DESIGN AND SIMULATION OF SOLAR POWERED SPRINKLER IRRIGATION SYSTEM FOR KETE DORI ONION FARM

A thesis submitted to the school of Mechanical and Industrial engineering in partial fulfillment of the requirement for the Degree of Master of Science in Mechanical Engineering (Thermal Engineering Stream)

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February, 2020

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This is to certify that the thesis prepared by Abenezer Tesema, entitled, "**Design and Simulation of Solar Powered Sprinkler Irrigation System for Kete Dori Onion Farm**" submitted in accordance with the requirements for the Degree of Master of Science (Thermal Engineering Stream) complies with the regulation of the university and meets the accepted standards with respect to originality and quality.

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Declaration

I hereby declare that the work which is being presented in this thesis entitled "Design and Simulation of Solar Powered Sprinkler Irrigation System for Kete Dori Onion Farm" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of my Knowledge.

______________________________ _________________________

Dr.-Ing. Eddessa Dribsa (Advisor) Date

ACKNOWLEDGMENT

I am privileged to work under my advisor Dr. Ing Eddessa Dribsa for allowing me to work on this project by providing me time, support and consistent guidance throughout the completion of this thesis. I would also like to thank W/ro Roman Eshetie for arranging a visit to the farmland without which this work would not be successful. I am very fortunate and grateful to have a colleague and a friend Mr. Abdi Mirgissa for his unreserved help to collect the necessary site and metrological data. Finally, I would like to thank my family Mom, Dad, little sis and baby, they are the bedrock of my work and life. I am very grateful for their support, and encouragement more than words can explain I could not have done without them.

ABSTRACT

Ethiopia is among one of the most populated countries where agriculture is dominant sector in which the seasonal dependency prohibits the productivity of the sector. The availability of many river basin clearly depicts the irrigation potential the country has. The application of solar water pumping technology for irrigation is an innovative and sustainable solution to address this issue. The implementation of this technology can lead to several benefits which include the maximization of productivity by halting the rainfall dependence and improves the living condition of farmers.

This research aims at designing and optimization of solar powered sprinkler irrigation system considering the climatic data as it directly influences the irrigation water requirement. Several models are adopted for the evaluation of techno-economic feasibility and environmental aspect.

The photovoltaic water pumping system with water storage tank that much the irrigation water demand is proposed and several economic analyses has been conducted to establish the cost effectiveness. Another investigated model is photovoltaic water pumping system with battery storage and conventional diesel fuel generator capable of delivering the same demand. The results show that implementation of both photovoltaic systems is technically viable having performance ratio of 0.779 and capacity factor of 0.22 which is promising. The economic feasibility assessment found that net present cost of $24,224, $25,807 and $77,651 and cost of energy and $0.06/kWh, $0.07615 /kWh and $0.3077/kWh for PV system with tank storage, PV system with battery storage and Diesel system respectively. The environmental perspective benefit has been also addressed by the evaluation of the greenhouse gas emissions. Replacing diesel fuel by PV system that will protect the environment from 17,500 kg/year of CO_2, 132kg/year of CO, 4.82 kg/year of unburnt HC, 42.9 kg/year of SO_2, 150 kg/year NO_x, 8.03kg/year of particulate matters.

This study shows that the application of the solar energy for irrigation is viable both technically and economically, and also leads to several environmental benefits including, carbon abatement cost.

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CHAPTER 1
INTRODUCTION

1.1 Background

In order to ensure the development of one's country improving the agricultural means play important role. This can be attained by minimizing seasonal dependency of the agricultural sector which in turn infers that regular water supply is required using different mechanisms. According to the Central Statistical Agency of Ethiopia, the total projected population in Ethiopia was estimated to be 100,000,000, about 85 percent of which lives in the rural areas depending on subsistence agriculture [1]. Though agriculture is the dominant sector, most of Ethiopia's cultivated land is under rain fed agriculture. Because water plays an important role in photosynthesis, cooling by transpiration and it is a driving force for the transportation of nutrients in various plants. Hence, adequate soil moisture availability in the crop root-zone is very critical for optimum crop production. The available soil moisture for crop is supplied by precipitation and consumed through evapotranspiration or crop water use. Therefore, water can be supplied using irrigation system.

Irrigation is one of a well-established procedure on many farms. It is practiced on various levels around the world. It allows diversification of crops while increasing crop yields. Since the pumps are used as a means of delivering water to the farm, various systems are employed for this purpose and classified depending on energy input as manually driven pump, combustion engine driven pumps and solar powered pumps.

In Ethiopia, most of the agricultural practice depends on the weather condition. Even those areas which have irrigation system uses manually driven pump which is inefficient to cover large farm lands which in turn results in reduction of production. Some other irrigation system uses combustion engine to drive the pump which results in environment pollution. Therefore, by employing renewable energy source solar powered irrigation system not only improves efficient use of energy, but also reaches the off grid rural farm areas.

Solar powered water pumps are electrically powered using DC current that is generated directly from the solar panels themselves. The photovoltaic panels generate electricity from the sun's light. Solar water pumps are specifically designed to operate using the direct current (DC) supplied from the panel array throughout the day which consists of PV panels, pump controller, pressuring and watering tank [2].

Therefore, adoption of high efficiency irrigation system is increasing in order to tackle rapid growing global water scarcity issues. Solar power is also more affordable than using a generator. There is always the upfront cost of the generator itself and furthermore one will continue to incur out of pocket expenses for maintenance and fuel. Solar powered sprinkler irrigation systems are easy to install, require no traditional nonrenewable energy, operate autonomously and are generally good for the sustainability.

In Ethiopia, most of the agricultural practice depends on the rainfall. Even those areas which have irrigation system uses manually driven pump which is inefficient to cover large farm lands which in turn results in reduction of production. Some other irrigation system uses combustion engine to drive the pump which results in higher running cost and additional maintenance and repair expenses. Beside that it results in environmental pollution. Therefore, by employing renewable energy source solar powered irrigation system not only improves efficient use of energy, but also reaches the off grid rural farm areas.

1.2 Problem statement

Ethiopia has huge amount irrigation potential and solar potential which if utilized can significantly contribute to economic development of the country. Utilization of this resource can enhance the development of the country. Though there have been various work conducted to study the different system of water pumping for irrigation in many countries, but in Ethiopia where more than 85% of the population depend on agriculture and where there is huge irrigation and solar energy potential, the research conducted for implementing solar water pumping for irrigation and determining the feasibility corresponding to this system is in infant stage. Most studies undertaken on the use of photovoltaic application in irrigation lacks systematic integration irrigation system design and the consideration of the dynamic effect of the irrigation water requirement, and water supply that has the great impact on the yield and growth of the crops.

There is still a gap in determining whether the proposed system is feasible when compared to the traditional diesel used as the source of power by considering the environmental effect in terms of both greenhouse emission and cost of carbon credit. The previous studies neither consider the effective design of the irrigation system in a manner that the climate and crop growth affect the water requirement nor performed comprehensible analysis on the application of photovoltaic system for powering the irrigation for the proposed system which leads to the first research question in "how to effectively design appropriate irrigation system that suffice the irrigation water requirement and integrate them with perspective photovoltaic application?".

Previous studies did not consider the technical suitability and availability of water resource. Possible merits and demerits of having different energy sources and storage which could be applicable for irrigation system is not conducted. This leads to the second research question "is it feasible to implement the solar energy source for irrigation purpose both in terms of technical and economic parameters compared to other system? Those different system models used for feasibility study should have optimal configuration implementing appropriate procedures in a manner that assesses of all the potential benefits.

Since the implementation of solar system has corresponding environmental benefits by reducing of the greenhouse gas emission, the final research question tries to quantify "how many equivalent weighs of greenhouse gases are saved if used conventional energy source that would have polluted the environment?"

1.3 Site description

The study site is found in Oromia region, Geju Woreda, Kete Dori village which is located around 150km south East of Addis Ababa and lies between $8^0$21'48''N longitude and $39^0$31''04''E latitude. The region is located around Awash River basin which covers the catchment area of 112,696km^2. [3] The river is could be used a potential source for irrigating the plantation nearby.

Figure 1. 1 Site description (source google earth)

The study site has an onion plantation which covers 5 hectares' farm land which has dimension of 250m along the lateral line and 200m along the main line and the supply line runs 150m from the water source until it reaches the mainline inlet.

The area is located in off grid region and traditional irrigation system is implemented which is not efficient from energy cost and crop growth perspective. And diesel generator is used to power the pump which has adverse impact on the environment. It is observed from the site that there is sufficient amount of water that could be used for irrigation.

Figure 1. 2 Onion farm and existing irrigation [L] and water resource[R]

1.4 Objectives

General Objective

- The main aim of this research is to design an optimized solar powered Sprinkler irrigation system for onion plantation and evaluate its technical and economic feasibility.

Specific objectives

- Obtaining field and metrological data
- Assessment of solar energy potential of the site
- Determining water resource availability
- Determining irrigation water requirement
- Designing pipe layout
- Design of irrigation system, selection of pump- motor unit integration, PV systems, inverter/convertors
- Modeling and simulation of the system
- Evaluating technical and economic feasibility

1.5 Scope of the Study

This research focuses on the development of solar powered sprinkler irrigation system of an onion farm from awash river. This work started by visiting sites and taking preliminary data and climatic data used for the site is taken from the Ethiopian Metrology Agency and all the standard design procedure is followed for sizing and selection of different components of the system. The accuracy of the design depends on the precision of collected data. The performance optimization each component is not performed since the equipment's are selected. In general, this project is conducted to find if solar energy could be suitable to replace the conventional diesel and if doing so is economical by implementing effective irrigation system, and also to study the environmental impact/contribution associated with them.

1.6 Methodology

Introduction

In order to answer each research question, this study is started by arranging the site visit aimed gathering the necessary data. The first data to be acquired was the field measurement which is locating the topography of the area, investigating the water resource availability and whether appropriate irrigation system is being used that corresponds to the type of plantation. [A1] Depending of the gathered information metrological data were collected from the Ethiopian metrological Agency.

After those data are collected which are the major inputs for the next step, the thorough investigation to design the irrigation system is conducted to determine the irrigation water requirement. The appropriate tool that facilitate this determination is developed by FAO called CropWat is implemented in the work. Then the design of the corresponding irrigation system is performed by following the standard procedures by ensuring the required amount of water to reach the intended location.

The simulation method generally utilized the PVsyst software which suited for water pumping system. The inputs of this software are the solar data, the total head, water demand, storage type and characteristics and type of the photovoltaic panel. The life time of controller, PV modules, pump are also another inputs that is used for optimization of the system. The output of the software included amount of supplied water by the system, amount of missing water, losses, excess energy generated by the PV panel system efficiency or performance ratio and also economic analysis is performed to determine the viability of the system. Another software implemented for simulation of different model is Homer which is developed for optimization and sensitivity analysis and accounts different variation in technology and energy resource availability. it is implemented for the battery storage and diesel model.

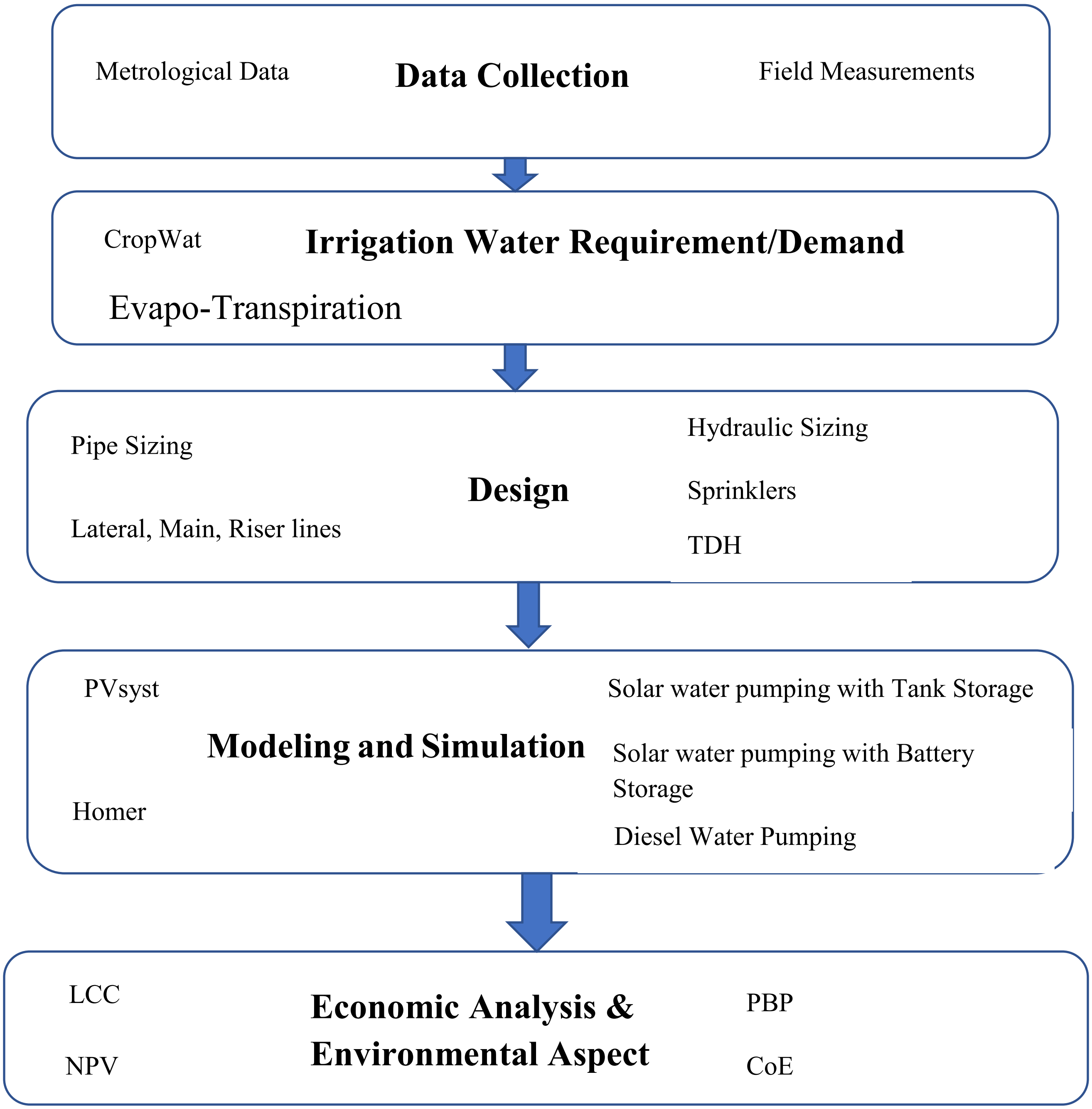


Figure 1. 3 Schematics of the methodology

1.6.1 Irrigation Water Determination

Prior to the design of any irrigation system it is compulsory to calculate the water requirement. In doing so the correct amount of water and the correct timing of the application should be adopted in order to have healthy and productive plantation growth. One of the recent technological advancement helps to identify irrigation scheduling that minimizes water demand by minimizing the impact on yield and yield quality. [17] One of the factors that should be known prior to making those decisions is evapotranspiration of the specific crop and it varies on the weather pattern. Land and Water development division of Food and Agriculture Organization (FAO) has developed software named CropWat to evaluate irrigation water requirement and it is adopted in this research.[27]

1.6.2 Modeling the Irrigation system in with Water Storage Tank using Pvsyst

After the determination of the irrigation water requirement and hydraulic analysis, the solar water pumping system is modeled in such a manner that it can deliver water that meets the maximum water demand under the assumption that the solar panels are not shaded with free horizon. There are many commercial tools for the sake of simulation and optimization of such system. Pvsyst is used for this purpose since it is considered as one of the most comprehensive for design and simulation. And also, unlike other the programs, PVsyst includes the tools for various PV water pumping application that can be adopted for specific type.

It is required to keep the water pressure in certain limits for sprinkler irrigation system in order to cover the farm land under the wetted diameter providing the designed discharge. Therefore, pressurization system is used for modeling such system on PVsyst.

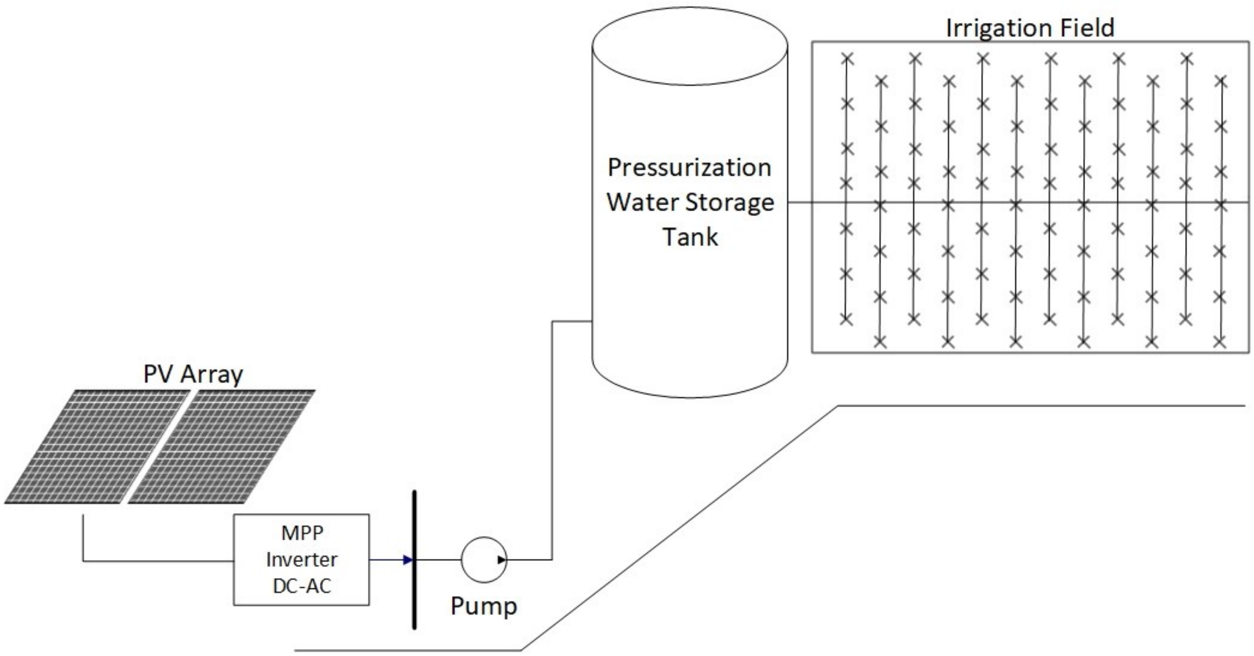


Figure 1. 4 Proposed PV/Water System Configuration

1.6.3 Modeling the Irrigation system with Battery Storage using Homer

Different methods can be employed to for optimization of photovoltaic water pumping system. One of the methods to do so is numerical optimization. There are many software's based on this method and Homer is one of these software's. Homer is commercial micro-power optimization and simulation software developed by the national renewable energy laboratory (NREL), USA. The simulation of the system is performed calculating the energy balance equation for 8760 hours in a year and compares the solution with various configuration and finds the best economically feasible solution. [28]

The irrigation water requirement is modeled as a deferrable load that can meet the same demand as of the proposed model for the purpose of economical evaluation, in homer because irrigation water requirement for crop can be delayed for 1-3 days depending on the irrigation frequency without any disturbance of the production. A deferrable load is type of electrical load that should be met within some duration period but the exact timing is not important. [29] in this proposed model the irrigation is system is associated with battery storage for the deferrable load.

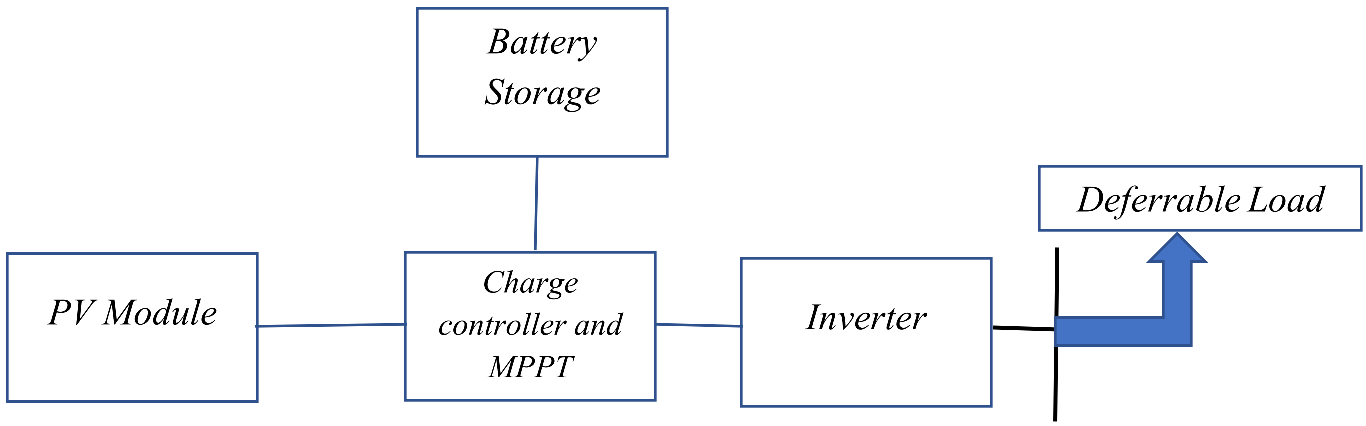


Figure 1. 5 Schematic Diagram of PV System with Deferrable load

1.6.4 Modeling the Irrigation system that uses Diesel

Fossil fuel source is modelled in order to investigate the economic evaluation and the environmental impact that would have been resulted when compared to the PV system. Diesel generator is specifically selected for this comparison due to the fact that they are available. Although the parameters required for the corresponding analysis is taken, the detail design of the system is not included in the scope of the work.

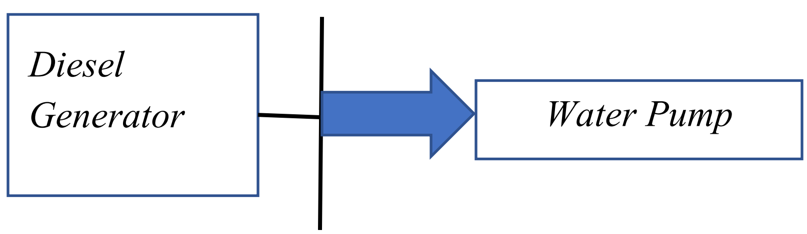


Figure 1. 6 Schematic Diagram of Diesel System with pump

1.7 Thesis Organization

This work consists of seven chapters and the brief summary of each is gives as follows in order to describe the overall structure.

Chapter 1: Introduction

This chapter provides the general background information, formulates the problem statement to be addressed, gives the site description, sets objectives and described the scope of the study and thesis structure and also the section describes and explains the methodology followed to conduct the work and the adopted models for design, analysis, simulation and economic evaluation.

Chapter 2: Literature review

In this section detailed review of the literature and work conducted that are relevant and it covers about solar water pumping for irrigation, agricultural sectors, solar radiation and related analysis.

Chapter 3: Design of irrigation and water pumping system

The sprinkler irrigation system is covered in this chapter. It starts by introducing the system then determines the irrigation water requirement, pipeline sizing hydraulics analysis and selection of accessories and fitting and finalize by determining the total dynamic head and Water Pumping System design

Chapter 4: Simulation and performance analysis of the water pumping system

This section covers theory, design, sizing and modelling of solar water pumping components and modelling and simulation various systems. The technical performance evaluation using relevant tools are performed, the simulation procedures and input parameters described and finally the performance analysis results are presented the discussion of those results are made.

Chapter 5: Economic Analysis and Environmental aspect

Economic is made and viabilities each model is investigated and corresponding results are presented and discussed and finally the benefit environmental aspect for the proposed model is presented.

Chapter 6: Conclusion and Future Work

The conclusion is given by adding up all the finding. It is used for introduction of potential further woks and recommendation.

CHAPTER 2
LITERATURE REVIEW

2.1 Solar Water Pumping for Irrigation

2.1.1 General

The economic growth and improvement of social life depends on the core foundation of energy. This energy demand determination primarily depends on the population growth rate, development of industrial sector and geographic distribution, whereas the amount of people that can be supported at acceptable quality of life strongly relies on the availability, cost and efficiency to which energy is produced. [4] the economic advancement urges the human society to demand more and more energy which results in extensive overuse of fossil fuels and this has been argued to be responsible for excessive levels of carbon dioxide and other greenhouse gases and eventually results in ecological, social and economic impact of the world. [5] meanwhile the limitation of the availability of this fossil energy [6] has given the rise to the ever-serious question and this recognition drives much active search for finding renewable energy resource.

The enhancement of the use of renewable energy is expected to increase the global energy production at the levels that would go without the use of the world limited energy resource and also reduce the human impact on the environment. Photovoltaic energy has received much attention as the a potential renewable energy resource on the past decades with a lucid advantage for regions like Ethiopia which has large potential of solar energy which can be seen form a recent survey made by the Chinese firm Hydro china Corporation and estimated to be around 2 trillion MW hours .[7] though, in spite of recent efforts to expand solar energy utilization, the solar power presently contributes only the small percentage of the country.

Historically, major concern regarding the application of sustainable solar power is cost related, cost to efficiency ratio regarding the variability of solar irradiance. These concerns are considerably decreasing due to the recent advancement in the solar panel manufacturing sector has led to dramatic drop in cost of solar energy production. [8] as the advancement in the PV manufacturing sector grows, the standardization of design and system installation will continue which is going to further reduce the cost related with PV energy production. [9]

There are many researches that are carried out around the world for using solar energy resource for water pumping application for irrigation but the technology is in the infant stage in Ethiopia. [6] even the performed review shows that the sizing of PV pumping irrigation system is not optimal.[6] not only due to nonsystematic approach but also by inappropriate irrigation method selection and poor design of irrigation system.

On the other hand, Ethiopia is a country that the agricultural sector leads the economy by covering 47.7 % of the total GDP. [10] it covers a land area of 1.13 million km^2 which is 99.3 % of the total land area. [11] although agriculture is the dominant sector most of Ethiopian cultivated land is under rain fed agriculture which results in progressive degradation of the natural resource on the highland areas that are coupled with climate variability, which in turn results in the poverty and food insecurity. Water resource management for agriculture includes both support for sustainability and rain fed agriculture and irrigation. [12]

The implementation of effectively designed irrigation system in Ethiopia, which has total irrigable land estimated around 3.7million hectares [10], not only minimized the seasonal dependency of the agricultural sector but also it enhances soil protection and maintaining soil fertility. Therefore the application of photovoltaic water pumping for irrigation has attracted the attention from the research community.

The main technological solution used for water pumping of off grid areas are manual hand pumping, PV and diesel pumping system are widely used for the intended application in the remote off grid areas. Photovoltaic system for water pumping for irrigation application consists of five main components: the PV panel, power control unit, pumping system, water storage unit and irrigation system.[13] several configurations of the system layout exits various technical components are available depending on the performance, reliability and economic aspect. [14]

In general most of the water pumping depends on the conventional electricity or diesel generated power. The use of the diesel fuel based water pumping system for irrigation not only requires expensive fuel, it also creates noise and air pollution. The overall capital, operation and maintenance cost of this system can go as high as 2-4 times than the photovoltaic pumping. Beside the photovoltaic system requires low maintenance, no fuel and environmentally friendly. [15] in recent years due to the diesel price shooting and non-availability of electricity in rural area of developing countries the application of the photovoltaic energy for water pumping is becoming promising. [15] compared to the conventional diesel energy, properly designed Photovoltaic system has significant and long-term cost saving opportunity. In addition, the water storage tank can be utilized instead of electrical battery storage. [16]

Since the agriculture is largely dependent on rainfall in our country and is adversely affected by the lack of water in summer, however, the maximum solar radiation availability attracts the application of Photovoltaic water pumping to supply the water in to the irrigation farm land. There is a vast potential which could play major role in fulfilling the irrigation water demand of the rural off grid area where the electricity is not easily available.

2.1.2 Current State of technology

The photovoltaic water pumping system consists of a PV array, DC/AC motor pumps, various controllers and frequently storage tank incorporated. The PV array is installed on the suitable structure, whereas the is pumped during the day where the solar radiation is available that can be used for directly for irrigation or could be stored in the storage tank to be used for night or cloudy day. The water tank in genera act as storage medium instead of the battery.

The direct coupling solar pumping which is introduced first in late 1970 had their own draw backs. But since then the rapid fall in price and the technological enhancement improves the performance and the reliability which in turn makes it economically viable for wide range of application. [17] though direct coupled systems are simple and reliable [17], it cannot operate at maximum power point of the panel as the radiation varies throughout the days. However, the incorporation of a maximum power point tracking (MPPT) and controllers with the system improves the performance of the PV water pumping.

2.1.3 Working principle of solar water pumping

The solar water pumping technology is a technology that converts sunlight into electricity for pumping water. The PV panels are connected with a DC/AC motor which converts the electricity in to mechanical energy by the pump. The capacity of the system to pump water depends on three main functions; flow, pressure and power to the pump. The elevation difference and pipe friction between the pump and storage tank determines the work which in the amount of energy which the pump has to draw from the PV array.

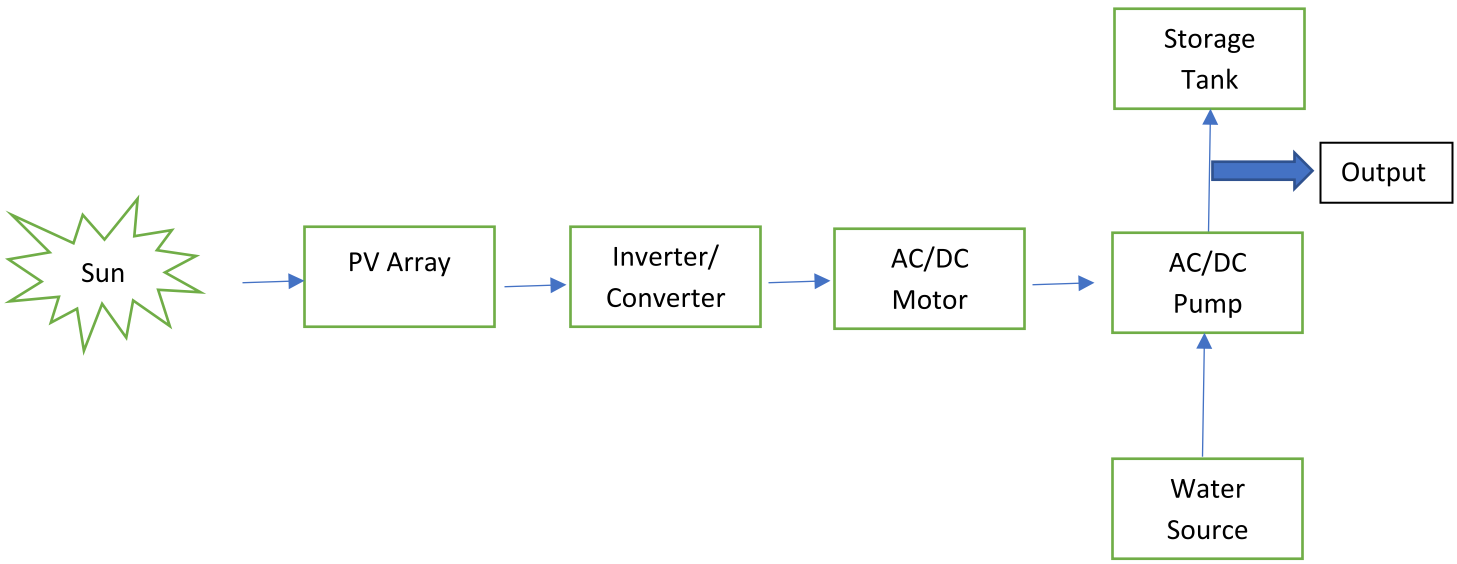


Figure 2. 1 Block diagram of a PV Water Pumping System

Water source

The water source for the system can be a pond, ground water, or rivers. The source has to recharge the faster than the pumping rate. The since case the main variables are the water reservoir volume, recharge rate and the cost of doing so.

2.1.4 Types of motors for PV based pumps

The PV panel produces direct current hence DC motors are most commonly used in a low power solar water pumping system. Although PV modules can be installed as either on a fixed array or a sun tracking system, most of the time for small irrigation fixed array is preferred due to low installation cost and no maintenance requirement. The selection of the controller depends on the pump motor type and whether direct or alternative current is used. If DC pump is used, the coupling is arranged with a DC/DC converter whereas if AC pump is used, the pump is connected to the PV array through a DC/AC inverter that transforms the DC power produced the PV module to AC used to drive the motor. [13] Different type of controller can be used, but most available one is the maximum power tracker. Though DC pump requires less expensive power controlling units, having higher initial investment cost makes them less preferable. Another advantage of employing AC pump is that large availability on the market which plays a major role for the availability of the spare parts for the remote off-grid area where it is going to be implemented. [13]

2.2 Literature Survey

The photovoltaic power for irrigation system is cost effective in comparison to the traditional and conventional energy sources for small scale irrigation system. since there is continuous reduction in peak watt cost of solar cell due to mass production photovoltaic system is becoming further economical in future. [12] A number of studies have been carried out on performance evaluation, optimization, sizing techniques, efficiency improvement and other factors which affect the system performance and economic aspects of PV system and some of them are discussed below.

2.2.1 Performance parameter factors and related work

The performance of the photovoltaic system strongly depends on the water flow rate which in turn is influenced by weather conditions of the site such as especially the solar radiation and the air temperature, hydraulic energy and PV array size affect. [19] The performance with various aspects have been reviewed [20] analyzed for data of various locations. They concluded that the cost can be reduced if the pump type, pumping head and daily load profile is consider during the simulation process. [21] Other study ….[22] reported that the solar water pumping performance depends on mainly operational head, PV array size and insolation.

[19] developed a method that helps to predict the long-term performance of a direct coupled PV pumping system that integrate the manufacturer data in the study. [23] determined the optimum PV array configuration which can supply energy to DC helical pump under the outdoor conditions in Saudi Arabia. [24] analyzed the operation of direct PV powered DC mount motor system for the selection of motor parameter and found that the performance of the system depends mainly on the incident solar radiation, operating cell temperature and propeller load parameter. [25] presented many stages of solar water pumping system to tackle water supply problem in Purwodadi village, india. The finding of the work suggested that important design parameters for effective analysis are analysis of piping system to determine the type of pump to be used and power system planning. [26] highlighted the potential of solar PV water pumping system and concluded that there are vast scope of replacing the diesel pumps with solar pumps at relatively higher cost. [27] discussed various components the water pumping system and the study reported that the utilization of PV energy for water pumping is reliable and cost effective. [28] reported the design and simulation aspects and corresponding simulation procedure that leads to performance enhancement of PV based water pumping system.

2.2.2 Optimal Sizing of solar water pumping system and related work

The sizing of stand-alone photovoltaic system is based on the fact that the electrical load is met with lowest average daily solar insolation on the array surface.

[29] Proposed a system which couples the pump to the PV array directly when the storage is full and the author suggested that the optimal solution is one that minimize the PV array size since it covers the major price of the system and increase the battery storage without increasing the array size has little effect on the performance of the system. [30] developed the optimal sizing model to optimize the capacity size of various component using a water tank for drinking and irrigation. [31] has investigated a PV powered water pumping system that is capable of meeting the additional electricity load beside the water pumping requirement. The result obtained by optimal sizing method is validated by experiment and it clearly shows that PV system with appropriate energy storage device can meet the demand. [32] described the procedure for design and sizing of a PV water pumping that is applied for drip irrigation of an Olive orchard located Spain and it contains the following stages:

- Determination of irrigation water requirements per the characteristic soil type and climate.
- Hydraulic analysis of the pumping system
- Determination of peak photovoltaic power requirement to irrigate.
- Impact of PV degradation on Water Pumping

The PV modules are susceptible to degradation due to humidity, temperature and system bias effect of the solar radiation. For a prolonged time of exposure to sunlight the efficiency of the solar panel decreases continuously because of the panel component ages.

Therefore, understanding the degradation of the PV generator modules of pumping system can lead to improve the performance of the pumping system. [33] have shown that multi-crystalline silicon modules have smaller degradation rate than the mono-Si modules. In more general essence the comprehensive review on various finding point out that the degradation of photovoltaic technology for long term reliability needs to emphasize the need to develop location specific stringent and additional quantitative standards for the qualification PV module testing for degradation.

2.2.3 Economic and environmental aspect related work

Due to the scarcity of conventional electricity and the rise in fuel price throughout the years, the rapid fall of PV module price the photovoltaic water pumping system is becoming financially attractive in recent times. Some of the financial assessment made a number of authors are presented below.

[34] compared the economic viability of photovoltaic system and diesel engine and found that the mismatch between the water demand and supply plays a major role in the economic viability. [35] carried out the hydraulic and electrical performance analysis to meet the water demand and the study recommended that using PV pumping system to supply water in remote area of sub-Saharan region for techno-economic development. [36] reported that the photovoltaic pumping system are viable alternatives when sufficient incentives are provided by government. [37] also reported considerable saving of PV system when compared to the conventional system for water pumping. [38] found out that the photovoltaic water pumping system reduces considerable amount of CO_2 over the 25 years life span.

In general several researches are conducted that deals with photovoltaic application for irrigation, in a manner that show how the solar powered irrigation can be considered as an attractive application of the renewable energy. [38] analyzed the technical and economic feasibility and finds out that there is no technical barrier. [39] presents the producer for designing the sprinkler irrigation system. The Land and Water Development Division of Food Agriculture Organization [FAO] gives the guideline for determination of the irrigation water requirement and developed software named CropWAT for the evaluation of the irrigation water requirement.[40]

The literature survey reveals that, studies undertaken in Ethiopia has a gap in considering the effective design of the irrigation system in a manner that the climate and crop growth affect the water requirement, nor performed comprehensible performance analysis on the application of photovoltaic system for powering the irrigation by proposing various models. The performance studies of the solar water pumping conducted for higher head for sprinkler system is less and this work aims at determination of the effect of variation of radiation on the performance of the pump, and solar system. the daily water discharge, hydraulic and electrical are evaluated in order to assess the technical viability and also economic profitability is not compared to other system. Moreover, this study focuses of actual ground problem that is currently occurring at the stated site that needs a solution in context with the climatic condition, and consideration performance parameters that critically affects the feasibility of the system. Therefore, there is the need to analyze performance of the proposed solar powered irrigation system for specified location starting from the effective design of irrigation system to ensure the technical viability by finding optimal configuration and implementing appropriate procedures in a manner that assesses the potential benefit including but not limited to economic and environmental aspect.

2.3 Agricultural Sector and Irrigation in Ethiopia

Ethiopia is a landlocked country which is geographical located between the latitude 5°N-15°N and the longitude 35°E and 45°E. [41] Agriculture is the mainstay of the Ethiopian economy. [9]

Most of the population of this country lives in highland area with over 85% being rural and depends on the agriculture with low level of productivity. Although agriculture is dominant sector most of the cultivated land uses rain fed agriculture. Due to lack of water storage and large variation in the rain fall there is inadequacy sufficient water for the farmers to produce more than one crop in a year these in turn results in the frequent crop failures due to dry spell and drought which resulted in food shortage in the country. [41]

The country has endowed with abundant water resources with 12 river basins with annual mean runoff volume 122 billion m^3 of water and an estimated up to 2.65 billion m^3 of ground water potential. [42]

Table 2.1 Irrigation Potential of various River Basin

River basin	Area (km^2)	Runoff (Bm^3)	Potential irrigable land (ha)	Estimated ground water potential (Bm^3)
Tekeze	82,350	8.2	83,368	0.2
Abbay	199,812	54.8	815,581	1.8
Baro-Akobo	75,912	23.6	1,019,523	0.28
Omo-Gibe	79,000	16.6	67,928	0.42

Rift Valley	52,739	5.6	139,300	0.1
Mereb	5,900	0.65	67,560	0.05
Afar/Denakil	74,002	0.86	158,776	
Awash	112,696	4.9	134,121	0.14
Aysha	2,223	-		
Ogaden	77,121	-		
Wabi-Shebelle	202,697	3.16	237,905	0.07
Genale-Dawa	171,042	5.88	107,4720	0.14

In Ethiopia, by which the agricultural production system is rain-fed though it has huge water resources, irrigation is considered to be a basic strategy to alleviate the food and enhance the food security. Recently 560 irrigation potential sites are identified with estimated potential of 3.7 million hectares of land to be irrigated. [11] Only about 10% of this irrigable land is actually irrigated [43] and about 2% of cultivated land are irrigated. As compared to its potential and rain-fed farming, the contribution of irrigation to the economy of the country is quite limited by only contributing about 2.5% of the overall GDP. [44]

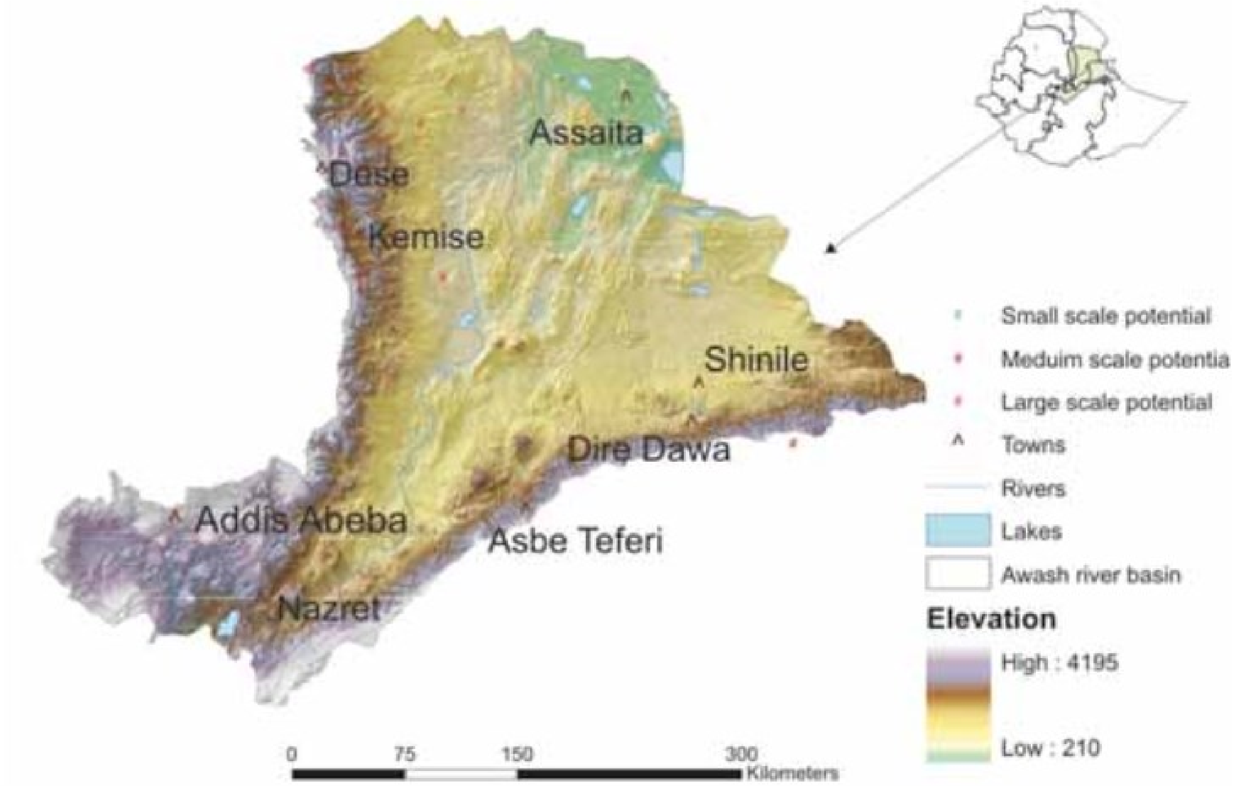


Figure 2. 2 Irrigation Potential of Awash River Basin

Although according to [45] there are some constrains regarding to the development of irrigation system in Ethiopia such as; primitive nature of the existing production system, shortage of the agricultural inputs and improved technologies, limited human skill and also heavy capital requirement, irrigation development plays a crucial role to the sustainable and reliable agricultural development and the government is therefore pursuing plans and programs in an effort to substantially create social change by substantially reducing poverty.

2.4 Solar Radiation Related Analysis

The sun is a spherically shaped hot gaseous matter with a dimension of 1.39 x 109 meters from one of its end to the other. Researches have shown that the effective black body temperature of the sun is about 5777 kelvins, whereas the temperature in its central interior regions could reach up to 40 x 106 kelvins. In relation, it has been studied that the sun can be perfectly assumed as a huge fusion reactor capable of supplying immense amount of energy to its surroundings, in effect; the earth. In general, the energy that has been produced in the interior of the solar sphere that could reach many millions of degrees should be transferred out to the surface and then be radiated to the space. The succession of both radiative and convective processes occurs with successive emission, absorption and re-radiation in to the sun core is in the form of gamma and x-rays in relation that increment in radiation accompanied by drop in temperature as the radial distance increases. [46]

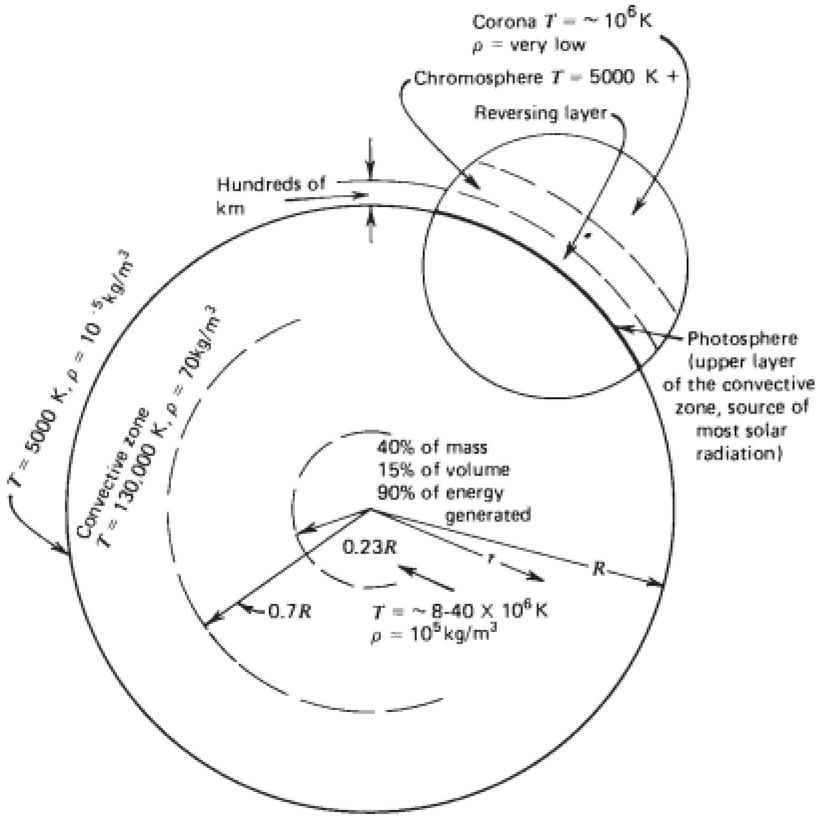


Figure 2. 3 The structure of the Sun

On the top of the total energy of the solar spectrum it is vital to know the spectrum distribution of the extraterrestrial radiation is been received in the absence of the atmosphere. The standard spectral irradiance curve has been compiled based on the altitude and space measurement and the following figure depicts this relation.

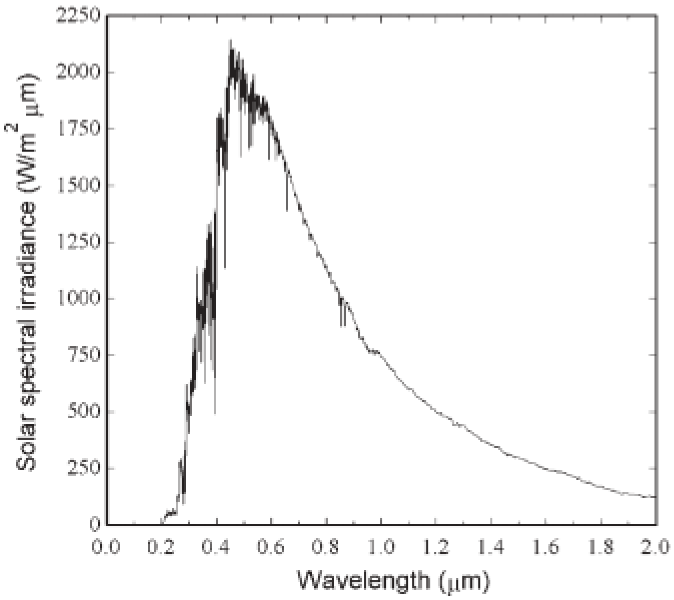


Figure 2. 4 Standard spectral irradiance curve at mean earth-sun distance

Solar Radiation Analysis

Design any equipment that uses solar energy as an input requires the precise knowledge regarding solar radiation analysis and available solar data of that specific location. In general, it is not practical to base prediction or estimation of solar radiation on attenuation of the extraterrestrial radiation by atmosphere. Adequate data can be obtained by using radiation measuring equipment's.

Pyranometers are instrument which is used for measuring the total radiation. These measurements are a response independent of the wavelength radiation over the spectrum and also independent of the angle of incidence of the solar radiation. [46] Due to the absence of this equipment, Ethiopian Metrological Agency is not providing the solar radiation data of the site by the date this document is compiled. Hence, the use of empirical relations for determining and estimating the solar radiation data seems inevitable. Meteorological data of the site for 11years (2006-2016G.C) is used in this work.

Estimation of Monthly Average Daily Radiation on Horizontal Surface

The empirical relation used for determining the average incident radiation uses the sunshine hour and the cloudiness for the estimation since both those value widely available. The sunshine hour implemented for this calculation is gathered from the meteorological agency for the site under investigation. The following mathematical relation is used; [46]

$$\frac{H}{H_O} = a + b\frac{s}{T_d} \ldots\ldots\ldots. (2.1)$$

Where a, and b are the constant parameters, s is sunshine hour, and Td is the time of the sunset or rise and the corresponding empirical relation for those parameter are given below.

$$a = -0.309 + 0.539 + \cos\phi - 0.0693 * Z + 0.29 * \frac{s}{T_d} \ldots\ldots\ldots. (2.2)$$

$$b = 1.449 - 0.533 * \cos\phi - 0.694\frac{s}{T_d} \ldots\ldots\ldots. (2.3)$$

$$T_d = \frac{2}{15}\omega_s = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \ldots\ldots\ldots. (2.4)$$

Where ϕ is the latitude of the site.

It is recommended to select the values of N and declination δ by months and is given in table below.

Table 2.2 Summary of recommended average day of month and value of n by month [47]

Month	N for ith Day of the month	Date	N	δ
January	I	17	17	-20.9
February	31+i	16	47	-13.9

March	59+i	16	75	-2.4
April	90+i	15	105	9.4
May	120+i	15	135	18.8
June	151+i	11	162	23.1
July	181+ i	17	198	21.2
August	212+i	16	228	13.5
September	243+i	15	258	2.2
October	273+i	15	288	-9.6
November	304+i	14	318	-18.9
December	334+i	10	344	-23.0

The declination δ can be calculated as follows:

$$\delta = 23.5\sin(360 + \frac{(284+N)}{365}) \text{ ……….. (2.5)}$$

The extraterrestrial solar radiation Ho (kW hr /m2/day) can be calculated as follows: [46]

$$H_o = \frac{24*G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right) * \left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \text{ ……….. (2.6)}$$

Where GSC is solar constant

For the locations where the sunset and sunrise angle is greater than 81.4° and the clearance index (kt) are in the range of 0.3-0.8. The average daily diffuse radiation on the surface is given by the following relations:

$$\frac{H}{H_d} = 1.311 - 3.022K_t + 3.427{K_t}^2 - 1.82{K_t}^3 \text{ ……….. (2.7)}$$

The average daily global radiation H is total radiation on the surface which is the summation of both average daily beam Hb and average daily diffuse radiation Hd.

$$H = H_b + H_d \; .... (2.8)$$

2.5 Photo voltaic System and Related Analysis

Theory

Photo voltaic system are used to convert light energy directly in to electrical energy using semiconductors.

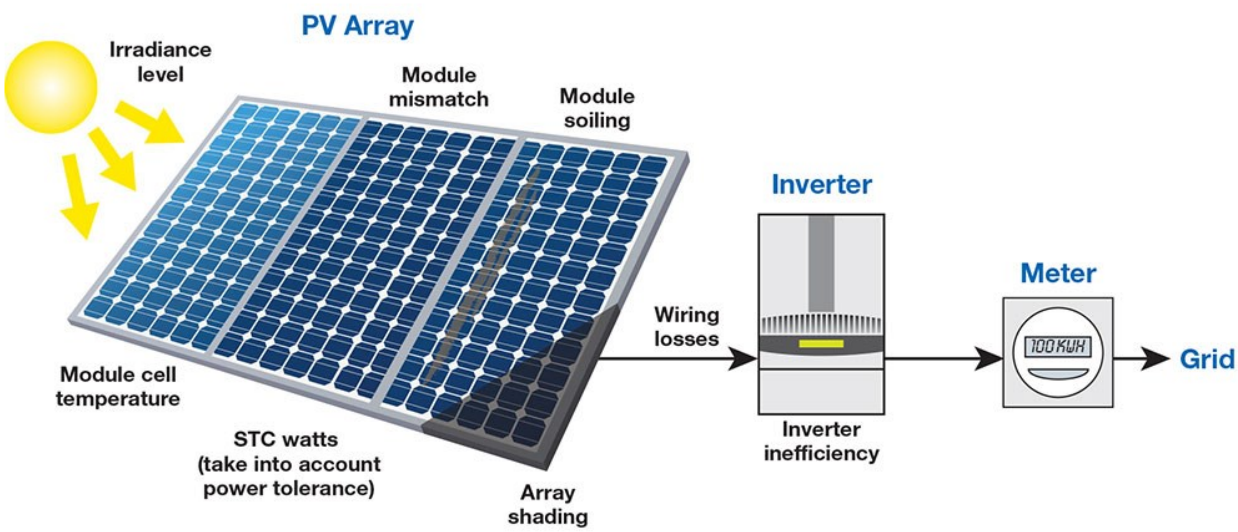


Figure 2. 5 Light energy converted to electricity [47]

Solar panels, which are comprised of many solar cells, are used to collect and absorb the sun light and convert it into the electricity whereas the solar inverter changes the electric current from AC to DC.

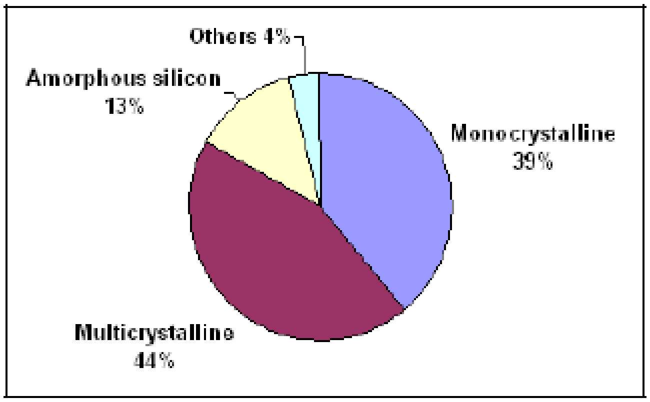


Figure 2. 6 Composition of PV material [25]

In order to calculate the electricity generated by the PV modules the intensity of the solar radiation is very important since the conversion of energy depends on the quantum nature of light that carry the energy E_{ph} which is given by:

$$E_{ph} = \frac{hc}{\lambda} \text{..........} \ (2.9)$$

Where h= the plant constant

C= the speed of light

λ= the wavelength of light

The photons which have excess energy in their band gap of semiconductor material is going to be converted into electricity by the solar cell.

A rough estimate of the current that can be generated by the solar panel is given by Equation below which does not take into account the losses in the cell.

$$I_L = qNA \text{ ....} \ (2.10)$$

Where N is the number of photon, q is the electron charge and A is the area of the module which is exposed to the light.

The maximum amount of voltage, V, that can be generated by the solar panel equals with the band gap of the semiconductor in use and it is expressed in electron-volts which means that the separation of holes from electrons at the terminal of the solar cell only continues until the electrostatic energy of the charges after separation Eg equals with the pair energy in the semiconductor.[25][48]

$$V = \frac{E_g}{q} \ldots\ldots\ldots..(2.11)$$

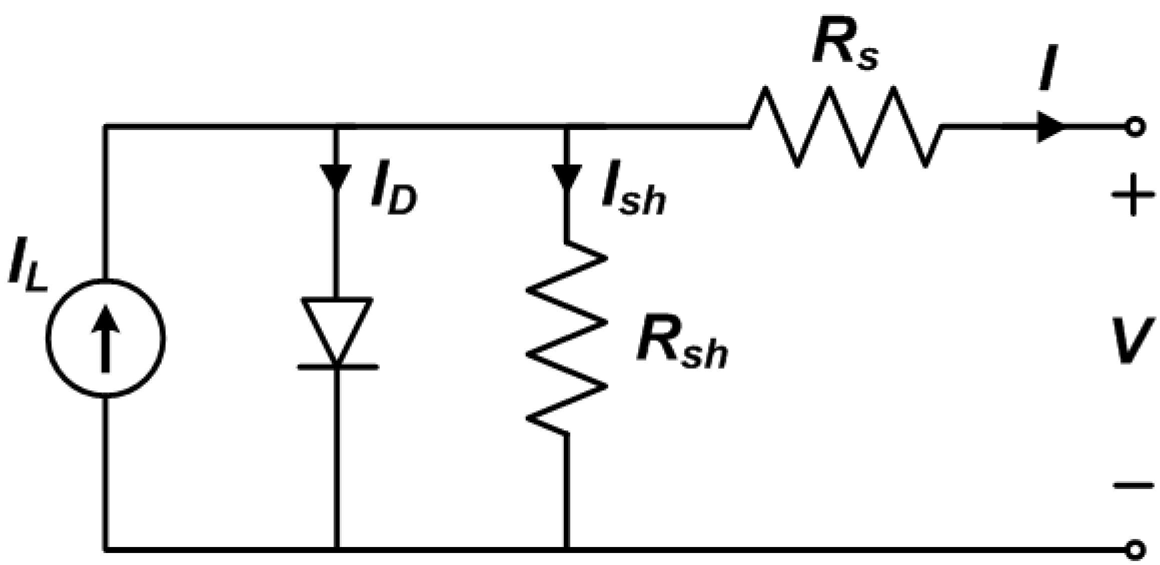


Figure 2. 7 I-V characteristics of the cell [48]

The governing equation of I-V characteristics of the cell in the above figure is given by:

$$I = (I_L - I_D - I_{sh}) = I_L - I_o \left[\exp\left(\frac{q(V+IR_s)}{mKT}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \ldots\ldots\ldots..(2.12)$$

Where: I_D is the diode current, Ish the shunt resistance current, I the load current, Io is reverse saturation current of diode, V voltage output, T working temperature of the cell and m the diode quality factor.

The voltage- power (V-P) and voltage current (V-I) characteristic curve for typical module which is governed by the above equation at the radiation level G, maximum power point Pmp the maximum current Imp, maximum power voltage Vmp and the open circuit voltage Voc is given in the figure below and each point is labeled at their respective points.

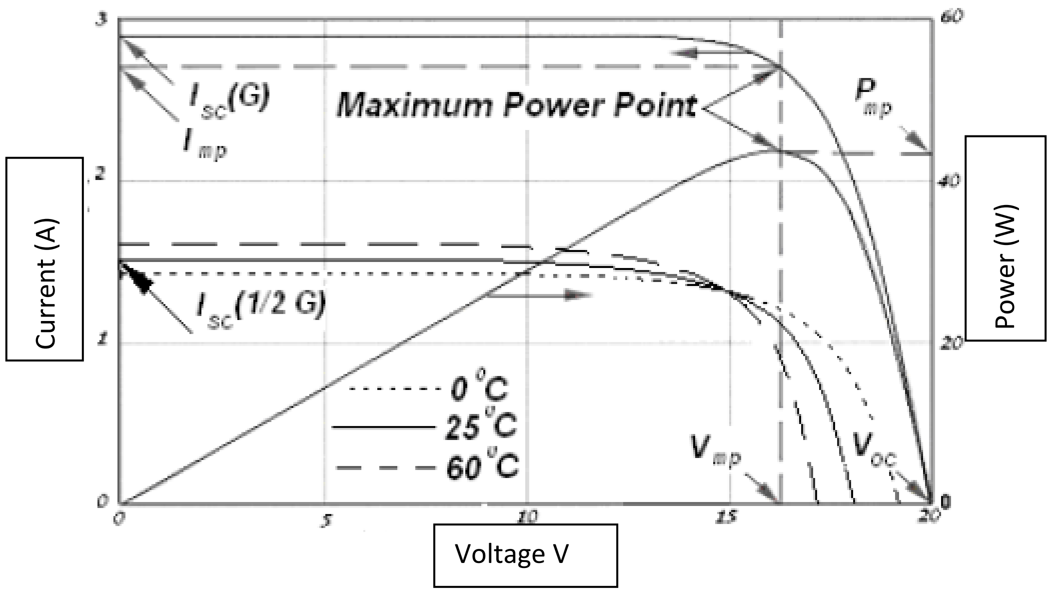


Figure 2. 8 I-V and P-V characteristic curve of PV module

It can be observed from the above figure that the maximum amount of power which could be obtained corresponds to the maximum area under the curve I-V and the Voc increment is logarithmically whereas Isc is in proportion with the solar radiation as long as the current axis does not intersect the curved portion of the I-V characteristic curve. [46]

2.6 PV system sizing

Modules are the building blocks of the PV system. In order to have more voltage or current those modules have to be arranged and connected either in parallel or series manner and then assembled together to form complete PV array. This PV array converts the solar energy to DC electrical energy output. The quality of power that is going to be converted is enhanced through the power conditioner and converted to AC using an inverter. The power output by the PV array, P_{op}, is calculated as below by [49]

$$P_{op} = A_{PV} G_T \eta_{PV} * \eta_{inverter} \text{ ....} (2.13)$$

Where as A_{PV} is the area of the PV array, G_T is the daily solar radiation and, η_{PV} *and* $\eta_{inveter}$ are the efficiencies of the PV module, inverter and wire respectively. η_{PV} is given by the following equation. [46]

$$\eta_{PV} = \eta_{PV,STC} [1 + \frac{\mu (T_a - T_{STC})}{\eta_{PV,STC}} + \frac{\mu (NOCT-20)}{\eta_{PV,STC}*800} (1 - \eta_{PV,STC}) G_{g,t}] \text{ .... (2.14)}$$

Where $\eta_{PV,STC}$ is the efficiency of the PV module at standard test conditions (%), η is the temperature coeffiecient of the PV module efficiency (1/oC), Ta is ambient temperature (oC), and NOCT is the nominal operating cell temperature (oC). The temperature output power η could be approximated by [46]

$$\mu = \eta_{PV,STC} \frac{\eta_{Voc}}{V_{mp}} \text{ .... (2.15)}$$

The area of the PV array A_{PV} is calculated by :

$$A_{PV} = \frac{E_h}{G_T \eta_{overall} * \eta_s} \text{ .... (2.16)}$$

Where $\eta_{overall}$ is the overall efficiencies of inverter, module and wire.

Accordingly, the required PV array power P_{PV}, is calculated as follows:

$$P_{PV} = \frac{E_h}{G_T * F * E} \text{ .... (2.17)}$$

Whereas F is the mismatch factor which is given between the range of 0.85 – 0.9 and E is the daily subsystem efficiency typically in the range of 0.2-0.6. [49]

2.7 Inverter

It is an essential component that converts the input direct current produced power by the PV array into the output alternative power which is connected and compatible to the pump power requirement. The efficiency of the inverter depends on the system load, currently there are inverters reportedly produced having the efficiency of 98% and higher.

CHAPTER 3
DESIGN OF IRRIGATION AND WATER PUMING SYSTEM

3.1 Introduction to Sprinkler irrigation system

Sprinkler irrigation system is a system for a given farm land on which sprinkling will be the method of water application. The spray is developed by the flow of the water that is passing through small nozzle under certain amount of pressure. This pressure is applied usually by the pump and sometimes if the water source is high enough, gravity can be used as to distribute the water to each nozzle.

Classification of sprinkler irrigation systems depend on many factors such as field layout, portability, equipment used and type of system being irrigated. Depending on the portability the system is classified as portable is all of its components are portable and permanent if none of its component can be moved. The most popular classification is listed below.

3.1.1 Fixed Sprinkler Irrigation System

A fixed sprinkler system has enough lateral pipe and sprinkler heads to avoid any of the lateral side from moving through the irrigation field. Thus, to irrigate the land the sprinklers only need to be cycled and on and off. The main types of fixed system are those with solid set system and buried laterals.

3.1.2 Solid set system

A system which remains in a single location throughout the season and irrigation eater is supplied by fixed pipe network connections to every sprinkler. Since there are many piping layout arrangements there is no unique field layout for this purpose. PVC pipes are usually used for the pipe connection and they are buried in the soil.

The main line pipe is supposed to be laid on the center of the longer dimension. The laterals pipe line which carries the sprinkler and riser is place perpendicular to the main line and the corresponding number is determined so as to produce effective precipitation to meet the crop water requirement.

The solid set irrigation system, a single component irrigates the entire surface without being moved which reduces the labor and maintenance cost.

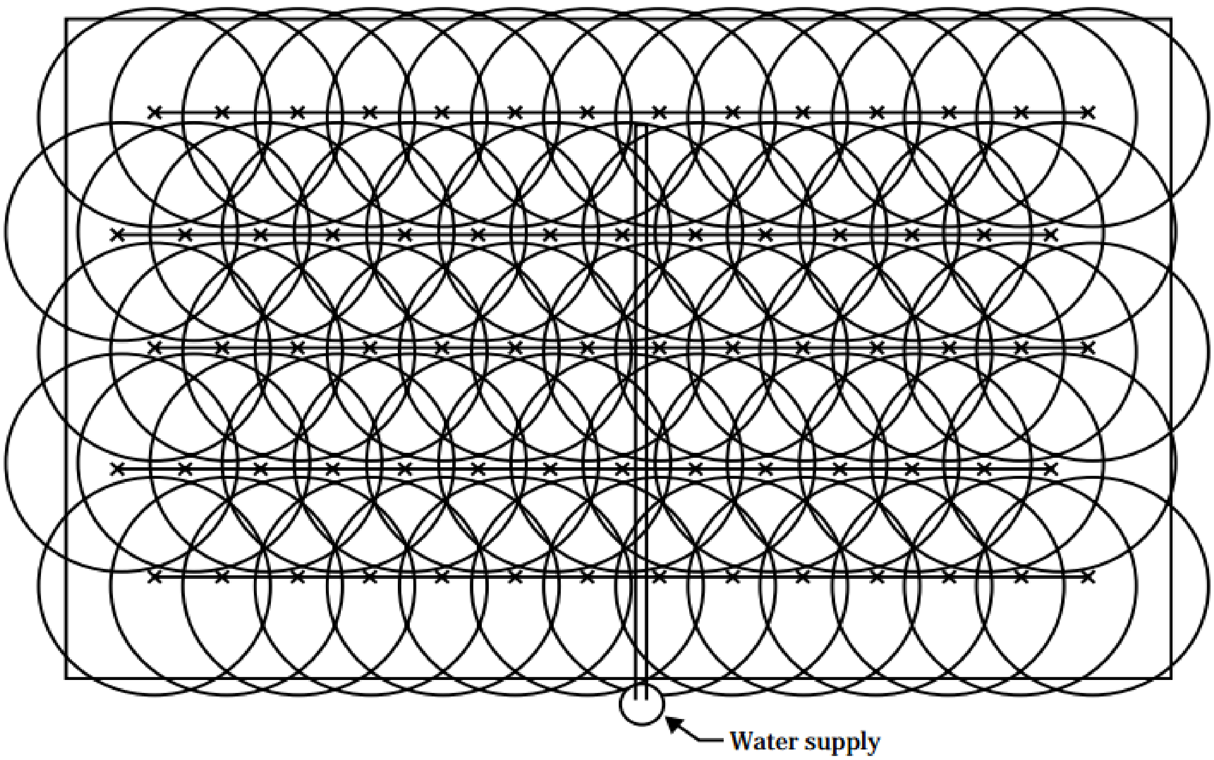


Figure 3. 1 Solid set sprinkler layout

3.1.3 Buried lateral system

This system has buried lateral line placed under ground deep with only the riser and sprinkler head above the ground surface.

Figure 3. 2 Periodic move sprinkler systems

In order to reduce the equipment requirement for irrigation and to minimize the interference with other operation this sprinkler is designed lateral pipeline from set to set either by hand or tractor towed. They require more labor and maintenance than solid set.

3.1.4 End-Tow lateral

An End-Tow lateral system has a similarity hand moves laterals except the fact that the system consists of rigidly coupled lateral pipe connected to a mainline. The mainline is is buried and positioned in the center of the field to have convenient operation. The laterals are towed along the length side over the mainline from one side to other side.

There are two available carriage types for end tow system. One with skid attached to coupler to slightly raise the pipe off the soil, for the purpose of protecting the quick drain valve and other is use small metal wheels at between each coupler in order to allow easy towing on sandy soils.

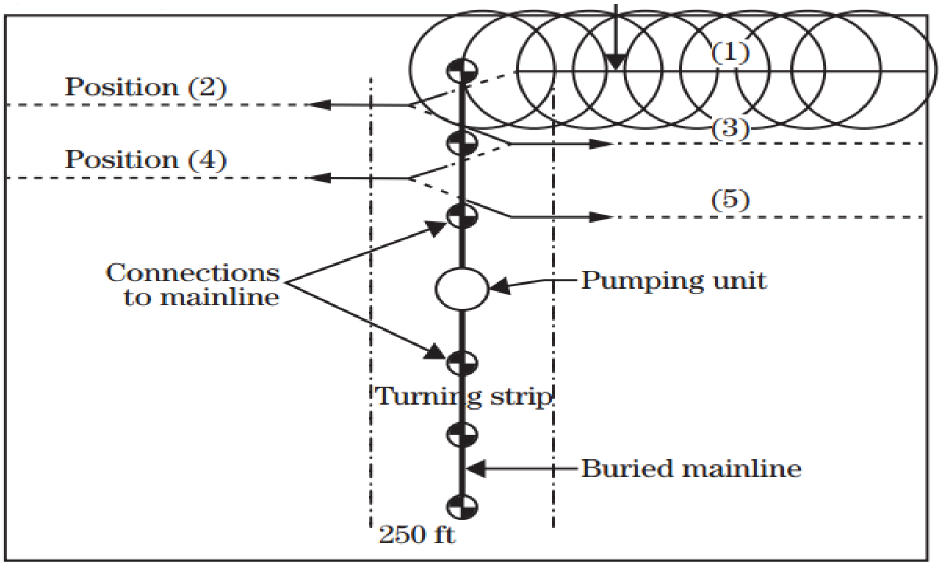


Figure 3. 3 Schematic of the move sequence end tow sprinkler with buried main line

3.1.5 Center-pivot system

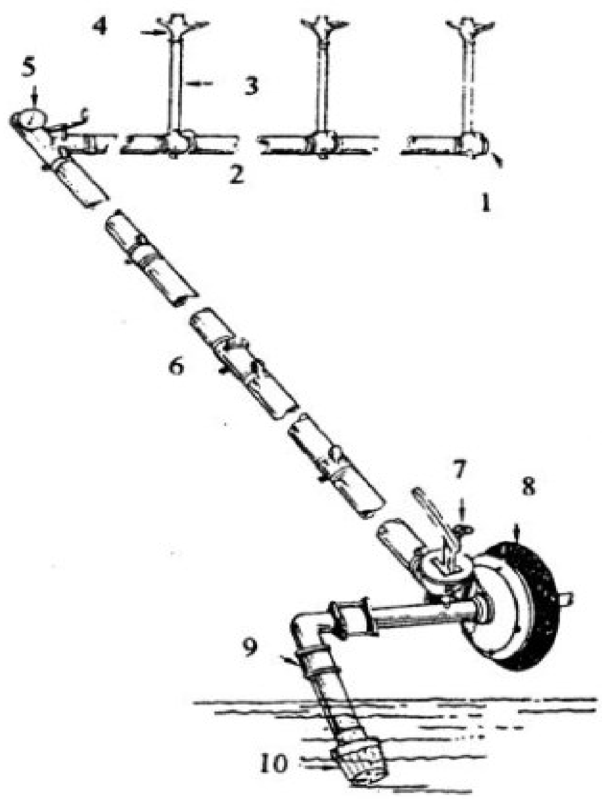
The center pivot lateral is fixed at one end and rotates to irrigate a large circular field. The end of the lateral is connected to the water supply line. A drive unit is consisting of A-frame supported on motor driven wheels. The downstream drive unit moves continuously to set the rotation speed and all other drive units move intermittently to maintain the lateral pipe in an approximately straight alignment.

Figure 3. 4 Travelling sprinkler

The travelling sprinkler is used for high capacity sprinkler irrigation that the water is fed through a flexible hose mounted on a self-powered chassis and travels along a straight-line during the watering. The unit is usually equipped with a water piston that reels in the cable that is connected to a pressurized water supply system.

3.1.6 Sprinkler irrigation component

Sprinkler irrigation is composed of several components and parts. The main components include various pipelines which is named as lateral, main, suction and riser pipelines depending on the function of the pipes, different valves and fittings, sprinkling components and the pumping units.



1. End Cap
2. Later Line
3. Riser
4. Sprinkler Head
5. Pressure Gauge
6. Main Line
7. Valve
8. Centrifugal Pump
9. Suction Pipe
10. Foot Valve

Figure 3. 5 Schematic of simple sprinkler irrigation components

3.1.7 Piping System component

The Main line

The main function of those main and sub main lines are to transport water in a required quantity to the desired design area at a pressure that required operating all the laterals under the maximum flow condition of the system.

There are various types of main lines in sprinkler irrigation system starting from short portable line to intricate network of buried main and sub main serving large systems. Buried main lines are fixed line to the areas that is going to be irrigated permanently whereas portable main line can be used on all over the areas. The choice between these types of main line is depending of their corresponding material is a matter of economics.

Typical PVC buried main line is used for this specific irrigation system due to the fact that the pipe is not handled after the initial installation contributes a much longer life and annual fixed cost is usually lower.

The entire analysis of the system has to be done in order to determine the maximum requirement of the flow capacity and pressure and the design of the main line has to be in such a way that these requirements are met.

The classic procedure is assuming a reasonable allowable range of friction loss and the computation of pipe size has to be aligned with delivering the required amount of water in a designed rate in a most possible economical way.

In addition to these considerations the velocity of the water inside the main line has to be restricted in order to eliminate excessive water hammering.

Lateral line

Lateral line is a pipe which delivers water from main line to the sprinkler. It could either be portable or fixed and it have smaller diameter compared to the main line. For the sake of convenience, it is preferred to have single pipe size.

Stand/Riser pipe line and sprinkler head

Risers are small diameter pipe which connects the lateral line with the sprinkler. Risers are important component for achieving optimal water distribution. When water is diverted to the sprinkler head from lateral turbulence is produced. This phenomenon is going to cause premature stream breakup that will result the reduction of the capacity of the stream to carry the wetted as per the manufacturer specification. The riser is going bring the stream back together which in turn will emit from the nozzle in well-knit stream that will provide the desired wetted diameter. The riser height determination is also important that to has to make sure the water distributed properly without being inhibited by the standing crop. [41]

The function of Sprinkler head is to distributing water uniformly over the field without runoff and excessive loss due to deep percolation. The various types of sprinklers are available all those can be categorized as fixed or rotating type. Since fixed type of sprinklers releases more water per irrigation area, rotating type is preferred and adapted for wide range of application rates and spacing.

3.2 Determination of Irrigation Water Requirement

In order to design effective irrigation system, the suitable amount of water and correct timing of application have to be determined since only a certain amount of falling rain or water may be effective in raising the soil moisture that is actually useful for plant growth. Hence, for proper crop growth, the correct amount of water demand has to be supplemented to the farming field by irrigation.

Crop water requirement is the total quantity of water required from its sowing time up to harvest. Under any naturally condition different crops could have various water requirements. depending upon the climate, method of cultivation, effective rain and type of soil. [40] Even for the same crop the total water required for its growth is not uniformly distributed throughout its entire life span which is also called crop period. [40]

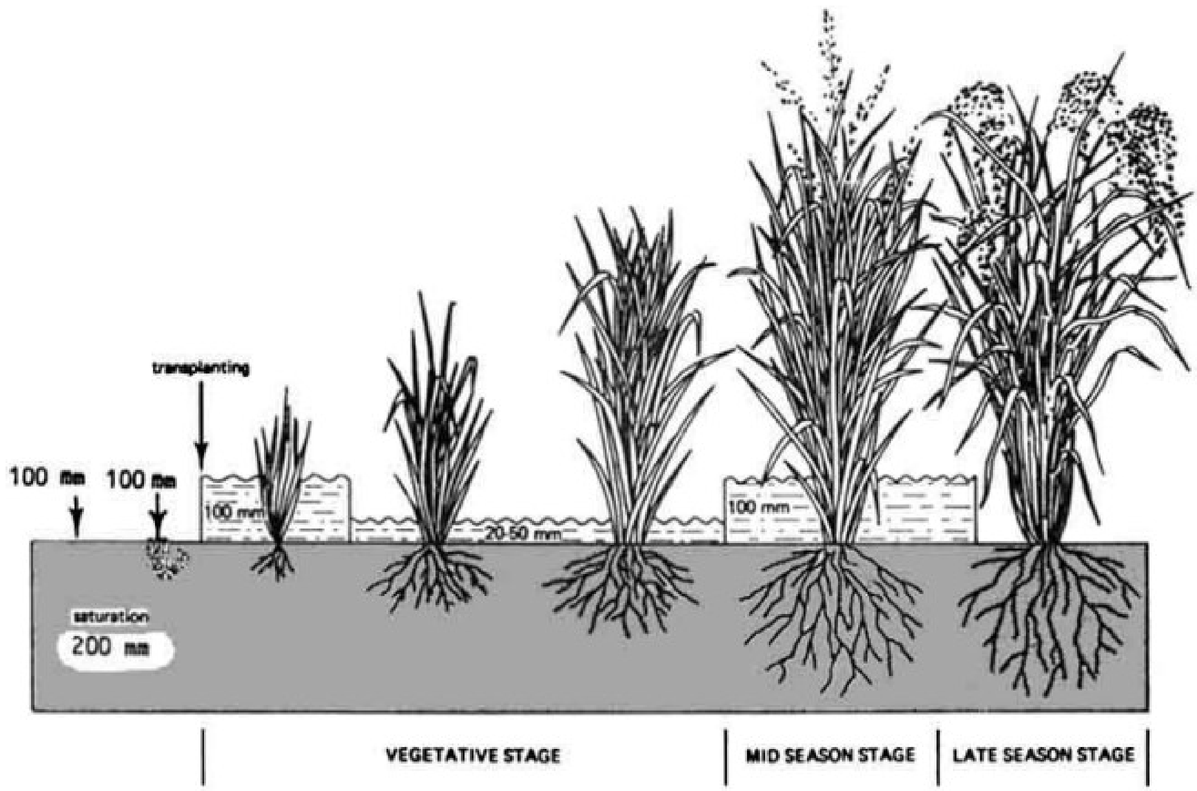


Figure 3. 6 Variation in water requirement for paddy stage of growing (Courtesy of FAO)

In order to determine optimal and effective water requirement studying the dynamic interaction between crop prevalent climates is of great importance for minimizing water demand with minimal impacts on yields and yield quality.

Roots of plants extract water from the soil but most of this water does not remain in the plant. It rather escapes to the atmosphere as vapor through the plants leaves and stems, a process which is called transpiration and occurs mostly during daytime.

The water which is found on soil surface as well as the water attached to the leaves, and stem crop during a rainfall also is lost to the atmosphere by evaporation. Hence, the water demand of the crop consists of not only transpiration but also additional evaporation, together called evapotranspiration which varies day to day on the weather pattern is one of the most important factors to be known prior to making and implementing any decisions for the design and management of water resources systems.

The major climatic factors which influence crop water need are listed below. [27]

- Sunshine hour
- Temperature
- Humidity
- Wind speed

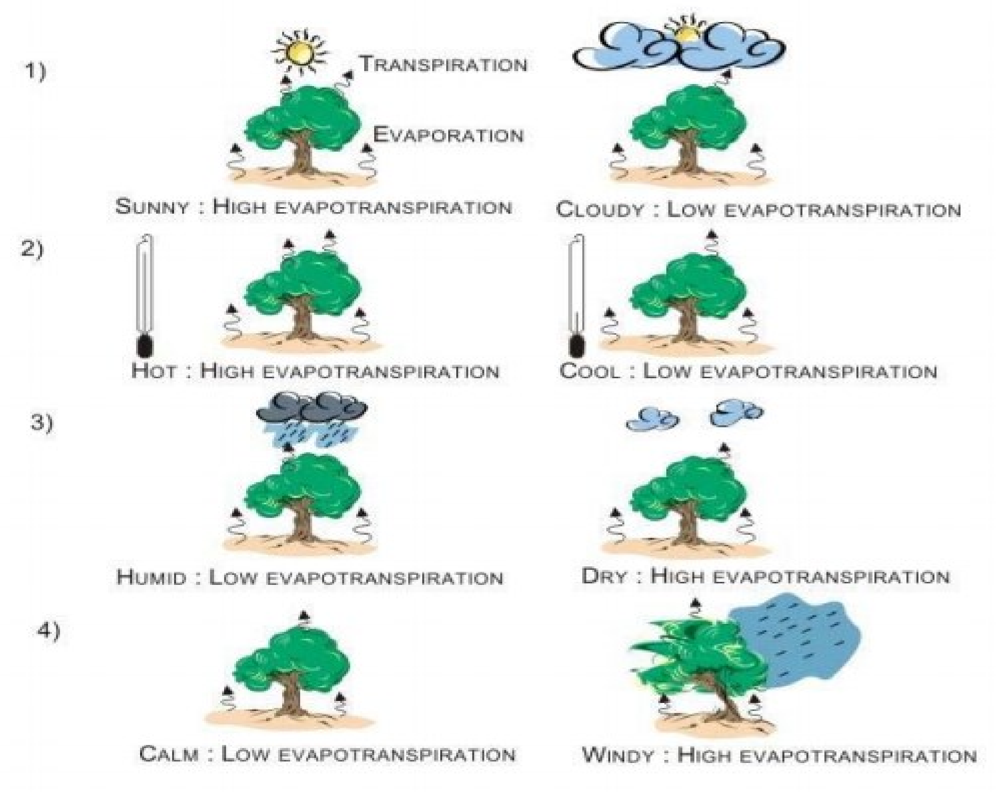


Figure 3. 7 Dependence of evapotranspiration on different climatic factor [27]

Evaporation and transpiration (ET) occur simultaneously and there is no easy way of distinguishing between the two processes. Crop evapotranspiration ET_c under standard conditions refers to the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions. [50]

In order to avoid the ambiguity of term ET the reference crop evapotranspiration (ET_o) was introduced which uses grass as standard for this purpose. It studies the evaporative demand of the atmosphere independently of crop type, crop development and management practices which only depends on climatic parameter. The FAO Penman - Monteith method is recommended as the sole method for determining ET_o. Based on this recommendation the software named as CROPWAT has been developed by land and water development division of FOA in order to evaluate the irrigation water requirement. [50]

The FAO Penman – Monteith equation for calculating the reference evapotranspiration (ET_o);

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma(\frac{900}{T+273})U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad \text{.......... (3.1)}$$

Where, ET_o =reference evapotranspiration [mm day^{-1}], R_n = net radiation at crop surface [$MJm^{-2}day^{-1}$], G= soil heat flux [$MJm^{-2}day^{-1}$], T=Mean daily air temperature [°C], U_2= wind speed [m/s], e_s = saturation vapour pressure [kpa], e_a = actual vapor pressure [kpa], Δ= slope vapor pressure [kpa $^oC^{-1}$], ϒ=psychometric constant [kpa $^oC^{-1}$]

Monthly ETo Penman-Monteith - C:\Users\32\Desktop\cropwat result\input...

Country: Ethiopia Station: Kete Dori

Altitude: 1630 m. Latitude: 8.47 °N Longitude: 39.38 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	13.8	27.1	55	10	8.3	19.9	3.27
February	14.9	28.8	50	10	7.0	19.2	3.35
March	16.2	30.4	51	10	8.1	21.8	3.97
April	17.6	29.1	52	9	7.5	21.1	3.89
May	18.2	30.8	55	8	7.4	20.4	3.86
June	18.2	31.4	50	11	7.5	20.1	3.85
July	17.0	29.1	64	10	6.5	18.7	3.66
August	16.6	27.6	68	7	6.4	19.0	3.63
September	16.6	27.8	66	4	6.2	18.8	3.55
October	15.3	28.1	54	5	6.9	19.2	3.43
November	14.1	27.3	58	7	8.2	19.9	3.41
December	13.1	26.0	53	9	8.5	19.7	3.15
Average	16.0	28.6	56	8	7.4	19.8	3.58

Figure 3. 8 Determination of reference evapotranspiration of the farm site

3.2.1 Onion water requirement

The amount of water needed to compensate the evapotranspiration loss from the Onion field is termed as crop water requirement (ET_c). crop evapotranspiration per decade is calculated by multiplying of the number of effective crop days using CropWAT 8.0 software. In order to convert monthly rainfall data to decade values linear interpolation is carried out and also values for first and third decade were calculated by interpolation with the preceding and successive month. [CropWAT 8.0 Manual, 2009]

Crop Water Requirements

ETo station: Kete Dori Crop: Onion

Rain station: Kete Dori Planting date: 01/04

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Apr	1	Init	0.50	1.96	19.6	0.9	18.6
Apr	2	Deve	0.53	2.06	20.6	1.1	19.5
Apr	3	Deve	0.71	2.76	27.6	1.0	26.5
May	1	Deve	0.91	3.53	35.3	1.0	34.3
May	2	Mid	1.00	3.86	38.6	0.9	37.8
May	3	Mid	1.00	3.86	42.5	0.8	41.6
Jun	1	Mid	1.00	3.86	38.6	0.7	37.9
Jun	2	Mid	1.00	3.85	38.5	0.6	37.9
Jun	3	Mid	1.00	3.79	37.9	1.0	36.9
Jul	1	Mid	1.00	3.73	37.3	1.4	35.9
Jul	2	Late	1.00	3.67	36.7	1.7	35.0
Jul	3	Late	0.97	3.52	38.8	1.8	36.9
Aug	1	Late	0.91	3.31	33.1	2.0	31.2
Aug	2	Late	0.86	3.11	31.1	2.1	29.0
Aug	3	Late	0.81	2.92	23.4	1.3	21.5
					499.5	**18.4**	**480.6**

Figure 3. 9 Crop water requirement for Onion

Crop water requirement is the amount of water that needs to be supplied to the crop to be irrigated; it is calculated as the difference between the crop evapotranspiration and effective rainfall. [51]

Table 3.1 Total available water [50]

Soil	Crop	Max root depth, Z_r	Field capacity, θ_{FC}	Wilting point, θ_{WP}	Depletion fraction, p
loamy sand	Onion	300mm	0.15	0.06	0.3

Total available water (TAW) is amount of water the crop can extract from its root zone. It is calculated as:

$$TAW = (\theta_{FC} - \theta_{wp})Z_R \text{ .... (3.2)}$$

$$TAW = (0.15 - 0.06) * 500mm$$

$$TAW = 45mm\ per\ irrigation$$

Crops are only capable to extract water from soil at certain depth which is effective rooting depth (Z_r) and soil water availability is the capacity of soil to retain water available to plant.

Field capacity (θ_{FC}) is the amount of water that a well-drained soil should hold against gravitational force.

Wilting point (θ_{WP}) as water uptake progress the remaining water is held to the soil particles by greater force that lowers its potential energy and making to more difficult for plant extract it.

Since, water availability until wilting point is only theoretical; the actual readily available water (RAW) is the fraction of TAW that can be extracted from root zone without suffering water stress.

Average fraction of total available soil water that can be depleted from root zone is denoted by (P) and it is listed on table for various crops and soil type. [50]

$$RAW = (TAW)P \text{ ………. (3.3)}$$

$$RAW = 45mm * 0.3 = 15mm$$

3.2.2 Net depth application of water

Net depth application (d_{net}) is the quantity of water which should be applied during irrigation to replenish the water which is lost due to evapotranspiration which is equal to readily available water.

$$d_{net} = RAW = 15mm$$

3.2.3 Irrigation frequency at peak water requirement

Irrigation frequency (I) is the time it takes crop to deplete the soil moisture at a given soil depletion level. The peak water requirement is calculated by subtracting the crop water requirement from the rainfall of the peak.[50] According to CropWat model result the peak water demand, ET_c is 4.16mm/day.

$$I = \frac{d_{net}}{ET_c} = \frac{15mm}{4.16mm/day} = 3.61days \text{ ………. (3.4)}$$

Therefore, the system should deliver 15mm of water every 3.61days. In order to avoid the fraction of days, the irrigation frequency have to be 3 days and corresponding moisture depletion is 27.73%.

3.2.4 Irrigation scheduling

In order to determine how much water is required to be applied the soil moisture condition should be known. At ideal condition irrigation schedule is set to manage an optimal agricultural production at the expense of minimal water use and cost. Though crop growth stage, climatic condition and soil moisture are the factors that determines depth of irrigation schedule by using fixed and center pivot irrigation systems it is possible to attain nearly perfect irrigation schedule.

Gross depth of water application

Gross depth of water (d_{gross}) application is calculated by dividing the net depth application by irrigation efficiency (E).

$$d_{gross} = \frac{d_{net}}{E} \quad \text{……….. (3.5)}$$

Irrigation efficiency of the farm depends on the average temperature of the site including the losses through the pipes. [50]

Table 3.2 Farm irrigation efficiency for sprinkler for different climate

Climate	Irrigation Efficiency
Cool	80%
Moderate	75%
Hot	70%
Desert	65%

Since the average temperature of the Kete Dori village is 22.3 ºC, according to FAO the climatic condition is classified as moderate with corresponding irrigation efficiency of 75%.

$$d_{gross} = \frac{d_{net}}{E} = \frac{12.48mm}{0.75} = 16.64mm \quad \text{……….. (3.6)}$$

3.2.5 Preliminary system capacity

The amount of flow rate or discharge of the irrigation system at which the water is supplied from the source to farm land is defined as preliminary system capacity (Q_s).

$$Q_s = \frac{A*d_{gross}}{I*T} \text{ .... (3.7)}$$

Where, A is total area to be irrigated, T is actual operating hours per day of the system by supplying the gross water depth d_{gross} according to the irrigation frequency (I).

$$Q_s = \frac{5\ hectare * 16.64mm}{3.61\ days} = 230\ {m^3}/{day}$$

The system has to be capable of providing the 230m^3 of water per day which is the irrigation water requirement for the vegetation.

3.3 Sprinkler system design

3.3.1 Irrigation field description

The field which is chosen for implementation of this system consists of 5 hectares' farm land which has dimension of 250m by 200m. The main line pipe is supposed to be laid on the center of the longer dimension. The laterals pipe line which carries the sprinkler and riser is place perpendicular to the main line and the corresponding number is determined so as to produce effective precipitation to meet the crop water requirement.

3.3.2 Sprinkler Head Design

With the sprinkle irrigation method, water is applied at the point of use by a system of nozzles with water delivered by or buried pipelines. [40] A sprinkler can have one or three nozzles. The main nozzle determines the reach, while the secondary nozzles determine the distribution uniformity. [32]

Figure 3. 10 Nozzle head [59]

The appropriate selection of sprinkler depends on how the best fit spacing with a certain pressure at which the water is provided and nozzle size that can deliver water at application rate that does neither cause runoff nor damage the crop at possible best uniformity under prevailing wind condition. [40]

When selecting sprinkler, the precipitation rate has to be compatible with the soil infiltration rate which is the maximum application rate and it depends on soil type. In accordance with soil of the study area maximum application rate is 10mm/hr for the slope less than 5%. Another consideration is to make is energy cost which depends on operating pressure of the nozzle. [32]

3.3.3 Sprinkler spacing pattern

There are three types of spacing patterns: rectangular pattern, square pattern and triangular patterns. Each of this patterns have their own advantages and under average condition best uniformity is can be resulted from square pattern but if the required CU is not compromised the triangular spacing has advantage from economic perspective since the sprinklers are located offset from adjacent row weakness overlapping coverage can be reduced and also additional distance is obtained from this pattern which means fewest number of sprinkler is going to used therefore cost of the system will be reduced.

As long as uniformity of the water application, which is measured by Christiansen Uniformity Coefficient (CU), is not compromised lower pressures are preferable from energy point of view.

As a guideline CU should not be less than 85% and also it is advisable to avoid lowest pressure as it usually correspond to lower CU values. [32]

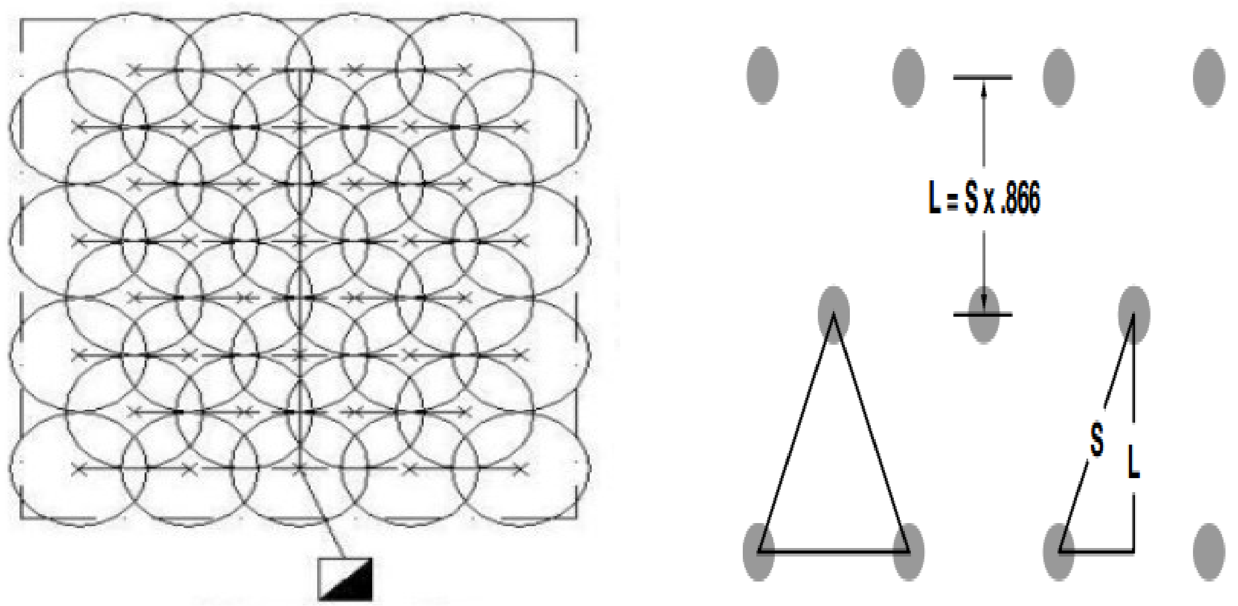


Figure 3. 11 Triangular sprinkler pattern

The required flow rate of individual sprinkler is a function of water application rate and two way spacing of the sprinkler to have uniformity in distribution of water which is achieved by overlapping on the lateral and between laterals. This overlapping depends on discharge rate, application rate and wind velocity of the site. [32]

Table 3.3 Maximum spacing related to wind velocity [58]

Site wind velocity	Maximum allowed spacing
0-5kph	60% of wetted diameter
6-11kph	55% of wetted diameter
13-19kph	50% of wetted diameter

The sprinkler nozzle that fits the requirement is selected and the corresponding specification is tabulated as follows.

Table 3.4 Specification of selected nozzle

Model	Wetted Diameter	Sprinkler discharge (Qa)	Nozzle Size	Operating pressure	Nozzle outlet trajectory
F32SV	25.6m	$0.56m^3/hr$	3.175mm	2.06bar (30PSI)	25^O

The precipitation rate of the nozzle which is 7mm/hr corresponds to triangular pattern. This rate is acceptable since it is less than the soil infiltration rate for selected area. [34] The maximum wind velocity of the study area is 5.76km/hr, in order to assure the uniformity of water distribution the maximum spacing is calculated accordingly. [32]

The head to head spacing between sprinklers is denoted as 'S' and the distance between consecutive lateral row of sprinkler is denoted as 'L'.

$$S = 0.55 \text{ wetted diameter} = 14m \ldots\ldots\ldots\ldots\ldots\ldots(3.8)$$

$$L = 0.866 * S = 0.866 * 14m = 12.1m \ldots\ldots\ldots\ldots\ldots(3.9)$$

According to triangular pattern criteria the maximum spacing of sprinkler and lateral is 14m and 12.1m respectively so that it can satisfy the wind requirement of the site.

3.3.4 Number of sprinklers on lateral line

Since the main line passes though the center of the lateral line ½*S dimension is left in each side and at both end the wetted radius of the sprinkler can cover S dimension in each side. Therefore, the available lateral dimension D_l:

$$D_l = 250m - 3S = 250 - 3 * 14 = 208m \qquad \ldots\ldots\ldots\ldots(3.10)$$

Number of sprinkler on lateral line (N_{sl}),

$$N_{sl} = \frac{D_l}{S} = \frac{208}{14} = 14 \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3.11)$$

The first lateral branch from the main line is located at distance S from main line and the last S can be covered by the sprinkler diameter. Accordingly, the available dimension of the main line, D_m:

$$D_m = 200m - 2 * 12.1m = 175.8m \text{ ....(3.12)}$$

Number of lateral N_L,

$$N_L = \frac{D_m}{L} = \frac{175.8}{12.1} = 14 \text{ ....(3.13)}$$

The above parameters are determined on the bases of minimum whole number. With all lateral operating the maximum number of sprinkler N_S for the system is 14*14=196.

The layout of the system must provide for simultaneous operation of the minimum number of sprinklers (N_{Sm}) that will satisfy the required system capacity.

$$N_{Sm} = {}^{Q_s}/_{Q_a} = \frac{43.35m^3/hr}{0.56m^3/hr} = 78 \quad \text{........(3.14)}$$

3.4 Irrigation Pipeline hydraulics

In any layout which uses pipe there is energy loss due friction depending on the viscosity of water. The change in energy between any two points is described as follows by Bernoulli equation:

$$Z_1 + H_1 + \frac{V^2}{2g} = Z_2 + H_2 + \frac{V^2}{2g} + h_f \text{ .... (3.15)}$$

Where Z static head which is elevation above some reference data, H is pressure head pressure divided by specific weight of water, V is velocity of flowing water, g gravitation constant and h_f is friction head loss which is energy required for water to flow to flow between two points, all at SI units.

Two hydraulic problems exist in sprinkler irrigation system: 1) evaluation of pipe without multiple out let and 2) evaluation of pipe with multiple out let (lateral line and manifolds).

The basis for designing will be selecting the minimum pipe size such that energy loss and velocity do not exceed beyond the recommended limit to ensure efficiency and uniformity.

The flow of water in pipes is always accompanied by pressure loss due to friction. The magnitude of the loss depends on the pipe material characteristic which is the roughness, and pipe diameter, viscosity of water and velocity of flowing water. These factors are expressed by friction coefficient based on experimental result.

The most commonly used formula for determining friction head loss in sprinkler irrigation is Hazen-Williams equation [16]

$$J = \frac{h_f}{L/100} = K * \left(\frac{Q^{1.852}}{C^{1.852}}\right) * D^{-4.87} \text{ ………. (3.16)}$$

3.4.1 Stand pipe riser design

Riser must be provided in order to remove turbulence in the direction of flow when diverted from the main line. The height of the riser is 500mm depending on both the manufacturer recommendation and must be higher than the onion height. The discharge of sprinkler is $0.56m^3/hr$ and sizing must provide the required flow rate at the minimal diameter without exceeding the velocity limit of 3m/s and the pressure loss is governed by Hazen- Williams equation. From the catalogue [35] using 200 Class PVC to minimizing cost, the minimum diameter which can provide the flow is tabulated as follows for each riser.

Table 3.5 Riser pipe specification

Pipe Material	Discharge	Velocity	Pressure loss	Dimension			
Class 200 PVC	$0.68m^3/hr$	0.433m/s	0.104bar/100m	Nominal	20mm	OD	27mm
			Pressure loss on entire length	ID	24mm	Wall thickness	2mm
			0.052bar				

Total pressure loss in riser, P_{rloss}, is determined by multiplying pressure loss per riser by riser height.

$$P_{r\,loss} = 0.052bar$$

In terms of head, the loss in the riser $H_{r,loss} = 0.54m$

3.4.2 Lateral Pipe Design

The principle to size the lateral pipe is to supply water to each sprinkler on the later line without exceeding the velocity limit of 1.5m/s to gather desired performance at the pressure of sprinkler operating pressure 2.07bar. Uniform pipe is selected to reduce the cost variable of valves and fitting and medium strength pipe that has good characteristics Class 200 PVC is chosen. The total discharge in the lateral is 0.68m^3/hr*14 sprinkler =9.52m^3/hr

The pipe with minimum diameter to provide the required lateral discharge is tabulated as follows for each lateral.

Table 3. 6 Lateral pipe specification

<table>
<tr><th>Pipe Material</th><th>Discharge</th><th>Velocity</th><th>Pressure loss</th><th colspan="4">Dimension</th></tr>
<tr><td rowspan="3">Class 200 PVC</td><td rowspan="3">10.206m^3/hr</td><td rowspan="3">1.2m/s</td><td>0.269bar/100 m</td><td>Nominal</td><td>50mm</td><td>OD</td><td>60mm</td></tr>
<tr><td>Pressure loss on entire length</td><td rowspan="2">ID</td><td rowspan="2">55mm</td><td rowspan="2">Wall thickness</td><td rowspan="2">3mm</td></tr>
<tr><td>0.673bar</td></tr>
</table>

3.4.3 Head loss for multiple, equally spaced outlet

The flow of water in pipe with multiple outlet each spaced equally will have head loss less than those pipes which transmits flow over the entire flow over the entire length since flow diminishes each time an outlet is passed. The method developed by Christiansen for multiple out let pipe flow computation introducing a factor 'F' which depends on spacing. To determine the head loss first determine the friction head loss without multiple outlet then multiplying with the factor 'F'.

For first outlet spaced at S distance from the main line F is computed as: [40]

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2} \text{ ……….. (3.17)}$$

Where m is constant which is equal to 1.85 for Hazen-Williams equation, and N is number of outlet in each side of the lateral which is 7.

$$F = \frac{1}{1.85+1} + \frac{1}{2*7} + \frac{\sqrt{1.85-1}}{6*7^2} = 0.43$$

The situation where the first outlet is only one half spacing from the main line:

$$F' = \frac{2N}{2N-1} * F - \frac{1}{2N-1} \quad \text{……….. (3.18)}$$

$$F' = \frac{2*7}{2*7-1} * 0.43 - \frac{1}{2*7-1} = 0.39$$

Total pressure loss in all lateral pipes, P_L, is determined by multiplying pressure loss in each lateral by Christiansen factor.

$$P_L = 0.39 * 0.673 bar = 0.264 bar$$

In terms of head, the loss in the lateral line $H_{L,loss} = 2.69m$

3.4.4 Mainline Design

The major function of the main line is to deliver the quantity of water to all parts of the design area at the pressure required to operate all laterals under the maximum discharge condition. The design of the main lime requires analysis of the entire system to determine the maximum requirement for pressure and capacity.

The line which runs from water source to the design area which is at the main line inlet termed as the supply line and it is 150m long measured from the site.

The maximum allowable pressure drop must be less than 20% of the pressure required in the lateral line and the velocity limit in the pipe must be 2m/s. [36]

Since the main line is under constant pressure the pipe must have good quality and high strength wall. Therefore, PVC Class 125 is used.

Table 3.7 Mainline pipe specification

Pipe Material	Discharge	Velocity	Pressure loss	Dimension			
Class 125 PVC	113.4m^3/hr	1.606m/s	0.131bar/100m	Nominal	160mm	OD	168mm
			Pressure loss on entire length	ID	158mm	Wall thickness	5mm
			0.262bar				

Pressure loss in the main line $P_{M,loss}$ which includes the supply line is given as:

Since the length of the supply line is 150m the total pressure loss, $P_{M,loss}$

$$P_{M,loss} = 0.262bar + \left(\frac{0.131bar * 150m}{100m}\right) = 0.4585bar$$

In terms of head, the loss in the main line $H_{M,loss} = 4.7m$

3.4.5 Selection of fittings velocity head determination

Faucet Tee joints

Faucet Tee joint is used to join the irrigation lateral line with the riser pipe. Since there are 196 sprinklers on each corresponding riser has to be connected by those joint.

Friction loss due to Tee:

$$h_{ftee} = k_r \frac{V^2}{2g} \text{ ………. (3.19)}$$

$$h_{ftee} = 0.5 * \frac{0.433^2}{2 * 9.81} = 0.0048m \; per \; each \; tee$$

$$h_{ftee} = 0.0048 * 196 = 0.94m$$

Couplings

Couplings are used for the solvent cement joining of two length pipes. Source line is the pipeline from water source to in let of the main line which has a length of 150m.

Main line: since the length of the main line is 200m having the same diameter as the source line which is 6 in. The total length of this pipeline is 350m. But since there is 6m standard pipe line the 59 couplings each corresponding nominal diameter of 6 in is selected.

The length of each lateral line is 125m on each side having a diameter of 2 in. By taking the standards pipe length of 6m total number of coupling required for the later line will be 588 with corresponding diameter of 2 in.

Friction loss due to coupling joint

$$h_{f coupling} = \left(k_r \frac{V^2}{2g}\right)_{main\ line} + \left(k_r \frac{V^2}{2g}\right)_{lateral\ line} \quad \text{.........(3.20)}$$

$$h_{f coupling} = (0.08 * 59 * \frac{1.606^2}{2 * 9.81}) + (0.08 * 588 * \frac{0.942^2}{2 * 9.81})$$

$$h_{f coupling} = 2.65m$$

Reducing Crossing joint

Reducing cross joints are used to join the lateral lines to the main line. The total of 14 reducing cross one per each lateral is selected from catalogue having the following dimension. Each of the outlets is sized with bushing.

Friction loss due to cross joint

$$h_{f cross} = k_r \frac{V^2}{2g}$$

$$h_{f cross} = (0.8 * 14 * \frac{1.606^2}{2 * 9.81})$$

$$h_{f cross} = 1.47m$$

Flow controlling valves

Water flowing in each lateral is controlled by ball valves. Each lateral must have distinct valves therefore total numbers of 28 valves are selected and the corresponding dimensions as follows:

$$h_{f ball\ valve} = k_r \frac{V^2}{2g}$$

$$h_{f ball\ valve} = (0.1 * 28 * \frac{1.2^2}{2 * 9.81})$$

$$h_{f ball\ valve} = 0.37m$$

Backflow prevention valve

Back flow is the reversal of water from its intended direction which could be caused due to the back pressure created. [26] It can be avoided using specific valve designed for this purpose. Accordingly backflow prevention valve that can be fit with the dimension of the mainline, which is 6'', is selected.

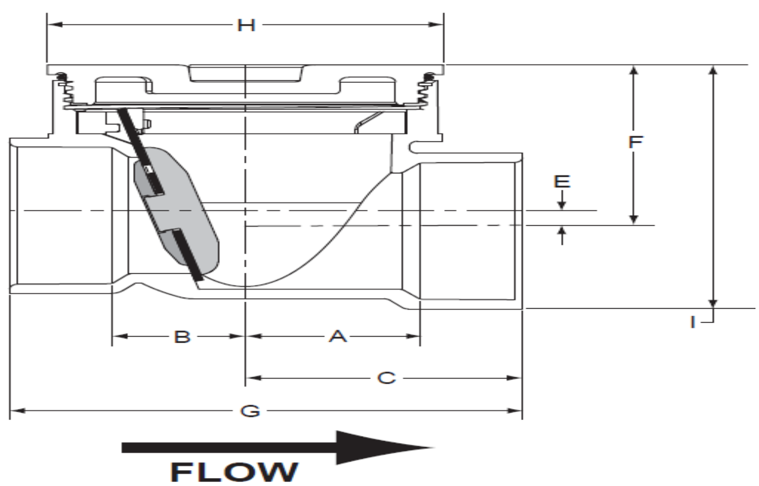


Figure 3. 12 Backflow preventer

The corresponding friction loss is determined as follows and the velocity head and resistance coefficient of the valve at the corresponding flow rate is 0.5ft and 4.6 respectively.

$$h_{f\ backflow\ valve} = k_r \frac{V^2}{2g}$$

$$h_{f\ backflow\ valve} = 4.6 * .5ft = 2.3ft = 0.7m$$

3.5 Suction system Design

Suction system design is very important section since it can cause trouble to the performance of the centrifugal pumps. The function of this line is to continuously supply an evenly distributed flow of water to the pump suction with the sufficient pressure to the pump by avoiding excessive turbulence. At the foot the suction pipe strainer is used as a screening mechanism as it would not allow the entrance of the solid matters into the suction pipe which otherwise may damage the pump. The vertical suction pipe is 6m long and the corresponding diameter should select in accordance with pump manufacturer recommendation and the nominal diameter, which is 150mm, has to be large enough or at least one size larger [40] so that it reduces the effect of cavitation. Elbow is required at the suction pipe and it should be in vertical position. Eccentric reducer is used for connecting the pipe with pump inlet. The friction drop in suction pipe depending on both the nominal diameter and flow rate is read from the graph [37] and is 3.22/100m and velocity of 1.689m/s^2.

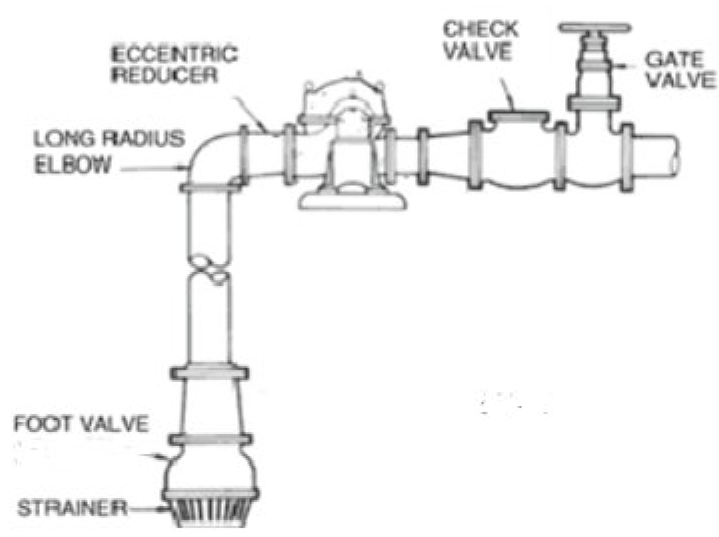


Figure 3. 13 Suction system layout [40]

The suction pipe friction loss is calculated as follows:

$h_{f\ suction\ line} = pressure\ drop\ per\ length * pipe\ length$ ………. (3.21)

$$h_{f\ suction\ line} = \frac{3.22m}{100m} * 6.5m = 0.21m$$

The friction loss on the suction side including elbow, eccentric reducer, and strainer is gives as:

$$h_{f\ suction\ fitting} = k_{r\ of\ elbow}\ \frac{V^2}{2g} + k_{r\ reducer}\ \frac{V^2}{2g} + k_{r\ strainer}\ \frac{V^2}{2g} \text{……} \quad (3.22)$$

$$h_{f\ suction\ fitting} = (0.28 + 0.02 + 0.8) * \frac{1.689^2}{2 * 9.81}$$

$$h_{f\ suction\ fitting} = 0.16m$$

Total friction losses in fitting, $h_{fitting}$

$$h_{fitting} = h_{ftee} + h_{fcoupling} + h_{fcross} + h_{fball\ valve} + h_{f\ backflow\ \ valve} + h_{f\ suction\ fitting}$$

$$h_{fitting} = 0.94m + 2.65m + 1.47m + 0.37m + 0.7m + 0.21m + 0.16m$$

$$h_{fitting} = 6.5m$$

The miscellaneous losses, $Miscellaneous_{loss}$, are typically estimated as 20% of the total friction losses. [16] thus it can be computed as: $20\% * 6.5m = 1.3m$

3.6 Determination of Total Dynamic Head

The Total dynamic head, TDH, is the head required for the irrigation system to deliver the specified total flow rate. It is computed as the sum of operating pressure of sprinklers, pipe friction losses, the elevation difference, fitting losses and miscellaneous losses.

$\mathrm{TDH} = \mathrm{H_{op}} + \mathrm{H_{Static}} + H_{r,loss} + H_{L,loss} + H_{M,loss} + H_{suc.,loss} + h_{fitting} + Miscellaneous_{loss}$ ………. (3.23)

$$\mathrm{TDH} = 21\mathrm{m} + 6.5\mathrm{m} + 0.54\mathrm{m} + 2.69\mathrm{m} + 4.7\mathrm{m} + 0.21\mathrm{m} + 6.5\mathrm{m} + 1.3\mathrm{m}$$

$$\mathrm{TDH} = 37.94\mathrm{m} \approx 40\mathrm{m}$$

3.7 Water Pumping System and Related Analysis

Various pumps are used for irrigation purpose. Those pumps can be classified in to two categories, positive displacement and centrifugal pump. Positive displacement pump is characterized by the operation that transports fluid by trapping a fixed volume and then forces the water to discharge to the pipe. Whereas, the centrifugal pumps transfer the kinetic energy of motor to the water by spinning impeller since as the impeller rotates it draws water causing increased velocity that transports the water and discharge into the pipe.

From the irrigations system design, it is found that the irrigation water requirement, IWR and total dynamic head to be 230m^3 and 40m respectively. The high volumetric requirement of water make the centrifugal pump the best candidate for the system.

Another factor to consider is the preferability of using AC vs DC centrifugal pump. If DC pump is used, the coupling is arranged with a DC/DC converter whereas if AC pump is used, the pump is connected to the PV array through a DC/AC inverter that transforms the DC power produced of the PV module to AC used to drive the pump-motor unit. Different type of controller can be used, but most available one is the maximum power tracker. Though DC pump requires less expensive power controlling units, having higher initial investment cost makes them less preferable. Another advantage of employing AC pump is that large availability on the market which plays a major role for the availability of the spare parts for the remote off-grid area where it is going to be implemented. [13] This makes the AC pump a suitable candidate for the system.

3.7.1 Water Storage Tank Sizing

The water storage tank plays a crucial role in the design of the solar irrigation system. Since the daily requirement of the irrigation water depends on the availability of the sunshine the tank should be sized to have sufficient capacity to store water for 1-3 days. [17] depending on this fact, the tank size is considered to be of 600m^3 capacity for more than two days autonomy.

$$V = \pi \frac{D^2}{4} * h \text{.................}(3.24)$$

3.7.2 Pump Sizing

The selection of pump depends on many variables. the proper selection should ensure that the flow is delivered at the required head and the power associated with it is hydraulic power, P_h.

$$P_h = \frac{\rho g Q_w TDH}{\eta} \quad \ldots\ldots\ldots\ldots(3.25)$$

Based on the technical and cost advantage the pump manufactured by Lowara model 12GS40 is selected. The corresponding performance data is given under the result section.

3.7.3 Cavitation

In centrifugal pump, cavitation has a significant effect on the performance as it degrades the performance, fluctuates the flowrate and head and also it erodes the impeller blades which results in destruction of the pump.

The quantity which is used to determine whether the pumped pressure is suspectable for cavitation or not is 'Net Positive Suction Head (NPSH)'. Available and required, $NPSH_A$ and $NPSH_R$ are determined to avoid the condition of cavitation.

$$\mathrm{NPSH_A} = H_S + H_{atm} - f_{friction\ loss} - H_{vap} \ldots(3.26)$$

Where H_S is suction head, H_{atm} is atmospheric pressure and H_{vap} is vapour pressure of the water.

$$\mathrm{NPSH_A} = -2m + 10.2m - 0.21m - 0.35m = 7.64m$$

The selected pump has available net positive suction head greater than the required one to ensures there is no cavitation issue.

3.8 PV Module selection

The selection of PV module should take into consideration the effect of the climatic condition. The daily average temperature of the site is taken in to account and the performance of the module is discussed in the later section. Based on this, the selected panel is manufactured by Sova Power ltd. the panel is Si-Poly model of Poly 310 Wp 72 cells and having efficiency of 16.18% which gives concrete reason that makes is suitable.

CHAPTER 4

SIMULATION AND PERFORMANCE ANALYSIS OF THE WATER PUMPING SYSTEM

Introduction

The Solar Water Pumping system has various components. Different models are developed to investigate the technical viability of the system. In order to have effective pumping system each component should be properly sized and system simulation should be performed to ensure the optimization. This section presents and describes the various component that is constituents of the system and how the sizing is performed by using various models and tools used for optimization and simulation. Finally, the simulation results are discussed.

4.1 Orientation of the PV panel or the tilt angle

The orientation of the PV panel to the sun plays a crucial role as it is supposed to collect as much solar energy as possible. Although the solar tracking system is best in regards to optimal collection. But the cost and operational difficulties make it less favorable. For this work the fixed array mount is selected and the tilt angle is optimizing using the PVsyst.

4.2 System Modelling and Simulation

Based on the theoretical background discussed so far, the feasibility of the system is carried out on three different model option which are developed to effectively represent the system. Those models are described and the simulation procedure and input parameters are presented in this section. The design of individual components and feasibility evaluation parameters will be given and discussed in the subsequent section.

4.3 Model 1: Modeling of Irrigation system with Water Storage Tank

After the determination of the irrigation water requirement and hydraulic analysis, the solar water pumping system is modeled in such a manner that it can deliver water that meets the maximum water demand under the assumption that the solar panels are not shaded with free horizon.

There are many commercial tools for simulation and optimization of such system. Pvsyst is used for this purpose since it is considered as one of the most comprehensive for design and simulation. And also, unlike other the programs, PVsyst includes the tools for various PV water pumping application that can be adopted for specific type and makes it preferable for the study.

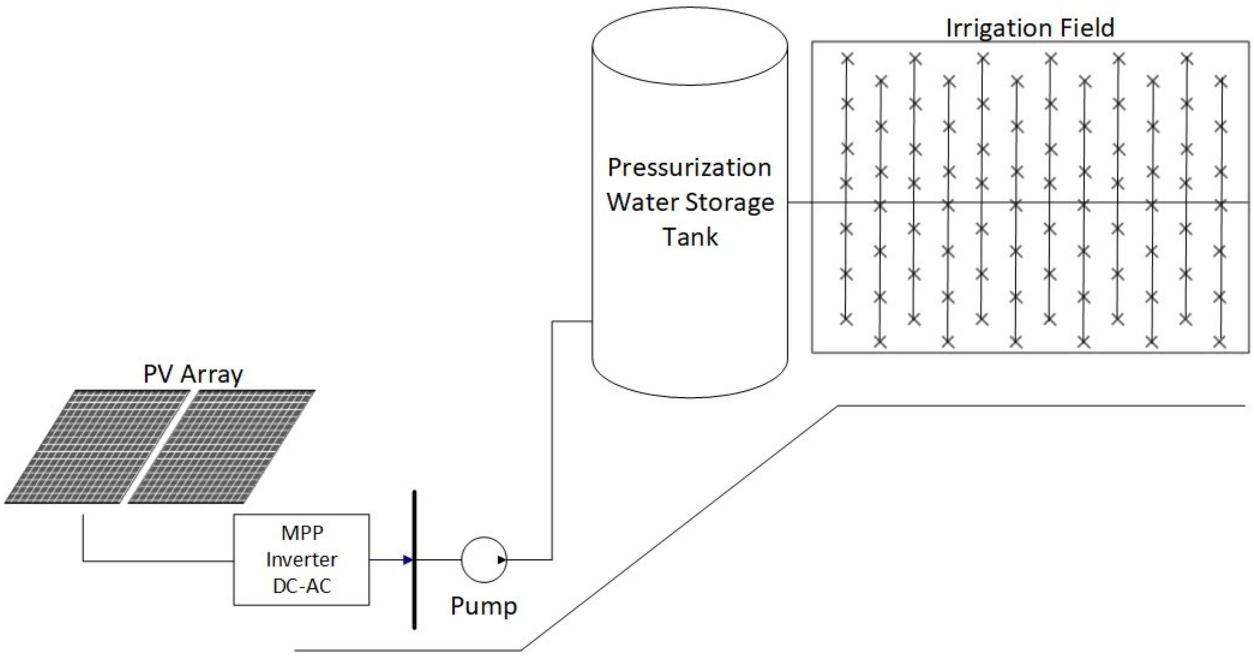


Figure 4. 1 Model 1. System Configuration

4.4 Introducing PVsyst and Technical performance Evaluation Parameters

In order to analyses the feasibility of the system, it is important to effectively model. The technical evaluation system should be analyzed in certain performance field. Various commercial software can be utilized when it comes to modelling energy system but Pvsts appears to have a simulation package which is vital for water pumping and produces reliable energy yield profiles.

In this study the metrological site irradiance data is used from NASA SSE database in order to ascertain the performance characteristic of the system. These performance characteristics employs the energy yield assessment of the site. The technical performances parameters are described as follows.

4.4.1 Energy Production

The electrical energy production depends on various factors such as incident angle, cell temperature, incident irradiance on the collector and many resistances and losses with the PV system. [65] the energy production is calculated as:

$$Energy\ Production\ (kWh) = Actual\ power * time \ldots .(4.1)$$

The performance of the PV module is measured by the total annual energy production, the temperature coefficient of the module expressed as a rate of change of the output power as a function of temperature.

4.4.2 Specific Yield

It is defined as the ratio of the solar PV system AC energy supplied in kWh over the actual STC rating of the solar system in kWp. [66] Depending on this definition, the factors affecting the annual yield production and variation that affect the specific yield can be deduced.

$$Specific\ Yield = \frac{Actual\ AC\ output\ kWh}{DC\ rated\ power\ of\ the\ PV\ module} \ldots..(4.2)$$

4.4.3 Performance ratio

It is a parameter used to indicate the quality that can be attained from the system if installed without necessarily quantifying the amount of energy generated. Findings of various study suggested that the higher the performance ratio, The higher the conversion rate of the solar energy into electrical energy. [67] The researches of the solar PV system, reported the performance value that range from 60%-90% as a finding of their work. [68-71]

$$PR = \frac{E_{system}}{E_{ideald}} \ldots\ldots(4.3)$$

The national renewable energy laboratory (NREL) report suggests that there are large seasonal variations in PR is strongly dependent on the temperature. [72] the normalized energy production which the temperature corrected energy production can be used to get effective value. Researches conducted in Netherlands reveals that PR value could on average reach 82.1% in winter and drops to 73.2% in summer. [73]

4.4.4 Plant performance degradation

Generally, there is an assumption that the performance of degradation of the solar system is caused majorly by the solar PV module. However, when evaluating the performance, it is recommended to consider climatic data and system balance. NREL report that a new system standard for Performance ratio is expected to be a minimum 77% that should be met for PV generators to resilient to degradation.[74]

4.4.5 Capacity factor

The capacity factor of a solar PV system is the ratio between the measured output of the power generated by the PV plant over a period of time and corresponding potential output if it had operated at the rated full capacity during the entire time. [75] It is calculated as follows:

$$CF = \frac{Energy\ Output\ kWh}{8760 * Installed\ capacity\ of\ PV\ module\ kWp} \ldots.(4.4)$$

The temperature, degradation, and environmental factors are the major contributor of the performance parameter. For the fixed tilt solar PV system according to the literature, the system is expected to have CF value between 20.8-26%. [62]

4.4.6 Model Description in PVsyst

Pressurization Tank Model

This model implementation takes an assumption that the pumping is done from the generic water source into a tank to ensure a water static pressure allowing for the distribution to the end user. The pressurization is gained through the compression process of the air in the closed impervious tank volumes when water level increases. The pump modelling parameter are the same except that the maximum capacity head are usually higher and this fact makes the modeling suitable for the sprinkler irrigation as the system operates at the higher pressure.

4.5 Simulation Procedure and Input Parameters

4.5.1 General

The PVsyst used for the system modeling is based on the single diode performance analysis in which the background described above. There are bundles of integrated manufacturer database with various components that is used for sizing and optimization. The system configuration is automatically done once the user defines the project and desired capacity. Based on these inputs the PVsyst proposes system configuration and the optimal sizing is done based on the acceptable overload loss throughout the year. The system definition and simulation procedure are presented below.

4.5.2 Input Parameters

I. Project Definition

The project design should be defined depending on the purpose of the study. Since various systems are available the water pumping is selected based on the goal of this work.

II. Geographical data of the site

Since there is no solar data of the site available at national meteorological agency of Ethiopia, the irradiance data are collected from the NASA-SSE data base which integrates with PVsyst. The geographical data; latitude, longitude, elevation and time zone of the site are the major inputs used to obtain the solar data.

Figure 4. 2 Geographical Site Parameter

III. PV panel orientation and field type

The solar data is to be used by the photovoltaic panel collector. The pabel field type should be decided whether it is fixed or tracking system and the optimal tilt angle of the plane which facilitates the effective irradiance collection should be entered.

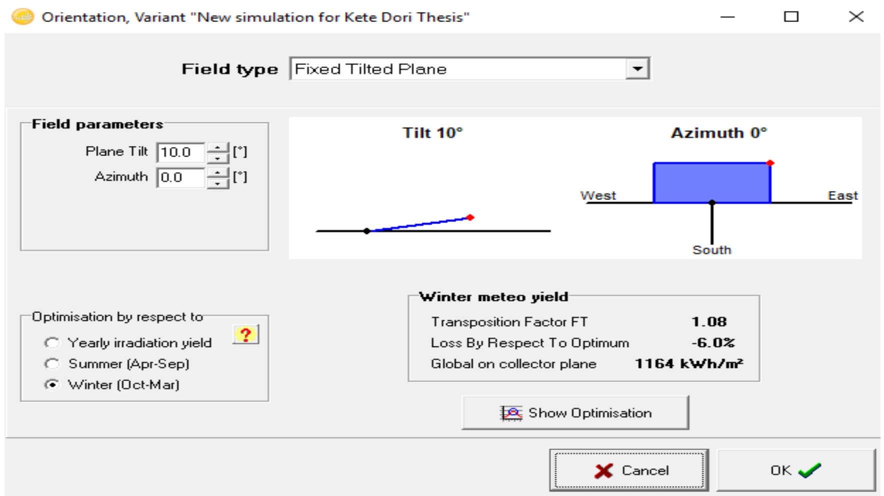


Figure 4. 3 Tilt angle orientation

4.5.3 Pumping System and Water need definition

The pressurization pumping system which is a selected model for this work should be defined. The water storage size, operating pressure of the system and the daily water requrement are another input parameters for the simulation.

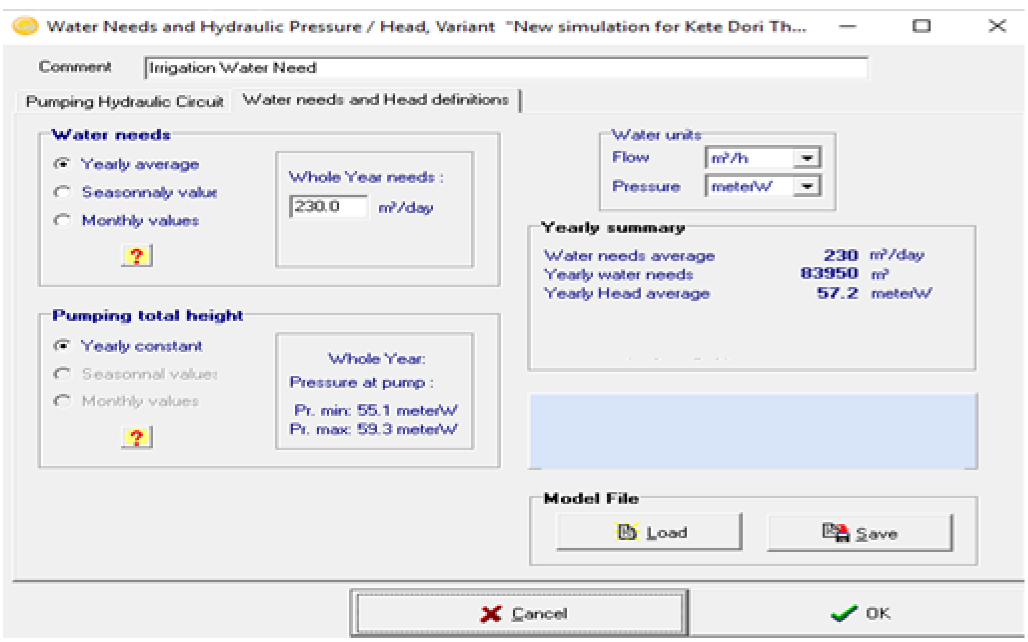


Figure 4. 4 Pumping system and irrigation water requirement

4.5.4 Photovoltaic array and Pumping system definition

Depending on the daily water need the pump selection is done and the PV module which can generate sufficient power to run the pump is selected in this section. Those data are preliminary for the system configurational optimization.

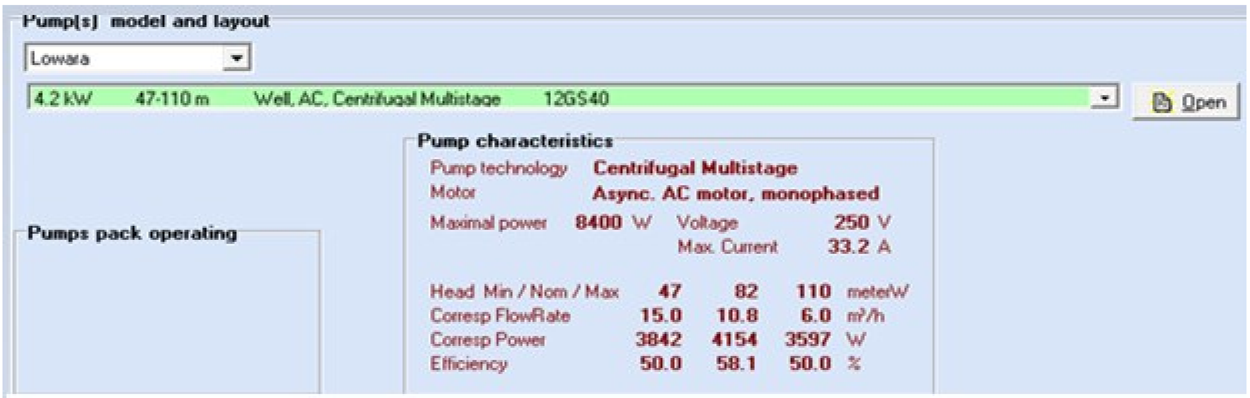


Figure 4. 5 Pump model and layout

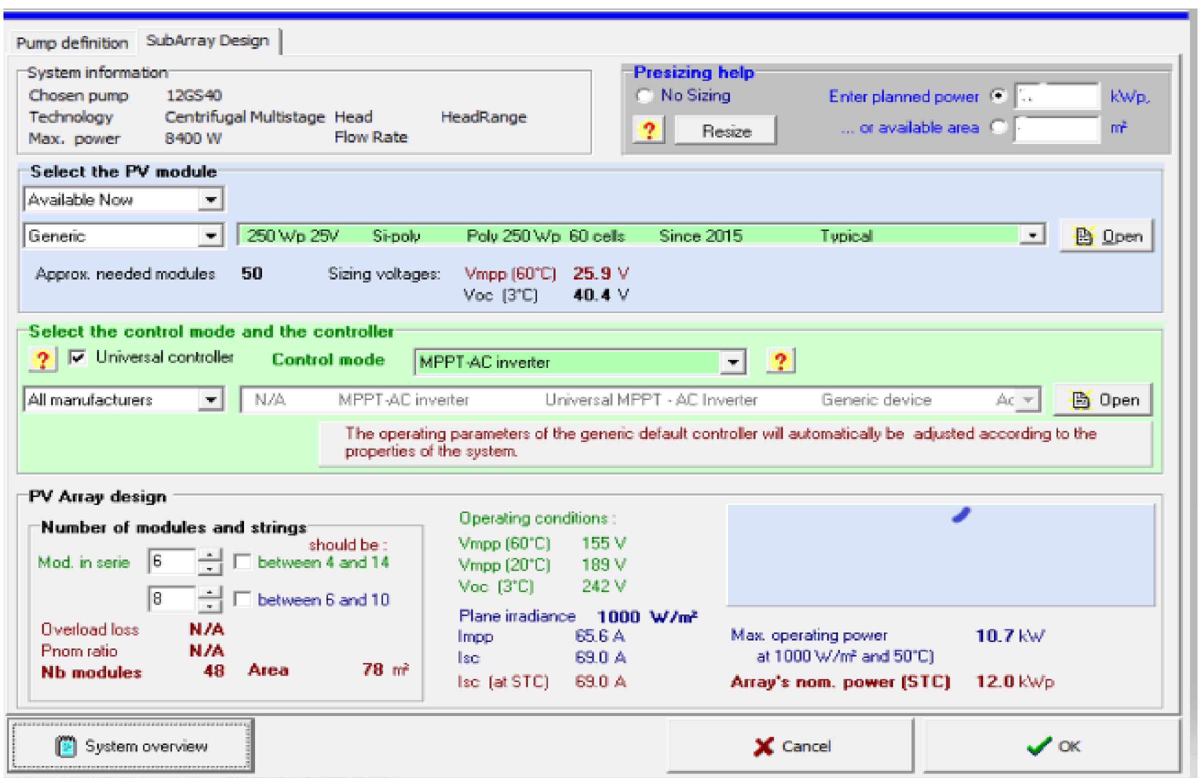


Figure 4. 6 PV-Module system selection

4.6 Results and Discussion on the performance analysis of Model 1.

A number of models are developed for carrying out the investigation of this study. Each model is proposed to deliver the same capacity of the required water demand for the irrigation system. The relevant characteristics feature of the site is parametrized which was later used as an input for system design. It was found that the effectiveness irrigation system strongly depends on the climatic data such as Temperature, rainfall, wind speed and sunshine hour which is presented under the section of metrological data result. The solar energy potential of the study site is studied and those finding are presented and used to assess whether there exists sufficient solar potential or not to pursue the technical and economic viability investigation for the photovoltaic water pumping models.

The finding of the feasibility study of the corresponding model is presented and discussed from technical performance evaluation point.

4.6.1 Metrological Data

The climatic data of the study area from 2006-2016 is collected from the Ethiopian metrological Agency. The monthly average Wind Speed, Relative Humidity and Sunshine hours are determined and those data are summarized based on the daily mean approach is given in table below.

Table 4.1 Climatic condition of the site from 2006-2016

Month	Mean Sunshine (Hrs)	Relative Humidity %)	Wind Speed (m/s)
JANUARY	8.36	55.45	1.47
FEBRUARY	7.05	50.53	1.53
MARCH	8.09	51.21	1.46
APRIL	7.50	52.02	1.39
MAY	7.82	55.23	1.22
JUNE	7.54	50.59	1.62
JULY	6.48	63.90	1.48
AUGUST	6.44	68.46	1.09
SEPTEMBER	6.51	66.87	0.70
OCTOBER	6.87	53.78	0.81
NOVEMBER	8.21	58.35	1.02
DECEMBER	8.55	52.71	1.37

The optimal and effective water requirement study of the dynamic interaction between crop prevalent and climate is of great importance for minimizing water demand with minimal impacts on yields and yield quality. The water found soil surface as well as the water attaches to the leaves and stem of a plant during a rainfall also is lost to the atmosphere by evaporation. Hence acquiring the sufficient historical weather data was found to be important for irrigation system design decision making and the water requirement is determined by these considerations.

Vital climatic parameter considered was the average temperature since the irrigation efficiency of the farm strongly depends on it. Based on the FOA classification the site falls in to moderate temperature zone. [50]

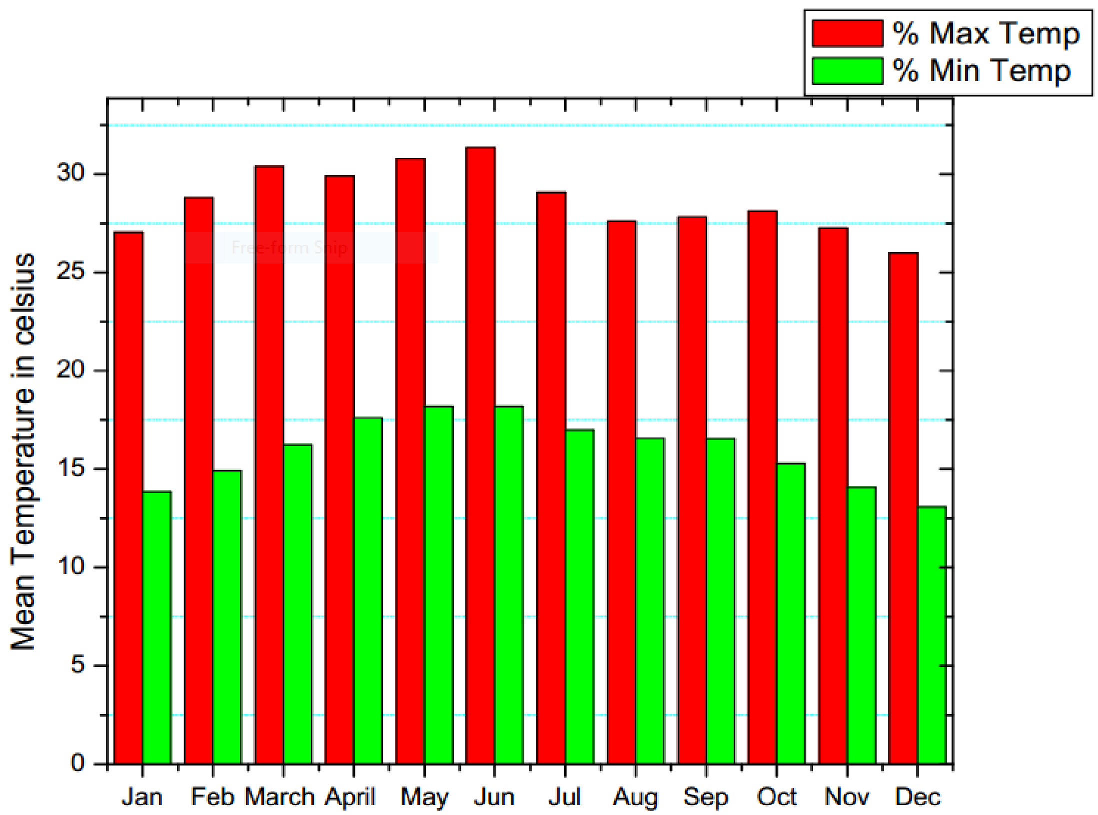


Figure 4. 7 Daily Mean Temperature of the Site

4.6.2 Solar Potential

The solar potential of the site is determined from NASA-SSE data base by entering the latitude and the longitude of the site since there is no radiation data available from national metrological agency. The determined data is shows in figure 38. along with the sky clearness index, which is the solar fraction of the radiation transmitted through the atmosphere and which strikes the surface of the earth. It's value ranges from 0-1 and hence it measures clearness of the atmosphere. The typical value for monthly average clearness index is 0.5 (very cloudy month) to 0.7 (very sunny month.

Figure 4. 8 Profile of solar radiation of the Site

4.6.3 Optimal Tilt Angle

The amount solar energy is collected by the solar panel depends on how the solar panel is mounted as whether it is fixed mount or solar tracking. Although the solar tracking panel is more effective the cost associated to the system makes it less desirable. For a fixed mount the optimal tilt angle is determined taking latitude into consideration for the period in which the irrigation water need to be lifted the pump.

After the simulation is performed the optimal tilt angle of the site is found to be oriented at 0-degree azimuth and 10-degree tilt facing the south.

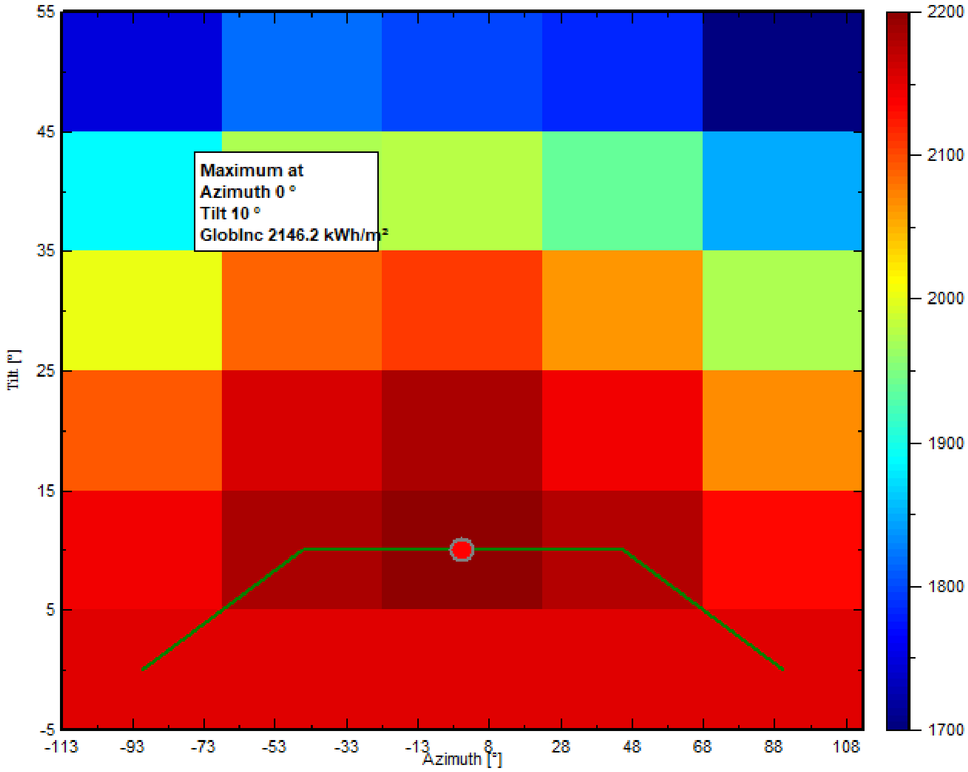


Figure 4. 9 Optimal tilt angle

4.6.4 Technical Evaluation of Model 1.

The extreme fluctuation of solar radiation and irrigation water requirement throughout the year makes the Solar water pumping system more complex. The system is designed to meet the peak demand of irrigation water requirement which is 230m^3/day based on the irrigation frequency. The irrigation of the onion could be delayed by 1-3 days without any disturbance in the production process. Based on this fact 600m^3 special water storage tank with pressurization model is selected for performance analysis since the sprinkler irrigation system requires consistent operating pressure of 2.01bar and this design decision avoids the need for additional booster pump. The model is considered to be deferable load which is a type of load where the demand needs to be met within some time but the exact timing is not important.

To meet the required water demand and energy requirement of the pump, adopting the pressurization tank requires additional head which is considered in the PVsyst during system simulation.

During the simulation process, parameters input to the software are the solar radiation, daily water need and the maximum power point tracking, MPP inverter is chosen. Once the type of pump is selected the according to corresponding configuration the simulation has managed to determine the optimal system.

Based on the water demand the simulation results shows that the total annual water requirement is 83, 950m^3 and results corresponding to the system production is given in below.

Table 4.2 PV-System Simulation Results

Pump		
	Model: 12GS40	Manufacturer: Lowara
Pump Technology	Centrifugal Multistage	Motor: Async. AC Motor
Associated Inverter	Type: MPPT	Voltage range 100-600V
Operating Condition	Min Head = 47m	Max Head = 110m
Required Power	P_{Nom} = 4.2kW	
Number of Pumps	2 in Parallel	
System Production		
Annual water need	83,950m^3	Pump Efficiency = 57.3%
Water Pumped Annual	73,329m^3	
Missing Water	12.7%	
Energy at Pump (Annual)	20,727kWh	

To meet the power and flow rate requirement of the irrigation, two centrifugal multistage AC pump are connected in parallel each having a nominal power of 4.2kW. The corresponding efficiency of each pump is 57.3% this implies the optimized system configuration facilitates the pump to operate under the acceptable efficiency range which is in close agreement with previous work. According to the finding 73,329m^3 water can be annually pumped by the system. Though it falls short of the annual water demand by 12.7%, which is missing to meet the annual water requirement. This is due to the fact that irrigation system design is based on the peak water requirement which falls on the month of May but there is surplus of water pumped in the remaining months of the season although the demand much less than the peak. And also, beyond the irrigation period the surplus of which is pumped can be used for drinking and house hold purposes. In order to maximize the profit further optimization needs to be addressed in such a way that the design should not be based on the worst-case scenario but by studying the effect of reducing pumped water have on the crop productivity.

4.6.4.1 Performance Characteristics Curves of selected pump

The hydraulic property of pumps depends on various characteristics. It is desirable if the pump operate closest to the best efficiency point beyond or below which if the volume flowrate increases or decreases the efficiency of the pump decreases.

The result in the fig.4.10-4.11 below shows that the operation of the pump at the design flowrate of 10.8m^3/hr in various head is near to its rated efficiency. This sheds a light on the technical importance and operation benefit of utilizing the pump in the proposed model.

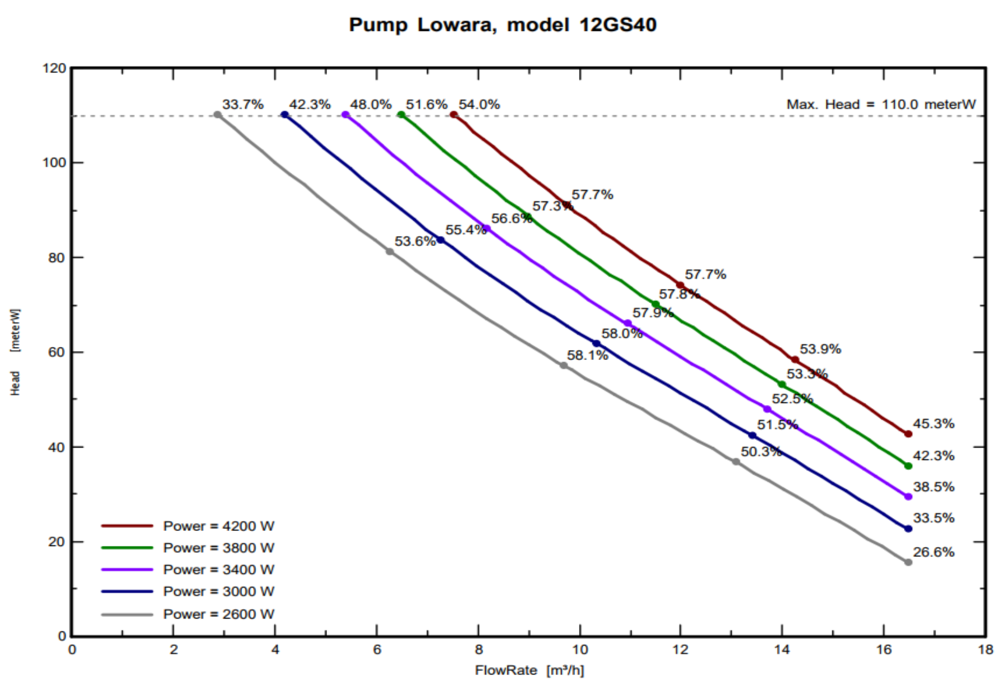


Figure 4. 10 Flow rate Vs Head

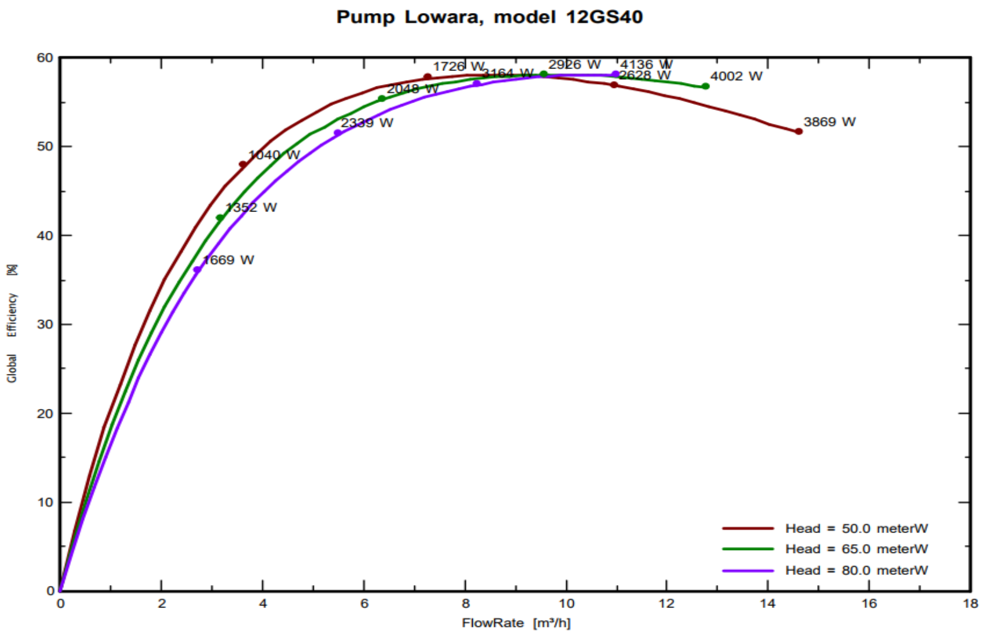


Figure 4. 11 Efficiency Vs Flowrate

Although the PV array with solar tracking system is able to reduce the area of the PV module by up to 30% compared to the fixed mount array the cost associated with makes them less favorable for application. The simulation results of the PV module integrated with MPPT-AC inverter is tabulated below.

Table 4.3 PV system component Characteristics summary

PV Array Characteristics	**Si-Poly**	**Model**	**Poly 310WP 72 Cells**
PV Module	Manufacturer	Sova Power Ltd	
Number of PV Modules	In Series 8 Modules	In Parallel 5 Strings	
Total Number of Modules	Nb. Module 40		
Array Global Power	Nominal (STC)	12.4kWp	
Array Operating Characteristics	Umpp=262V	Impp= 42A	
Total Area	Module Area = 76.8m^2	Cell Area = 70.1m^2	
Control Device	MPPT-AC Inverter		
	Nom. power = 4.2kW	100-600v	
Unused PV Energy annually = 62kWh			

The PV module is automatically integrated with the MPPT-AC Inverter in such a way that it consistently balances the available electrical energy. The module has a rated power of 310Wp having efficiency of 16.18% at STC. The panel covers the area of 76.8m^2 having maximum voltage of 262V and current of 42A which is integrate with MPPT-AC Inverter.

During the site visit as one of the parameters that possibly affect the technical suitability of the system, the availability of the panel installation area has been investigated. Based on that field measurement and preliminary observation the available area is more than sufficient to accommodate the panel areal requirement.

4.6.4.2 PV Module performance Characteristics Curve

Since the performance of the PV module depends strongly on the solar intensity understanding the effect at various irradiance is important. In this regard the performance parameter show for the PV module for the irradiance range of 200W/m^2 1000W/m^2 is given in figure below. It can easily be seen from I-V and P-V curves that the current parameter is strongly dependent on the solar intensity level. The current output is almost linear as depicted in fig. 4.12 until certain voltage is reached. On the contrary to the current parameter the voltage of the panel is less affected the solar radiation. Clearly the model result shows that the voltage logarithmically increases with the solar radiation and the maximum power out rises when the radiation increases and that in turn also increases the current. It can be seen for both figures that the PV module operates near its maximum operating point since the MPPT controller is used for the system that makes it technically suitable for operation.

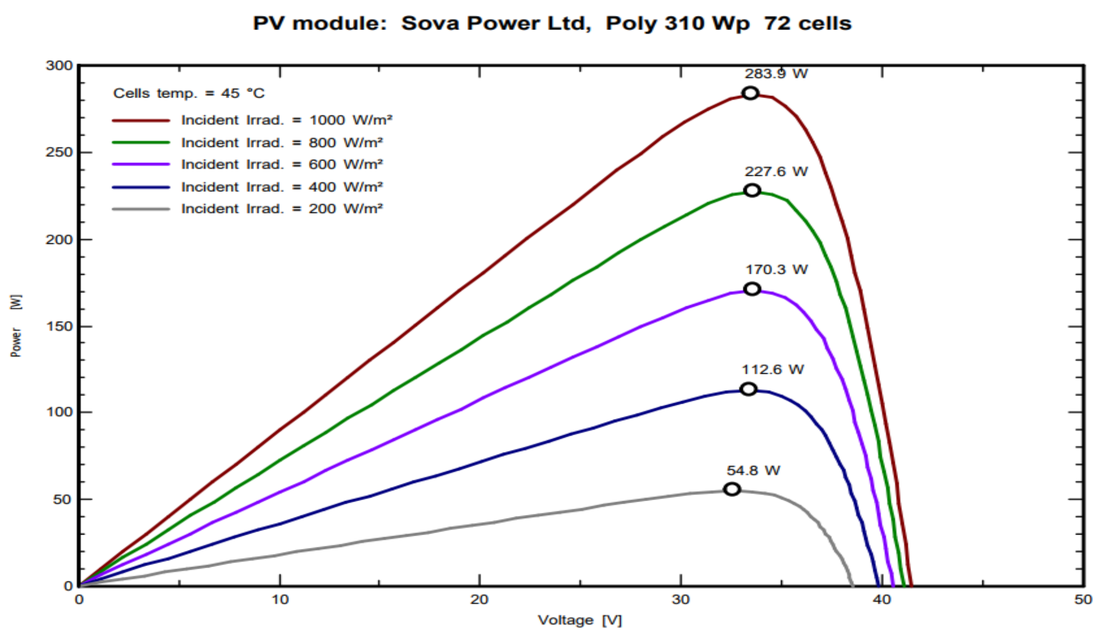


Figure 4. 12 Output P-V characteristics of PV Module with different Irradiance

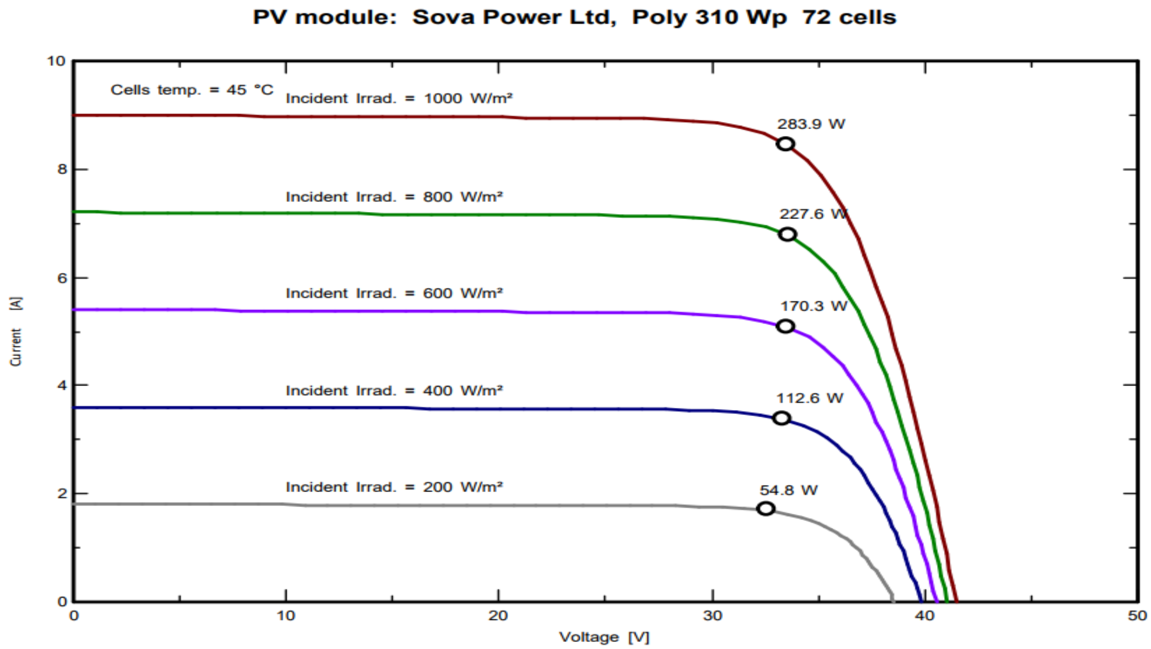


Figure 4. 13 I-V Characteristics curve of MPP Module

The following figure depicts the performance parameter at various solar intensity and the impact of the temperature on the efficiency of the PV module. From the data from metrological agency, the ambient temperature of the site varies from 17 ºC - 32 ºC. The PV cell temperature is modelled in real operating condition that ranges from 10 ºC - 70 ºC depending on the solar intensity. From the fig. 4.13 it can clearly be seen that the efficiency of the module considerable decreases with the increase in the cell temperature. The solar intensity increases the power, it can be seen from the curve that after certain solar intensity level is reached even though the radiation is increased further, the efficiency of the module is nearly constant Depending on the climatic data, the daily mean temperature of the site is slightly over 22°C which is closest to the best efficiency point of the curve. This gives green light to technical advantage of implementing the PV module for the site.

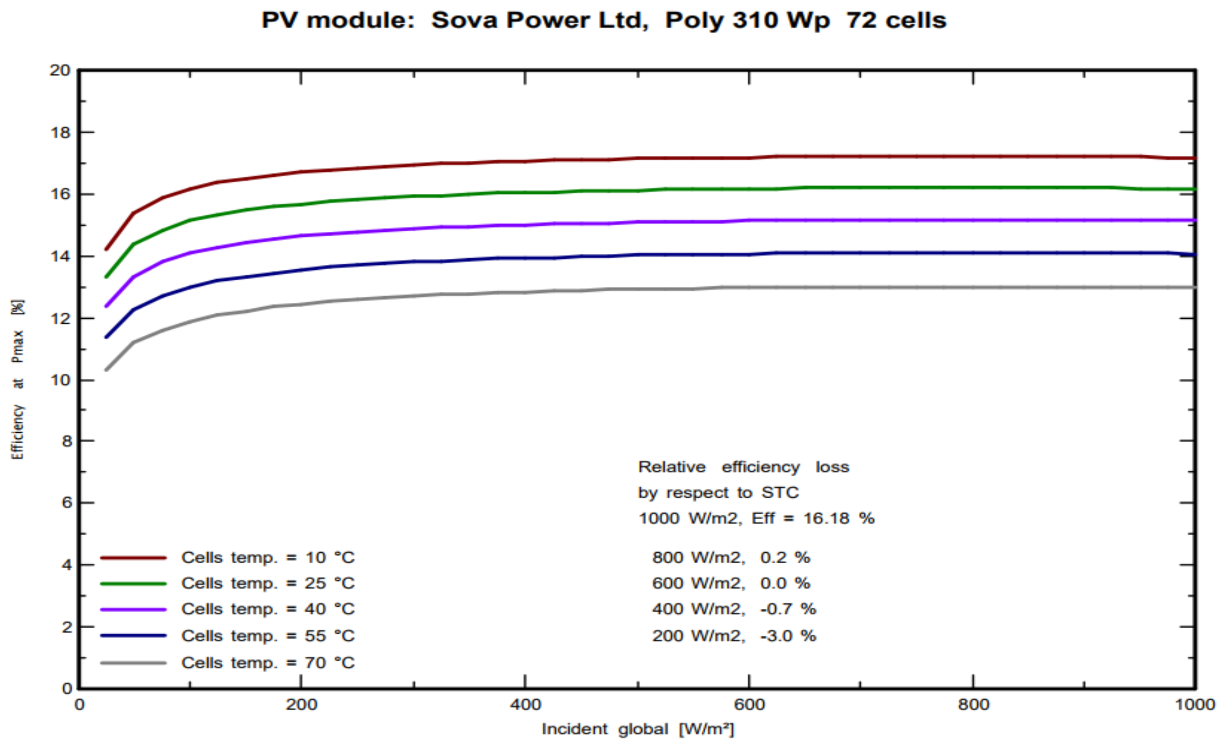


Figure 4. 14 Efficiency vs Irradiance at various temperature

4.6.4.3 Daily output performance of the array

Another useful performance parameter is the average daily power conversion of the PV array. The figure below clearly shows that the output of the array depends on the available radiation. The effective output energy is maximized the irradiance is higher.

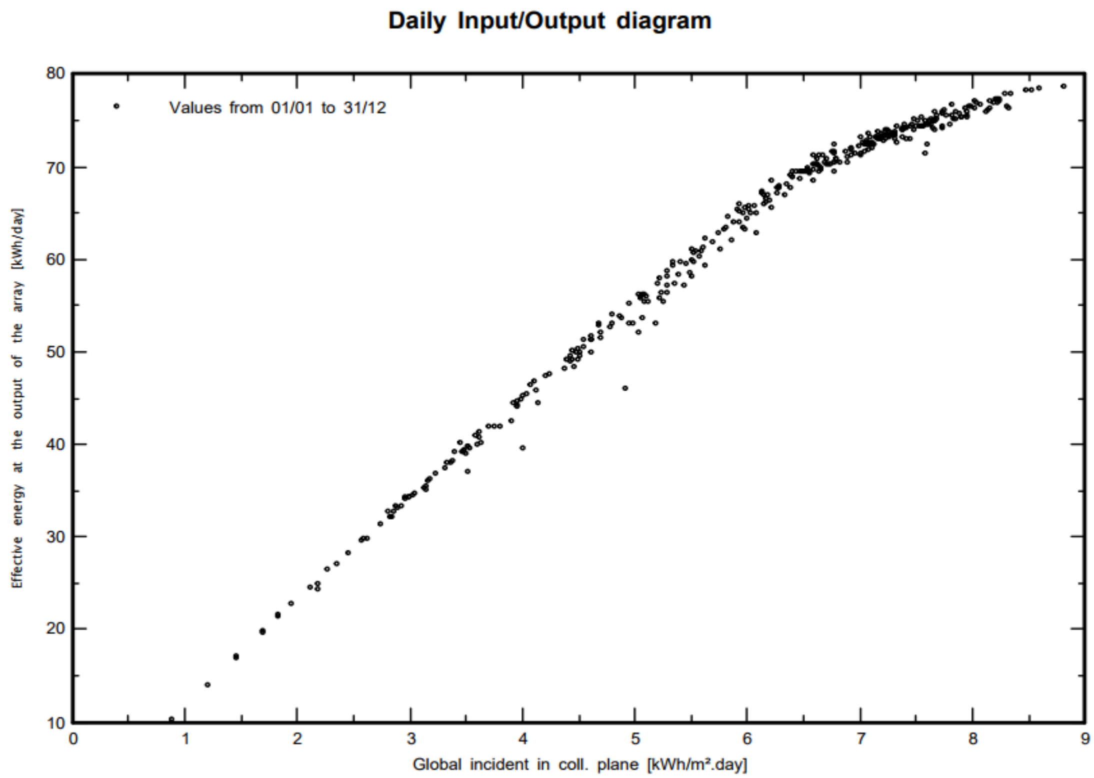


Figure 4. 15 Daily input vs output of the array

4.6.4.4 Daily Water Production performance

The solar intensity is a non-linear source that affects the power generation of the pv arrays. The operating power input to pump the water is investigated and the corresponding daily water production of the system is shown in fig. 4.16. The solar intensity of the site which is presented in figure below gives the range of the solar energy. It can clearly be seen from figure below that the daily water production/ flowrate of the pump increases almost linearly with increase in plane radiation. During the months which have cloud days the irradiance level is low this resulted in lesser pumped water. Since much of the months have irradiance value greater than 5kWh/day, the performance curve shows that solar water pumping for the site is technically promising to supply sufficient water to meet the irrigation demand in a given range of solar intensity of the site.

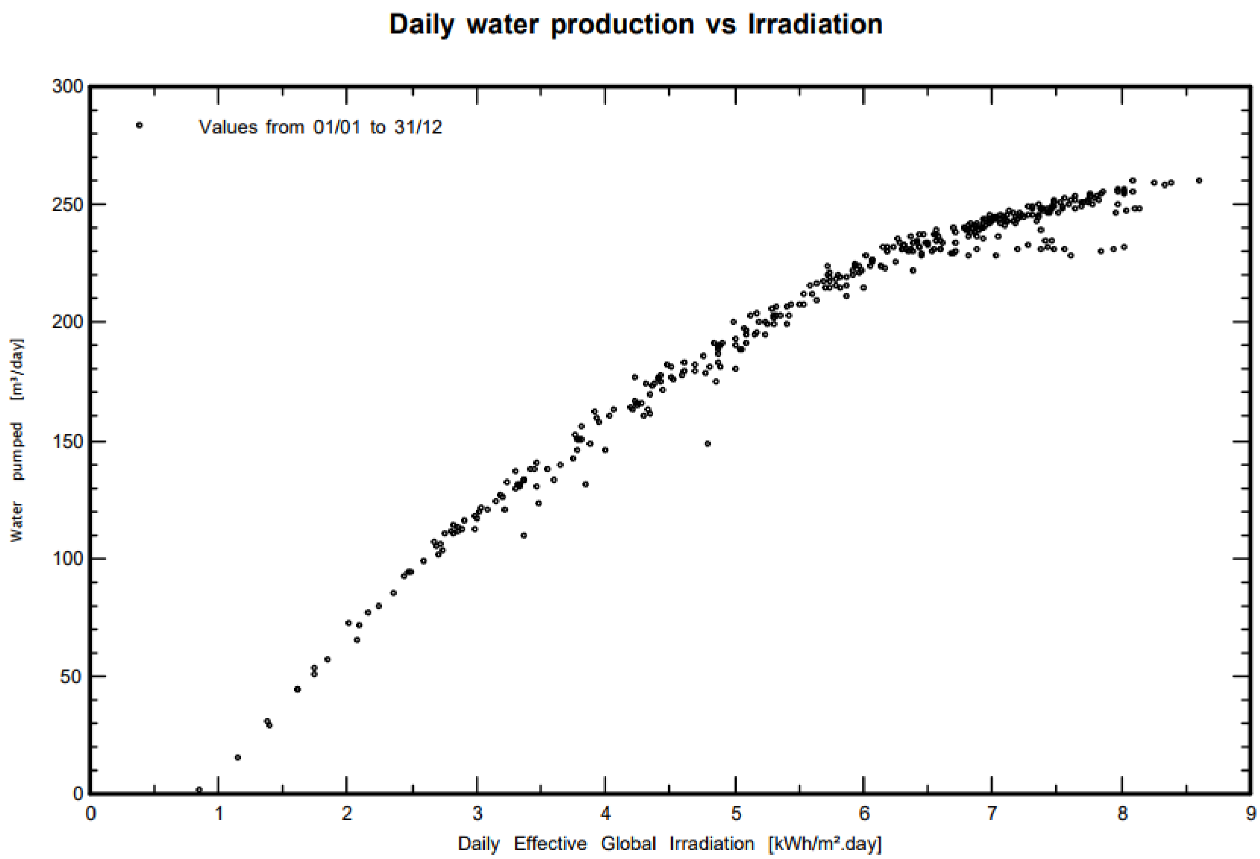


Figure 4. 16 Daily water Production vs irradiance

4.6.4.5 Global Pump Efficiency vs irradiance performance

The evaluation of the pump efficiency at various solar intensity is very important parameter. The aspect of pump efficiency characteristics is discussed hereafter. The profile in fig.4.17 shows that the best efficient point of the pump is attained when the available irradiance is higher. At a lower solar radiation, when the input power available to the solar water pumping system is lesser, the total efficiency is very less. With the increase the solar radiation input to the system starts to enhance the efficiency which in turn causes component to operate near the rated condition. Once the rated power is achieved the corresponding efficiency is also be achieved and the effect of further increment of the radiation becomes insignificant to affect the efficiency of the system. Therefore, since it was found from the solar potential assessment result that the minimal mean monthly solar radiation is to be greater than 5kWh/m^2.day, the performance plot shows the system operates at best efficiency point when the irradiance is somewhat greater than 4kWh/m^2.day. This makes the system technical suitable to be employed of irrigation by operating closest to the best efficiency point throughout the year.

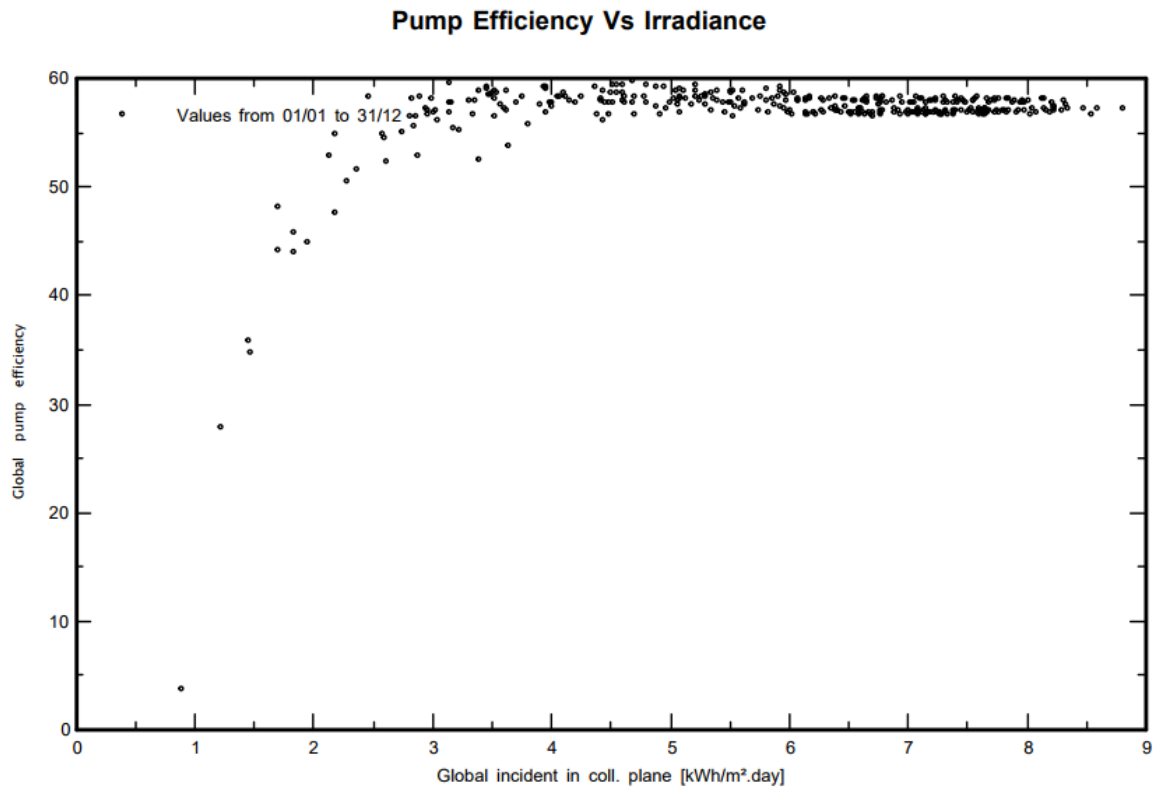


Figure 4. 17 Pump efficiency vs available irradiance

4.6.4.6 Monthly water production and Balance of Main results

The main results that depicts the energy balance and water production is tabulated below. The water amount of pumped water depends on the energy available at the pump. The amount of the pumped water from the result in table below shows that the irrigation water requirement can be met the proposed system. And also, the amount of energy available when the tank is full shows that the amount of excess energy that is unused and this excess energy is found in months where there is higher irradiance with respect to other months.

Table 4.4 Monthly water production and main balance results.

	GlobEff kWh/m²	EArrMPP kWh	E_PmpOp kWh	ETkFull kWh	H_Pump meterW	WPumped m³	W_Used m³	W_Miss m³
January	185.8	2061	1865	0.00	59.34	6587	6454	676
February	168.9	1856	1660	12.09	59.53	5865	5760	680
March	192.4	2107	1891	14.14	59.75	6612	6647	483
April	171.4	1890	1680	8.53	59.28	5948	5924	976
May	169.2	1880	1710	0.00	59.03	6120	6179	951
June	158.8	1787	1655	0.00	58.76	5886	5955	945
July	146.0	1653	1508	0.00	58.65	5298	5185	1945
August	151.3	1708	1562	0.00	58.79	5505	5598	1532
September	162.6	1808	1593	0.00	59.08	5635	5655	1245
October	187.0	2059	1821	3.39	59.38	6485	6394	736
November	195.2	2150	1893	14.41	59.87	6707	6665	235
December	191.0	2115	1888	9.40	59.68	6680	6690	440
Year	2079.5	23074	20727	61.97	59.26	73329	73106	10844

4.6.4.7 Energy production

The energy production of the system is directly proportional to the solar radiation. The fig. 4.18 shows the simulation result of the energy balance of Model 1. It should be noted that the model employed in the study is accurate in representing the seasonal variation of radiation and its effect on water pumping.

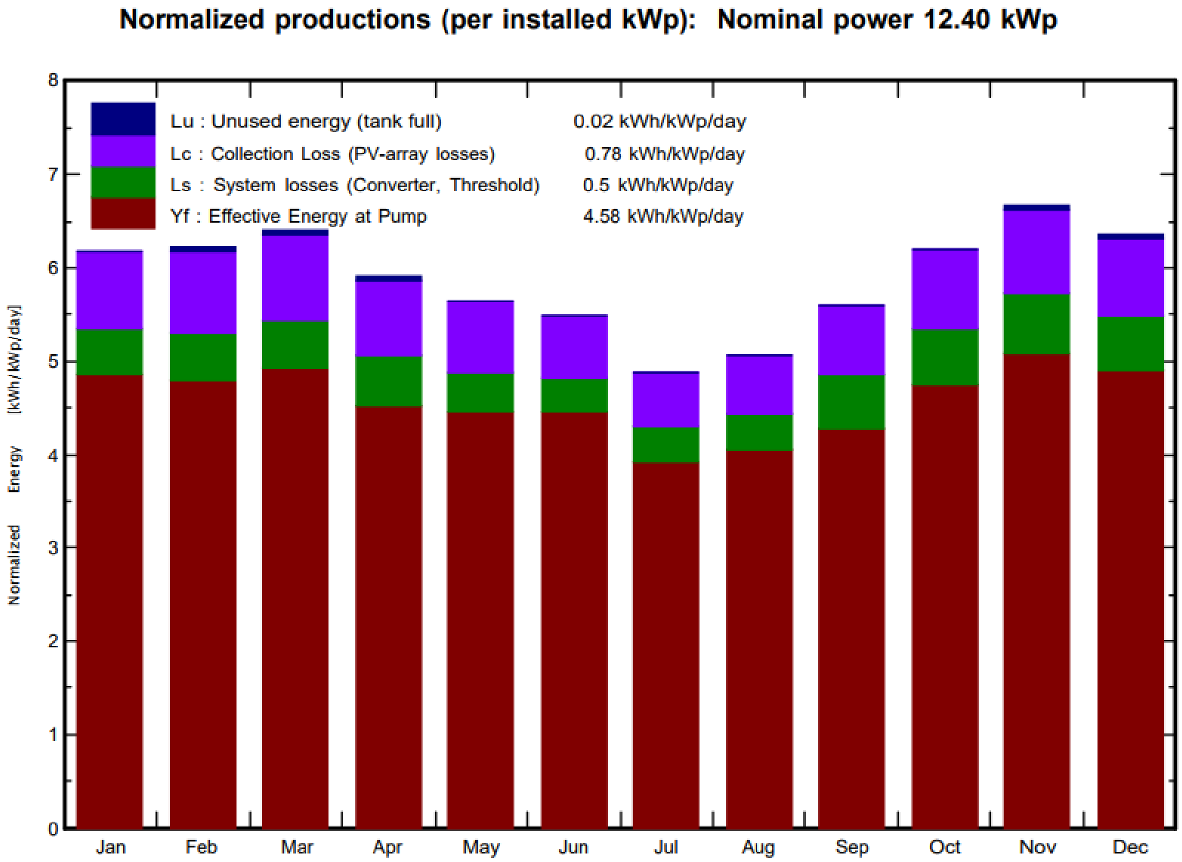


Figure 4. 18 Annualized monthly energy production

The normalized values of the effective energy, collection loss and unused energy in the system is given in above fig shows that the total electricity production from the PV system is not fully utilized by pump to meet the water requirement of the irrigation.

The amount of excess electricity produced accounts about 0.3% of the electricity demand. Although the excess electricity production depends on the storage medium, it was found that insignificant amount the surplus is obtained. It can be inferred from the this result that the unused energy is very low which make the system considerably effective in utilizing the available energy since the system is designed based on maximum power point tracking.

4.6.4.8 Performance ratio of the system

Performance ratio is another parameter for determining the technical feasibility is the performance ratio which relates the actual yield of the PV system to the target yield. The monthly performance ratio (PR) of the system is presented in figure 4.19.

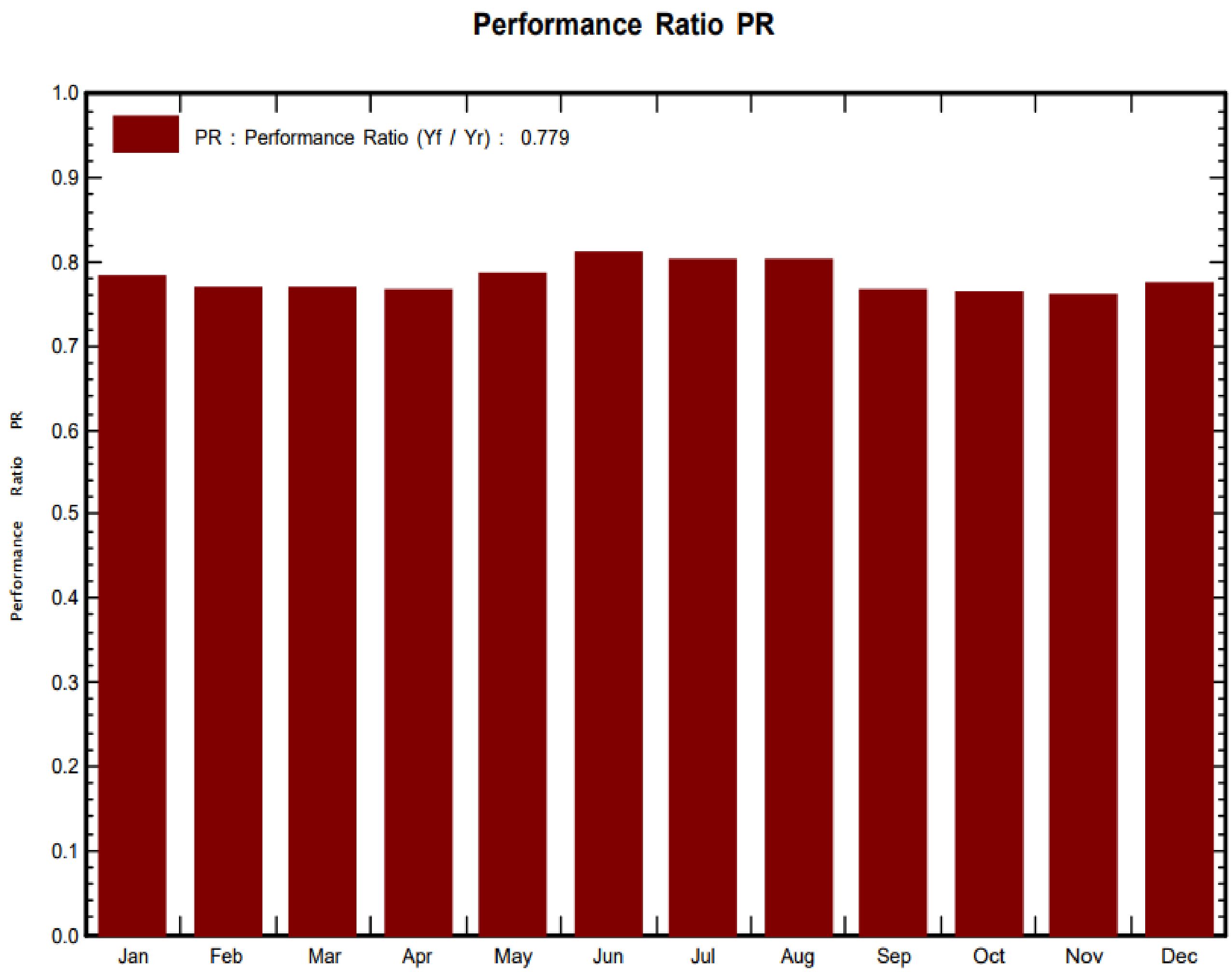


Figure 4. 19 Annualized Monthly Performance ratio

The performance ratio for the simulated system is found to be 77.9% which is the annual average PR value. There is slight variation in PR value on monthly basis which can be seen from the Fig. 4.19. Those variation occurs in months which have relatively higher temperature as the solar panel is affected by the cell temperature. As mentioned in literatures [73] the technical viability of the solar pumping system requires higher value of the PR. This parametric value is used also for setting the minimum standard that the system has to meet for in regards of plant degradation which is 77%. [73] This result depicts that the system is technically suitable and it has operational benefit as the corresponding performance ratio exceeds the minimal standard requirement which is considered for plant degradation.

4.6.4.9 Array Losses and Mismatch

Another result obtained from the simulated study is that the Sankey loss diagram, which helps in analyzing the various losses which are going to be encountered during the system installation. The Sankey loss diagram show in figure 4.20 represents various losses that occurs in the system. The global irradiance on the horizontal plane is 2,109kWh/m^2, but the effective irradiance on the collector is 2080kWh/m^2. This results in energy loss of 0.4% due to the irradiance level. When effective irradiance falls on the surface of the photovoltaic module, electrical energy is produced. Then the array nominal energy at STC is found to be 25,833kWk after the PV conversion. The annual virtual energy at the MPP is 23,074kWh. The various losses accounted in this stage, 10.4% is loss due to temperature, 0.7% loss is due to light induced degeneration, 0.3% loss is due to module array mismatch and 0.4% loss is due to ohmic wiring loss. The available energy on the annual basis at the output of the inverter is 20,789kWh and the possible losses are 3.3% loss during the inverter operation, 5.8% loss due to nominal inv. Power and 1.3% loss under the pump producing threshold. Finally, the energy available at the pump on the annual basis is 20,727kWh.

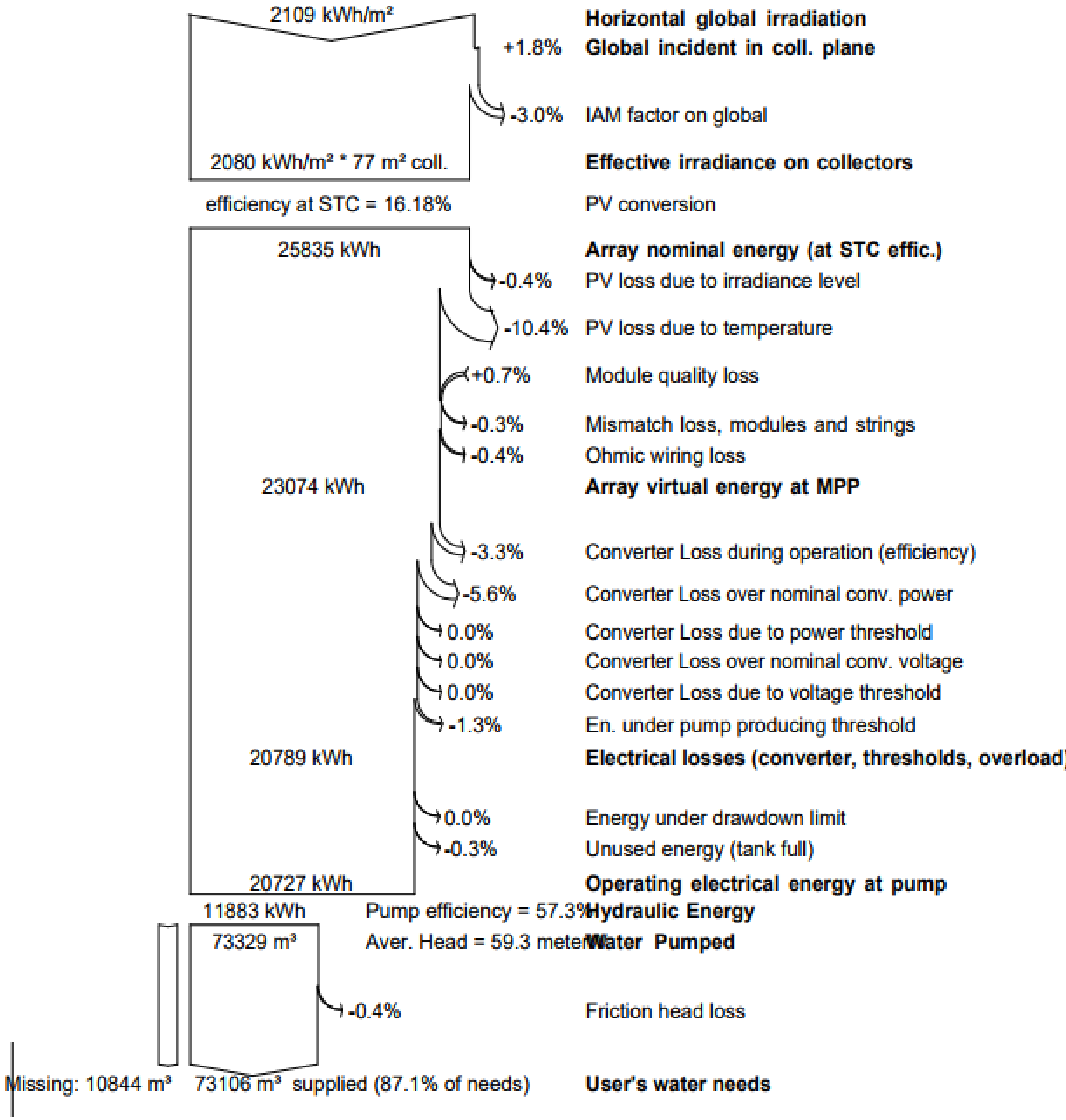


Figure 4. 20 Sankey Loss diagram over the whole year.

Based on the performance investigation the performance of various sub system of the solar water pumping constituents is performed. It is found that the PV module conversion efficiency is nearly constant with irradiance variation where as it is influenced by the ambient temperature. On the other hand, performance of the motor-pump system is sensitive to various parameters especially the irradiance intensity. But for the available radiation of the site the pump operates nearly at it best efficiency point by delivering the amount of irrigation water demand. The performance ration of the whole system high enough that it falls in a region where it is recommended range for the plant degradation. Therefore, result discussed above makes the application solar energy for pumping water to deliver the required water in such a way that system incorporates the water storage tank found to be technically viable and the economic feasibility and environmental aspect of this system and other alternative models are presented in the following chapter.

4.7 Model 2. Modeling the Irrigation system with Battery Storage

Different methods can be employed to for optimization of photovoltaic water pumping system. One of the methods to do so is numerical optimization. This model is developed to evaluate the technical and economic viability by replacing the water storage tank with battery and it is capable of supplying the same amount of irrigation water requirement and the same type of inverter is used for the modelling. There are many software's based on this method and Homer is one of these software's and it is used for the simulation of this model.

4.7.1 Introducing Homer

Homer is commercial micro-power optimization and simulation software developed by the NREL, USA. The simulation of the system is performed by calculating the energy balance equation for 8760 hours in a year and compares the solution with various configuration and finds the best economically feasible solution. [52]

The software provides various component and corresponding characteristics and also provide information about data source, source of power which includes components such as PV panels, wind turbines, generators batteries, etc.

Homer helps to find the least price combination of components that will meet the load requirement based on the hourly analysis of the input variables.

4.7.2 Model Description

Deferable Load

A deferrable load is a type of an electrical load that should be met within some duration of time but the exact timing is not important. [53] in this model the irrigation is system is associated with battery storage is considered to be deferrable load.

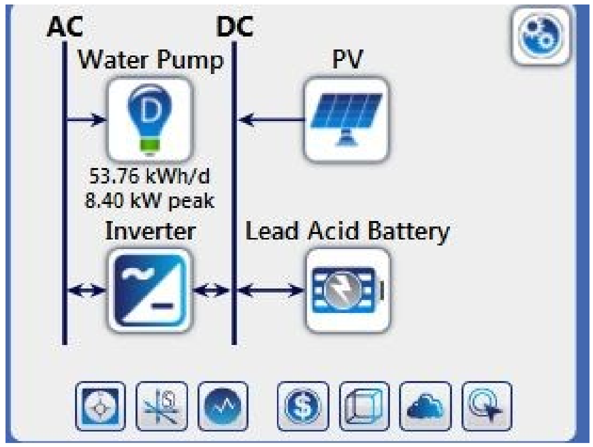


Figure 4. 21 Model 2. with battery

4.8 Model 3. Modeling the Irrigation system with Diesel Generator

Fossil fuel source is modelled in order to investigate the economic evaluation and the environmental impact that would have been resulted when compared to the PV system. Diesel generator is specifically selected for this comparison due to the fact that they are available and relatively convenient to use. Since this model is used for economic comparison the detailed result is report in the following section.

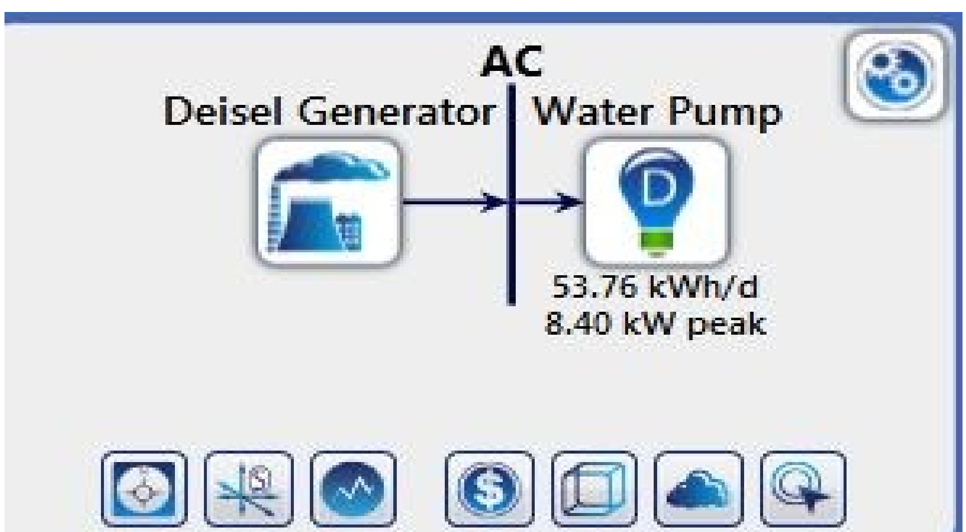


Figure 4. 22 Model 3. Using diesel generator

CHAPTER 5
ECONOMIC ANALYSIS AND ENVIRONMETAL ASPECT

5.1 General

One of the most important factors in any system design to consider is the determination of costs that are required to start and operate the system during its entire lifetime. The general feasibility of photovoltaic water pumping system depends not only on the perspective of technical viability but also economic viability. The economic analysis of the system is computed based on the life cycle cost (LCC) and cost of energy (CoE) method which determines the whole cost of the system. This analysis is done for each model by considering the price of various components including installation but in the case of direct water pumping the cost of the water storage tank is ignored whereas other equipment costs are described below. These costs of energy and life cycle cost of the PV system includes the cost of design, installation labor, site preparation, operation and maintenance cost. The life cycle cost LCC is calculated as follows:

$$LCC = C_{capital} + \sum_1^n C_{O\&M} * R_{pw} + \sum_1^n C_{replacement} * R_{pw} - C_{Salvage} * R_{pw} \text{ .... } (5.1)$$

The various components are taken in to account when calculating the LCC value as follows; capital cost $C_{capital}$, replacement cost $C_{replacement}$, maintenance and operation CO&M and salvage value $C_{salvage}$, R_{pw} represents the value of each factor of which is calculated using the future sum of money (Fm) over the given year range (n) at a given discount rate (i):

$$R_{pw} = \frac{F_m}{(1+i)^n} \text{ .... } (5.2)$$

The cost of energy is calculated as follows:

$$CoE = \frac{LCC}{\sum_1^n E_{PVannual}} \text{ .... } (5.3)$$

Where $E_{PVannual}$ is the annual energy production of PV system.

5.2 Economic assessment

In order to carry out this assessment economic factors such as life time of the system, discount rate and inflation rate should be determined. The system also depends on configuration as well as the components. These factors can be reflected in some technical decisions involved in the installation of the DC or AC pumps, fixed or solar tracking arrays, and battery or water storage systems. Comparison of between battery or water storage for fixed array is conducted in this study. Though the storage system becomes so crucial in cases where the irrigation electric load is defers from the PV electricity production in cases where night irrigation is required.

5.2.1 Cost of Photovoltaic array and charge Regulation unit

This system is connected form many modules arranged in parallel and series in such a way that to enhance the effectiveness of collecting the solar radiation. Though the cost of PV panels depends on many factors, the cost of the system is calculated per watt peak produced and the bigger the size the higher the cost is. The cost per watt peak of the modules had been dropped from $76.6 to 0.36 in the years 1997-2014 due to the fact that the use of renewable energy source is rapidly growing led to many companies PV manufacturing companies entering the market. The proposed PV panels have estimated capital cost of $1.4/W. The estimated lifetime is 25years and a derating factor was selected to be 90%.[62]

In order to match the generated power of PV panel with the power required by the user power regulating component is needed. For the case of DC pump, converter, for the case of AC pump inverter is required to balance the power. The charge controller unit has a lifetime up-to 15 years with 94% efficiency and with estimated price of $0.5/W.

5.2.2 Cost of Storage Unit

In this study two types of storage tank or battery are used for comparison to sore energy when the sun is not available. Though there are different choices of tank installation, for this research elevated water tank storage is considered to obtain the pressure required. The tank has the capacity to store water for one irrigation schedule which is sufficient to meet the water requirement for 3 days which has estimated cost of $2,500. Battery is used to store energy of PV module as a form of chemical. The economic evaluation took in to consideration of the lowest price of lithium ion battery which is estimated to be $98/kwh and the lifetime to be 15years.

Table 5.1 Input Parameter for Economic Evaluation

Capital cost of PV module	**$17,500**
Capital cost of inverter	$4,400
Cost of water Tank	$2,500
Maintenance Cost	$250
Operating Cost	$200

5.3 Economic Assessment of Diesel Pumping

For the sake of comparison fossil fuel generator had been simulated in a manner that it is capable of supplying the same amount of water per year as required. Diesel fuel is selected since it is the most frequently used in Ethiopia, more efficient and has a longer compared to others. In order to investigate the economic analysis, the lifetime of diesel and PV panel is taken as the same which is 25years. The cost of both storage and pumping unit is not considered because it is assumed to be the same in both systems and also the daily operating hour is also taken to be the same. The specific fuel consumption is the selected for the corresponding generator. Generic 10kW fixed capacity diesel Genset generator is considered for the analysis and corresponding price is $5,000 and it has the same power rating as the PV system and the technical information data is taken depending on the database of the manufacturer. Since in Ethiopia the price of diesel fuel is subsidized by the government, the work employs this price which is $0.65 per liter. [63]

5.4 Economic Evaluation of each of the three options

5.4.1 Economic Evaluation of Model 1.

The economics of model 1. irrigation system depends on the configuration of the system component as well as the benefit produced. The profitability of any system depend on the market price of the harvested drop and increased productivity yields due to the implementation of the system. During the economic feasibility study the market price of the crop is not considered but it is assumed to be the same for each model. The economic parameters of net present cost, NPC, and cost of energy, CoE, is used for the investigation. This analysis NPC and CoE neglects additional investment related to the irrigation system, installation, labor, wiring, supports and integration and also since the same type of pump is assumed to be used in each model the corresponding price is omitted and the corresponding economic parameters are given in table below.

Table 5.2. Economic Results of Model 1.

Pumping PV System			
Net Present Cost	**Water Cost**	**Cost of Energy CoE**	**Resource (Fuel Cost)**
$24,224	$0.02/m^3	$0.06/kWh	$0

5.4.2 Economic Evaluation of Model 2.

The intention of this section is to present the finding of the investigation made when the water storage tank is replaced with battery storage which have the same capacity of irrigation autonomy. This model is capable of supplying the same amount of irrigation water requirement and the same type of inverter is used for the modelling. In the results, numerous feasibility alternatives are considered in the simulation by calculating energy balance of the operational system and comparing to different configuration.

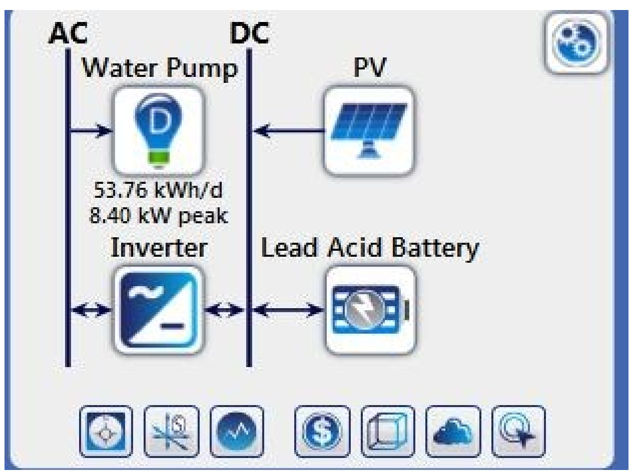


Figure 5. 1 Model 2.

The suggested PV module for the simulation is generic flat plate panel with nominal capacity of 10.6kW. The suggested battery storage has the nominal capacity of 40.9kWh which is used is 12V bus and 3408 Ah capacity with estimated cost $4,000. It worth mentioning that the software does not take into consideration the temperature variation or any degradation in the performance of the battery. Moreover, the modelled inverter has the efficiency of 94% being able to operate at the nominal capacity of 7.7kW. The brief summary of the components is given in the table below.

Table 5.3. Technical Specification of the PV system with battery storage

Component	**Generic Flat Plate PV**		
Rated Capacity	10.6kW		
Capacity factor	22%	Excess Electricity = 642kW/year (3.14%)	
Electricity Production	20,484 kWh/year	Deferable Load = 19, 039kWh	
Component	**Inverter - Studer Xtender XTH 8000-48**		
Rated capacity	7.7kW		
Capacity Factor	28%		
Component	**Battery – Enersys Power safe SBS 3100**		
Nominal Capacity	40.9kWh		
Expected life	15years		

After the simulation is run in Homer numerous feasible results are list according to system minimum net present cost (NPC) and cost of energy (CoE) show in the table 17. The simulation output suggested that the optimal system configuration is achieved when the system is composed of the components listed on the above table. The optimal cost of this model has total NPC of $25,807 and the cost of energy equals to $0.07615/kWh.

Table 5.4 Economic Result of Model 2.

		Total NPC = $25,807		**Levelized CoE=$0.07615 /kWh**		
Component	Capital cost	Operating Cost	Replacement cost	Salvage cost	Resource (Fuel) cost	Net Present Cost
Generic Flat Plate	$14,891	$0	$0	$0	$0	$14,891

Enersys Powersafe SBS 3100	$4, 000	$890	$2,114	$-534.33	$0	$6,469
Other	$0	$178	$0	$0	$0	$178
Studer Xtender XTH 8000-48	$3,852	$0	$513.68	$-96.47	$0	$4,269
System	$22,743	$1,068	$2,627	$-631	$0	**$25,807**

The generated energy from the PV system is determined and the system availability is calculated as the percentage time that the system is capable of meeting the load requirement and it is found that only 2.54% of the required load is unmet.

5.4.3 Economic Evaluation of Model 3.

Fossil fuel generator is simulated for the sake of economic and environmental comparisons to supply the same amount of irrigation water throughout the year as shown in fig. 53. Though there are various types of generators are available, diesel generator has been used for the investigation since they are available, efficient and has longer life compared to the other types of fuel.

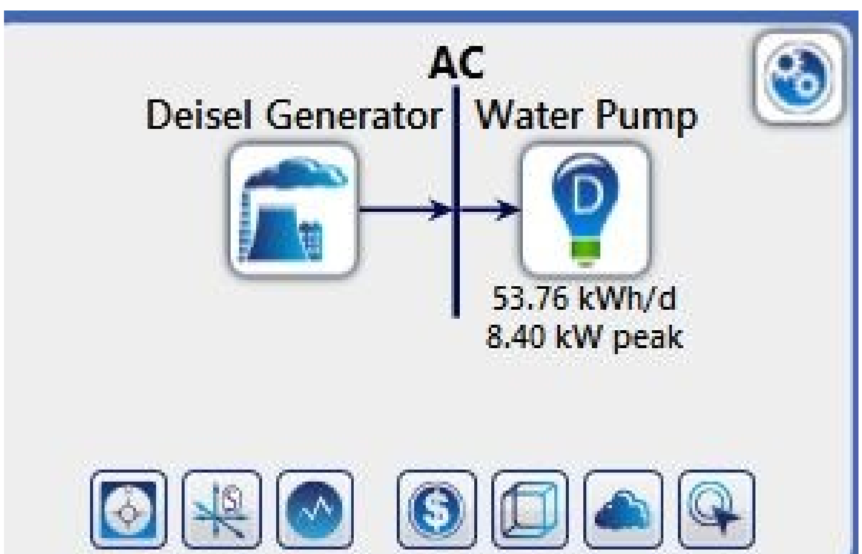


Figure 5. 2 Model 3.

The Generic 10kW fixed capacity diesel Genset generator is considered for the analysis and corresponding price is $5,000.

The simulation and economic optimization of Model 3 is done, for both technical and economic aspect, based on the manufacturer database integrated into the Homer. and performed. The technical finding is tabulated in table below.

Table 5.5 Technical Specification of the Diesel Generator

Component	Generic 10kW Fixed Capacity Genset		
Electricity Production	19,522 kWh/year	Mean Electrical output = 8.4kW	Sfc=0.343l/kWh
Consumption	Deferrable Load	19,522kWh/year	
Excess Electricity	0kWh		

The generator is able to produce 19,522 kWh/year to pump the irrigation water requirement which is modelled as deferrable load. The corresponding specific fuel consumption is determined and used for the projecting of the cash flow of implementing the system for 25years.

To compare the proposed PV system with the diesel generator 10kW the analysis estimates that the capital, operational, replacement cost to be $5,000, $9013, $7,501 respectively over the course of the projected year and it is summarized in the table 19. More over the cost of energy (CoE) and Net present cost (NPC) is found to be $0.3077/kWh and $77,651 which is considered to be higher than the other proposed systems.

Table 5.6 Diesel System economic Results.

Component	Generic 10kW Fixed Capacity Genset			Levelized CoE=$0.3077/kWh	
Capital cost	Operating Cost	Replacement cost	Salvage cost	Resource (Fuel) cost	Net Present Cost
$5,000	$9,013	$7,501	$-151.72	$56,288	**$77,651**

5.5 Environmental aspect assessment of Greenhouse Gas Emission

Currently, one of the trending problems the world is facing is the global warming. In order to avoid the global warming, it is necessary to reduce the emission of the greenhouse gases. Since a global study of the size and cost of measure to reduce those gases emission yields important insight for the policy makers. The emission that would have been generated by the adoption of the conventional diesel fuel is considered in this study to show the benefit that PV system has to protect the environment from harmful gases and table 18 shows the polluted emission generated the modelled diesel fuel. Furthermore, beside protecting the environment there is carbon abatement cost which give a sound economic advantage for the PV system which is about 40£ per ton of carbon dioxide. [64]

Table 5.7 Diesel system Greenhouse Gasses Emission

Green-house Gas Emission summary	
Pollutant	Quantity
Carbon Dioxide	17,500 kg/year
Carbon Mono-Oxide	132kg/year
Unburnt Hydrocarbons	4.82 kg/year
Particulate Matter	8.03kg/year
Sulfur Dioxide	42.9 kg/year
Nitrogen Oxides	150 kg/year

CHAPTER 6
CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this study, solar water pumping has been designed for irrigation of onion farm which found in Kete Dori village. The main focus of this study can be classified into two categories. The first category is concerned with the effective design of the sprinkler irrigation system. Preliminary data collection is under taken to understand the required parameters. Based on those data sprinkler means of irrigation is selected since it has advantage of having more efficient use of water and avoids the water conveyance channels, the evenly distribution of water has shown to increase the crop yields and it is suited for row, and field crop such as Onion and all types of soil except heavy clay and reduce the risk of soil erosion since it limits the system soil disturbance. The system is designed to fulfill the irrigation water requirement of 5 hectares of onion vegetation which is based on peak water requirement.

The second section is concerned with the design and simulation solar water pumping system with tank and battery storage. But supporting the irrigation system strongly depends on the availability of the solar radiation. This paves the way for the solar potential assessment of the site. The daily average of the lobal irradiance data is obtained from NASA-SSE satellite database. The finding shows that the site has considerable potential which is viable for the implementation of the PV system.

The technical and economic assessment of the system is conducted. The optimal system components have been selected based on the technical and economic merit. Accordingly, the system has two pumps connected in parallel to deliver the water demand each having 4.2Kw nominal capacity, and PV module implemented to power has 12.4kWp nominal capacity and integrated with MPPT inverter which is fixed mount based on the optimized tilt angle of 10 degree. The proposed system is found to have a system efficiency of 89.8% which is based on the optimal system configuration. The corresponding water tank has the capacity of storing water for up to 3 days of irrigation frequency. The performance characteristics of the system is investigated to assess the technical feasibility. The performance ratio is found to be a yearly average of 77.9% which makes the implementation of the system technically viable. The economic evaluation of the proposed system is investigated based on the economic optimization. It has also been found that the proposed system is capable of providing daily average of 230m^3 water per day at costs of energy of $0.06/kWh and throughout the 25-year projection the minimal net present cost associated is $24,224.

A solar water pumping model with battery storage is also carried out to the investigate economical and technical viability of adopting the system in comparison with the proposed model. Based on that the feasibility study, the results show that the system capable of meeting the same amount of irrigation water demand is comprised of PV module with rated capacity of 10.6kW integrated with MPP inverter and it has the capacity factor of 22%. This implies that the technical aspect of implementing this system is viable since the typical value of capacity factor is around 21%. [75] Moreover the economic study and optimization conducted over the same projection year found that delivering the same load as the proposed system, has a cost of energy of $0.07615/kWh and the minimal net present cost is found to be $25,807. Depending on those results although the system with battery storage medium is technically feasible, the corresponding NPC and CoE hinders the economic viability in comparison. Besides the additional issue associated with the disposal of the battery after the end of life time sets another technical barrier. The NPC of $25,807 and CoE of $0.06/kWh makes the proposed system both technically and economically feasible.

In addition, for the sake of investigating the environment impact and economic perspective diesel fuel power system, Model 3, which is capable of delivering the same load is also simulated. Although the price of fuel in Ethiopia is subsidized, a conservative approach is followed by taking the subsidized fuel price which is $0.65/l for the economic analysis. It is found that the diesel system which is capable of meeting the irrigation water requirement has the minimal net present cost $77,651 and cost of energy of $0.3077/kWh which is clearly higher than the previous models.

The economic and technical investigation conducted is this study strongly depicts that the implementation of the proposed model is both technical and economically feasible. Moreover, the analysis also shows that replacing the diesel fuel with PV system will protect the environment from the greenhouse gases emission of 17,500 kg/year of CO_2, 132kg/year of CO, 4.82 kg/year of unburnt HC, 42.9 kg/year of SO_2, 150 kg/year NO_x, 8.03kg/year of particulate matters and also it worth mentioning that there is economic merit of the greenhouse gas abatement cost.

6.2 Future Work

The main finding of the work is able to provide the effective irrigation design, optimization and technical and economic feasibility assessment of the solar water pumping system. The conducted work is able to meet the objective in those perspective. Some of the issues that requires further study are listed below.

- The effect of climate on irrigation water requirement is essential and accurate data metrological data collection is essential is both system optimization and solar potential assessment.
- The technical assessment parameters have to be experimentally investigated using appropriate tools to get more comprehensive assessment results.
- The irrigation water requirement is based the peak water requirement, the effect tis on crop yield and productivity should be investigated in order to decide the technical viability and profitability.
- Further investigation has to be conducted in order to verify the possibility of using another or a combination of various renewable sources in such a way that the implementation will both technically and economically viable.

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APPENDIX

A1. Field Data Collection form

System categories	Data to be collected		Description	remarks
Water source	Location	Kete Dori Village	The river used is of Awash Basin	Arsi zone, Geju woreda
	Details of availability	Available Water for irrigation		
	Static Head	**6.5m** until it reaches the irrigation/ farm surface		
	Peak water requirement			
	Distance required (water source and irrigation ground)	**100m**	Is after the well reaches the irrigation surface	
	Infiltration system	**NONE**		
Layout of the system	Topography/ location	Latitude	**$8^0$21'48''N**	
		Longitude	**$39^0$31''04''E**	
	Area to be irrigated	**5 hectares**		
	Slope	**2^0 downward**		
Vegetation/ plantation	Type of plant	**Onion**		
	Plant spacing	**25 X 25cm**	Space between consecutive rows and roots is the same a specified	
	Root zone depth			
	Soil texture/type/properties	Clay/Clay loam		
Irrigation system	Type of irrigation	Traditional/ surface irrigation	Sprinkler is proposed	

	Evapotranspiration data	**Have to be determined from literature**		
	Precipitation rate		Metrological data is available	
	Frequency of irrigation	2 Times per day	2hrs each	4hrs
	Number of wells			
Pumps	specification	Type		
		Rating	3600rpm	
	Required pressure			
	Design discharge	$40m^3/hr$		
	Total head	16m		
Diesel engine	Model	**CHANGFAZS1125G**		
	Max power output	27.5hp/2200rpm		

A2. Table. sprinkler manufacturer catalogue

F32SV — Single Nozzle w/vane — 3/4" Aluminum Arm

NOZ. PSI	7/64" GPM	7/64" DIA. FT.	1/8" GPM	1/8" DIA. FT.	9/64" GPM	9/64" DIA. FT.
25	1.73	78	2.25	82	2.88	85
30	1.89	79	2.47	84	3.15	87
35	2.05	80	2.68	85	3.40	89
40	2.19	81	2.87	86	3.64	91
45	2.32	82	3.05	87	3.86	92
50	2.45	83	3.22	88	4.07	93
55	2.57	84	3.38	89	4.27	94
60	2.68	85	3.53	90	4.46	95
65	2.79	86	3.68	91	4.65	96
70	2.90	87	3.82	92	4.83	97
75	3.00	88	3.96	93	5.00	98
80	3.10	89	4.09	94	5.17	100

A3. Faucet Joint

Product Code	Size DN	C	C1	L	L1	S
36390	15x15	15.5	15.5	43.2	43	17.1
36400	20x15	20.5	15.5	43	42.4	17.1
36410	20x20	20.5	20.5	43	42.4	20
36420	25x15	26.8	15.5	46.2	46.2	17.3
36430	25x20	26.8	20.5	46.2	46.2	19.7
36440	25x25	26.8	26.7	46.2	46.2	23.6
36450	32x15	33	15.5	52.5	35	16
36460	32x20	41.7	20	48	45.8	19.7
36470	32x25	41.7	26	48	45.8	22.8
36480	40x15	38	15.5	58.5	37.5	16
36490	40x20	47.7	20	50.9	49	19.7
36500	40x25	47.7	26	50.9	49	22.8
36510	50x15	48	15.5	74	47	16
36520	50x20	59.7	20	57	55.1	19.7
36530	50x25	59.7	26	57	55.1	22.8

A4. Cross connection specification

Part Number	Size	G	G1	H	H1	L	L1	M	M1	Approx. Wt. (Lbs.)
420-101[1]	3/4x3/4x1/2x1/2	1-7/16	1-1/16	1-9/16	1-13/16	3-1/8	3-5/8	1-5/16	1-5/16	.17
420-131	1x1x3/4x3/4	23/32	5/8	1-5/8	1-5/8	3-1/4	3-1/4	1-7/8	1-17/32	.30
420-167[1]	1-1/4x1-1/4x3/4x3/4	1-1/8	1-21/32	2-11/32	2-21/32	4-11/16	5-5/16	2-1/32	2-1/32	.71
420-168[1]	1-1/4x1-1/4x1x1	1-3/32	1-9/16	2-11/32	2-5/8	4-23/32	5-7/32	2-1/16	2-1/16	.56
420-248	2x2x3/4x3/4	11/16	1-7/16	2-7/32	2-7/16	4-13/32	4-7/8	2-29/32	1-13/32	.55
420-249	2x2x1x1	13/16	1-3/8	2-3/16	2-1/2	4-3/8	5	2-3/4	1-5/8	.39
420-250[1]	2x2x1-1/4x1-1/4	1-9/16	2-1/16	2-15/16	3-15/16	5-27/32	6-5/8	2-13/16	2-13/16	1.34
420-251[1]	2x2x1-1/2x1-1/2	1-17/32	1-25/32	2-29/32	3-1/8	5-13/16	6-1/4	2-25/32	2-25/32	1.18
420-288[1]	2-1/2x2-1/2x3/4x3/4	1-21/32	3-3/32	3-21/32	4-3/32	7-11/32	8-7/32	3-3/8	3-3/8	2.33
420-289	2-1/2x2-1/2x1x1	7/8	1-23/32	2-11/16	2-7/8	5-11/32	5-3/4	3-1/2	1-3/4	.97
420-335[1]	3x3x1x1	1-15/16	3-1/4	3-15/16	4-3/8	7-7/8	8-3/4	4	4	3.12
420-336[1]	3x3x1-1/4x1-1/4	2	3-1/8	3-15/16	4-3/8	7-7/8	8-3/4	4	4	3.11
420-337[1]	3x3x1-1/2x1-1/2	1-31/32	3-1/16	3-31/32	4-3/8	7-15/16	8-23/32	4-1/32	4-1/32	3.14
420-338[1]	3x3x2x2	2-1/16	2-5/8	3-31/32	4-9/32	7-29/32	8-9/16	4-1/32	4-1/32	2.72
420-339[1]	3x3x2-1/2x2-1/2	1-15/16	2-11/32	3-15/16	4-11/32	7-7/8	8-11/16	4	4	2.97
420-420[1]	4x4x2x2	2-1/2	3-17/32	4-1/2	4-29/32	9-1/32	9-13/16	5-1/32	5-1/4	4.99
420-420F	4x4x2x2	4-1/2	4-1/4	6-3/4	6	13-1/2	12	5-1/16	2-11/16	3.37
420-421[1]	4x4x2-1/2x2-1/2	2-1/2	2-15/16	4-1/2	4-15/16	9	9-7/8	5	5	5.08
420-422[1]	4x4x3x3	2-1/2	2-15/16	4-1/2	4-15/16	9	9-7/8	5	5	4.90
420-528F	6x6x2x2	5-1/8	5-5/16	8-3/8	7-1/16	16-3/4	14-1/8	7-3/16	2-11/16	7.71
420-529F	6x6x2-1/2x2-1/2	5-3/8	5-13/16	8-5/8	7-13/16	17-1/4	15-5/8	7-3/16	3-1/4	9.21