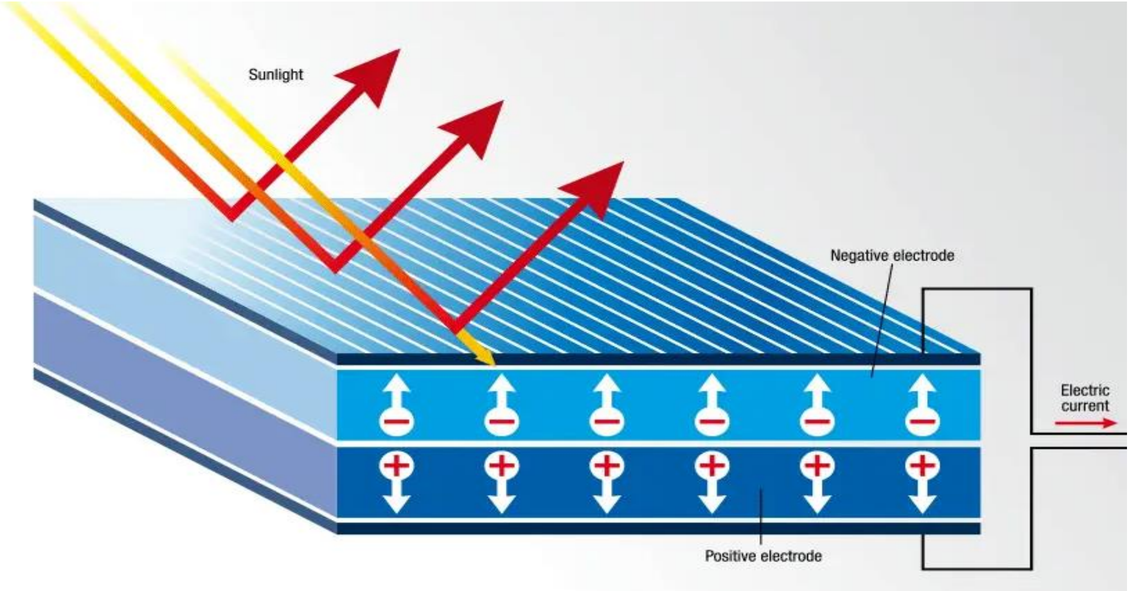

Figure 2.4: The cross-section of solar cell [15]

The working principle of PV Panel

When doped silicon absorbs some of the sun’s energy, it dislodges some free electrons in the process. In the electric field of a solar panel system, the electrons are routed to flow in one direction, establishing an electric current.

The solar cell's electric field causes a voltage. The mathematical product of current and voltage is power used to run pumps, household appliances, and heat or cool your home.

Other components of a solar cell include an anti-reflective coating since silicon's natural luter would cause sunlight to reflect off of it which is not what should happen if you want to create electrical power [15, 19].

The silicon crystals of the solar cells are grouped inside an electric field and then covered in glass to protect all components from weather.

Monocrystalline solar panels:-Constructed from a single silicon crystal that's been sliced into wafers, monocrystalline solar panels contain rows and columns of these wafers. Since the silicone crystal (also called an ingot*)* is cylindrical, slicing them into wafers causes them to have rounded edges.

Polycrystalline solar panels: - Polycrystalline (multi-crystalline) solar panels have solar cells containing multiple crystalline fragments of silicon. The fragments may be the leftover pieces from monocrystalline solar production. They are arranged irregularly. Then they're melted together and formed into solid blocks before being cut into wafers. Each wafer is more rectangular than its monocrystalline counterparts.

Thin-film solar panels: - is called second-generation solar cells, thin-film solar panels can be made of a variety of materials including:

- Amorphous silicon (no crystal lattice)
- Gallium arsenide
- Copper indium gallium selenide (CIGS)
- Cadmium telluride (CdTe)

Each wafer of a thin-film cell is super-skinny compared to the other types, making it flexible. They may be applied by an adhesive directly to a surface (like your roof, boat, or RV), or set up into durable frames (rack) much like the other common types of solar panels [15].

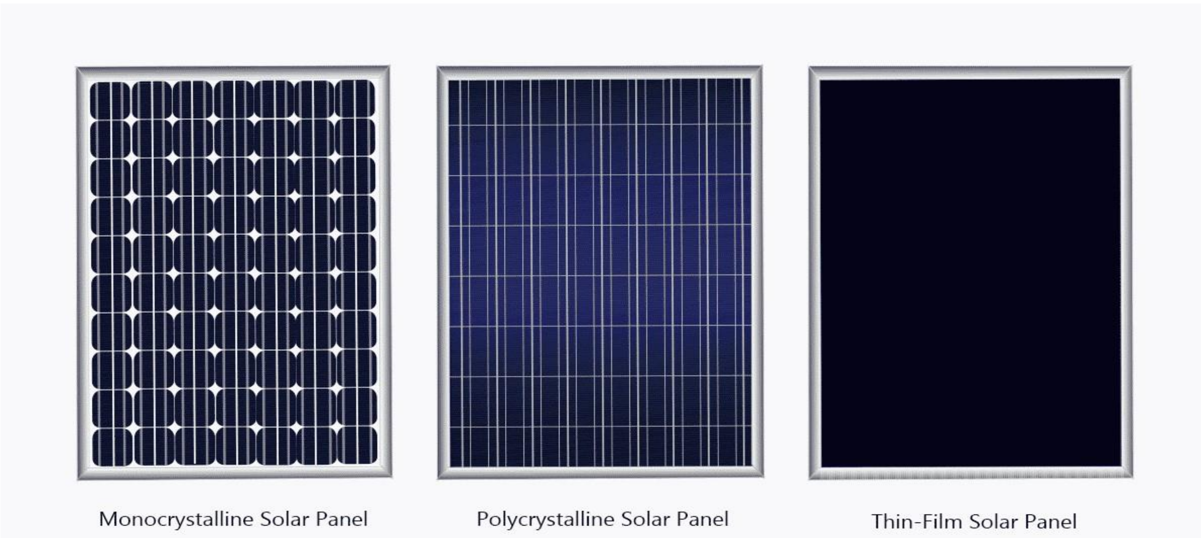

Figure 2.5: Types of most available PV panels in the market [15]

B. Motors: - Solar pumps are integrated with electric motors which can be either AC or DC motors, two types. They are explained below as follows:

DC motors: - DC motors operate under a Direct Current source, thus making the motor more applicable where the direct coupling with PV panels is required. When opting for DC motors, it's necessary to consider a highly efficient motor. The permanent magnet that exists in the brushless DC motor communicates with the stator electronically to lessen the requirement for brushes. When the motor opted is DC motor type the there is no need to convert the DC from panels to AC by using DC/AC Converter [21]. DC motors are extensively applied in small applications with a capacity below 3 kW [22]. Samatha et al. Concluded that DC motors are very expensive since they require regular maintenance of the brushes [11].

AC motors:-These Motors use Alternating Current to operate, they are widely used and commercially available at different ranges. According to Shrestha and others, Induction motors and asynchronous motors are the basic two types of motors available [23]. El-Shaikh et al. described that AC motors can be further be divided into single-phase motors (up to 3hp) and three-phase motors which go beyond 3hp. 1kW or less motor is not suitable for PV-powered systems due to their tendencies of having low efficiencies. Additionally, to deliver the high starting current power conditioning circuitry needs to be added [24]. There are about five starting methods of AC motors which are: DOL, Star-Delta, Auto Transformer, Soft Starter, and VFD. Connecting a DC motor directly from the PV system is considered the least expensive method of pumping water by using the solar energy but as mentioned above by Jenkins this should be more applicable to a system with less than 3kW. Based on 2014 prices, AC motor was economic compared to DC motors for PV pumps where: (Flow rate ×Water head) >600 m^3/day [24]. Apart from the other comparisons, AC motors are reliable and cheaper compared to DC motors, thus choosing either to use AC or DC motors can be a complicated exercise. Girma identified five criteria that should be used for choosing a motor pump for a PV system, these criteria are; price, efficiency, reliability, availability, and wattage [25]. By considering the simplicity of operation, cost, as well as environmental friendship merits, AC-type motor, have been chosen for this project.

C. Solar battery

The battery which stores the solar energy in the system is very important when there is a need to pump water during the night and where there is a low level of solar intensity. There are many types of batteries but the most commonly used type is Deep Cycle Lead acid. This energy can be delivered to the pump either in DC or AC with the help of an inverter. They are constructed by a group of cells with each cell delivering 2 Volts, thus 6 lead-acid cells connected in series create a 12V battery. Good performance batteries are worth the investment but are they are too costly, in a solar pumping system, a water storage tank can be offered into the system to avoid incorporating the battery into the system to reduce the cost [2, 12].

D. Charge controlling unit

The Charger controller is part of the power supply component and it's intended to protect the battery from overcharge or over-discharge.

The main characteristics of charger controllers are [13, 14];

- Rated nominal voltage (12, 24, 48V)
- They can handle maximum current (to avoid overcharge)
- Lights or alarms are the communication or indicators
- Low voltage disconnection (to avoid over-discharge)
- Basic voltage regulation using a charge or discharge controller

2.3.2 Pumps

It is a device that is used to draw water from the well or surface water source to storage tanks or users directly [28]. The selection of solar pumps is depending on the site condition, flow required and nature or type of water resource (surface or underground). Thus, there are two major types of solar pumps depending on the location of the water source; Surface pump and Submersible pump [29].

A. Surface pumps

Surface pumps are commonly applicable in surface water sources such as ponds, lakes, shallow wells, and streams, the water to be pumped should not be more than 7 meters below ground level or pump inlet as suction lift. This suction lift needs to be maintained to a minimum limit to ensure system reliability and pump efficiency [11]. This allows easy access to the pump itself, but because of the environment, they may require access more often.

B. Submersible pumps

They are completely submerged in a clean water source. This gives them many advantages over their unprotected counterparts.

- ✓ One great merit is their efficiency; water pressure will naturally force water into a submerged pump rather than utilizing energy to do so.
- ✓ Being submerged all the time,
- ✓ Submersible pumps do not require manual priming, which can easily become a very time-consuming chore.

2.3.3 Submersible pumps versus surface pumps

Solar water pumps are typically divided into two categories: submersible pumps and surface pumps. A submersible pump is installed underwater, usually in a well, but can also be in a pond or stream if raised off the bottom. A surface pump is installed above the water, with an intake hose feeding the pump from the water source, and the output hose feeding the tank. Pumps can push water out much higher than they can suck water in, so then they need to be close to the water source. Keep the head, or the height difference between the water and the pump, as low as possible [17, 18, 19].

Figure 2.6: Submersible solar pump (left) versus a surface pump (right)[33]

2.4 Performance evaluation reviews

The performance of the PV panel is calculated under standard conditions; with solar irradiation of 1000 (W/m^2) of surface, a temperature of 25°C, and equal to 1.5 spectral distribution. But the yield outputs of photovoltaic panels are not constant, it also varies substantially depending on several factors, such as [20, 21, 22, 23]:

- The characteristics and performance of the different materials as per as it's manufactured (monocrystalline, polycrystalline, amorphous), of the inverters, and of the other components of the system
- The Correct direction of the modules alignment to solar radiation
- The tilt angle of the panel
- The effect of shading
- Operating temperature of PV panel
- Composition of the light spectrum

Scholars have been working on the analysis of the performance of solar water pumping system to dig out and dwell on the gaps within previous works. Here some of them are going to be discussed with their results accordingly. The performance evaluation methodologies used in various studies are reviewed to provide further insight into the project work.

Elrefai et al. (2017):- they studied about the designing of direct coupled solar water pumping system without using batteries. Technical, economic and environmental parameters are considered in the design procedures. Performance evaluation of solar water pumping system is studied using three expressions; yield factor (YF), wire to water energy efficiency (WWEE) and system performance index (SPI). A full monitoring system is presented to evaluate the operation of the system. The proposed monitoring system measures a real time data of system parameters. A case study of 45 kWp solar water pumping system in El Wahat, Egypt is studied. The recorded data using the monitoring system shows that the average daily water volume was 788 m^3 over one year. The maximum output water volume was 887 m^3 in summer with yield factor 5 (kWh/kWp/day) [37].

Kazem et al. (2015):- intuitive and numerical methods were used to design the system. HOMER software as a numerical method was used to design the system to come up with optimum design for Oman. Also, REPS.OM software has been used to find the optimum design based on hourly meteorological data. They found that the system annual yield factor is 2024.66 kWh/kWp. Furthermore, the capacity factor was found to be 23.05%, which is Promising. The cost of energy and system capital cost has been compared with that of diesel generator and systems in literature. The comparison shows that the cost of energy is 0.180, 0.309, and 0.790 USD/kWh for PV-REPS.OM, PV-HOMER, and diesel systems, respectively, which sound that PV water pumping systems are promising in Oman [38].

Parmar et al. (2020):- studied on a 0.1HP, 80Watt, DC surface pump was analyzed for operating voltage of 12V, 24V and 36V. It has been observed that, at maximum head (22 m), the wire to water (WTWE) efficiency is 42.21% and input power is 39.72W. The maximum WTWE efficiency is observed to be 43.64% at input power of 37.8W and operational head 20 m. Estimation of wire to water efficiency with respect to rate of discharge of water and input DC power for a DC centrifugal surface pump at 24V is shown in Figure 8. At the maximum head (22 m). The WTWE efficiency is observed to be 46.47% and input power drawn is 44.56W which corresponds to its maximum WTWE efficiency. The maximum WTWE efficiency of 48.97% is also recorded for operational head of 8.5 m with input power of 88.31W due to increased irradiance [39].

Treephak et al. (2015):- In Thailand, they studied results of the economic costs of the four

Pumping systems, show that, the solar pumping system can be used to replace the gasoline water pumping system. The DC solar pumping system has a payback less than 10 years. The systems that can payback fastest is DC solar pumping system without the battery storage system. The system can payback slowest is the AC with battery storage system. In terms of the net present value, the DC solar pumping system without battery system has profit return of more than 97,000 THB. Whereas the AC solar pumping system with battery system cannot payback because in 25 years NPV loss more than 7,900 THB. Finally, the IRR of the AC solar pumping system with battery storage system is 2.89%. It is the only system with a rate less than the average inflation rate of 3.36%. Therefore, it can be concluded that water pumping for rice cultivation using DC solar pumping system without the battery storage system has the highest economic value. Moreover in generally AC motors are easier to maintenance than DC motor because it is more commonly used [4].

Khan et al. (2012):- designed a solar photovoltaic water pump by adding a DC-DC buck converter to provide current boosting to the DC pump. And here too, no battery, and the inverter is used in the system to reduce the cost and maintenance. The highest no-load speed goes up to 3000–3200 revolutions per minute (rpm). The results from the no-load test revealed that the integration of the DC motor with the centrifugal pump has matched quite perfectly. A direct-coupled system without a Power conditioning unit (PCU) is compared with a DC-DC convertor type system. The DC motor operating voltage, operating current, shaft rpm, and the discharge rate at different pressures during different times of a day for both systems are measured and improvement in the electrical power output is found in the designed DC water pumping system [40].

Gad et al. (2009):- developed a methodology for performance prediction of a direct-coupled PV water pumping system in South Sinai, Egypt using a computer simulation program. The program simulates the hourly performance of the system on any day of the year, under different PV array orientations. The system is found to be capable of pumping 24.06 l/day, 21.47 l/day, and 12.12 l/day in the summer solstice, equinoxes, and winter clear sky days respectively. The estimated PV array efficiency ranges from around 13.86% in winters to 13.91% in summers [41].

Kazem et al. (2015):- Studied, the cost and emission measures for diesel generator and PV, were determined for a PV water pumping system used for irrigation applications in Sohar, Oman, in rural area applications. The recommended system has a daily load of 2.22 kWh/day, four batteries (12 V and 200 Ah), 0.84 kW PV modules and 0.8 kW inverter. The optimum cost of the PV system energy is 0.309 USD/kWh, making it an attractive option compared to the diesel engine energy cost of 0.79 USD/kWh. The study analysis shows that using a PV system instead of a diesel generator protects the environment from greenhouse gas emissions. The employment of this option eliminates about 924 kg/year of CO_2, 2.28 kg/year of CO and 0.253 kg/year of NO_x. It prevents 0.172 kg/year of HC, 1.86 kg/year of SO_2 and 20.4 kg/year of suspended particles from emission to the environment. The system was implemented and tested, and the PV array can produce enough power without the need for batteries or a tank in the peak hours [38].

Katan et al. (2018):- The main objective of this paper was to develop dynamic models for both battery-less and battery-based system to run a motor-pump set using solar energy to lift ground water for irrigation purpose. Sizing was done for battery-based system in HOMER which was also validated using hand calculation. Water tank equivalent battery storage was also calculated for battery-less system. The system is designed based on data of an existing project in Lalmonirhat, Bangladesh. The system comprises a 38.4 kWp solar photovoltaic array, inverter, AC motor, and pump set, which can discharge a maximum of 1,930 cubic meter of water per day. MATLAB simulation is performed with two types of energy storage system: (i) electric energy using a battery bank and (ii) stored water in a large water tank. A large battery bank and a transformer are needed in the former one, which turns out as a costly solution. The latter one requires a boost converter and a large water tank to store around 2,000 cubic meter of water, which is also a costly solution. A combination of both systems yields an efficient and economical solution [42].

Mokeddem et al. (2011):- investigated the performance of a directly coupled DC-powered PV water pumping system. The system operates without battery and electronic controls. The motor-pump efficiency did not exceed 30%, which is typical for a directly-coupled photovoltaic pumping system; yet such a system is suitable for low head irrigation in remote areas. The efficiency of the system can be increased by selecting the size of the PV array, its orientation, and the motor-pump system. Maurya et al. developed relationships between array power and borehole depth per capita water use, rainfall, borehole depth, and capital cost of solar photovoltaic water pumping systems in Nigeria which would lead to increased performance, reliability, cost-effectiveness, and adoption of the technology [43].

Kaka and Gregoire (2015) studied the performance of a PV water pumping system in a village at 30 km of Keita (Niger) to meet the water needs of 500 persons and reported that the cost of one cubic meter of water pumped by the PV system is more advantageous than other systems. PV water pumping is found to be well suited for arid and semi-arid areas due to the existence of underground water potential, and large solar energy potential of more than 6 kWh/m² [18].

Padmavathi and Daniel (2016) analyzed various photovoltaic water pumping options and domestic water requirements for Bangalore city in India and concluded that PV panels ranging from 60 Wp to 500 Wp are sufficient for residential buildings in Bangalore and suggested that government policies and regulations are required for the promotion of using PV water pumps in the urban domestic sector [19].

Aboagye et al. (2021):- studied about the temperature affects, the efficiency of solar photovoltaic modules and hence the electrical power production. They identified a suitable coolant that could best reduce the temperature of solar photovoltaic module and increase the efficiency of the solar module. Experiment was designed for the application of each of the four coolants. The performance of each coolant was evaluated and the best coolant was selected. The study identified sugar solution, water, Abro radiator coolant and soluble oil as the potential suitable coolants. The percentage increase in efficiency for soluble oil was 5.3% followed by 3.8% for water and then 3.5% for sugar solution whiles the Abro radiator coolant was last with 3% after the application of the coolants [44].

Sargunanathan et al. (2020):- they studied experimentally investigation of the possibility of improving the performance of the standalone rooftop SPV module used in the residential and office buildings during peak solar irradiance and ambient temperature with active cooling of the rear surface alone by spraying water and the front surface alone by water overflowing over it and cooling of the rear and the front surfaces simultaneously. The underneath of the SPV module is attached with a tray with a length of 1580 mm, a width of 640 mm, and a depth of 100 mm. It is filled with 40-70 litres of water. Accouters are made for water overflowing from the tube over the front surface of the module and cooling of the rear surface by spraying water. The rear surface cooling, front surface cooling, and simultaneous cooling of both the surfaces reduce the average operating temperature of the module by 15.52°C (maximum 18.6°C), 24.29°C (maximum 28.7°C), and 28.52°C (maximum 34.7°C), respectively. This temperature reduction leads to the increase in the power output of the 150W module by 10.70 W, 18.48 W, and 20.56W and percentage increase in efficiency by 8.778%, 15.278%, and 16.895% for rear, front, and simultaneous cooling of surfaces, respectively. The net power output of the module with the front surface cooling by overflowing (0.9 litre/min) water is higher, i.e., 15.88 W/150W, and produces installation capacity of 0.4234 watt-hour (Wh) of more energy per watt during the test period 10 AM to 2 PM in a day [45].

Odeh et al. (2017):- developed and validated a simulated model against laboratory and field data, using TRNSYS, for an AC PV water pumping system, utilizing real field data obtained from a system installed in Jordan. Authors studied the mismatch of pump characteristics, well system characteristics and average performance ratios for the system, effect of insolation frequency, and the PV array size, which affect PV system performance [46].

Ziyad and Dagher (2018):- presented a technique to improve the performance of a photovoltaic water pumping system by coupling a PV-powered permanent magnet DC motor between a PV array and a screw-type volumetric water pump. In this method, the authors used a solid-state Electrical Array Re-configuration Controller (EARC), which senses the radiation as low, medium, or high. Accordingly, the controller chooses one desired set of *I–V* characteristics for starting and another desired set of *I–V* characteristics for steady-state Operation. Authors report that using this technique considerably improves the pump's performance, particularly in the early morning, late evening, and cloudy days thus providing a wide range of irradiance levels for operation and extra pumping hour [47].

Abdolzadeh et al. (2016):- Investigated the effects of spraying water over the photovoltaic modules of PV water pumping system performance under different operating conditions. The performance of a PV water pumping system with two and three photovoltaic modules of 225 W each is studied by spraying water in parallel. It is found that due to a high module temperature, the module performance decreases, and system performance also decreases. Spraying water on the PV modules decreases the module temperature and increases the module performance; in turn, the pump flow rate increases considerably when the modules are cooled [19].

Abdolzadeh and Ameri (2018):- investigated the possibility of improving the performance of a photovoltaic water pumping system, by spraying water over the PV modules. The results show that spraying of water can achieve 12.5% mean PV efficiency. The mean flow rate at 16 m head on the test day was about 479 l/h in case of a system without water spray over PV modules whereas it reached 644 l/h for the system sprayed with water. Spraying of water on the photovoltaic modules leads to cooling of modules, therefore, improves the system and subsystem efficiencies [35].

Joao and Luis (2011):- proposed a new converter for PV water pumping systems without storage batteries. They designed a converter that drives a three-phase induction motor. The results show a peak efficiency of 91% at the rated power of 210 W for the DC/DC converter with three-phase voltage source inverter (VSI) and a peak efficiency of 93.64% for the DC/DC converter and suggested that the proposed solution is a viable option for more reliability [48].

Eduard et al. (2015):- proposed a PV water pumping system using a six-step square-wave inverter, both as a variable-frequency source and as a peak-power tracker, which is coupled with a centrifugal water pump, and the controller is used to sense the changing conditions. Authors suggest that the system can be implemented by a simple microcontroller which requires control variables such as power, voltage, and current output of PV array to be fed back to the microcontroller. The insolation level is simulated by changing the coefficients of the voltage and current at different times [18].

Table 2.1: Comparison of cost of energy from some literature reviews

S.No.	Reference	Cost of energy ($USAD/kWh)	Power source
1	Subsidy diesel system	0.790	Diesel
2	Non-subsidy diesel system	1.228	Diesel
3	Kazem et al. (2020)	0.309	PV
4	Bakelli et al. (2011)	0.401	PV
5	Abdul-Salam et al. (2013)	0.561	PV
6	Kazen et al. (2013a)	0.389	PV
7	Al-Smairan (2012)	0.200–0.580	PV–diesel
8	Al-Badi et al. (2012)	0.21–0.304	PV
9	Al-Badi et al. (2012)	0.327–0.361	PV

2.4.1 Effect of ambient temperature

For the higher ambient temperature, a decrease of the pump flow and the global efficiency has occurred; however, a large solar radiation increase both the global efficiency and the pump flow. From many scholars' experimentation perspective, the performance of the PV module is decreasing while the ambient temperature increase above its operating condition (25°C). It has been also concluded that these performances are maximal in the midday, but are degraded when the meteorological parameters are disturbed [49].

2.4.2 Benefits of solar water pumping

Solar water pumping offers several benefits to users in Agriculture and Water supply, according to Lorentz in a case study in Morocco, the following are the highlighted benefits of solar water pumping [50].

- No fuel cost is needed in a solar water pumping system, thus reducing the energy bills and saving time by avoiding refilling of the fuel.
- Operation costs, fuel supply, and transportation are not part of the problem since the sun is reliable and an endless source of energy.

- No many moving parts in the solar water pumping system which reduces the maintenance and repair costs hence giving a good return on investment compared to other types of energy.
- Solar energy is an environmentally friendly energy source since the supply is done without emission.

2.5 Summary of literature reviews

Recently, Solar powered water pumping technology becoming more popular in the world as the result of its enormous regard of technical, environmentally and economics. Considering its merits, many scholars are actively involved to modify the system efficiency accordingly. In the above literature review, main classifications of the system are discussed, and the basic components were briefed as its functioning. According to the performance evaluation of the system, by using different methods, i.e., analytical, numerical and experimental; many researchers worked on it in the world. Some researchers worked on the sources which is PV based only and the other considered hybrid with diesel generator, various scholars studied the system by considering the effects of components. Therefore, after reviewing papers, the researcher worked on the direct coupled solar water pumping system without battery storages to reduce its economic, environmental and technical effects. The researcher used three techniques for the accomplishment of the thesis and discussed briefly in the next chapters.

2.6 Research gap

Water is one of the most primary need for the irrigation and agricultural production. For the sake of making the water available at a far distance from the source such as lake or river, free solar energy source can be used. For fulfilling the energy requirements, solar energy is used as one source of the best solutions, due to abundance and easily availability. In the area (Mirab Abaya Lake), there is no research work done to solve the significant problem of the farmers and to combat this problem and help the local society in the area of agriculture production without keeping the seasonal annual rainfall. That is why this thesis research is proposed to solve the problem of farmers living around the Abaya Lake. This research will allow the farmers to produce at least three times per year. The research aimed to design and evaluate the performance of solar powered water pumping system.

CHAPTER THREE

3. METHODS AND MATERIALS

3.1 Introduction

The design and performance estimation of solar water pumping system for irrigation depends mainly on the site parameters, such as solar irradiance, type of crop to be cultivated, crop water requirement, flow rate, number of sunshine hours with the ambient temperatures on the farm site, the required hydraulic energy demand, and the total dynamic head of the system. The following techniques are used, the analytical method for the system design, Numerical method by using Homer pro software used to estimate the life cycle cost analysis of the system and finally the experiment were done for the performance evaluation of M-60W PV panel power output in the Mirab Abaya, Birbir town. Here, some of the basic design steps of the system are shown in the Figure 3.1.

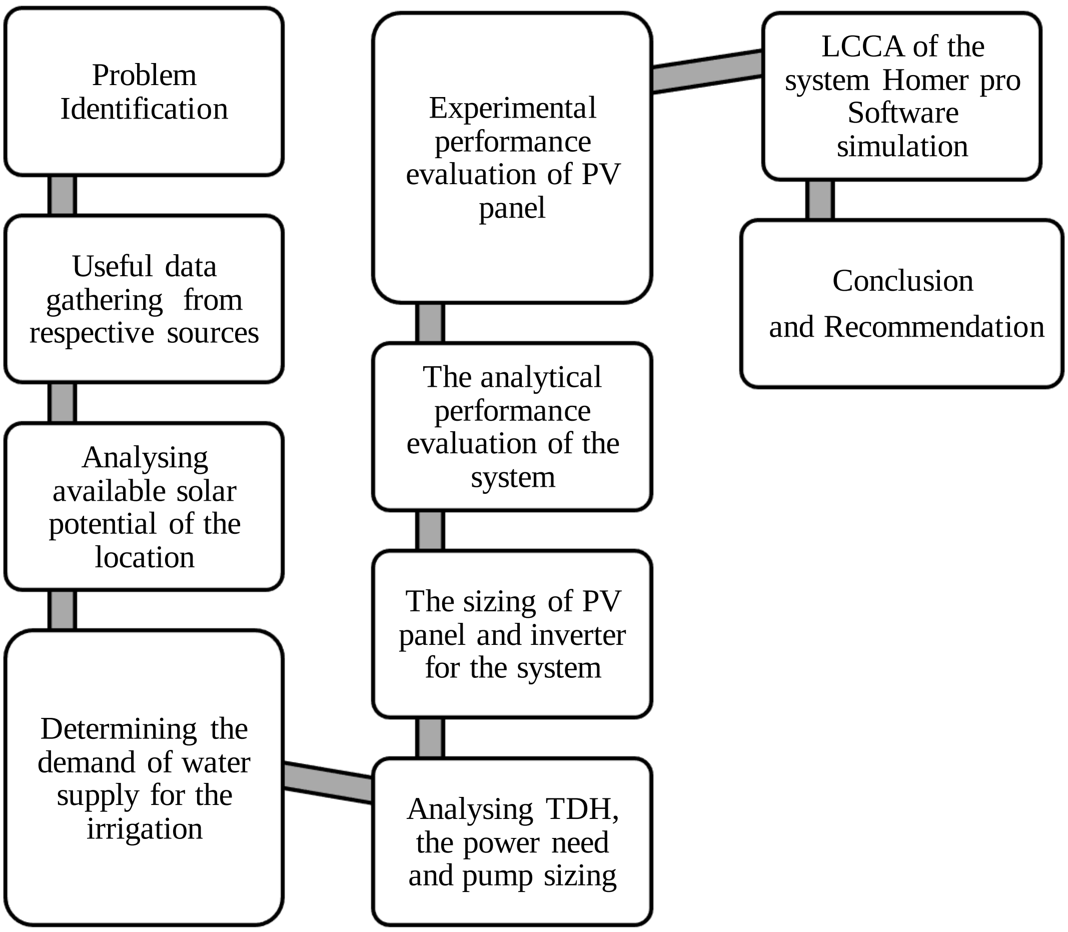

Figure 3.1: Basic steps for the system design

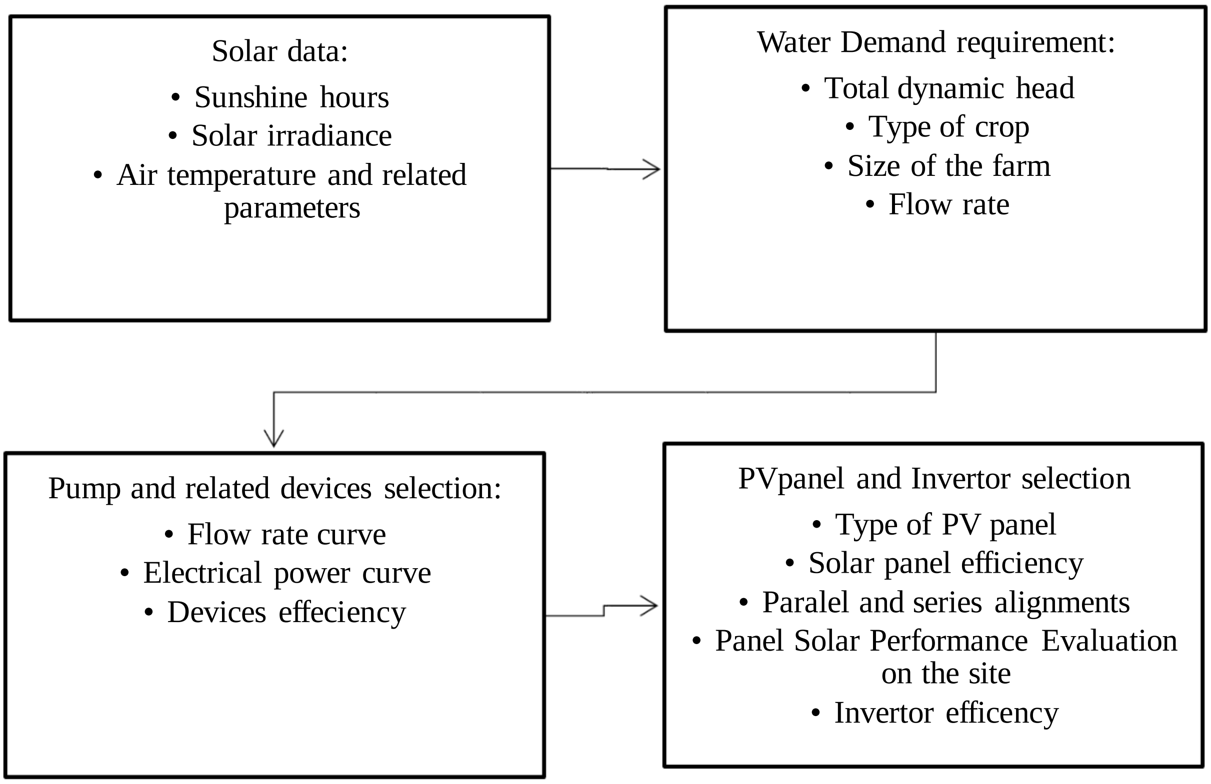

Figure 3.2: Some of basic design considerations for the system

3.2 Description of the system

The implementation of solar photovoltaic as a power source in water pumping applications has become one of the known and valuable solar energy-based applications. Understanding system design and selection of appropriate design parameters are before attaining consistent and economically viable merits of the system. To design a solar water pumping system collection of the information regarding the system components and local climate data of the selected location are required. This information helps to obtain preferred to optimized design and analyzing of results. In this research work, the design of the PV system is done by using simulation of CROPWAT 8.0 and RETScreen expert. This simulation software helps to design the system and shows how the different parameters affect the system performance results. Selection of PV array, controller, pumping unit, water supply network is useful to fulfill design requirements. The analytical and simulation results are used to understand the system design and its performance by considering different parameters effect.

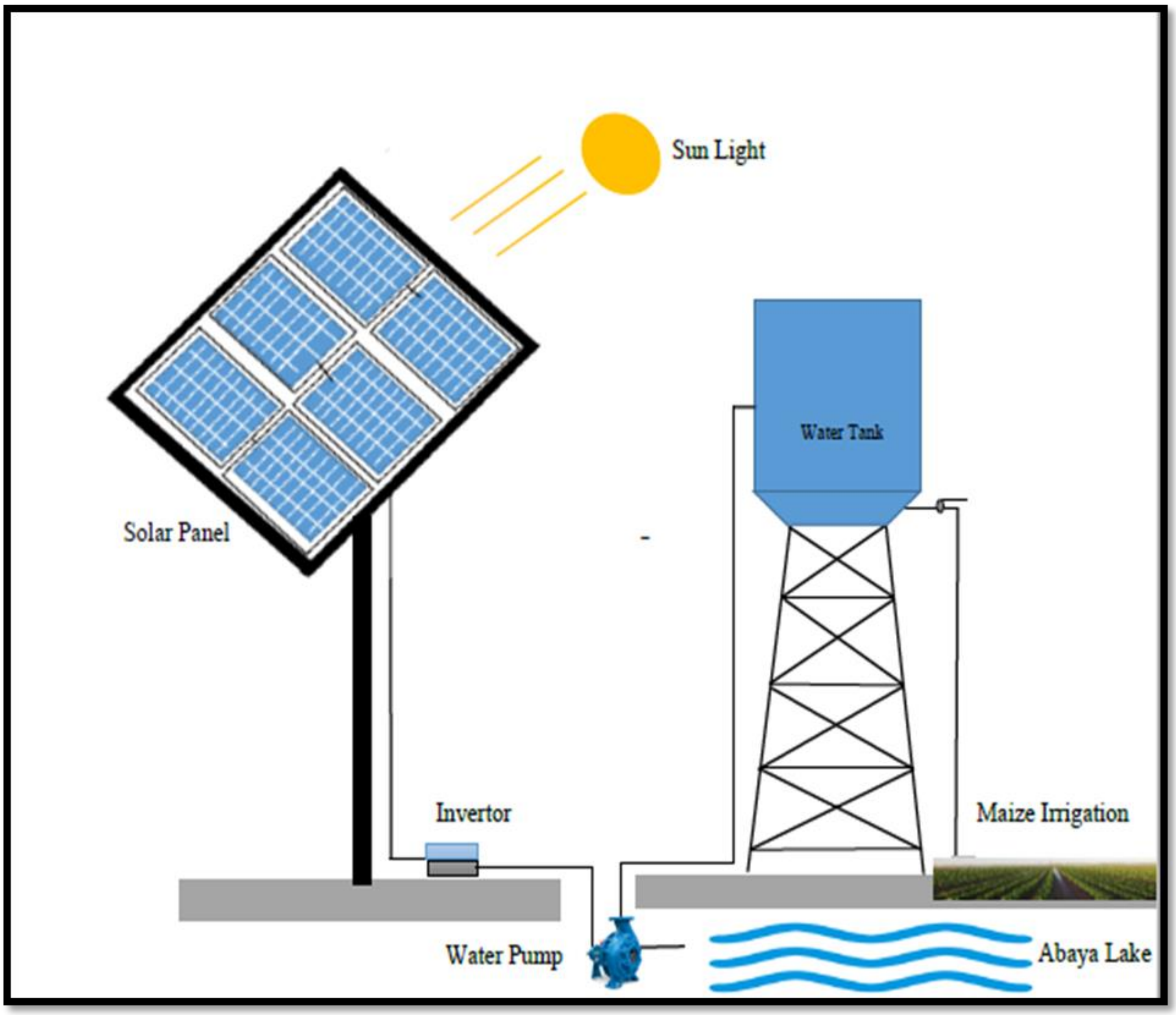

Figure 3.3: Schematic diagram of a direct solar-powered water pumping system

3.3 Data collection

3.3.1 Primary data

Well gathered and analysed data is pillar for the viable designs and this research work done after collection of respective data from perspective sources. The primary data like sunshine hour collected from the National Meteorology Agency of Ethiopia from the South Nation Nationality Station (NMAE) Hawassa branch office service and solar irradiance were analysed. The researcher visited mirab abaya lake area farmers and collected their feedback about the farm, crops, their irrigation systems and challenges which they are facing on agricultural activities. Another data source for specific data for the research is the direct measurement of parameters from the selected planting site and mathematical or analytical method has been used.

3.3.2 Secondary data

Standard data are used from Textbooks, handbooks and International published journals and manufacturing industries outlines. Solar data was collected from different websites. Website based solar radiation data were collected from:

- HelioClim-1 Database, http://www.soda-is.com, the data provider is MINES ParisTech -Armies (France)
- MERRA-2 meteorological data, http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2, the data provider is National Aeronautics and Space Administration (NASA)/ Goddard Space Flight Centre
- RETScreen expert 4.0 software

3.4 Material selection

3.4.1 Pump selection

A pump is a device that converts electrical power into mechanical energy that is converted into hydraulic energy to drive the intended task. Factors like flow rate, head lift, pump efficiency, and power source flexibility add to the total quality a solar-powered water pump for irrigation will offer. Then the ease of maintenance and resistance to corrosion will determine how long you get to use your solar pump.The selection of an affordable pump for the system is the main part of the work since the design of solar water pumping depends on the water flow (m^3/hr) and pumping total head [11]. Therefore, considering its many merits along, the researcher selected a surface pump for the system because of the following mentioned advantages:-

- ❖ Low cost compared to submersible one
- ❖ It's high reliability
- ❖ Simplicity, they don't require any valves, or many moving parts and this makes them easy to produce with many different materials.
- ❖ Its sufficient availability in local market

Figure 3.4: HFMSeries 1.5hp cryogenic centrifugal pump (Source: OTONO Company)

3.4.2 PV panel selection

Photovoltaic panels are manufactured in different textured materials and that makes it most flexible to drive the different activities and applications. Photovoltaic, in its simplest terms, means the conversion of sunlight into electrical energy directly. For this research work, the selected PV panel is polycrystalline because of its less expensive cost to buy, it is reliability as monocrystalline and less expensiveness to manufacture that enhances its mass availability in the market. For each, PV panel has 340W peak power production, and to function the system we need 6 panels which demand 2.03 kW.

Figure 3.5: Polycrystalline-JSTY340 PV panel (Source: sunpower company)

3.4.4 Inverter selection

The inverter rated output is 19 percent less than the maximum power of the array since there is be loss of power in sunny conditions [17, 32]. The sizing and choice of the variable frequency inverter will take into account the following constraints:

- ✓ The nominal power of the solar inverter must be in the range power of [80%P_{pv}; 120%P_{pv}] [4, 8].
- ✓ The output voltages and frequency specifications of the solar inverter must be compatible with those of the chosen pump. Besides, the rated current $I_{n\text{-inverter}}$ of the Inverter must be 150% higher than the rated current $\boldsymbol{I}_{n\text{-mp}}$ of the pump [13, 14].

- ✓ By respecting the sizing constraints, the nominal power of the inverter to be chosen must be in the range [1600W; 2400W]. The inverter's output voltages must be 380/400 V, 50/60Hz three-phase. And the nominal current I_n of this inverter must be greater than of the pump.

Figure 3.6: Solar inverter JETECH1600H type (Source: JETECH company)

3.5 Soil type for farming and its effect

Maize can be grown on soils with a wide range of textures, from light, sandy soils to heavy, clay soils. Mirab Abaya has sandy soils which are preferable and favorable with pH levels: 6.0-6.5. At higher or lower pH levels micronutrients become less available for plant uptake. And Temperature is the primary factor influencing all stages of development of the plant: vegetative growth, flowering, fruit set, and fruit ripening. Growth requires temperatures between 10°C and 30°C [51].

3.6 Data analysing software

3.6.1 Life cycle cost analysis software: HOMER PRO

HOMER is the hybrid micro-power optimization model, helps to design off-grid and grid-connected systems. HOMER can be used to perform analyses to explore a wide range of design questions using its optimization and sensitivity analysis capabilities. It finds the least-cost combination of components that meet electrical and deferrable loads. HOMER simulates thousands of system configurations, optimizes for lifecycle cost, and generates results of sensitivity analyses on most inputs. It is used to compare the use of diesel generators, PV water pumping systems.

Optimization: After simulating all of the possible system configurations, HOMER displays a list of feasible systems, sorted by lifecycle cost. The least-cost system can be easily found at the top of the list, or the list can be scanned for other feasible systems. The total net present cost (NPC) is HOMER's main economic output. HOMER ranks all systems according to the net present cost.

Sensitivity analysis: Sometimes it may be useful to see how the results vary with changes in inputs, either because they are uncertain or because they represent a range of applications. A sensitivity analysis can be performed on almost any input by assigning more than one value to each input of interest. HOMER repeats the optimization process for each value of the input so that the effect of changes can be examined in the value on the results.

3.7 Summary of methods and materials

In this chapter, the methodology and the main part of the system has been discussed. The techniques applied to do the task are analytical method; used for whole system performance evaluation, PV panel power output performance; evaluated experimentally and finally, life cycle cost analysis with system optimization; numerical simulation done by using Homer Pro Software.

Materials are selected according to the preference of the base requirements of equitable device as far as its specifications. In the above sections, the surface centrifugal AC 1.5Hp pump, polycrystalline PV panel; each rated with 340Wp, six sets are selected and for the power conditioning unit that converts and regulate the solar DC power input, 1.6 kW inverter were selected.

CHAPTER FOUR

4. DESIGN AND SPECIFICATIONS

4.1 Solar potential estimation

For the equivalent estimation of the solar data that is required to calculate the irradiance and to obtain the energy availability into those showing and those not showing monthly variation. The main basic parameters that are considered for estimation are the global irradiance on a horizontal surface (H), average temperature (T_{avg}), and the representative day of the month (n). The constant known data are the angle of inclination (δ), the solar constant (I_{sc}), the irradiance under standard conditions (I_{STC}), the performance decay coefficient because of the rising temperature of the cell (d), the cell temperature under standard test conditions (T_{STC}), the latitude angle (ϕ), the peak power generated by the PV modules (P_p), the asynchronous motor efficiency ((η_{am}) and the converter efficiency (η_{fc}).

Since the earth's orbit is elliptical, the earth-sun distance varies during a year, Therefore, the extraterrestrial radiation, I_o, also varies by the inverse square law [48].

$$I_o = I_{sc}\left(\left(\frac{D_O}{D}\right)^2\right)\ldots\ldots 4.1$$

Then it is approximated without significant accuracy loss to:

$$I_N = I_{sc}\left[1 + 0.034cos\left(\frac{360n}{365.25}\right)^0\right]\ldots\ldots 4.2$$

Where $I_{sc} - solar\ constant$

n - Day of the year

Extraterrestrial radiation incident on a horizontal surface is the product of extraterrestrial radiation incident normal to horizontal surface and zenith angle.

$$\mathrm{I_N}=\mathrm{I_{sc}}\left[1+0.034\cos\frac{360\mathrm{n}}{365.25}\right](\cos\phi\cos\delta\cos\omega+\sin\phi\sin\omega_s)\ldots\ldots 4.3$$

From the integration of the above-given equation, in terms of solar time angle; daily extraterrestrial solar radiation outside the atmosphere (Ho) can be derived that is known as the Klein relationship:

$$H_o = \frac{24x3600}{365}I_{sc}\left[1 + 0.033\cos(\frac{360n}{365.25})\right](cos\phi cos\delta sin\omega_s + \frac{\pi\omega_s}{180}sin\phi sin\delta)\ldots\ldots 4.4$$

4.1.1 Estimation of solar radiation on the horizontal surface

Table 4.1: Day of the year and the representative days of the month[52]

Month	N representative days of the month	Day of the year(n)
January	17	I
February	16	31+i
March	16	59+i
April	15	90+i
May	15	120+i
June	11	151+i
July	17	181+i
August	16	212+i
September	15	243+i
October	15	273+i
November	14	304+i
December	10	334+i

4.1.2 Average peak-sun hours

Table 4.2: Monthly average sunshine hours (Source: Ethiopia National meteorological agency)

Months	Aver. Solar hours	Months	Aver. Solar Hours
January	9.2	July	5.2
February	8.88	August	6.06
March	8.44	September	6.42
April	7.4	October	7.26
May	7.85	November	8.76
June	6.8	December	9.5

Table 4.3: Average annual Global irradiance for Mirab Abaya Location

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
I(kW/m^2)	6.27	6.45	6.46	6.14	5.91	5.44
Month	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
I(kW/m^2)	4.78	5.28	5.8	5.84	6.29	6.21

For the designing condition, the researcher chooses the month with the least average solar radiation, for that, the system will work for whole months throughout the years. As per the data shown above in the table, **July is** a month that has 4.78 kW/m^2, thus, the least irradiation month. Then so, the representative day of July is 17, and the day of the year (n) =181+i

$$n=181+17=198$$

4.1.3 Sun-earth angles

Sun-Earth angles are essential for the estimation of solar intensity throughout the year for any surface at any place with a desired inclination and orientation. These Sun-Earth angles are defined below.

Declination (δ):

It is defined as the angle between the line joining the centres of the Sun and the Earth, which also determines the direction of the direct rays coming from the Sun and their projection on the equatorial plane as shown in the figure below.

The declination is calculated by the following relation:

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+n)\right] \ldots\ldots 4.5$$

$$= 23.45 \sin\left[\frac{360}{365}(284+198)\right]$$

$$=21.18^{o}$$

Where n is days of a year (1-365)

Equation of spencer as cited by [52]

$$\delta = \left(\frac{180}{\pi}\right)(0.006918 - 0.399912cosB + 0.070257sinB - 0.006758cos2B + 0.000907sin2B - 0.002697cos3B + 0.00148sin3B) \ldots\ldots 4.6$$

Where the value of B is calculated as,

$$B = (n-1)\frac{360}{365} \ldots\ldots 4.7$$

Latitude (ϕ):

The latitude of an observer (location) on the Earth's surface is the angle made between the radial line joining the observer (location) with the centre of the Earth, and its projection on the equatorial plane. For an observer in the northern hemisphere, latitude is positive, whereas for the southern hemisphere it is negative. The approximate latitude of Mirab Abaya is taken as **6.17**°.

Hour angle (ω):

The hour angle is the angular displacement of the Sun from the local meridian because of the Earth's rotation around its axis. The hour angle corresponding to 1hr is 15°.

Expression for the hour angle is given by

$\omega = (ST - 12)x15°$……………………………………………………..…….4.8

Where;

ST is the local solar time and the total hour angle from sunrise to sunset is $2x\omega_s$. The $\pm\omega_s$ correspond to an hour angle regarding sunrise and sunset, respectively.

Solar time: - is a reckoning of the passage of time about the position of the Sun in the sky, which has the fundamental unit of a day.

The solar time is calculated as:

Solar time - standard time= $4(L_{st} - L_{loc}) + E$………………………………………..4.9

$E = 229.2(0.000075 + 0.001868cosB - 0.032077sinB - 0.014615cos2B - 0.04089sin2B)$……………………………………………………………………….4.10

Where the value of B is calculated as,

$$B = (n-1)\frac{360}{365} = 194.3$$

E= - 6.009,

n is the number of the given in the year

The average ST= 7.65

Zenith (θz):

The angle between Sun's rays; the line perpendicular to a horizontal plane is known as the "zenith angle"

$\theta_z = 90 - \alpha$ ………………………………………………………………….... 4.11

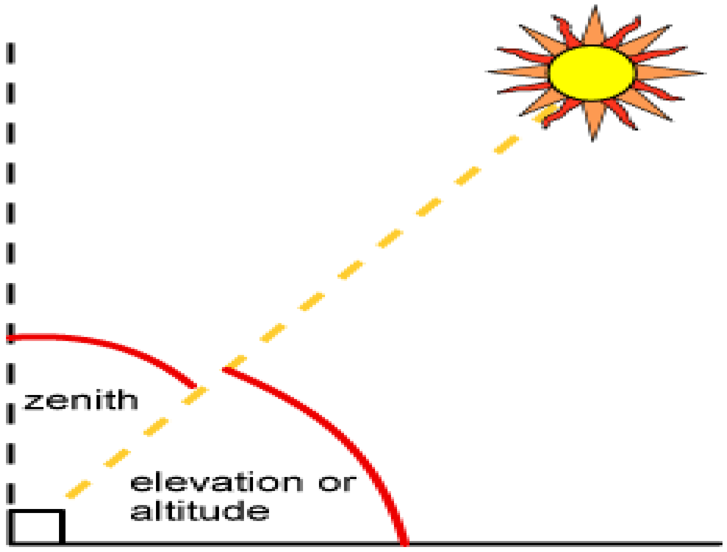

Figure 4.1: Zenith angle toward the sun

Altitude or solar altitude angle (α):

The angle made between a horizontal plane and the Sun's rays is known as the "altitude angle."

$$\alpha = 90 + \phi - \delta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \; 4.12$$

$$= 90 + 6.17 - 21.2 = 75°$$

The maximum elevation angle at solar noon (α) is a function of latitude and declination angle (δ).

Tilt angle (β):

It is the angle between the plane surface under consideration and the horizontal surface (tangential plane at observer). The angle is always positive and between 0° and 90°. When solar panels are completely flat, the angle is 0°, whereas the angle is 90° when panels are perfectly vertical, perpendicular to the ground. In the analysis of the sunphotovoltaics solar energy parameters calculator platform, the fixed yearly optimum tilt angle, and seasonal calculated tilt angle are shown below respectively.

❖ For the entire year, the fixed solar panels on Mirab abaya location optimum inclination angle is 15°.

Table 4.3: Optimum tilt angle for twice adjusted solar panel

Months	Optimal Tilt Angle
March to August	17°
September to February	28°

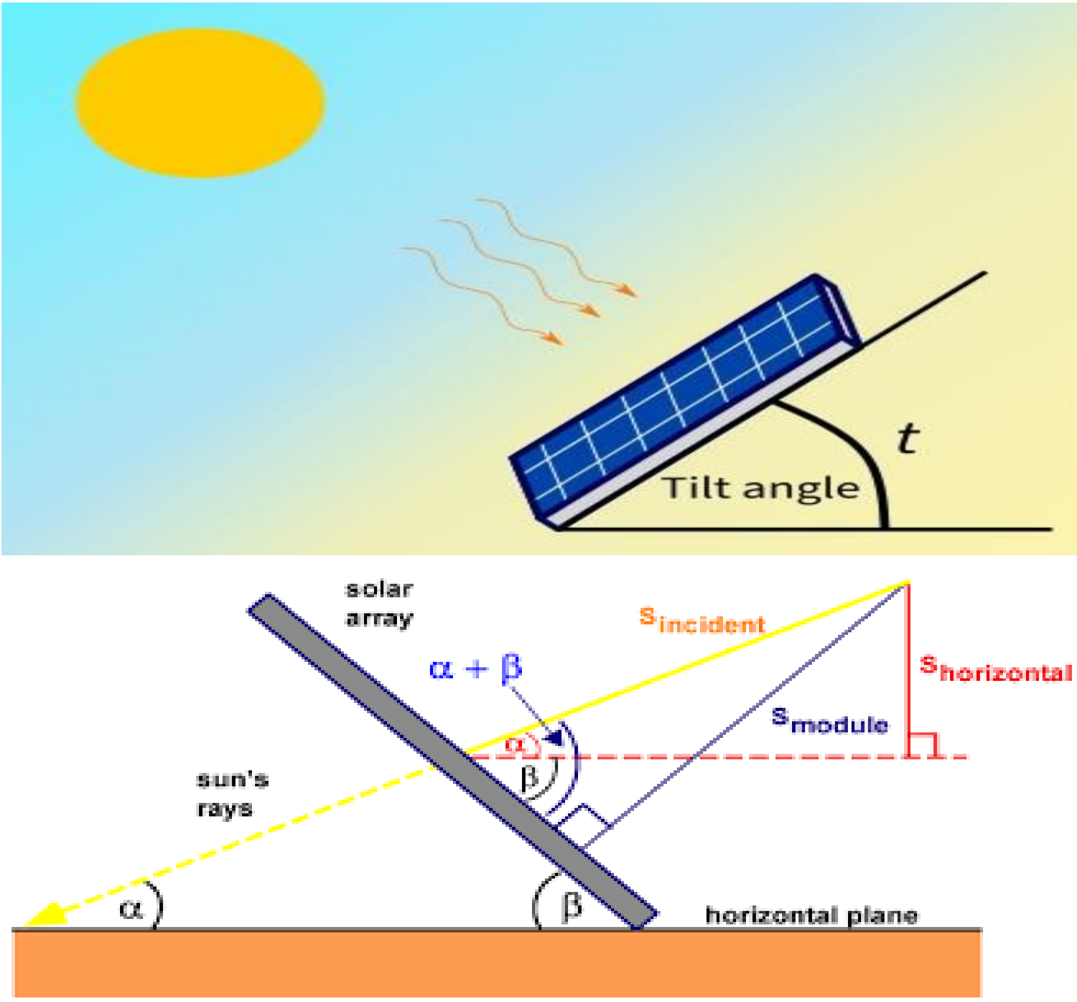

Figure 4.2: Tilt angle along the horizontal surface

Surface azimuth angle (γ):

It’s an angle that’s between in the line due south and the projection of normal to the inclined surface on the horizontal plane (tangential plane at observer on the surface of the Earth).

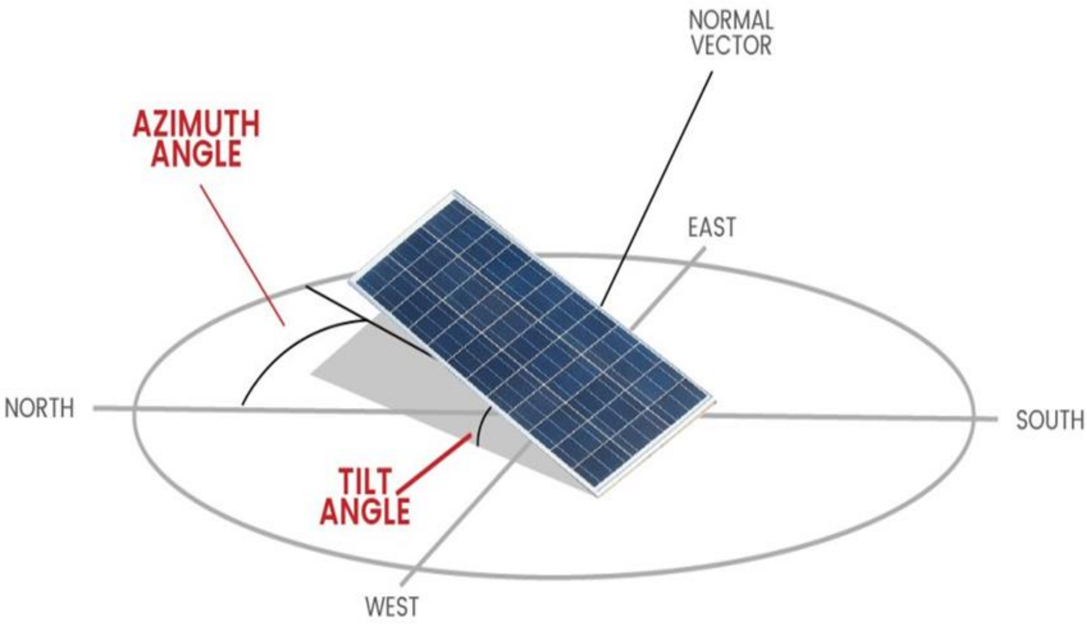

Figure 4.3: Azimuth and tilt angle in solar panel alignment

4.1.4 Solar panel direction

By using the time zone of selective location and coordinates (latitude and longitude) calculation of the best solar direction for fixed solar panels, twice adjusted solar panels, quarterly (seasonally) adjusted solar panels, and monthly adjusted solar panels can be optimized. The solarsena.com website platform calculator gives the optimal directions for all four possible scenarios (fixed, twice adjustable, seasonally adjustable, and monthly adjustable). And they are displayed in the following tables.

For a fixed solar panel, the optimum direction of alignment is to the south.

Table 4.5: The direction for twice adjusted solar panel

Months	**Optimal direction**
March to August	North
September to February	South

Table 4.6: Direction sun for quarterly (seasonally) adjusted solar panels

Months	Optimal direction	Northern hemisphere
March to May	Northeast	Spring
June to August	Northeast	Summer
September to November	South	Fall
December to February	South	Winter

4.1.5 Monthly average daily solar radiation estimation

4.1.5.1 Global monthly average daily radiation

In Ethiopia sunshine, data-based solar energy estimation has been used frequently in different researches for solar radiation energy estimation and for designing purposes of the solar system. Neway (1996) estimated solar radiation energy on a horizontal surface, for nine meteorological stations in Ethiopia. He computed solar radiation by using sunshine data based on Ångström relations and compared with their corresponding global solar radiation on horizontal surface values; he also obtained Regression coefficients and determined correlation equations to predict the global solar radiation. He explained based on the results, Ångström relations are valid for Ethiopian locations, and the correlation equations can be used to predict the monthly mean daily global solar radiation in the locations considered in the study [52].

The Angström-Prescott model between sunshine duration and the amount of global solar radiation is as follows:

$$\frac{H}{H_o} = a + b\frac{n_s}{N} \qquad 4.13$$

$$a = -0.11 + 0.235cos\varphi + 0.323\left[\frac{n_s}{N}\right] \qquad 4.14$$

$$b = 1.449 - 0.533cos\varphi + 0.694\left[\frac{n_s}{N}\right] \qquad 4.15$$

Where,

H is the daily total amount of global solar radiation at the ground surface,

Ho is the daily total amount of global solar radiation outside the atmosphere, n is the sunshine duration,

N is the maximum possible sunshine duration, and a and b are constants

4.1.5.2 Diffuse monthly average daily radiation

Diffuse solar radiation is solar radiation that reaches the piles of the earth's surface after being scattered in the atmosphere. Prediction of monthly average daily diffuse radiation on a horizontal surface ($\boldsymbol{H_d}$) can be given as

$$H_d = H\left[0.931 - 0.814\left(\frac{ns}{Ns}\right)\right] \ldots\ldots 4.16$$

4.1.5.3 Beam monthly average daily radiation

Beam solar radiation is direct solar radiation that reaches the earth's surface without scattering in the atmosphere. Monthly average daily beam radiation on a horizontal surface (H_b) is the difference between global and diffuse monthly daily average radiation.

$$H_b = H - H_d \ldots\ldots 4.17$$

The Sunshine data is used to single out the radiation components in the global solar radiation, so it should be calculated from averaged solar radiation.

From averaged global solar radiation, the ratio of measured average sunshine to possible maximum sunshine (ns/N) can be calculated as follows:

Let us assume, ($x = \frac{ns}{N}$) to substitute in the Ångström relations [48].

$$\frac{H}{H_O} = [-0.11 + 0.235cos\varphi + 0.323x] + [1.449 - 0.533cos\varphi - 0.694x]\text{x} \ldots\ldots 4.18$$

It becomes;

$$-0.694x^2 + 1.241x + \left[0.1242 - \frac{H_a}{H_o}\right] = 0 \ldots\ldots 4.19$$

In quadratic equation form: $ax^2 + bx + c = 0$

Solution for x is

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

4.1.6 Monthly average hourly solar radiation estimation

4.1.6.1 Global hourly solar radiation estimation

Prediction of monthly average hourly global radiation on a horizontal surface (I)

$$\mathrm{I} = \frac{H\pi}{24}(a + b\cos\omega_s)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.20$$

Where;

$$a = 0.409 + 0.5016\sin(\omega_s - 60)$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60)$$

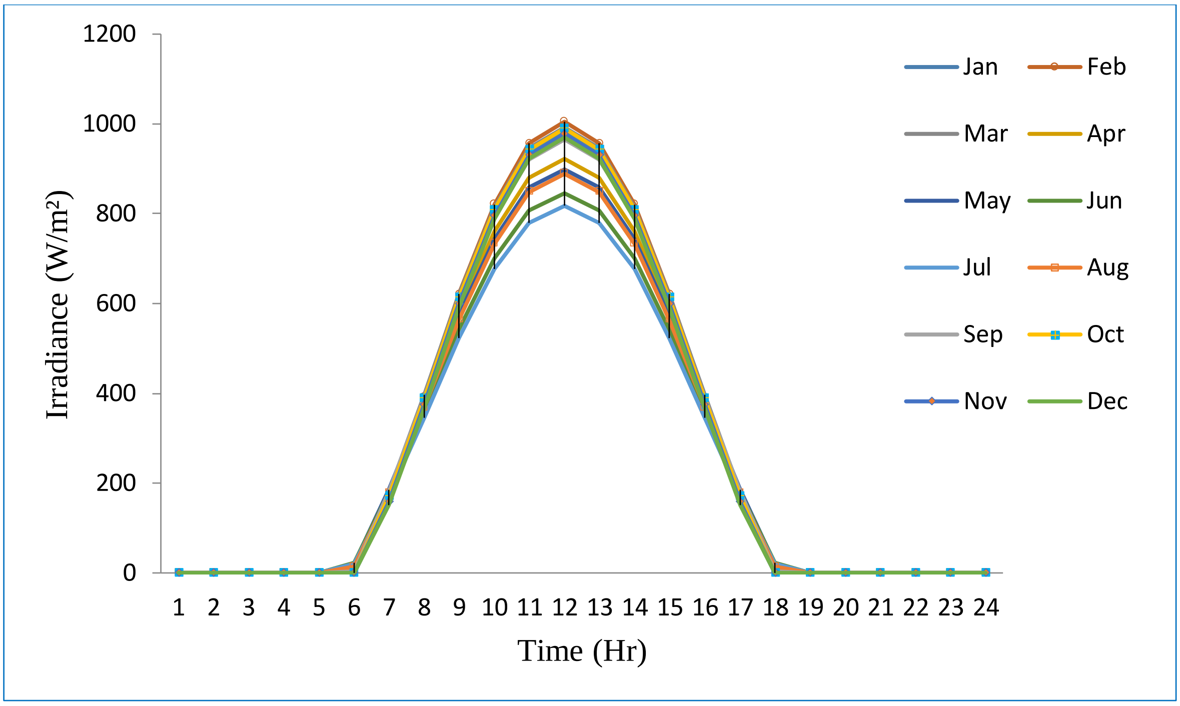

Figure 4.4: Monthly Average Hourly Global Radiation on Horizontal surface ($\bar{\mathrm{I}}$)

4.1.6.2 Diffuse hourly solar radiation estimation

Prediction of monthly average hourly diffuse radiation on a horizontal surface (I_d)

$$I_d = \frac{H_d\pi}{24} x \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.21$$

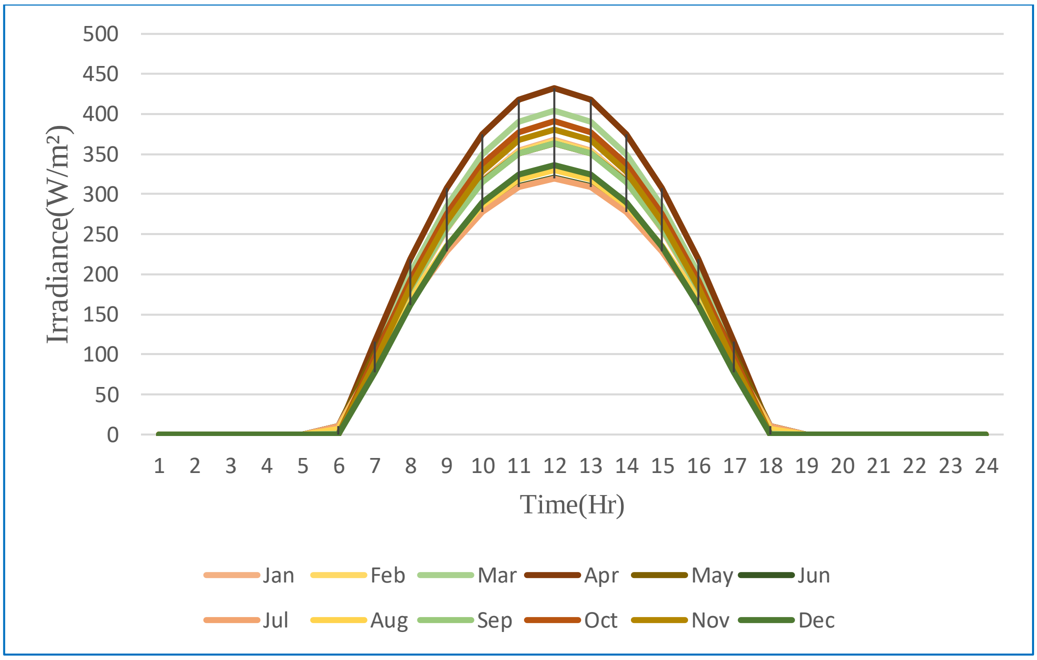

Figure 4.5: Monthly Average Hourly Diffuse Radiation on Horizontal surface ($\bar{I}$d)

4.1.6.3 Beam hourly solar radiation estimation

Estimation of monthly average hourly beam radiation on a horizontal surface (I_b)

$$I_b = I - I_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.4.22$$

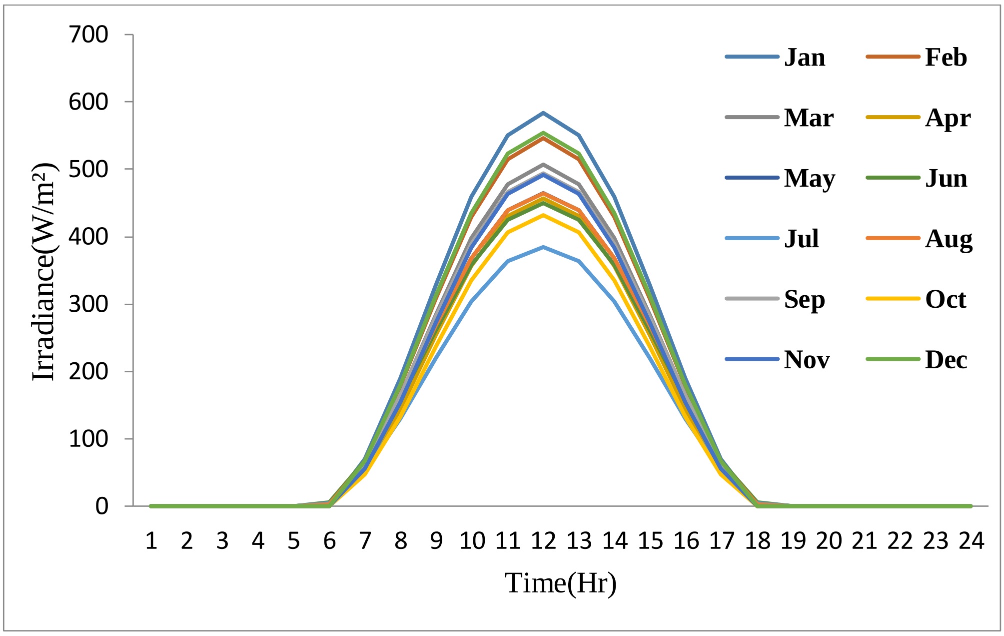

Figure 4.6: Monthly Average Daily Beam (Direct) Radiation on Horizontal surface (Ib)

4.2 Calculation of crop water requirement

The type of water source and its location influence the configuration of the solar water pumping system**,** these water sources can either be surface or subsurface sources [53].

4.2.1 Calculation of the required water demand for irrigation

The crop water needs mainly depend on:

- The climate: for example, in a sunny and hot climate crops need more water per day than in a cloudy and cool climate
- The crop type: crops like maize, rice, sugarcane need more water than crops like beans and wheat
- The growth stage: grown crops need more water than crops that have just been planted

Table 4.7: Effect of major climatic factors on crop water needs [54]

Climatic factor	**Crop water need**	
	High	**Low**
Sunshine	Sunny (no clouds)	Cloudy (no sun)
Temperature	Hot	Cool
Humidity	Low(dry)	High(humid)
Wind speed	Windy	Little wind

4.2.2 Effect of crop type on the seasonal crop water needs

The crop type not only influences the daily water need of a fully grown crop, i.e., the daily peak water need, but the crop type also influences the duration of the total growing season of the crop, and thus on the seasonal water need.

The duration of the total growing season has an enormous influence on the seasonal crop water need. There are, for example, many rice varieties, some with a short growing cycle (e.g., 90 days) and others with a long growing cycle (e.g., 150 days). This has a strong influence on the seasonal rice water needs: a rice crop that is in the field for 150 days will need in total much more water than a rice crop that is only in the field for 90 days. Of course, for the two rice crops, the daily peak water need may still be the same, but the 150-day crop will need this daily amount for a longer period. The time of the year during which crops are grown is also very important. A certain crop variety grown during the cooler months will need substantially less water than the same crop variety grown during the hotter months.

Table 4.8 gives some approximate values for the duration of the total growing season for the various field crops.

Table 4.8: The total growing period of some selected crops (Source: MAWAO)

Crop	**Growing period (days)**	**Crop**	**Growing period (days)**
Onion green	70-95	Maize	125-180
Onion dry	150-210	Carrot	100-150
Potato	105-145	Cotton	180-195
Cabbage	120-140	Pea	80-100
Tomato	135-180	Sorghum	120-130
Banana	300-365	Melon	120-160

Table 4.9: Approximate values of seasonal crop water needs (Source: FAO)

Crop	**Crop water need (mm/total growing period)**	**Crop**	**Crop water need (mm/total growing period)**
Onion	350-550	Maize	500-800
Potato	500-700	Carrot	400-600
Cabbage	350-500	Cotton	700-1300
Tomato	400-800	Pea	350-500
Banana	1200-2200	Sorghum	450-650

The farmland in Mirab abaya is an approximately semi-arid climate zone with an average daily temperature of 18-25°C. The crops usually cultivated in the area are carrot, cabbage, tomato, onion, maize, and bananas. To determine the total amount of water needed for irrigation is by considering the crop of highest water needing and largest growing period for this design purpose [13]. Therefore, Maize is the selected crop for the area having 500-800 mm/total growing period and 125-180 days total growing periods.

The daily water need of maize is equal to the maximum millimetres of water need/total growing period divided by the total growing period.

Thus, taking average its water need, 650mm/total growing period:

650/180 = 3.6111 mm/day

=0.00361m/day, the required water in the one-meter square

The total volume of water required daily to irrigate a 1-hectare farm of the community in Birbir village, Mirab Abaya is obtained by multiplying the value by the area of the land. So, the area of 1-hectare land is 10,000m^2 and the volume of water requires is:

The discharge rate of needed water is;

Q*= 0.003611m/day* 10,000m^2= 36.11m^3/day

Thus, 36.11 cubic meters of water are needed for each day of a total 180 maize growing period cultivated on a 10,000m^2 farm. By considering the loss of water from storage by evaporations and water at the flow ways of the gravity flow, the water amount in the storage reservoir should be at three times that of the required amount.

Therefore, the total amount of water for required pumping is [11, 16, 54];

$$Q^{**} = 3*36.11 m^3/\text{day} = 108.33\ m^3/\text{day}$$

The flow rate per hour is:-

$$Q = {Q^{**}}/{SH} \text{ ....4.23}$$

$$= {108.33}/{7.65} = 14.16\ m^3/\text{hour} = 0.00393\ m^3/\text{sec or } 3.93 \text{ L/sec}$$

Where SH: average sunshine hour

There are 180 days for the total growing period of maize, thus 26 weeks and let assume as per as farmers feedback; thus, the crops are irrigated for three days in the week and the pump for one day become;

Therefore for the total growing period, maize crop on the one-hectare farm needs,

=36.11 m^3/day x 3 day/week x 26 total growing period weeks

= 2816.58 m^3/total growing period of 10,000m^2 farm size.

Where 180 is the total growing period of maize,

Lake Abaya is landlocked over the surface of the earth which has not that much depth from farmland level but the storage should be some height from the level of farmland that it is available for the free natural gravitational flow of water to use when ever needed. The height of the water reservoir is decided by considering crop type and farming land size conditions.

4.2.3 Dimensioning the diameter of pipe

The economic internal diameter of the discharge piping was calculated as [54, 56];

$$D_i = 0.586 T^{0.25} x \sqrt{Q} \text{ ....3.24}$$

$$0.586 x 7.65^{0.25} x \sqrt{0.00393}$$

$$D_i = 0.061\text{m} = 61 \text{ mm}$$

Where:

D: economic internal diameter of the head pipeline, m;

T: daily operation time, h/ day; and

Q: pumping flow rate, m^3/sec

4.2.4 Calculation of total dynamic head (TDH)

The Head is a measurement of the amount of pressure required to successfully deliver the fluid pumped at the desired flow. Level differences in a system give out the head, the total head of the pump is the summation of static head, suction head, and friction losses [59]. The expression is below shown by Hazen William used for the calculation of the Total Head in the system:

Table 4.10: Hazen William coefficient values for some pipe materials

Pipe material	Hazen- William coefficient(C)
PVC	150
Asbestos cement	140
Welded steel	100
Concrete	100
Cast iron	100
Copper or brass	130
Corrugated steel	60

TDH= Static head + suction head + friction head

Static head, H_s= 2 m

Suction or dynamic Head H_d = 5 m

Length, L= 100 m

The inner pipe diameter is , D_i = 0.061 m

To find friction losses,

$$h_f=10.67\left(\frac{Q}{C}\right)^{1.852} x \ \frac{L}{D^{4.655}} \ldots\ldots 4.25$$

$$h_f=10.67\left(\frac{0.00393}{150}\right)^{1.852} x \ \frac{100}{0.061^{4.655}}$$

$$h_f=1.57 \text{ m}$$

$$TDH= H_s+H_d+h_f \ldots\ldots 4.26$$

$$= 2+5 + 1.57 \approx 9 \text{ m}$$

Where,

Q: flow rate in m^3/sec

D: pipe inside diameter in m

L: length of pipe in m

f: friction factor

C: Hazen- William coefficient

4.2.5 Calculation of power requirement for the pump

The power out of the pump is the work that the pump does while pushing the water through the pipes line for a certain height. Work input of pump on the fluid to be equal to the power that must be getting from PV panel. The input and output power of the pump is related to the efficiency of the pump.

So, to size PV panel to derive pump to force the water for a certain height, the input power of the pump should be known first and calculated by using the formula below

$$P_{in} = \frac{TDHxgx\rho xQ}{\eta x3600} \ldots\ldots 4.27$$

$$\frac{9 \text{ x } 9.81\text{x}1000\text{x}36.11}{0.8 \text{ x}3600} = 1106.99\text{W}$$

$$= 1.48 \text{ Hp}$$

We can’t get the exact valued pump in the market and therefore let us approximate the pump input power as:

$$P_{in} \approx 1.5 \text{ Hp} = 1.12\text{kW}$$

Where;

TDH-the total dynamic head,

g - Gravitational acceleration m^2/sec,

Q - Volumetric flow rate m^3/hour,

ρ- Density of fluid,

η- Efficiency of the pump.

Table 4.11: Specification of the selected surface pump

Specifications	Values	Units
Type	HFMSeries 1.5hp Cryogenic Centrifugal Pump	-
Nominal power	1.5	Hp
Three-phase voltage	380/400	V
Frequency range	0 to 50/60	Hz
Nominal current	6.5	A
Max.Flow:	40	m^3/h
Hmax	15.5	M
Outlet and inlet	2	Inch
Number of stages	11	--
Nominal speed	3450	Rpm

4.3 Calculation of PV panel and inverter requirement

The inverter has specific operating ranges that must correspond to the electrical characteristics of the PV panel and those of the selected pump. Its total peak power requirement is calculated as follows [5, 14, 39] :-

$$P_{pv}=\frac{P_n x N_h}{\frac{G_{irr}}{P_i} f_p x \eta_{inv}} \text{ ....} 4.28$$

$$\frac{1.057 \text{ x } 7.65}{\frac{4.78}{1} \text{x}0.85\text{x}0.98} \;;\; P_{pv} = 2.03 \text{ kW}$$

Whereas;

P_{pv}:- The peak PV power of the panels

P_n:-Nominal power of the selected panel

N_h:- operating solar hours

G_{irr}:-global radiation

η_{inv}:- inverter efficiency

P_i:- the illumination PV panel power at standard test conditions

The recent model inverters have an efficiency became up to 98%, I considered η_{inv}=98%. The loss factor fp is due to temperature, dust, connection cables, and orientation. This factor is well-chosen equal to 85%. The number of operating hours N_h of the pumping system is approximately about 7.65 hours. The worst month of the summer season is July. In this month, the global radiation G_{irr} is estimated to 4.78KWh/m^2 [11]. P_i is the illumination power at standard test conditions, it has a value of 1000W/m^2 [11]. The calculated P_{pv} value is 2030 W. The peak power of the PV generator to be considered in this project is P_{pv}=2.03 kW.

Table 4.12: Specification of JSTY340P-92 Solar panel

Mechanical characteristics		Electrical characteristics	
Solar cell type	Polycrystalline	Max. power at STC(Pmax)	340Wp
Type	JSTY340P-92	Module efficiency	17.5%
Dimensions (LXWXD)	1650mm x 992mm x 40mm	Cell efficiency	16.80%
		Optimum operating voltage (VMP)	17.50
Number of solar cells	36	Optimum operating current (Imp)	5.71A
Junction box	IP-65 rated	Open circuit voltage (VOC)	41.8 V
Connector	MC4	Short circuit current (Isc)	6.26A
Operating temperature	-40 to +85 ℃	Power tolerance	±5

Table 4.13: Specifications of JETECH1200H type inverter

Parameters	**Values**	**Units**
Nominal power	1.6	kW
Output voltage (3 phases)	380/400	V
DC Input voltage range	55---95	V
Nominal DC input voltage	62.5	V
Nominal DC input current	7.1	A
Max DC input current	41.5	A
Frequency range	0 to 50/60	Hz
Efficiency	98%	--
MPPT efficiency	99%	--

The number of modules connected in series n_s is defined by the quotient of the maximum inverter input voltage $V_{inv,Max}$ by that of the open circuit V_{oc} of the selected PV module [10]:

$$n_s = \frac{V_{inv,Max}}{V_{oc}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.29$$

$$\frac{95}{41.8} = 2.27$$

$$n_s = 2$$

For $V_{inv,Max}$=95V, and V_{oc}=43.36V, modules to be connected in series is $n_s = 2$

The number of modules connected in parallel n_p, or the number of strings, is given by the relation [10]:

$$n_p = \frac{P_{pv}}{P_{mpp}} x \frac{1}{n_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots 4.30$$

$$= \frac{2030}{340} x \frac{1}{2}$$

$$n_p = 3$$

P_{pv} And P_{mpp} are respectively the peak power of the PV panel and the selected PV array. The calculations give a value of n_p = 3.

With a PV peak power of 2030W demand, six arrays of 340W are intended to supply; two series modules constitute a string. The combination of 3 strings in parallel forms the structure of the PV panel to be installed to perform the duty of irrigation in the selected research site.

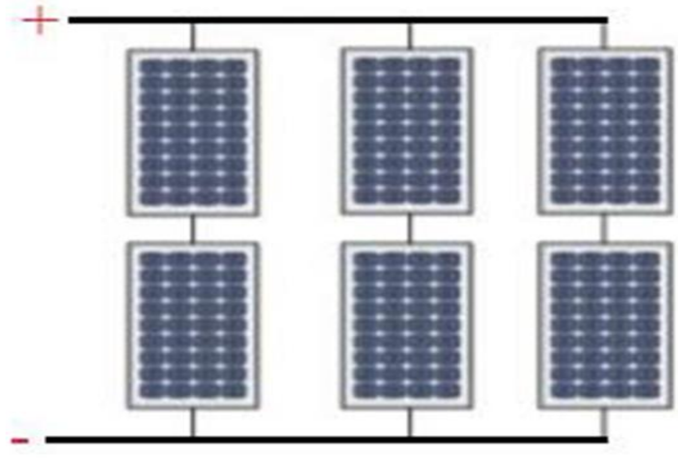

Figure 4.7: PV panels alignment

4.4 Calculation of PV panel performance

The calculation of the performance correlates the power, open-circuit voltage, and short circuit current flow over the surface of the PV panel implanted on the 28º tilted angle. The mathematical formula to evaluate the performance of PV panels is as follows:

Efficiency of PV panel = (Power / Area / 1000) * 100 …………….4.31

The power is the peak power expressed in W, the surface is the surface of the panel in square meters including the frame, 1000 is the irradiance of $1000\mathrm{W/m^2}$, 100 is used to obtain the efficiency in percentage.

Table 4.14: The specification of PV Panel undergoing on experiment

PV model	M-60W
Peak power(Pmax)	60W
Power tolerance	0~3 %
Voltage(Vmp)	13.7V
Current(Imp)	4.38A
Open circuit voltage(Voc)	16.8 V
Short circuit current (Isc)	4.78A
Max system voltage	1000VDC

4.5 The working principles of Homer pro software

4.5.1 Deferrable load calculation

Deferrable load is electrical load that must be met within some time period, but the exact timing is not important. Loads are normally classified as deferrable because they have some storage associated with them. The deferrable load is second in priority behind the primary load, but ahead of charging the batteries. Under the load following strategy, HOMER serves the deferrable load only when the system is producing excess electricity or when the storage tank becomes empty. Under the cycle charging strategy, HOMER will also serve the deferrable load whenever a generator is operating and able to produce more electricity than is needed to serve the primary load. Regardless of dispatch strategy, when the level of the storage tank drops to zero, the peak deferrable load is treated as a primary load.

Table 4.15: Deferrable loads description in Homer Pro software

Variables	Description
Storage capacity	The size of the storage tank, expressed in kWh of energy needed to fill the tank
Peak Load	The maximum amount of power, in kW, that can serve the deferrable load. In a water pumping application, it is equal to the rated electrical consumption of the pump.
Minimum Load Ratio	The minimum amount of power that can serve the deferrable load, expressed as a percentage of the peak load.
Electrical Bus	Specifies whether the deferrable load must be served by alternating current (AC) or direct current (DC) power

4.5.2 The Components in Homer pro

A component is a piece of equipment that is part of a power system which includes PV, generator, wind, storage, converter, hydro, reformer, hydrogen tank, hydrokinetic, grid, and thermal load controller.

PV panel: The PV window allows you to enter the cost, performance characteristics and orientation of an array of photovoltaic (PV) panels as well as choose the sizes you want HOMER to consider as it searches for the optimal system. Both flat panel and concentrating PV technologies can be represented by the PV component. Whether or not a PV is concentrating can be specified in the library.

Inverter: If the "Electrical Bus" is set to "AC" or “DC”, inverter parameters are specified here.

MPPT: If the "Electrical Bus" is set to "DC", the parameters of the maximum power point tracker (DC to DC converter) are set here.

Advanced Inputs: where the setting of certain advanced variables

Temperature: specify whether to consider the effect of ambient temperature on panel efficiency, and if so set the relevant inputs.

Costing: the costs box includes the initial capital cost and replacement cost per kilowatt of the PV system, as well as annual operation and maintenance (O&M) costs per kilowatt. When specifying the capital and replacement costs, all costs associated with the PV system, which may include:

- ✓ PV panels
- ✓ Mounting hardware
- ✓ Tracking system
- ✓ Wiring
- ✓ Installation

➢ **How Homer pro Calculates the PV array power output**

The software uses the following equation to calculate the output of the PV array:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) \left[1 + \alpha_P (T_c - T_{c,STC})\right] \ldots\ldots 4.32$$

Whereas;

Y_{PV} - The rated capacity of the PV array, meaning its power output under standard test conditions [kW]

f_{PV} - The PV derating factor [%]

$\bar{G}_T$ - The solar radiation incident on the PV array in the current time step [kW/m²]

$\bar{G}_{T,STC}$ - The incident radiation at standard test conditions [1 kW/m²]

α_P - The temperature coefficient of power [%/°C]

T_c - The PV cell temperature in the current time step [°C]

$T_{c,STC}$ - The PV cell temperature under standard test conditions [25 °C]

➢ The HDKR model calculates the global radiation incident on the PV array according to the following equation:

$$\bar{G}_T = (\bar{G}_b + \bar{G}_d A_i) R_b + \bar{G}_d (1 - A_i) \left(\frac{1+\cos\beta}{2}\right) \left[1 + f \sin^3\left(\frac{\beta}{2}\right)\right] + \bar{G}_{\rho g} \left(\frac{1-\cos\beta}{2}\right) \ldots\ldots 4.33$$

Whereas

$\bar{G}_b$ is the beam radiation [kW/m²]

$\bar{G}_d$ is the diffuse radiation [kW/m²]

β is the slope of the surface [°]

ρg is the ground reflectance, which is also called the albedo [%]

4.5.3 Life cycle cost analysis (LCCA)

It is the technique of assessing the cost of the system; this method can be used to identify the most cost-effective system through a comparison of two or more systems. The following equation is summarizing the LCCA of solar water pump;

$$LCC = CC + MC + IC + RC + SC \quad \text{...} 4.34$$

Where; SC is the Salvage cost which is the net worth in the final year of the life-cycle period Capital costs (CC); involves an initial investment cost of the project, installation and transport cost, as well as the cost of physical elements (panels, pump, pipes, water storage tank, water meters, stands, inverter) are involved in the Capital cost.

Net Present Value of the system (NPV):-

The difference between the discounted total benefits and that of discounted total cost gives the NPV of the project. Calculated benefits of the project become much higher when the NPV is greater. NPV can be used to calculate the NPV;

$$NPV = \left\{\sum_{t=0}^{n} \frac{B_t}{(1+d)^t}\right\} - \left\{\sum_{t=0}^{n} \frac{C_t}{(1+d)^t}\right\} \text{.....................................} 4.35$$

Where;

Bt is the project benefits during year t,

Ct is the project costs during year t,

d is the discount rate, and

n is the total number of years.

Internal Rate of Return is the measure of the profitability of the prospective investment. The following formula can be used to crosscheck the value of IRR which makes NPV equal to Zero.

$$NPV = \sum_{t=1}^{n} \frac{F_t}{(1+IRR)^t} - I = 0 \quad \text{...} 4.36$$

Whereas:

Ft is Cash flow during year t,

I is Initial Investment of the project,

n is the number of years of the investment

Payback Period (PBP):- is the number of years required to recover the cost of project investment; it is obtained by dividing the total investment cost by the annual return of the same project. The project is considered to be profitable when the payback period is shorter. The following formula is used in calculating the PBP.

$$\text{Payback period} = \frac{\text{Invetment Cost}}{\text{Annual Income} - \text{Expenditure}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.37$$

4.6 Summary of design and specifications

In this fourth chapter, the researcher discussed about the availability solar potential of the location with its latitude, longitude, altitude, direction and tilt angle of solar panel for the system implementation. The averaged 7.65(hr) solar sunshine hours of the location resulted high amount of solar energy at the minimum of 4.78 and the maximum of 6.46 kW/m^2 respectively. Next, for the assumed one hectare farm land; the crop water need, pipe dimensioning, total dynamic head (TDH) calculation for system, the power requirement to pump the water, sizing of PV panel and DC to AC inverter, and the performance evaluation of PV panel model M-60W. As the design analysis, the water demand for the maize crop is 36.11 m^3/day per hectare, for TDH is 9 m and to pump this amount of water 1.5 Hp Surface pump were selected. After the analysis of pump driving energy requirement, 2.03 kW Polycrystalline (17.5%) PV panel were selected. In the next chapter, the results of the design analysis and discussions has been done with relative parameters.

CHAPTER FIVE

5. RESULT AND DISCCUSSION

5.1 Average solar isolation

Solar radiation data for Mirab Abaya has been calculated by using the sunshine hour of the location, collected data from websites and software i.e. RETscreen and HOMER, and its average has been calculated to use as the input for designing of solar powered water pumping system specifically for agricultural purpose. Radiation data from helioclim-1 database is obtained from HelioClim-1 Database of Daily Solar Irradiance which is derived from satellite data. HelioClim-1 database of Daily Solar Irradiance is provided by MINES ParisTech- Armines (France) and it is available in their website (www.soda-is.com). NASA surface meteorology and solar energy database is one of radiation data sources which provided also twenty two years averaged data (July 1983- June 2005). National Solar Radiation database (NSRD) is provided averaged data in different cell midpoint in latitude 6.17ºN and longitude 37.47ºE with cell dimension of 40 km x 40 km. Both NASA surface meteorology and solar energy and National Solar Radiation database are available in HOMER Pro software.

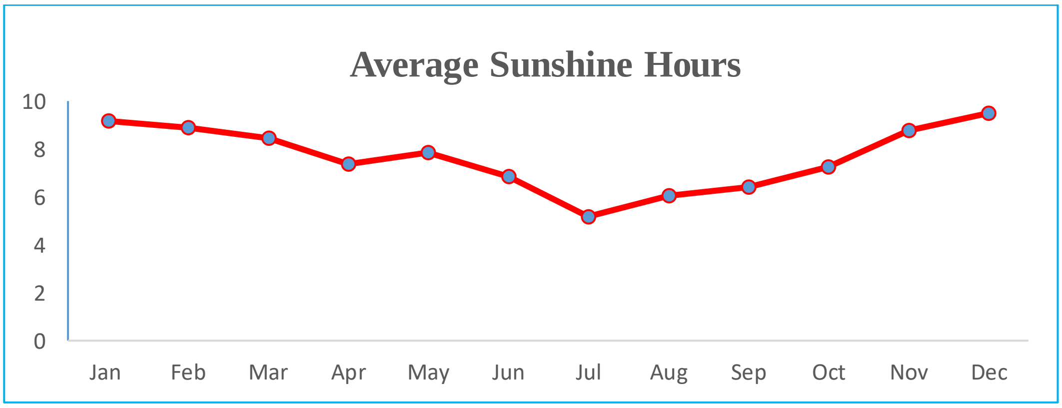

Figure 5.1: Average sunshine hours

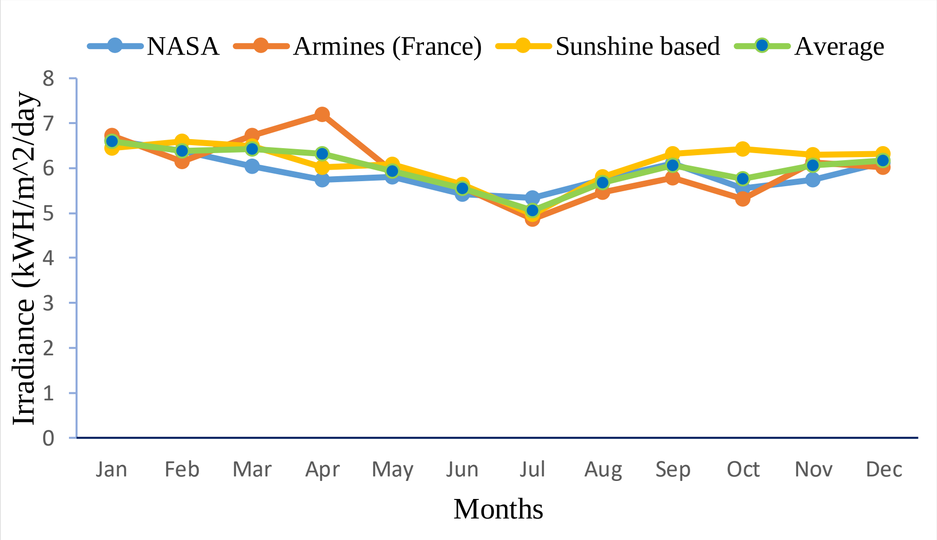

Figure 5.2: Monthly average daily solar radiation

The site nearby data of National Meteorological Agency (NMA) of Ethiopia from Mirab Abaya station was collected from SNNPR, Hawassa NMA branch. Therefore it is possible to take an average solar radiation from different recorded data bases for the selected site except from nearby NMA sunshine based data of Mirab Abaya, then averaged result is shown in Figure 5.3 as per as seasonal weather condition of the location.

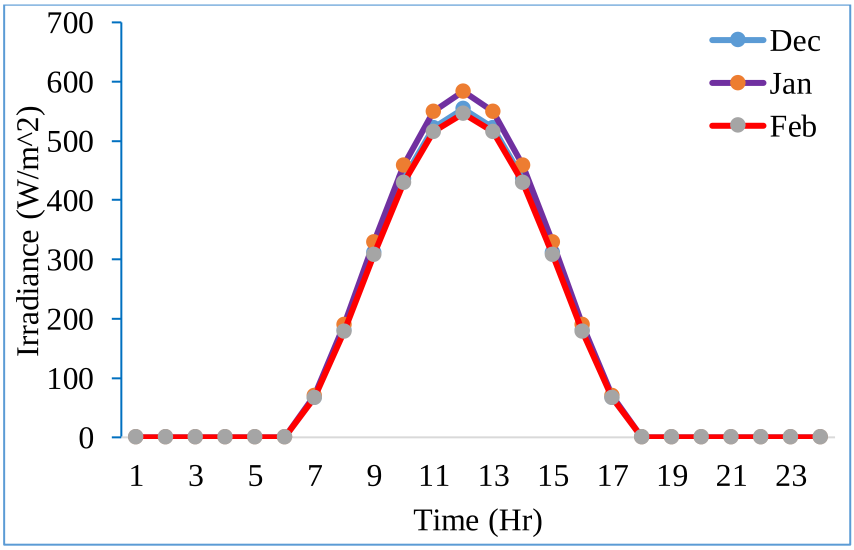

Figure 5.3: Monthly average Hourly direct (Beam) solar radiation of Winter Season

In the above figure 5.3, the monthly average hourly direct solar radiation for the winter season is shown, the average maximum and minimum irradiance are between 600 to 500W/m^2 respectively.

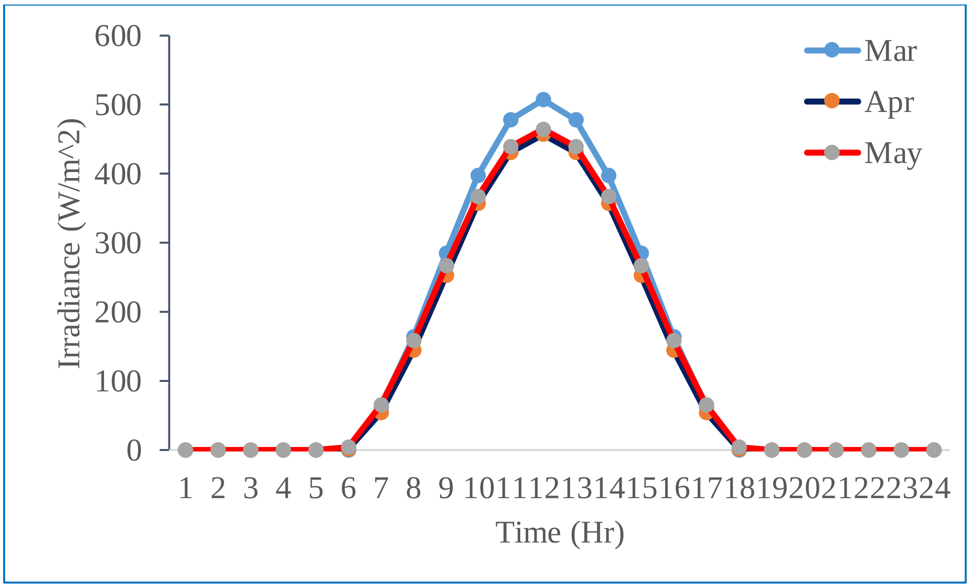

Figure 5.4: Monthly average Hourly direct (Beam) solar radiation of Spring Season

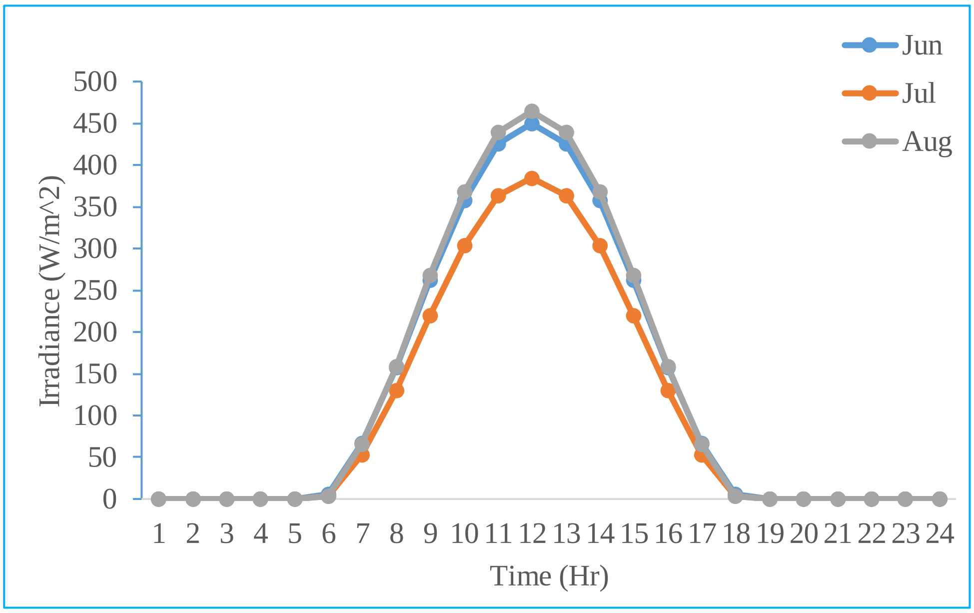

Figure 5.5: Monthly average Hourly direct (Beam) solar radiation of Summer Season

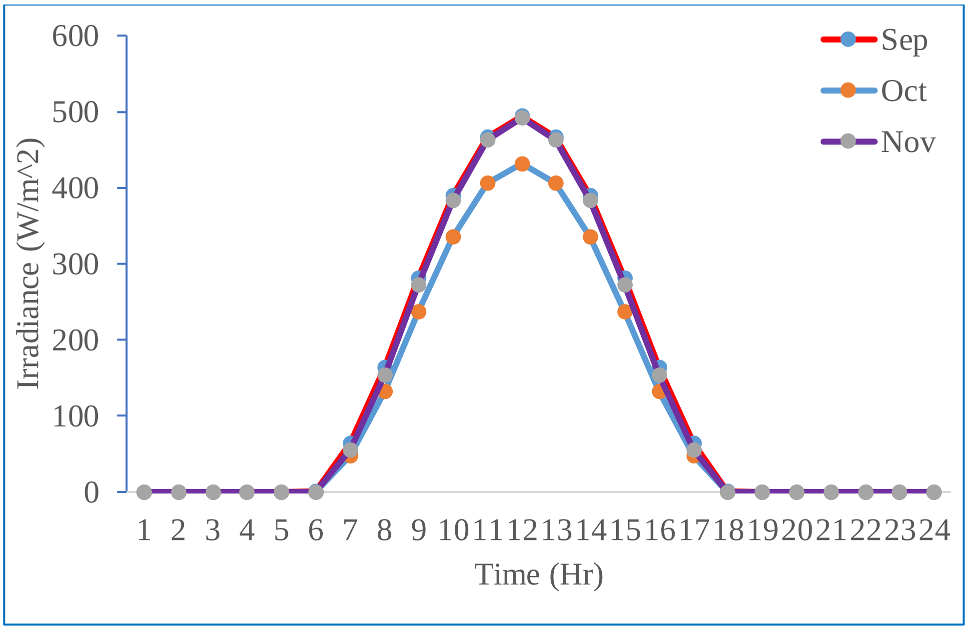

Figure 5.6: Monthly average Hourly direct (Beam) solar radiation of Autumn (fall) Season

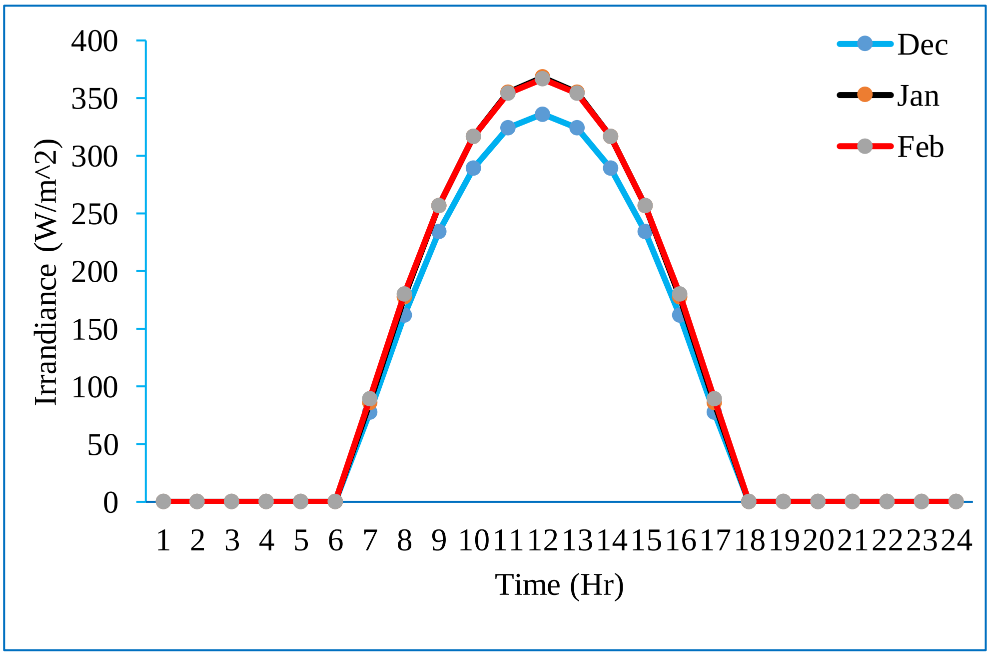

Figure 5.7: Monthly average Hourly diffuse solar radiation of Winter Season

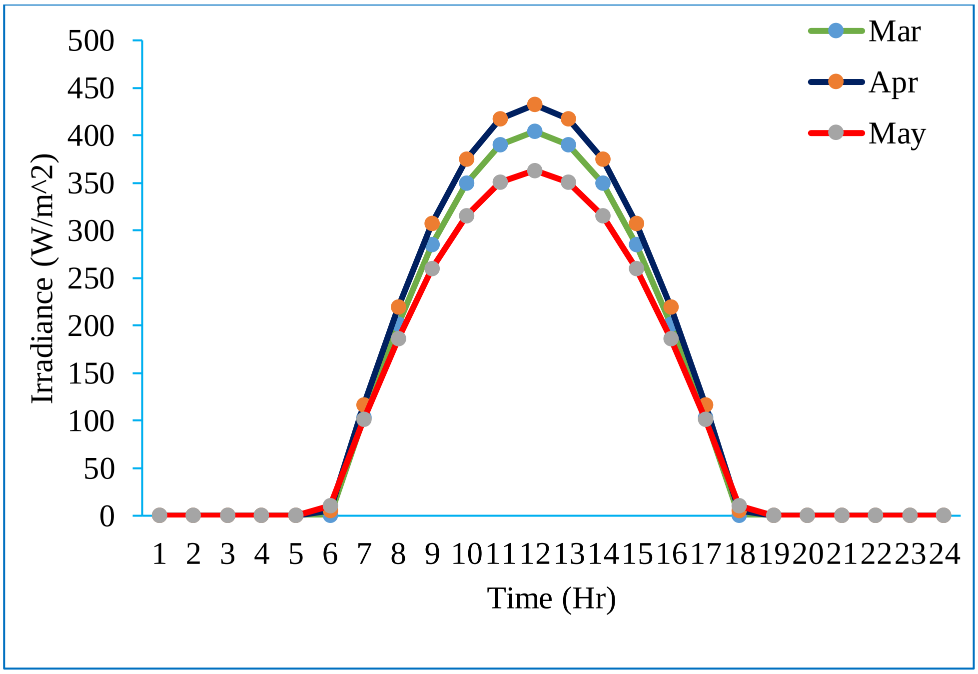

Figure 5.8: Monthly average Hourly diffuse solar radiation of Spring Season

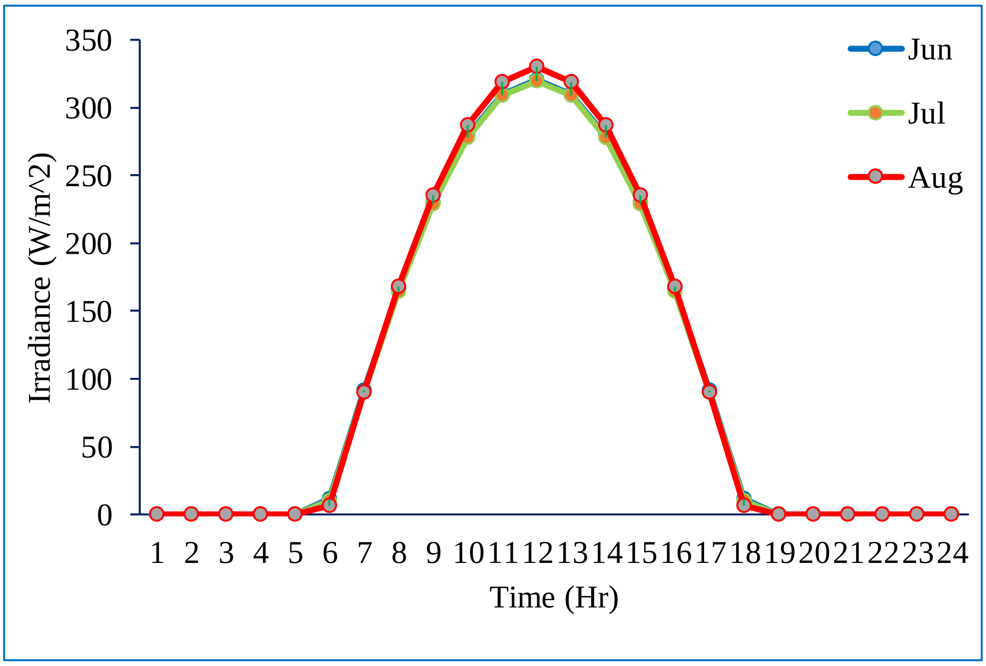

Figure 5.9: Monthly average Hourly diffuse solar radiation of Summer Season

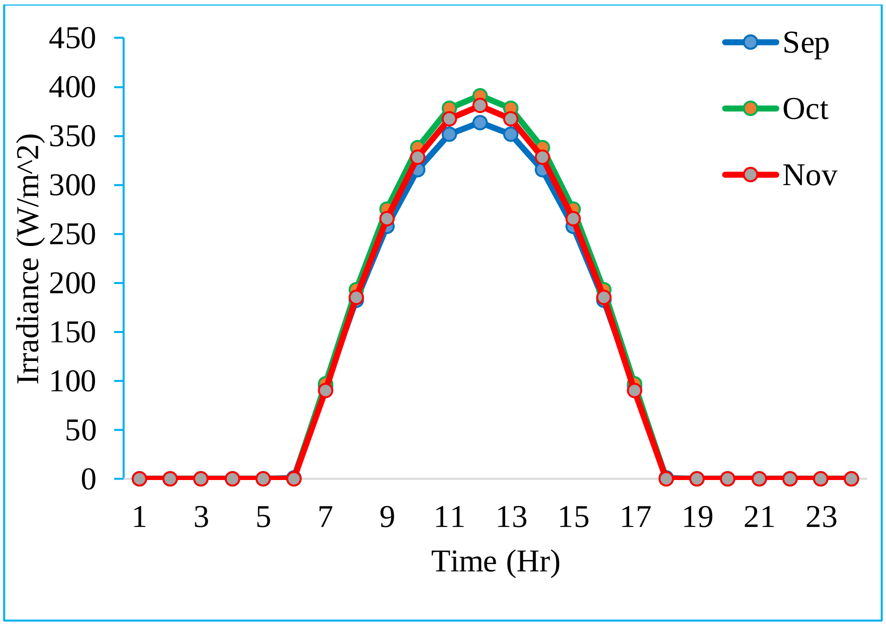

Figure 5.10: Monthly average Hourly diffuse solar radiation of Autumn (fall) Season

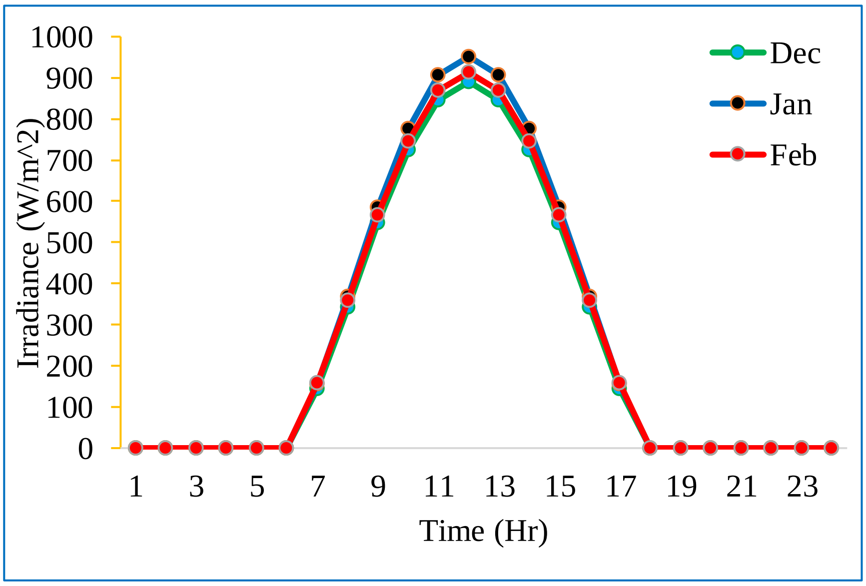

Figure 5.11: Monthly average Hourly Global solar radiation of Winter Season

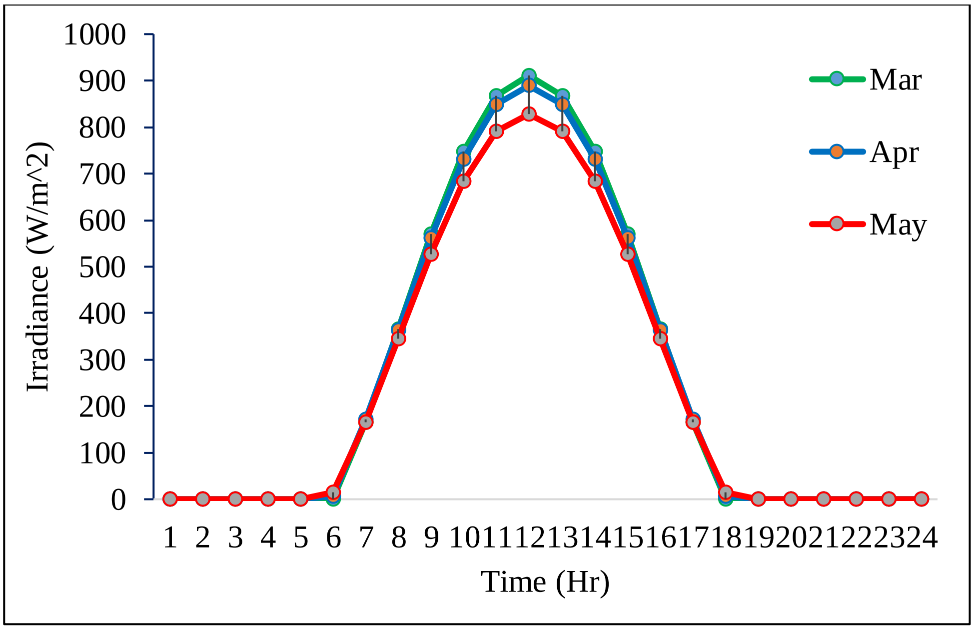

Figure 5.12: Monthly average Hourly Global solar radiation of Spring Season

The seasons which shown in above figures; figure 5.11 and 5.12 respectively are the driest season that crops need more of irrigation water supply and in the same period of time, there is high generation of solar energy availability. Hence, one of the great advantage of the solar water pumping system (SWPS) is its more availability and feasibility when most driest season which crop cultivation fully depends on the irrigation. But, beside of its merits, the increment of cell temperature with respect to ambient temperature of the environment reduces the efficiency of solar panel. Therefore, side by side water spraying over PV panel when irrigating the crop is best and cost free solution to solve the effect.

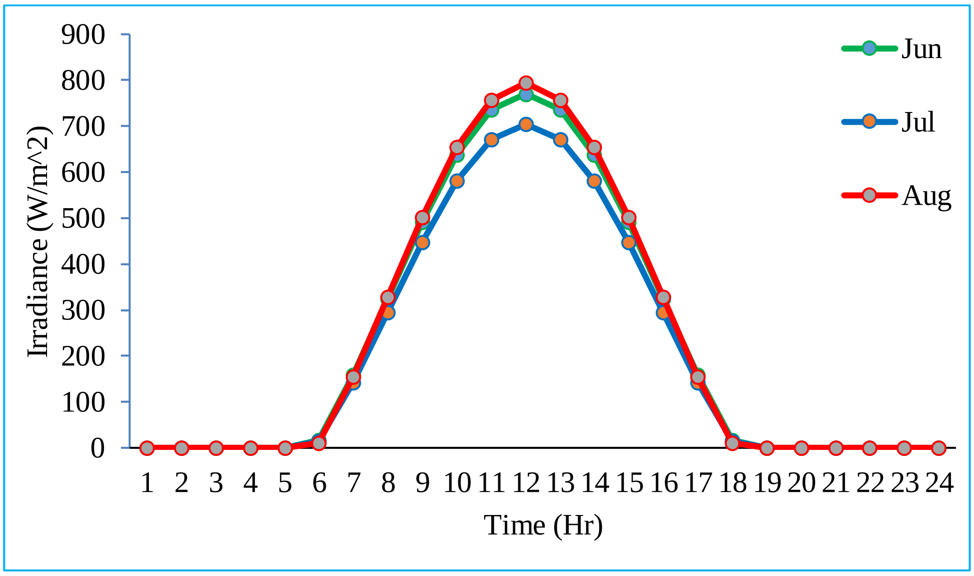

Figure 5.13: Monthly average Hourly Global solar radiation of Summer Season

The figure 5.13 shown in above is the least radiance figured from four annual seasons. The summer season is commonly rainy in the case study location, Mirab Abaya and mostly the crops get water through rainfall. For the designing procedure, July is considered as least solar energy operating period with having low sunshine hours. Hence, this makes the designed system capability to be on standby mood whenever it needed.

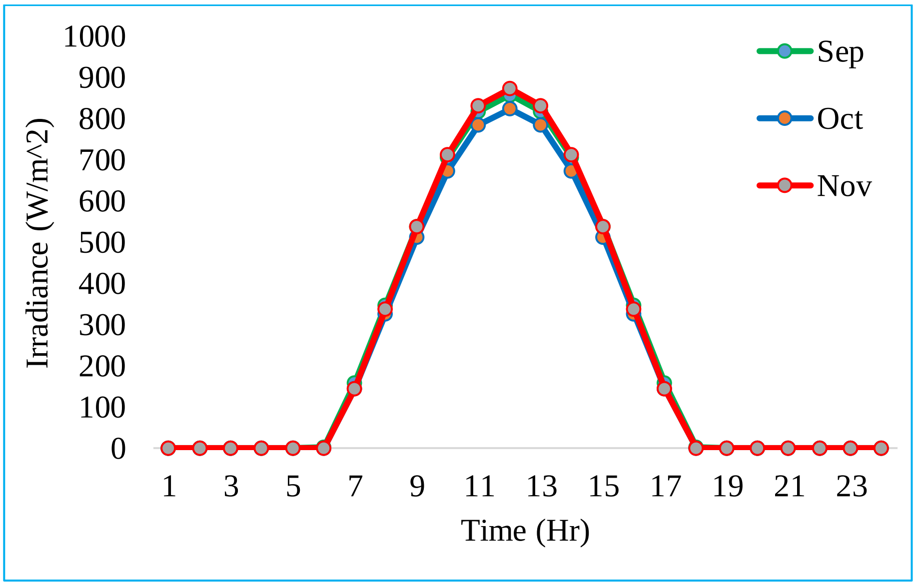

Figure 5.14: Monthly average Hourly Global solar radiation of Autumn (fall) Season

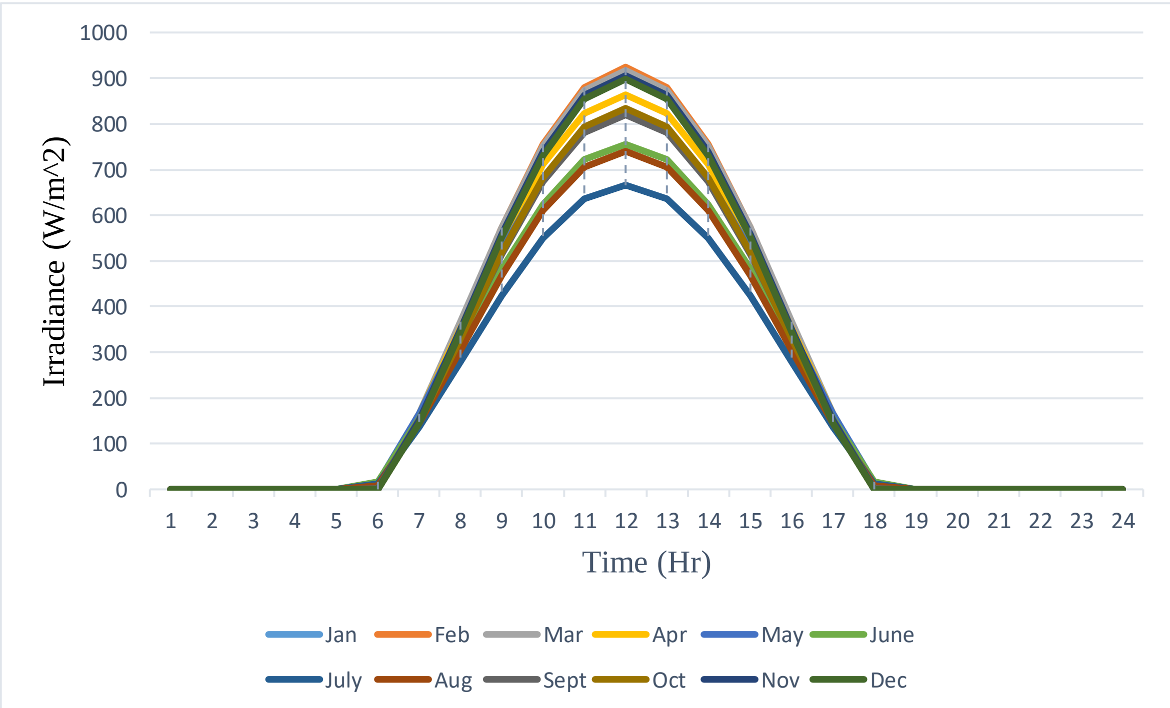

Figure 5.15: Monthly Average Hourly Global Radiation on Horizontal surface

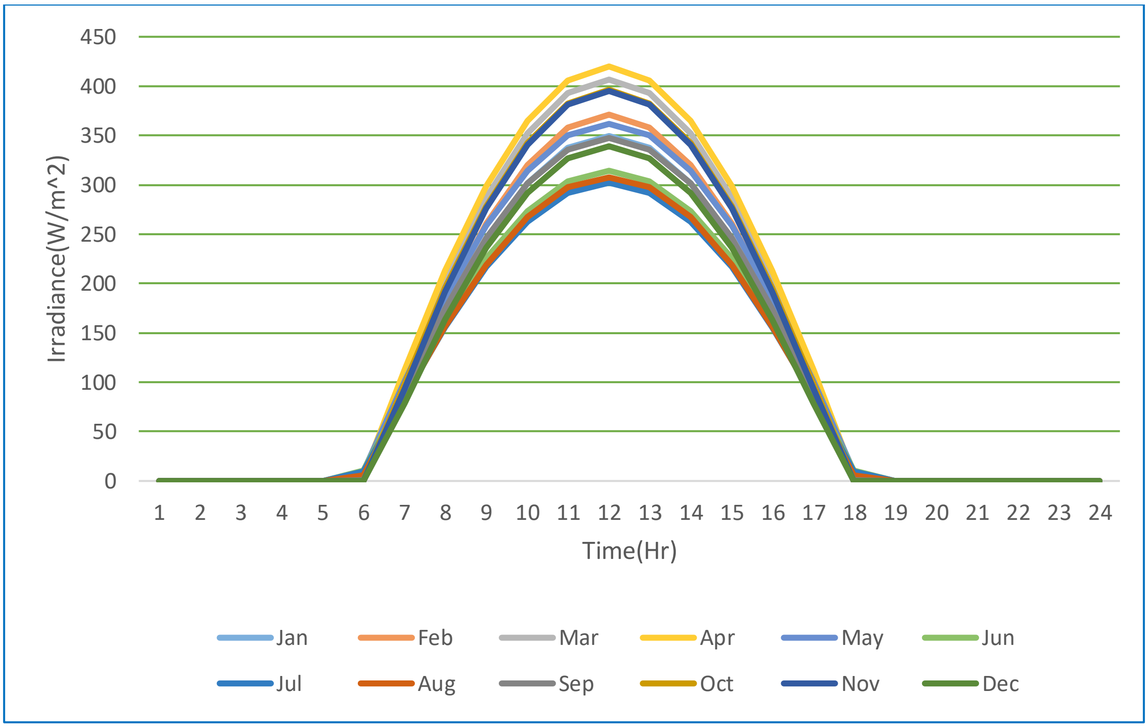

Figure 5.16: Monthly Average Hourly Diffuse Radiation on Horizontal surface

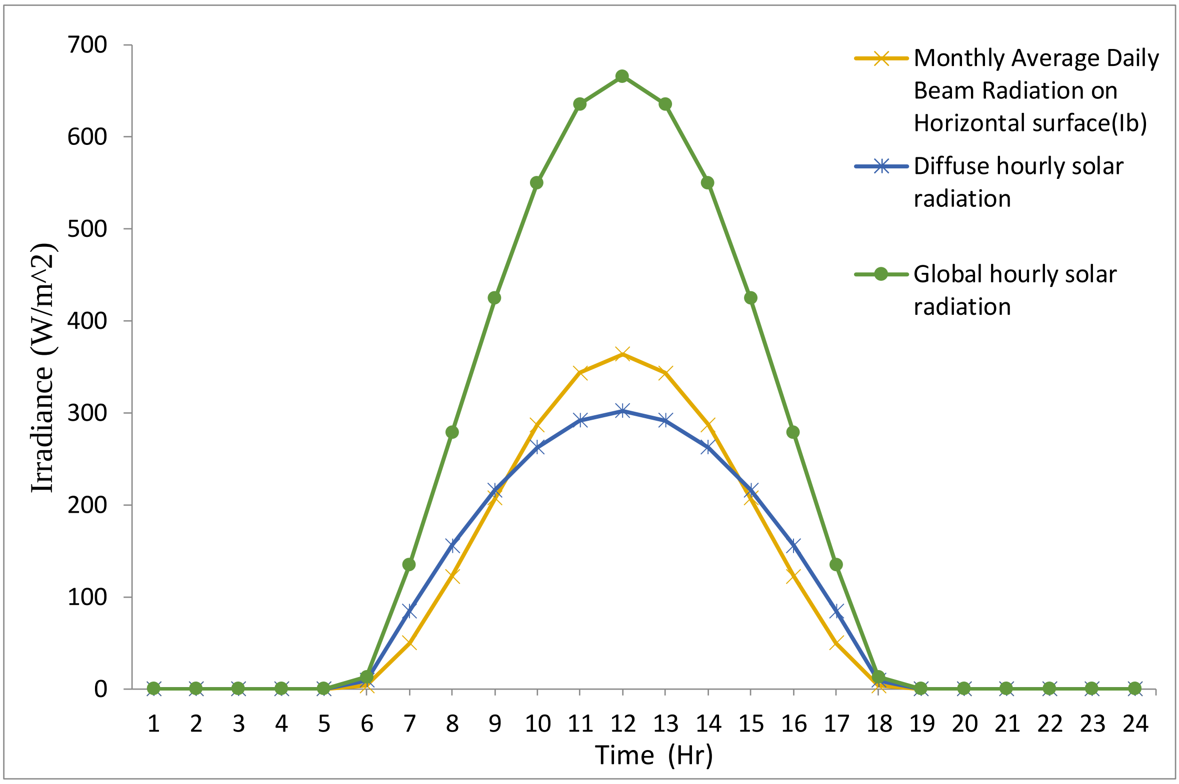

Figure 5.17: Monthly Average Hourly Radiation on Horizontal surface for July

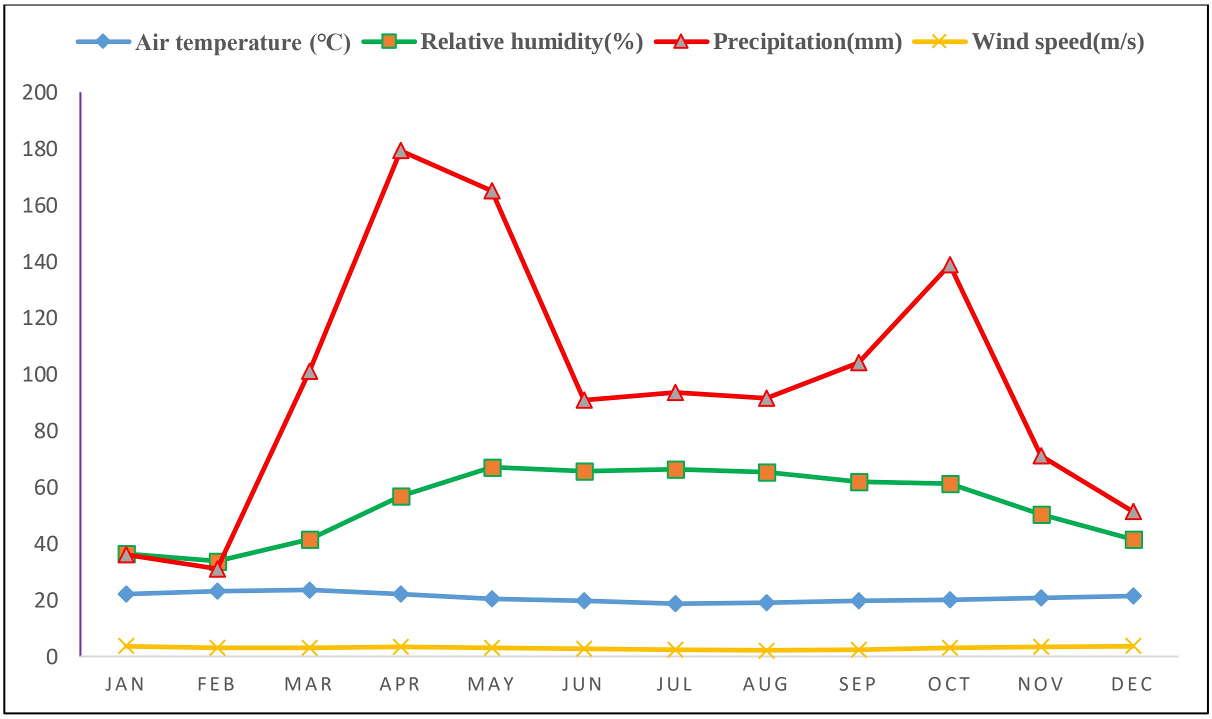

Figure 5.18: Weather condition of Mirab Abaya (Source: RETScreen software)

The figure 5.15 shown above is the monthly average hourly global radiation on the horizontal surface of Mirab Abaya that varies between 600 to 1000W/m^2. As in figure 5.17 shown, for the least irradiance designing July month, the monthly average hourly global radiation reaches up to 700W/m^2 at middle of the day. This result shows us that, the case study area has a plenty and most high solar potential generating environment that can serve to implement the solar driven water pumping system and another solar power based system operations in the location.

5.2 Analytical performance evaluation of the system

Three expressions are applied to evaluate the technical performance of the system mainly capacity factor, yield factor (YF), wire to water energy efficiency (WWEE) and system performance index (SPI) [36, 37, 38]

5.2.1 Yield factor

This expression presents the ratio between the daily YF (kWh/kWp/day, output energy to the installed PV array.

$$\mathrm{YF} = {}^{\mathrm{E}\left(\frac{\mathrm{kWh}}{\mathrm{day}}\right)}\Big/_{\mathrm{PV\ (kWp)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.1$$

$$= \frac{8.57}{2.03}$$

$$= 4.22 \text{ kWh/kWp/day}$$

The output energy from installed PV panel is about 4.22kWh/kWp/day and annually 1540.3kWh/kWp could be produced from 2.03kWp PV panel. Since this much energy available from free and clean sunlight source, the system is very promising to replace the diesel pumping system in the location.

5.2.2 Capacity factor

Full rated power (P_R) is known as the ratio of the actual annual output energy to the amount of the generated energy from the PV array. When the system operates for 24 h per day for a year, it represents the annual capacity factor that is calculated as follows:

$$CF = \frac{yield\ factor}{8760} \quad \text{...} \quad 5.2$$

$$\frac{1540.3}{8760} = 0.176 \text{ or } 17.6\%$$

Generally, solar energy is in the range of 10-25%. One of the key reasons for this low ratio is the nature of renewable power. Solar energy has main limitation, thus there is absolutely no energy production during night. Fortunately, solar energy has many distinct advantages such as easy maintenance, long lifetime and decreasing prices that still make it the renewable energy of choice for many purposes**.**

5.2.2 Overall efficiency of the system

This expression presents the overall system efficiency during the day given by:

$$\eta_o = \frac{\text{Hydraulic energy of the water delivered (Wh/day)}}{\text{PV energy supplied } (Wh/day)} \quad \text{..........................} 5.3$$

$$= \frac{1.12}{2.03}$$

$$\eta_o = 0.552 \text{ or } 55.2\%$$

Overall efficiency is wire to water efficiency which is the commonly used metric to determine the overall efficiency of a solar water pump; it is the ratio of the hydraulic energy of the water coming out from the pipe outlet to the energy that came in over the electrical wires through solar panels. Because of the system’s solar panel power production dependency on sunlight occurrence, the performance of system highly affected on panel.

5.2.3 System performance index

This term presents the total daily sum of the water delivered per the PV station capacity (Wp) of the PV station capacity.

$$SPI = \frac{\text{Water delivery (} m^3\text{/day)}}{\text{PV station capacity (Wp)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.4$$

$$= \frac{108.33}{2030}$$

$$= 0.0533\ m^3/Wp/day$$

The water delivered to the water storage tank for irrigation purpose is about 0.0533 m^3/Wp/day. Within each watt production, there will be 0.0533 cubic meter water delivered to the tank.

5.3 Performance evaluation of PV panel

The three basic parameters; open circuit voltage, short circuit current, power output, and efficiency of the M-60W model panel under the 28º tilt angle alignment where tested for ten consecutive days on the location within each 20 minutes gaps starting from 7:50pm -5:50am.

- **Open circuit voltage (Voc):-** the maximum voltage produced from a device, corresponding to zero.
- **Current flow power (DC):-** In DC circuits, power is given by the product of the voltage and current P = V x I (where P is the power in watts).
- **Short circuit current (Isc):-** the maximum current produced by a device, corresponding to zero voltage.

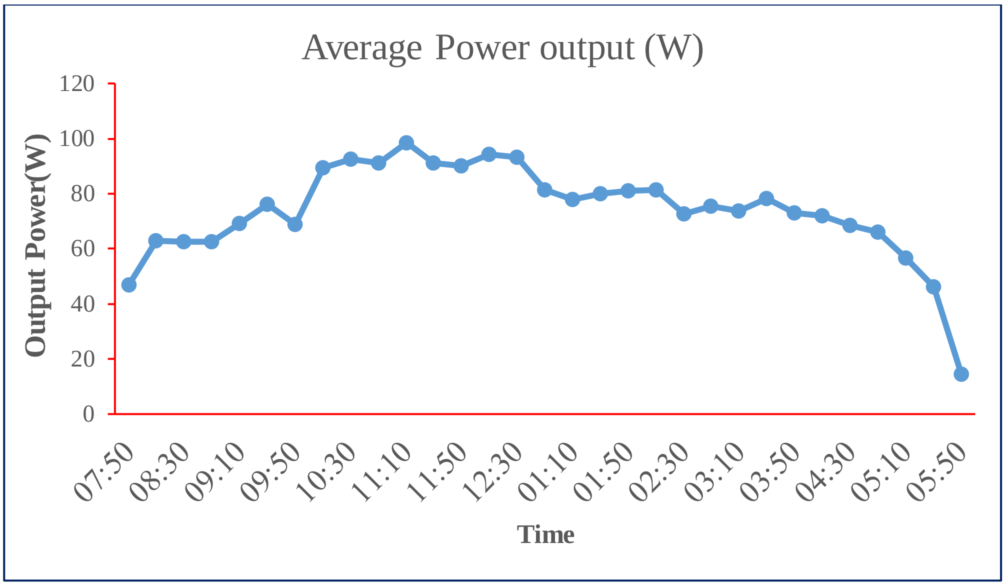

Figure 5.19: PV power output performance

As in the above figure shown, the power output of the PV panel result up to the maxima of 98.98W on the 10:30 am and the minimum power output is 14.50W on 05:50 pm and then the values are fluctuating with the variation of radiation and temperature. In fact, the increment of sunshine exposure at noon enhance the availability of solar energy with respective limited panel standard temperature. The temperature of panel is limited for 25℃ standard testing condition and the increment of temperature result a declination of its efficiency. Therefore, as the researcher discussed in the literature, and since its free, excessively available resource; spraying cold water over the PV panel is the best way to keep the panel temperature in the normal condition. Therefore, the researcher sprayed cool water over the PV panel for the noon testing (12:10 pm- 4:10 pm) period of time.

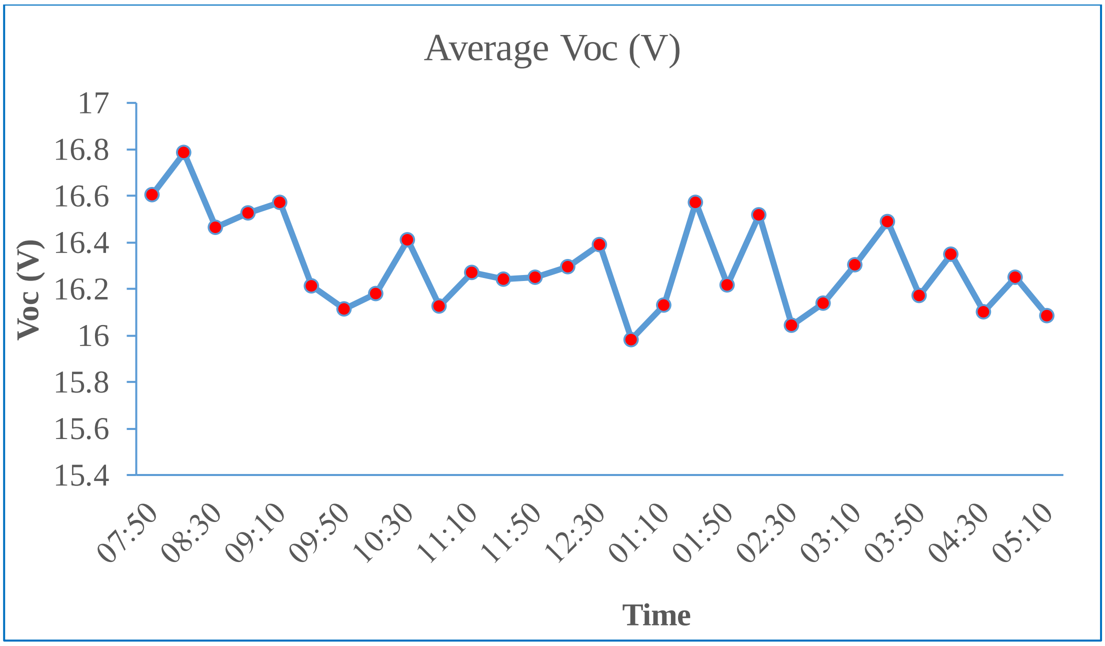

Figure 5.20: The average Open circuit Voltage of PV Panel output

From the above shown figure 5.20; open circuit voltage result, the average maximum voltage produced from the panel is at the morning period of time and its 16.803V on 8:10 am, the average minimum value is 15.802V on 5:50 pm. Hence, it's decreasing slightly throughout the sunshine hours.

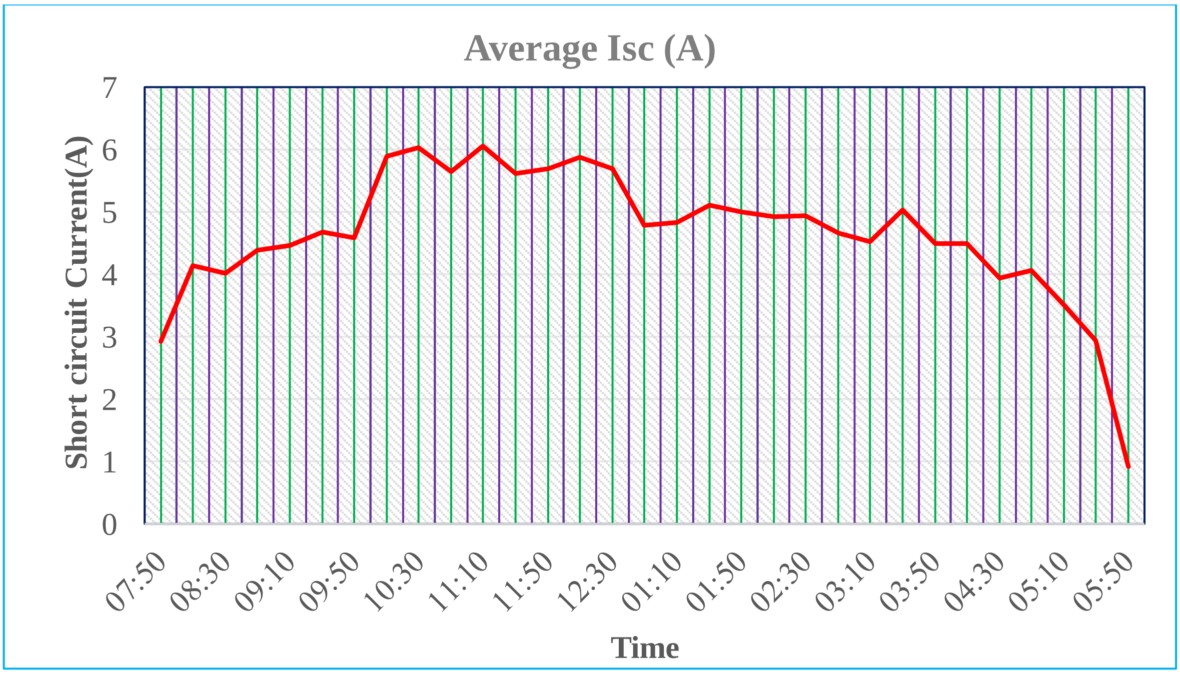

Figure 5.21: The average short circuit current of PV panel

The short-circuit current is due to the generation and collection of light-generated on the panel area and it is the largest current which may be drawn from the solar cell. The normal standard condition Isc value of the experimented panel is 4.78A. As the above figure 5.21

shown, the tested maximum value of panel is 6.051A on 11:10 am and the minimum is 0.91A on 11:50 pm. The test result show that, Isc is increasing from the morning, peak at the middle of the day and decreasing slightly to the afternoon period of time. Starting from 3:30 am to 4:10 pm the current is more than that of the experimental panel standard. Mainly, the performance depends on a number of factors which are; the area of the solar cell, the number of photons since it is directly defendant on the light, the spectrum of the incident light, the optical properties (absorption and reflection) of the solar cell and the collection probability of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

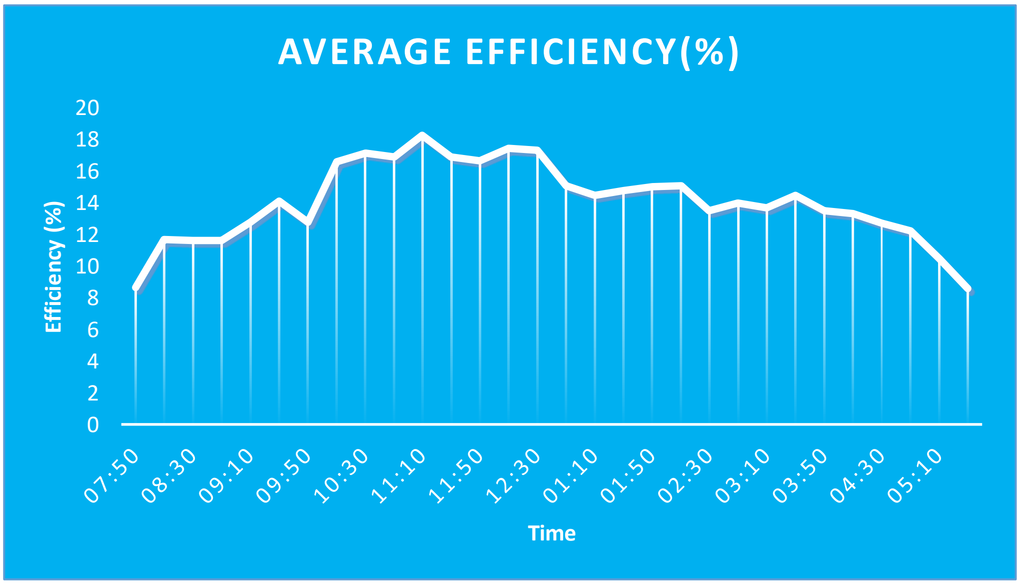

Figure 5.22 The efficiency of PV panel

The conversion efficiency of a PV cell is the percentage of the solar energy shining on a PV device that is converted into usable electricity. The researcher measured the performance of a photovoltaic (PV) device to predict the power the cell can produce. Electrical power is the product of current and voltage. Current-voltage relationships measure the electrical characteristics of PV devices. Efficiencies are obtained by exposing the cell to a constant, standard level of light while maintaining a constant cell temperature, and measuring the current and voltage that are produced for different load resistances. The figure shown in the above, the maximum efficiency of panel is 18.33% on 10:30 am and the minimum one is 2.68% on 5:50 pm, starting from the morning the efficiency increasing and after temperature become more than the standard, it decrease slightly if there is no cooling. The result is calculated from Voc, Isc and 0.54 m^2 area of the tested PV panel.

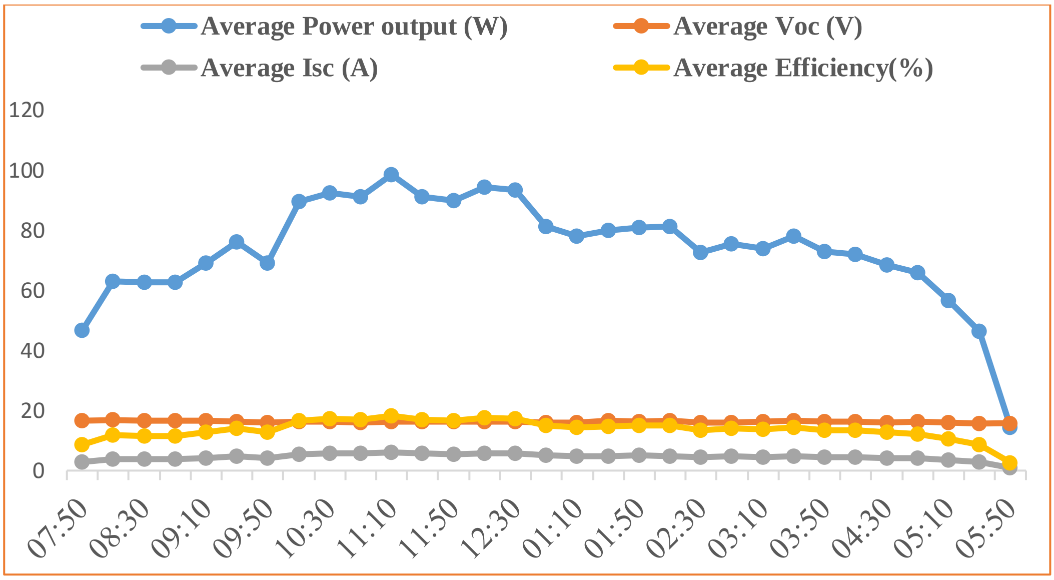

Figure 5.23: Power output, Open circuit Voltage, Short circuit Current and Effecency

5.4 Life cycle cost analysis of the system

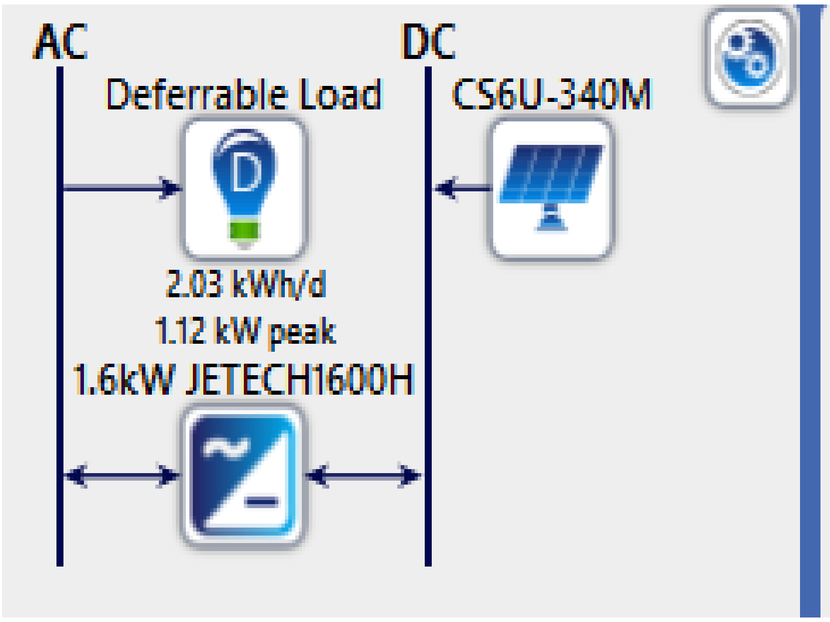

Figure 5.24: The schematic view of the system in Homer Pro Software

The above schematic figure 5.24 shows that, the given input data is depending upon the researcher designing perspective results. It included 2.03kW deferrable average load per day, the peak load (rated pump power in kW), 1.6 kW JETEH1600H model inverter, CS6U-340M model 6 panels, and load and cycle controller are considered for the simulation and optimization of the system software. For the life cycle cost analysis (LCCA), total system cost is given with solar panel and the inverter cost considered independently. After the simulation, the cost of energy (CoE) is 0.128$USAD/kWhr and its payback period is 5.44 years.

Table 5.1: Sensitivity variable values for homer pro simulation Result

Variables	Values	Units
Deferrable peak load	1.12	kW
Deferrable scaled average load	2.03	kWh/day
Deferrable load storage capacity	8.65	kWh
Solar reserve	80	%
Total capital cost	*3172*	*$USAD*
Total Net Present Cost	1220.33	$USAD
Levelized Cost of Energy	0.128	$USAD/kWh
Simple Payback time	5.44	Yr

Table 5.2: Maxpower CS6U-340M Electrical and statics simulation summary

Quantity	Value	Units
Levelized cost	0.059	$USAD/kWh
Rated Capacity	0.531	kW
Mean Output	0.106	kW
Mean output	2.54	kWh/d
Capacity Factor	19.9	%
Total production	926	kWh/yr

5.5 Summary of results and discussions

This chapter is the main part of the thesis which deals with results and discussions. Firstly, the researcher studied about the solar irradiance variation with respect to daily, monthly and seasonal solar potential availability on the location; secondly, by using the techniques which mentioned in chapter three; the performance evaluation of solar water pumping system has been analysed. Hence, by using analytical method, the technical feasibility were evaluated; in the experimental test, for the M-60W model PV panel, the performance of Panel is analysed considering the parameters which are namely; Voc, Isc and area of the panel and their effects were discussed. Finally, the Numerical method is used in the Homer Pro software and life cycle cost analysis (LCCA) has been simulated. All these results and discussions has been made for the chapter. The optimized outcome for each parameters has been discussed and in the next last chapter, the overall conclusion and recommendations for the future work about the research is discussed.

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Solar energy based technologies are becoming more popular and promotion of solar photovoltaic (PV) sources for power supply is one of the leading sources among the renewable energies and the trend is envisaged to continue in the coming years. PV panel is the heart of solar powered systems and recently the good news is, the cost of PV Panel is decreasing dramatically year to year. In this research, the design and performance evaluation of solar powered water pumping system for Mirab Abaya woreda on Abaya Lake near Birbir town has been studied. The design and performance evaluation has been done by using three basic techniques, such as analytical, numerical and experimental methods were employed. The system works without battery storage instead it uses water storage tank. Storing the water in the water storage tank at sunshine hours enables the system for two basic scenarios; first, for the saving of reserve water for cloudy hours and for the distribution of water to the irrigating crop by using natural gravitational potential energy. Absence of battery storage boosts the system to cost effectiveness and advances overall lifetime smooth operation. Hence, in the consideration of research target group i.e. farmers; the system total capital cost and complexity were optimized.

The study considered Lake Abaya as a source of irrigation for a hectare farm land for maize crop cultivation. The analyzed water need for 1ha maize crop is 36.11 m^3/day with TDH of 9m. The hydraulic power required to pump the water is 1.12kW power. To drive the pump, 2.03kW PV panel electrical power input was sized. For design of the system; the July month, the least global irradiation, 4.78kW/m^2 is considered to make the system functional throughout the year. Then, JSTY340P model each 340Wp PV panels were selected and aligned in three parallel ways (two series rows) arrangement. The analytical performance evaluation were done for the system such as yield factor, capacity factor. Wire to water energy efficiency and system performance index were calculated. Finally, life cycle cost analysis (LCCA) has been done and resulted CoE as 0.128$USAD/kWhr and payback period is 5.44 years. According to the cost, the researcher found feasible result in the Homer Pro software. In the regard of environmental issues, the designed system is cost effective, technically feasible, free from emission and environmentally friendly.

6.2 Recommendations

After completion of the research work, the follwing recommendations has been given:-

- ✓ Spraying water on the PV panels reduces the panel temperature and increase its performance; in return, the pump flow rate increases considerably when the panels are cooled. Hence, One way of improving the efficiency of PV system is to maintain a low operating temperature by cooling it down during its sunny and hottest operation period, therefore the farmers shall spray the cool water over PV panel surface frequently to keep the PV panel surface temperature in at standard condition throughout.
- ✓ Dust accumulation on the PV panel surface leads to a reduction in energy output and decreases the overall efficiency of the solar water pumping system; therefore, daily cleaning of the photovoltaic panels is essential to get the necessary power output.
- ✓ Since a minimal amount of the solar array is in the shade, the effect on the performance of the whole photovoltaic system can have a considerable impact, the PV system installation area shall be selected very carefully to avoid any shading effects.
- ✓ In the implementation of the project, mechanical, electrical and civil engineers shall participate for efficient system installation.

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APPENDICES

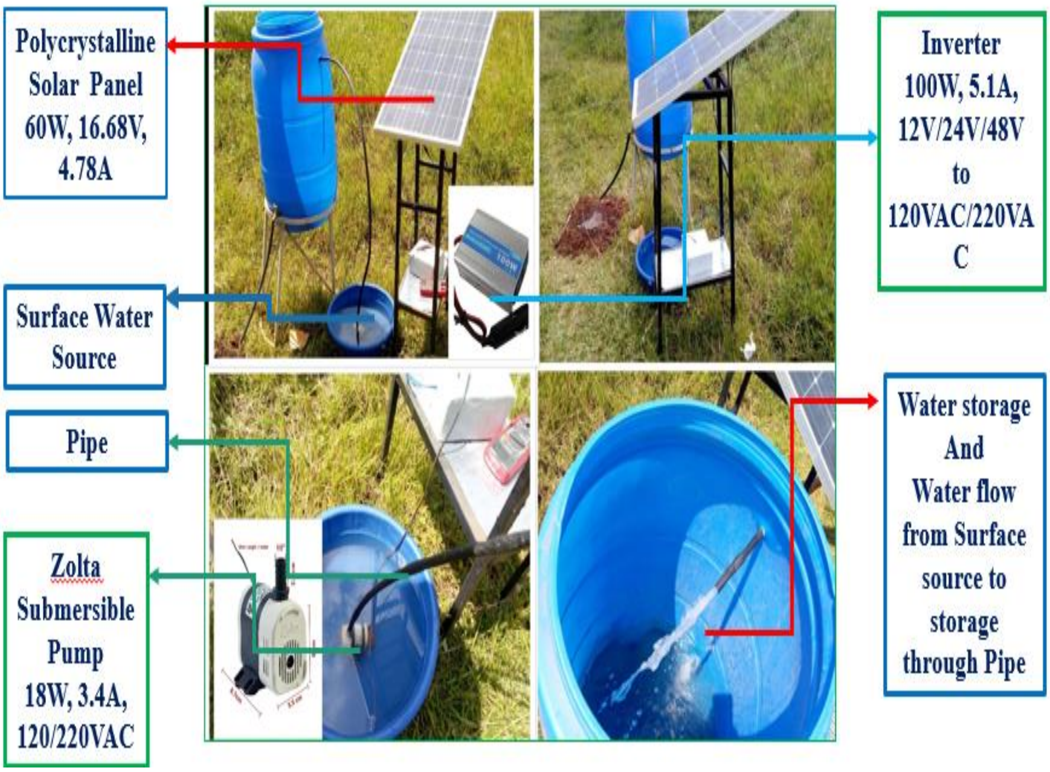
Appendix: A

A-1: Farmers and the pump which they are using for irrigation in Mirab Abaya

A-2: Lake Abaya and the nearest unplowed land

Appedix: B

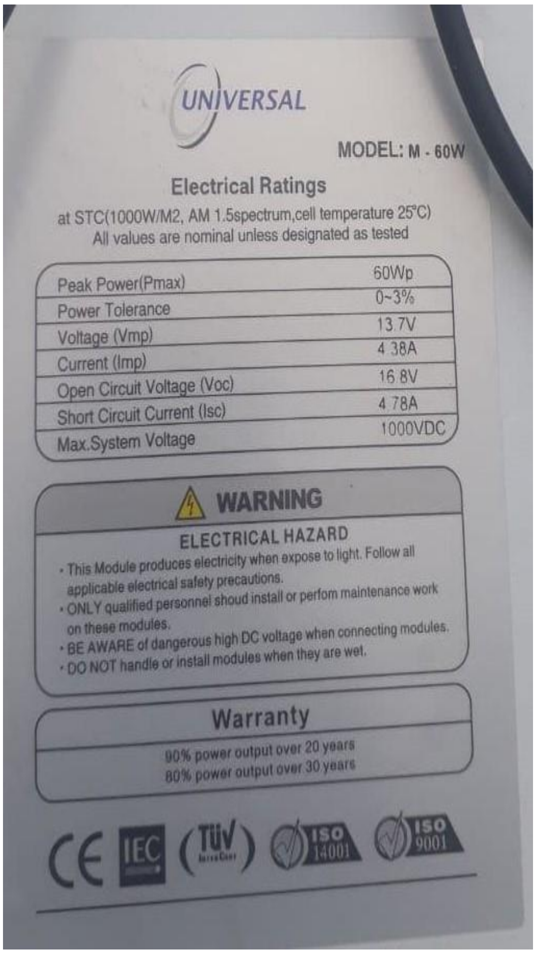
B-1: The Sample prototype of Solar Water pumping system without battery storage



B-2:- Total Breakdown cost of the Solar Water pumping system (SWPS)

No.	Equipment	Amount	Total cost of equipment (birr)
1	PV Panel	6 X 340W	71400
2	Invertor	1 x 1.8 kW	17500
3	Pump	1x1.5Hp	6500
4	Water storage	3x15000L	8500
5	Pump controller	1	1500
6	Wire	10m	850
7	Pipe	100m	7000
8	PV Panel Stand	-	6500
9	Water Storage Stand Construction	-	5500
10	Labor payment	100x3daysx26weeks	7800
11	Transportation	-	5000
	Total		155050.00

B-3: The specification of experimental M-60W PV panel



Appendix: C

C-1: Weather condition of Mirab Abaya from RETScreen Software

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m^2/d	kPa	m/s	°C	°C-d	°C-d
January	22.2	36.3%	36.21	5.96	83.8	3.6	25.7	0	379
February	23.3	33.8%	31.09	6.33	83.8	3.2	27.2	0	373
March	23.6	41.6%	101.07	6.30	83.8	3.1	27.5	0	420
April	22.0	56.9%	179.27	5.91	83.8	3.3	25.0	0	360
May	20.3	67.1%	164.90	5.71	83.9	3.0	22.4	0	320
June	19.6	65.7%	90.75	5.19	84.0	2.7	21.6	0	287
July	18.7	66.5%	93.57	4.68	84.1	2.3	20.3	0	269
August	19.0	65.2%	91.44	4.97	84.1	2.2	20.6	0	278
September	19.8	61.8%	104.03	5.55	84.0	2.5	21.7	0	293
October	20.0	61.4%	138.76	5.77	83.9	3.1	21.9	0	309
November	20.6	50.5%	71.19	6.07	83.9	3.5	22.9	0	317
December	21.4	41.4%	51.25	5.97	83.9	3.6	24.3	0	352
Annual	**20.8**	**54.1%**	**1,153.54**	**5.70**	**83.9**	**3.0**	**23.4**	**0**	**3,957**
Source	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA
Measured at					m	10	0		

C-2: Average annual Global irradiance for Mirab Abaya Location

Months	Sunshine based	Armines (France)	NASA	Average (kW/$\boldsymbol{m^2}$)
Jan	6.71	6.13	5.96	6.27
Feb	6.88	6.15	6.33	6.45
Mar	6.85	6.22	6.3	6.46
Apr	6.33	6.19	5.91	6.14
May	6.09	5.93	5.72	5.91
Jun	5.54	5.58	5.19	5.44
Jul	4.9	4.77	4.69	4.78
Aug	5.62	5.26	4.97	5.28
Sep	6.06	5.77	5.56	5.8
Oct	6.44	5.31	5.77	5.84
Nov	6.67	6.13	6.07	6.29
Dec	6.64	6.02	5.97	6.21

Appendix: D

D-1: Performance of M-60W Model PV Panel Power output

Time	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Average (W)
07:50	65.2	41.4	42.2	34.4	32.2	46.8	50.4	63.1	56.4	53.9	**48.6**
08:10	77.4	78.6	65.4	67.2	58.6	80.8	60	68.6	68.5	70.2	**69.5**
08:30	63.6	60	70.9	74.3	61.7	74.7	55.7	64	67.8	67.2	**66**
08:50	82.6	86.3	68	68.2	54.1	88.1	60.3	74.4	72.3	71.5	**72.6**
09:10	73.4	89.6	54.4	87.8	75	69.6	74.8	64.8	66.8	83.2	**73.9**
09:30	78.9	80.1	75.6	74	75.8	78.7	56.5	78	77.4	84.9	**76**
09:50	76	61.4	24.7	74	72.5	112	72.7	95.7	76.1	76	**74.1**
10:10	102	105	67.1	109	92.9	89.7	92.5	113	82.8	103	**95.6**
10:30	119	107	106	81.8	106	73.1	90.1	111	92.4	103	**99**
10:50	119	82.6	69.3	105	82	107	104	72.3	85.7	83.3	**91.1**
11:10	91.5	115	114	102	95.6	92	83	96.6	114	80.7	**98.5**
11:30	82.5	102	84.5	96.4	81.3	84.5	101	101	92.3	86.3	**91.3**
11:50	75.2	114	103	114	106	54.7	115	58.5	91.5	94.4	**92.7**
12:10	78.6	80.5	118	109	83.4	103	78.8	81.1	114	113	**95.9**
12:30	91.2	81.7	81.6	74	79.4	112	96.8	96.1	114	106	**93.3**
12:50	80.8	77.4	86	82.3	81	87	53.3	99.6	79.9	36.6	**76.4**
01:10	92.2	77.5	83.5	66.9	71.7	82.6	84.2	44.9	97.6	79.2	**78**

01:30	89.3	82.1	105	68.8	83.9	89.8	83.6	85.5	89.3	70.8	**84.8**
01:50	80.7	95.5	81	71.7	79.1	81.6	78.6	78.8	81.2	81.4	**81**
02:10	85.5	75.9	80	80.9	83.7	78.2	78.2	77.9	93.5	79.8	**81.4**
02:30	68.3	83.6	84.1	102	68.2	86.4	75.3	69.3	84.6	70.4	**79.2**
02:50	76	82.4	75.5	72.9	78.3	69.4	68	80.2	72.5	78	**75.3**
03:10	76.9	80.1	82.4	67.8	76.4	56.1	75	79.2	85.8	58.3	**73.8**
03:30	72.7	95.1	75.9	98.4	81.8	96.9	78.8	77	82.9	71.5	**83.1**
03:50	79.8	77.3	79.1	77.2	32.1	80.5	80.1	79.8	79.8	63	**72.9**
04:10	65.7	83.6	99	79.9	61.7	67.7	65.5	62.8	83.7	65.5	**73.5**
04:30	66.6	69.4	70.6	47.3	69.8	67.4	78.3	77.7	65.8	22.2	**63.5**
04:50	72.4	77.3	74.7	74	73.5	25.3	42.4	72.4	73.9	73.7	**66**
05:10	52	60.9	71	54.8	68.1	51.2	50.7	51.6	53.1	51.9	**56.5**
05:30	37	46	21.1	37	61.6	55.3	53.8	48.1	49.6	53.6	**46.3**
05:50	17.5	12.1	10.8	15.5	8.25	18.1	10.6	19.9	19	13.2	**14.5**
Average	**77.04**	**79.4**	**75**	**76.4**	**72.1**	**76.2**	**72.5**	**75.6**	**79.5**	**72.4**	**75.6**

D-2: Performance of M-60W Model PV Panel Open circuit Voltage (Voc)

Time	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Average Voc (V)
07:50	17.2	17	16.6	16.3	17.1	16.3	16.6	16.8	16.4	16	**16.6**
08:10	17	16.9	16.9	16.7	17	16.9	16.5	17	16.7	16.7	**16.8**
08:30	16.9	17	15.3	16.4	16	16.4	16.3	16.6	17	16.9	**16.5**
08:50	16.8	16.2	16.5	16.6	16.2	16.6	16.5	16.7	16.7	16.6	**16.5**
09:10	16.5	16.4	15.7	16.5	16.8	16.7	16.8	16.8	16.9	16.8	**16.6**
09:30	16.9	16.5	16.2	15.5	16.5	15.8	15.4	16.3	16.1	17	**16.2**
09:50	16.6	16.3	15.6	15.7	15.8	16.2	16	16	16.6	16.6	**16.1**
10:10	16.9	16.3	15.9	16	16.1	15.9	16	17	15.8	16	**16.2**
10:30	16.7	16.4	16.2	16.3	16.3	16.1	16.3	16.9	16.7	16.4	**16.4**
10:50	17	15.7	16.2	15.7	15.6	16	15.7	16.9	16.3	16.3	**16.1**
11:10	16.2	16.3	16.4	16.6	16.3	15.4	16.7	16.3	16.4	16.2	**16.3**
11:30	16.1	16.2	16.2	16.4	16.3	16.2	16.1	16.3	16	16.5	**16.2**
11:50	16.3	16.6	16.4	16.1	16.1	15.9	16.4	16.2	16.3	16.3	**16.3**
12:10	15.8	16.4	16.7	16.8	16.7	16.7	15.8	16.3	16	15.9	**16.3**
12:30	15.8	17	15.8	16.8	14.9	16.1	16.8	16.8	16.8	17	**16.4**
12:50	15.5	15.4	16.5	16.4	16.3	15.7	16.3	16.2	15.2	16.5	**16**
01:10	15.9	16.3	16.3	16.3	15.1	15.9	16.4	16	16.8	16.5	**16.1**
01:30	16.8	16.9	16.6	15.8	16.7	16.7	16.8	16.3	16.8	16.4	**16.6**

01:50	16.8	16.4	16.3	14.8	16.5	15.8	16.3	16.1	16.8	16.3	**16.2**
02:10	16.4	16.2	16.2	16.9	16.7	16.3	16.7	16.3	16.8	16.7	**16.5**
02:30	16	16.8	16	16.2	15.9	15	16	16.2	16	16.5	**16**
02:50	15.9	16.4	16	16.4	16.4	15.9	15.9	16.8	15.4	16.3	**16.1**
03:10	15.4	16.9	16.6	16.1	16	16.2	16.5	16.5	16.5	16.4	**16.3**
03:30	16	16.5	16.4	16.4	16.4	16.8	16.6	16.9	16.5	16.4	**16.5**
03:50	16.2	16.6	16.5	16.2	15	16.2	16.3	16.2	16.2	16.2	**16.2**
04:10	16.7	16.8	16.7	16.2	15.7	16	16.6	15.7	16.7	16.6	**16.4**
04:30	16.2	16	15.9	15.2	16.6	16.4	16.5	16.2	16	16.4	**16.1**
04:50	15.9	16.9	16.4	16.2	16.1	16.2	16.6	15.9	16.2	16.2	**16.2**
05:10	16.1	16.1	15.9	16.9	16.1	15.7	15.7	16.1	16.4	16	**16.1**
05:30	15.9	16	16	15.9	15.4	15.9	15.9	15.9	14.9	16.1	**15.8**
05:50	15.8	15.7	16.2	16	15.6	15.8	15.8	15.8	15.7	15.8	**15.8**
Average	**16.3**	**16.4**	**16.2**	**16.2**	**16.1**	**16.1**	**16.3**	**16.4**	**16.3**	**16.4**	**16.3**

D-3: Performance of M-60W Model PV Panel Short circuit Current (Isc)

Time	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Average Isc (A)
07:50	3.79	2.43	2.54	2.11	1.89	2.87	3.04	3.76	3.43	3.36	**2.92**
08:10	4.56	4.66	3.87	4.03	3.45	4.79	3.65	4.04	4.11	4.21	**4.14**
08:30	3.76	3.54	4.63	4.54	3.87	4.56	3.41	3.87	3.99	3.98	**4.02**
08:50	4.92	5.32	4.12	4.12	3.35	5.32	3.65	4.47	4.32	4.32	**4.39**
09:10	4.46	5.46	3.46	5.34	4.47	4.16	4.46	3.86	3.96	4.96	**4.46**
09:30	4.68	4.87	4.68	4.76	4.61	4.99	3.66	4.78	4.8	4.98	**4.68**
09:50	4.59	3.78	1.59	4.72	4.59	6.89	4.55	5.99	4.59	4.59	**4.59**
10:10	6.02	6.45	4.23	6.78	5.76	5.65	5.77	6.65	5.23	6.44	**5.9**
10:30	7.11	6.54	6.54	5.01	6.54	4.54	5.54	6.59	5.54	6.32	**6.03**
10:50	7.01	5.27	4.27	6.72	5.27	6.71	6.62	4.27	5.27	5.12	**5.65**
11:10	5.64	7.08	6.98	6.13	5.87	5.98	4.98	5.94	6.98	4.98	**6.06**
11:30	5.12	6.32	5.22	5.88	4.98	5.21	6.28	6.22	5.76	5.22	**5.62**
11:50	4.61	6.89	6.31	7.11	6.61	3.44	7.01	3.61	5.61	5.79	**5.7**
12:10	4.99	4.92	7.06	6.49	4.99	6.19	4.98	4.99	7.11	7.09	**5.88**
12:30	5.76	4.81	5.16	4.41	5.32	6.95	5.76	5.71	6.76	6.26	**5.69**
12:50	5.22	5.02	5.22	5.02	4.98	5.55	3.26	6.16	5.27	2.22	**4.79**
01:10	5.81	4.75	5.11	4.11	4.76	5.21	5.15	2.81	5.81	4.81	**4.83**
01:30	5.32	4.87	6.32	4.36	5.02	5.37	4.98	5.25	5.32	4.32	**5.11**

01:50	4.8	5.81	4.98	4.84	4.8	5.16	4.83	4.89	4.83	4.99	**4.99**
02:10	5.2	4.69	4.93	4.79	5.03	4.79	4.69	4.77	5.57	4.78	**4.92**
02:30	4.27	4.98	5.27	6.27	4.29	5.78	4.71	4.27	5.29	4.27	**4.94**
02:50	4.78	5.02	4.71	4.45	4.78	4.37	4.28	4.78	4.71	4.78	**4.67**
03:10	4.98	4.75	4.98	4.21	4.77	3.46	4.56	4.79	5.21	3.56	**4.53**
03:30	4.55	5.78	4.62	5.99	4.98	5.78	4.76	4.56	5.01	4.35	**5.04**
03:50	4.92	4.67	4.78	4.76	2.14	4.96	4.92	4.92	4.92	3.88	**4.49**
04:10	3.94	4.98	5.94	4.94	3.94	4.24	3.94	4.01	5.02	3.94	**4.49**
04:30	4.12	4.34	4.45	3.12	4.22	4.12	4.76	4.81	4.12	1.36	**3.94**
04:50	4.56	4.58	4.56	4.56	4.56	1.56	2.56	4.56	4.56	4.56	**4.06**
05:10	3.24	3.78	4.46	3.24	4.24	3.27	3.24	3.21	3.24	3.24	**3.52**
05:30	2.32	2.88	1.32	2.32	3.99	3.47	3.38	3.02	3.32	3.32	**2.93**
05:50	1.11	0.77	0.67	0.97	0.53	1.15	0.67	1.26	1.21	0.84	**0.92**
Average	**4.71**	**4.84**	**4.61**	**4.71**	**4.47**	**4.73**	**4.45**	**4.61**	**4.87**	**4.41**	**4.64**

D-4: Performance of PV Panel Efficiency(%)

Time	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Average (%)
07:50	12.1	7.66	7.82	6.38	5.97	8.67	9.33	11.7	10.4	9.97	**9**
08:10	14.3	14.6	12.1	12.4	10.8	15	11.1	12.7	12.7	13	**12.9**
08:30	11.8	11.1	13.1	13.8	11.4	13.8	10.3	11.9	12.5	12.4	**12.2**
08:50	15.3	16	12.6	12.6	10	16.3	11.2	13.8	13.4	13.2	**13.4**
09:10	13.6	16.6	10.1	16.3	13.9	12.9	13.9	12	12.4	15.4	**13.7**
09:30	14.6	14.8	14	13.7	14	14.6	10.5	14.4	14.3	15.7	**14.1**
09:50	14.1	11.4	4.58	13.7	13.4	20.7	13.5	17.7	14.1	14.1	**13.7**
10:10	18.8	19.5	12.4	20.1	17.2	16.6	17.1	20.9	15.3	19	**17.7**
10:30	21.9	19.9	19.6	15.1	19.7	13.5	16.7	20.6	17.1	19.1	**18.3**
10:50	22	15.3	12.8	19.5	15.2	19.9	19.2	13.4	15.9	15.4	**16.9**
11:10	17	21.4	21.2	18.9	17.7	17	15.4	17.9	21.2	14.9	**18.2**
11:30	15.3	19	15.7	17.8	15.1	15.6	18.7	18.8	17.1	16	**16.9**
11:50	13.9	21.2	19.1	21.1	19.7	10.1	21.3	10.8	16.9	17.5	**17.2**
12:10	14.6	14.9	21.8	20.1	15.4	19.2	14.6	15	21	20.8	**17.8**
12:30	16.9	15.1	15.1	13.7	14.7	20.8	17.9	17.8	21.1	19.7	**17.3**
12:50	15	14.3	15.9	15.2	15	16.1	9.86	18.4	14.8	6.77	**14.1**
01:10	17.1	14.4	15.5	12.4	13.3	15.3	15.6	8.31	18.1	14.7	**14.4**
01:30	16.5	15.2	19.4	12.7	15.5	16.6	15.5	15.8	16.5	13.1	**15.7**

01:50	15	17.7	15	13.3	14.6	15.1	14.6	14.6	15	15.1	**15**
02:10	15.8	14.1	14.8	15	15.5	14.5	14.5	14.4	17.3	14.8	**15.1**
02:30	12.6	15.5	15.6	18.8	12.6	16	13.9	12.8	15.7	13	**14.7**
02:50	14.1	15.3	14	13.5	14.5	12.9	12.6	14.8	13.4	14.4	**13.9**
03:10	14.2	14.8	15.3	12.6	14.2	10.4	13.9	14.7	15.9	10.8	**13.7**
03:30	13.5	17.6	14.1	18.2	15.2	17.9	14.6	14.3	15.3	13.2	**15.4**
03:50	14.8	14.3	14.6	14.3	5.94	14.9	14.8	14.8	14.8	11.7	**13.5**
04:10	12.2	15.5	18.3	14.8	11.4	12.5	12.1	11.6	15.5	12.1	**13.6**
04:30	12.3	12.8	13.1	8.76	12.9	12.5	14.5	14.4	12.2	4.12	**11.8**
04:50	13.4	14.3	13.8	13.7	13.6	4.68	7.86	13.4	13.7	13.7	**12.2**
05:10	9.63	11.3	13.1	10.2	12.6	9.48	9.4	9.55	9.83	9.62	**10.5**
05:30	6.84	8.52	3.91	6.84	11.4	10.2	9.97	8.91	9.18	9.92	**8.57**
05:50	3.24	2.24	2.01	2.88	1.53	3.36	1.96	3.68	3.52	2.45	**2.69**
Average	**14.3**	**14.7**	**13.9**	**14.1**	**13.4**	**14.1**	**13.4**	**14**	**14.7**	**13.4**	**14.11**

Appendix: E

E-1:- Homer pro simulation report

HOMER PRO

System Simulation Report

www.homerenergy.com

File:

Author: TSEGAYE PAULOS

Location: 6Q99+XX Feregosa, Ethiopia (6°13.2'N, 37°46.2'E)

Total Net Present Cost: $1,220.33

Levelized Cost of Energy ($/kWh): $0.128

Notes: LCCA OF SOLAR POWERED WATER PUMPING SYSTEM FOR MIRAB ABAYA AREA

Sensitivity variable values for this simulation

Variable	Value	Unit
Deferrable Load Peak Load	1.12	kW
Deferrable Load Minimum Load Ratio	0.950	%
Deferrable Load Scaled Average	2.03	kWh/d
Deferrable Load Storage Capacity	8.56	kWh
Solar Reserve	80.0	%

E-2:- The Result of PV panel performance evaluation in Homer pro

PV: CanadianSolar MaxPower CS6U-340M

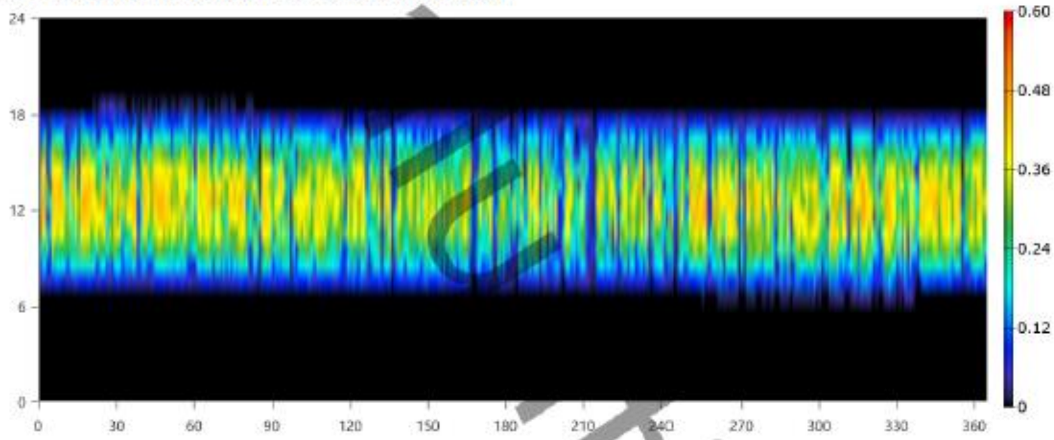
CanadianSolar MaxPower CS6U-340M Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.504	kW
PV Penetration	0	%
Hours of Operation	4,488	hrs/yr
Levelized Cost	0.0590	$/kWh

CanadianSolar MaxPower CS6U-340M Statistics

Quantity	Value	Units
Rated Capacity	0.531	kW
Mean Output	0.106	kW
Mean Output	2.54	kWh/d
Capacity Factor	19.9	%
Total Production	926	kWh/yr

CanadianSolar MaxPower CS6U-340M Output (kW)



E-3:- The simulated result of inverter performance in the Homer Pro software

Converter: 1.6kW JETECH1600H TYPE

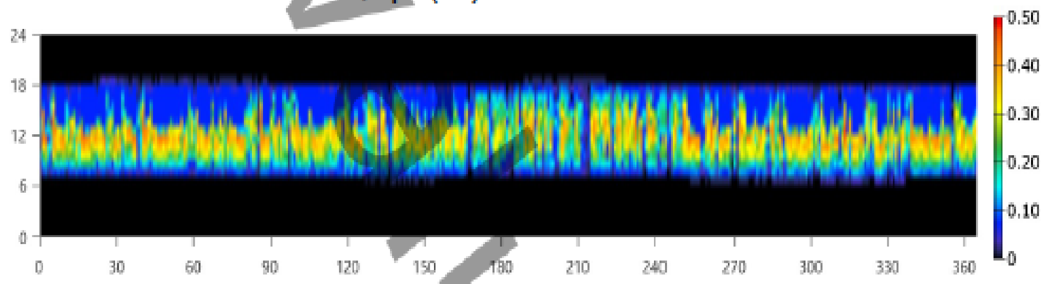
1.6kW JETECH1600H TYPE Electrical Summary

Quantity	Value	Units
Hours of Operation	4,222	hrs/yr
Energy Out	740	kWh/yr
Energy In	755	kWh/yr
Losses	15.1	kWh/yr

1.6kW JETECH1600H TYPE Statistics

Quantity	Value	Units
Capacity	1.83	kW
Mean Output	0.0845	kW
Minimum Output	0	kW
Maximum Output	0.494	kW
Capacity Factor	4.61	%

1.6kW JETECH1600H TYPE Inverter Output (kW)

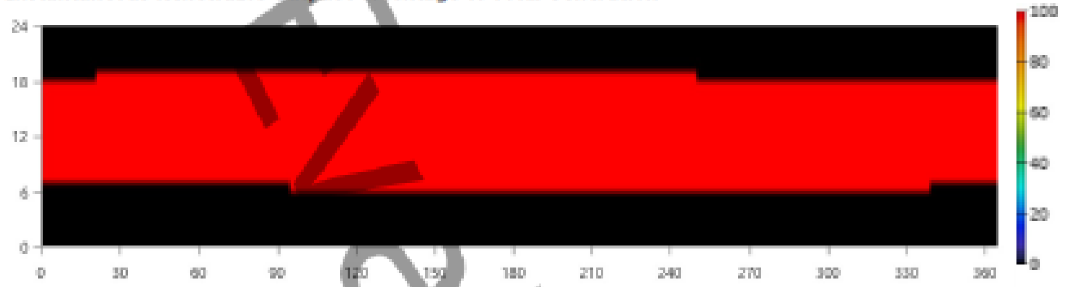


E-4:- The Renewable energy summary

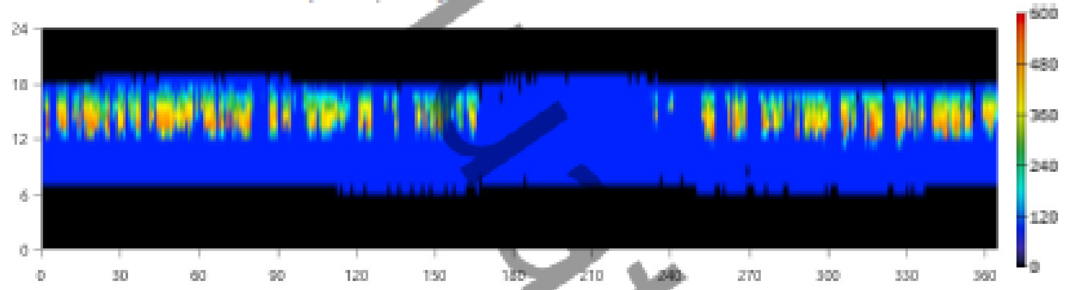
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	**Value**	**Unit**
Total renewable production divided by load	125	%
Total renewable production divided by generation	100	%
One minus total nonrenewable production divided by load	100	%
Peak values	**Value**	**Unit**
Renewable output divided by load (HOMER standard)	593	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

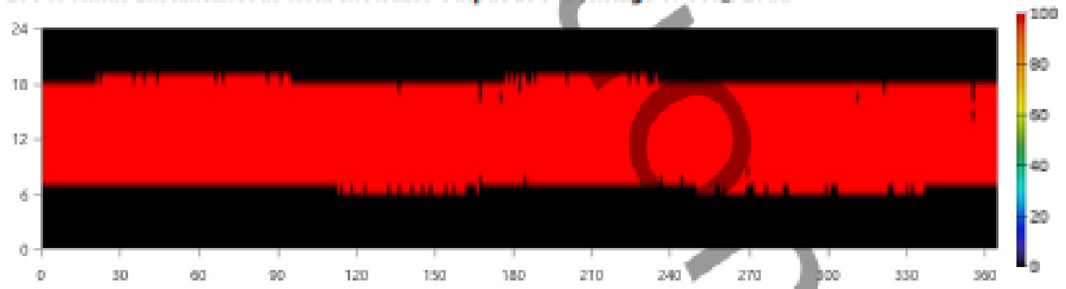
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



E-5:- The Economic comparison

HOMER PRO

Compare Economics

Architecture					Cost	
			CS6U-340M (kW)	1.6kW JETECH1600H (kW)	NPC ($)	Initial capital ($)
			0.531	0.979	$1,480	$909.14
			0.531	1.83	$1,220	$1,132

Base case is highlighted in green.

Metric	Value
Present worth ($)	$260
Annual worth ($/yr)	$20
Return on investment (%)	12.7
Internal rate of return (%)	17.1
Simple payback (yr)	5.44
Discounted payback (yr)	6.75