Optimization of a Directly Coupled PV Water Pump for Irrigation Purposes

By

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MSc. In EEE

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Declaration

It is hereby declared that

1. The thesis submitted is my own original work while completing degree at Brac University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.

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Abstract

Bangladesh is an agricultural country where agriculture sector plays an important role in boosting the economic growth. But during dry season, collecting adequate amount of water becomes challenging to farmers. The use of photovoltaic as the power source for pumping water is one of the most promising areas. Solar pumps are cost-effective and environment-friendly. This paper deals with an optimized design for solar powered pumping system that can fulfil the requirement of water for irrigation purposes without the use of batteries or generators during the day. In Bangladesh, from February to April and from September to November are the cultivation periods. Among these periods, November and February are the most critical month due to insufficient rainfall. This work aims to the water requirement for irrigation mainly during two mentioned cultivation periods. Here, optimum tilt angle for the panel is calculated for which the required panel size is minimum that can supply the required amount of water for irrigation during the cultivation period.

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Dedication

This thesis is dedicated to my beloved parents, my husband, my son and specially to my supervisor who have supported me all the way since the beginning of my studies. Without my supervisor it will not be possible for me to pursue my degree.

Acknowledgement

By the Grace of Almighty Allah, I have completed my thesis and able to achieve the goal. I would like to thank my supervisor Prof. Dr. Md. Mosaddequr Rahman for giving me the opportunity to work under his supervision. He always helped me by giving suggestions, ideas and supports to solve my problems and guided me to develop this thesis for this semester. I also would like to thank my parents and family for making it possible to study and for their constant help and support they always give me. I would like to thanks my colleagues and senior faculty members who always give me mental support and help me to achieve the goal. Hopefully, this work will be appreciated by my supervisor and respected faculties.

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List of Acronyms

PV	Photovoltaic
SPWPS	Solar-Powered Water Pumping Systems
MPPT	Maximum Power Point Tracker

List of Symbols

AM	Air Mass
δ	Declination angle
θ_Z	Zenith angle
L	Latitude
ω	Hour angle
φ	Solar Altitude Angle
λ	Optimized tilt angle
I_{SC}	Short circuit current
V_{OC}	Open circuit voltage
I_S	Saturation Current
η	Efficiency
n	Ideality factor
R_{SH}	Shunt Resistance
R_S	Series Resistance
I_{ph}	Light generated current
K	Boltzmann's constant
T_C	Cell temperature
G	Solar irradiance
N_P	No. of cell in parallel
N_S	No. of cell in series

Chapter 1

Introduction

Agriculture plays a vital role in economic sector in Bangladesh and many countries. Water is the one of the significant elements for the agriculture. During dry seasons, collecting desired amount of water is the most challenging part for irrigation. Therefore power generated water pumps are mostly used by the farmers to irrigate crops which are mainly run by fossil fuel like natural gas, coal and other types of oil. These primary energy sources are not only limited but also the prime cause environmental pollution. Therefore, there is a widespread use of water pumps to irrigate the lands which is supported mostly by the grid electricity at present. This puts huge pressure on power grids causing load shedding. To overcome these problems, researchers and scientists are working to find an efficient solution based on renewable sustainable energy which will be environment friendly and also cost efficient [3-5].

1.1 Literature Review

Increasing awareness about the evolving energy crisis in the world, solar-powered water pumping systems (SPWPS) have been created focus of interest for researchers now a days. Several researches have been done all over the world to investigate and analyze the performance of the solar powered water pumping system.

The meet the required amount of water pumping lies partly with the elimination of the intermediate phase, namely the battery bank, for energy storage. The mostly efficient form of direct-coupled systems is when the water is stored to storage tank by pumping, thus the electrical energy from the panels is converted to potential energy, to be used on demand, by gravity [4]. The overall efficiency that has been recorded to exceed 3% in 2005 from sunlight to water flow.

After economic analyzing, it is shown that solar water pumping system for irrigation in Bangladesh is more feasible than Diesel engine pumping system. In economical point of view, PV pumping system is a little bit higher than the diesel engine pumping system due to high cost of PV module and its components [6]. This system is environment friendly and easy to implement for irrigating fields. To further enhance the daily pumping rates tracking arrays can be implemented. Even though there is a high capital investment required for this system to be implemented, the overall benefits are high and in long run this system is economical [7].

There is a huge potential for solar water pumping technology in Algeria for drinking and irrigation purpose. Amina et al. proposed a model of standalone solar water pumping system. The effect of the optimum design of PV water pumping system and the influence of metrological conditions of Adrar city of Algeria on the performance of the system was studied in this paper [8]. In Iran, 20.5 billion kWh electricity can be consumed from groundwater pumping and 2 billion liters of diesel and contributes about 3.6% of the total carbon emissions. Kerry A. Sado et al. investigate a PV-powered DC Water Pump System for Irrigation in Duhok City considering the optimum tilt angle, the effect of solar radiation on motor power, current, and water discharge [9]. Maidi et al. conducted a research to calculate of solar and wind resources and compare the efficiency of water pump using a battery energy source with a pump that only use a charged battery with solar and wind power in Indonesia [10]. To make it easier for agriculture land by utilizing solar and wind pump technology is the purpose of this research. For this research author used submersible pump having specifications of Power: voltage: 220 Volt, 45 Watt, and maximum head: 4 meters, 1200 liters/hour water flow and Water tank with a capacity of 50 liters of water. The observations that they found from their results are: The intensity of solar radiation and wind speed are very powerful as a pump drive solar and wind energy.

In 2018, Mansur Aliyua et. al. has published a review paper on solar powered water pumping system (SPWPS) [11]. They present a detailed intensive review of SPWPS as reported in the literature. Authors gathered several recent papers in this article covering survey, analytical, experimental, design, assessment, optimization, modelling and simulation. A lot of research has been focused on increasing the overall efficiency of SPWPS. The advancements in this field have been focused on solar collection system, water pump, pump head, control systems, and also data acquisition system, and the maintenance of these components and systems. In another review paper, Rathorea et. al. analyzed in detail the government policies and support system for the growth of solar photovoltaic water pump (SPVWP) in India [12]. It describes in brief the technology used and discusses in detail the opportunities for SPVWP development and current status of SPVWP in India and in the world. The author has summarized some of the key barriers to the growth of the SPVWP market due to which farmers are not able to adopt sustainable ways of irrigation. At the end, the author concludes with some policy recommendations.

In Bangladesh, the Infrastructure Development Company Limited (IDCOL) is implementing the solar irrigation pump program in support with Non-governmental organization, micro-finance institutions, and private sector companies. It has already installed 108 solar water pumps and has approved 241 pumps to be installed [13]. Md Tanvir et al. represents a paper with the design and performance analysis of a DC photovoltaic water pumping system [14]. A DC solar water pump has been with a direct connection from solar array. This design is completely built in various Laboratory of Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. Another designing and analyzing of a small scale solar powered water pumping system has been described by Shahidul et al. [15]. In this research the design, technical and economic analysis of a low cost 1 hp (746 W) small size dc photovoltaic water pumping system for irrigation has been discussed. They investigated that higher panel efficiency and higher operating voltage will improve the performance of the pump. It is shown in this research that the locally developed solar water pumping system are not so much costly than the imported one. Mohammad Nadim et al. find the optimized tilt angles for various divisions of Bangladesh in their paper using two methods [16]. One optimized tilt angle for a whole year and the other two tilt angles for two halves of a year. Additionally, checked the benefit that might occur from using more complex systems involving more tilt angles. The one best system was proposed considering the minimum increase in complexity of installation and resultant increase in output.

Many researches, investigation and surveys have been done on the solar powered water pumping system in Bangladesh. Besides the designing of small scale solar powered water pumping systems many researches have been placed on the perspective, present scenario and future aspects of solar powered water pumping system.

But there is still opportunity to work for low cost solar water pumping system design and optimization. Proper energy estimation, tilt angle optimization, motor and pump selection and system design is necessary to understand the performance of different system. In this work, necessary work is done to find an optimum tilt angle for the panels that will maximize the energy collection during the cultivation season and make the system efficient and cost-effective by requiring minimum panel size. Also detailed calculation has been done for water output for studied system.

1.2 Objective

The aim of this study is to design an efficient solar powered water pumping system for irrigation purposes. Producing electricity from solar energy may be a promising prospect for Bangladesh due to its geographic location. Solar energy is available in abundance during the dry season when irrigation water requirements are the greatest [18].

The main focus of this paper is the desired water requirement for irrigation during two cultivation periods, one from February to April and the other from September to November, since during these two cultivation periods weather is mostly dry and the amount of rainfall is low . As a result crop cultivation depends mainly on ground water. Moreover, these two cultivation periods are the prime time for irrigating of rice and for the cultivation of winter vegeTables. Water requirement for crop cultivation during summer season is not that critical as it is accompanied by frequent rain.

1.3 Scope of work

For this designing process, no external resource or battery has been used for powering the pump. This process is known as directly coupled system. In SPWPS, electricity from the solar panel module is sent directly to the pump. The reason behind choosing this system is that it is simple requires minimum maintenance and is least expensive which will make it economically affordable and technologically feasible for the farmers in remote villages.

In order to optimize the solar powered water pump system, panel size that can produce the energy necessary to pump the required amount of water all through the cultivation season needs to be minimized. One of the main factors that affect the panel output is the sun's position in the sky which varies from sunrise to sunset in a day and also from day to day throughout the year [19]. For the countries that are situated in the northern hemisphere like Bangladesh, sun is tilted south, and to maximize the energy collection by the panels, panels are mounted at an angle facing south. It is a standard practice to mount the panels with a tilt angle equal to the latitude angle to maximize the energy collection for the whole year.

However, the two crop cultivation seasons considered in this work spans from September to April, and will therefore need a different tilt angle to maximize the energy collection. In this work, first attempt has been made to find an optimum tilt angle for the panels that will maximize the energy collection during this period and make the system efficient and cost-effective by requiring minimum panel size. This is followed by a detailed calculation of water output by the pump using the estimated panel size for different tilt angles to verify that the designed system does meet the requirement.

1.4 Thesis organization

In this thesis the sections have been organized in following manner:

Chapter 2 gives a brief background about the agriculture and a brief overview of the location selected for this study

Chapter 3 explains how the Solar Powered water Pumping System works and different types of the water pumping systems

Chapter 4 describes the mathematical formulations used for calculating incident solar energy for different tilt angles and the optimized tilt angles for different time periods

Chapter 5 describes the detailed results and analysis of the daily average solar energy for different months obtained for different optimized tilt angles and estimation of optimum panel size

Chapter 6 provides validation of the solar powered water pumping system design.

Chapter 7 provides conclusion.

Chapter 2

Agriculture and Climate of Bangladesh

2.1 Agriculture sectors in Bangladesh

Agriculture plays a vital role in our economic and employment sector in Bangladesh. Now a days this sector has blooming improvement in our employment generation, diminishing poverty, development of human resources etc. A large portion of people in Bangladesh depend on Agriculture. It becomes more challenging to increase crop production which is accelerated by the rapid population growth. Besides food security, the sector alone contributes about 12% of the GDP and employ 44% workforce of the country [8]. Agriculture is one of the most risky sector which is depend on climatic factors such as temperature, rainfall, light intensity, radiation and sunshine duration. Bangladesh is one of the most climate vulnerable countries in the world. It is Located between the Himalayas and the Bay of Bengal. Our main crops like rice and wheat can be harvested several times in a year due to fertile soil and sufficient amount of water. Seasons are mainly three types in our country: hot season, rain season and dry season. Hot seasons are from March to June, increased precipitation will worsen the flood situation, which will have negative effect on agriculture production, Rain season are from June to September, and dry season are from October to February. Less rainfall during dry season due to climate change will lead to a decrease in moisture content of the topsoil, as well as less recharging of the ground water.

Crops

Crop any plant material fully grown, harvested or collected for human use. Over eighty crops area unit fully grown worldwide, providing folks with the main a part of their food and supply fibers, construction materials, prescription drugs, beverage, rubber, dyes and different materials. Crops area unit sometimes recognized beneath four major teams. Major crops that area unit fully grown on simple fraction or a lot of of the gross-cropped space (GCA) of a rustic. In Asian country, main crops- Rice (73.94%), Wheat (4.45%), Jute (3.91%), Rape and Mustard (3.08%), Lentil (1.54%), potato (1.13%), sugarcane (1.12%), and hot pepper (1.05%) area unit fully grown on one % or a lot of the crop surface area (14.61 million ha) . Rice influences the cropping pattern throughout the Asian country and categorized into 3 types. They are- Aman, Boro, and Aush consistent with the season during which they're harvested, in December-January, March-May and July-August severally. Again, of those varieties Aman is that the most vital and covers concerning forty six.30% of the paddy space, Boro (26.85%), Aush (17.59%) [20]. Transplanted Aman is fully grown nearly all over in Asian country, whereas broadcast Aman is usually fully grown within the low-lying areas of the south and northeast. Boro is fully grown to a definite extent in each district, particularly within the irrigated half, whereas Aush may be a well scattered crop. Next to rice, wheat is that the most vital crop in Asian country. It fully grown in the main within the drier elements of the north and is cultivated solely as a winter crop. Jute leads the country's list of export crops however is hierarchical third in terms of space cultivated. it's confined in the main to the low-lying areas of the Brahmaputra-Jamuna and Padma floodplains[20]. Mustard (including rape) is that the fourth vital crop. Masur (lentil) and Lathyrus sativus (chickling vetch) area unit the 2 vital styles of pulses created in Asian country. Potato is that the most important of the winter vegeTables and widely grown. Sugarcane is that the eighth vital crop the country. Minor crops that area unit fully grown on but simple fraction of the gross cropped space (GCA) of a rustic. In Asian country gram (0.78%), millets and maize (0.60%), onion (0.58%), black gram (0.51%), sweet potato (0.45%), groundnut (0.40%), garden pea (0.36%), sesame (0.33%), linseed (0.30%), garlic (0.20%), pea (0.12%), barley (0.10%), etc, area unit sometimes thought of as minor crops[20]. additionally, some crops, as well as vegeTables, spices, etc, occupy an insignificant proportion of the GCA (i.e. but zero.10% to every crop), and that they altogether account for one.57 percent. Tea, a minor crop in terms of space, comes second as associate export crop. The collective pattern of crops (crop combination) has been analyzed with the assistance of a combinatory technique. The technique consists of examination the particular share of cropped areas occupied by totally different crops with their theoretical distribution in associate enumeration unit. Cropping season environmental condition kind related to a specific time of the year that determines the cropping pattern. attribuTable to geographical location within the semitropical region, Asian country has favorable temperature vary for crop cultivation throughout the year

2.2 Climate of Bangladesh

Bangladesh has a subtropical monsoon climate characterized by wide seasonal variations in rainfall, high temperatures and humidity. Bangladesh extends from 20°34'N to 26°38'N latitude and from 88°01'E to 92°41'E longitude [21]. Bangladesh is located in the tropical monsoon region and its climate is characterized by high temperature, heavy rainfall, often excessive humidity, and fairly marked seasonal variations. There are three distinct seasons in Bangladesh: a hot, humid summer from March to June; a cool, rainy monsoon season from June to October; and a cool, dry winter from October to March. January is the coldest month in Bangladesh. Average temperatures in April vary from about 27°C in the northeast to 30°C in the extreme west central part of the country [21]. After April, temperature decreases slightly during the summer months, which coincides with the rainy season. March and April are the least humid months over most of the western part of the country. The relative humidity is everywhere over 80% during June through September. In Bangladesh, the cloud cover has two opposing seasonal patterns, coinciding with the winter monsoon and the summer monsoon. As a result of the flow of cold-dry winds from the northwestern part of India during the winter season, the cloud cover is at a minimum. On an average, the cloud cover in this season is about 10% almost all over the country. After the withdrawal of the summer monsoon, the cloud cover decreases rapidly, dropping to 25% in the northern and western parts, and 40-50% in the southern and eastern parts. The single most dominant element of the climate of Bangladesh is the rainfall. Because of the country's location in the tropical monsoon region, the amount of rainfall is very high. Most parts of the country receive at least 2000 mm of rainfall per year[21] Because of its location just south of the foothills of the Himalayas, where monsoon winds turn west and northwest, the regions in northeastern Bangladesh receives the greatest average precipitation, sometimes over 4000 mm per year. About 80 percent of Bangladesh's rain falls during the monsoon season.

2.3 Irrigation

Irrigation is the alternate way of water supply for dry season agricultural land by using barrage, channels and other devices.it is also used in wetter areas to grow certain types of crops such as rice. In Bangladesh there is a huge proportion use of shallow and deep tube wells for irrigation purpose especially in dry seasons (September to April). In Bangladesh, about 94% of the irrigated land is under small and minor irrigation [22]. Motorized pumps and Manual pumps are the commonly used irrigation devices in our country. Motorized pumps are the largest irrigation device which is used for pumping groundwater for irrigation and domestic purposes. The lifting device which is used for this type of purposes is deep tube well. For small scale of irrigation the lifting device which is used is shallow tube well. With the introduction of deep tube wells and low-lift pumps water management, Bangladesh started systematic irrigation in the early 1960s[22]. Before that farmers were dependent on growing crops under rain fed conditions. The rice crop alone occupies 90-95% of the irrigated area and only 5-10% is left for other crops. In Bangladesh, optimum use of irrigation water plays a vital role in increasing agricultural production. Major development of the country's agricultural sector will require year-round use of irrigation facilities for productive use of water. The country will benefit through improvements in the allocation and distribution of the available water. In Bangladesh about 95% of the rainfall occurs during April to October, leaving the winter months, i.e. November to March, very dry. As a result, irrigation is necessary for obtaining high achievements during the dry season. The demand for irrigation water is increasing day by day and the cost is also increasing rapidly. About 76% of the cultivable area can be irrigated of which about 64% are presently under irrigation with the water potential of the country. About 79% of the irrigated area use groundwater because of the fluctuation in availability and lack of control over surface water.

2.4 Location of this study

Although this work is applicable for irrigation in any location, in this work in paper, a village of Shibpur Upazila, Narshingdi Bangladesh has been chosen where agriculture is the main occupation for the 55% of the population. This village of Shibpur Upazila is located in between 23°56' and 24°07' north latitudes as shown in Fig. 1. The land which is selected for this work is 10 acres in size and the water requirement is approximately 220 thousand litres per day. This amount of requires water is supplied by a diesel powered centrifugal pump which pulls up the water from the ground about 80-85 feet below. Here paddy ‘BRRI Dhan 28’ and ‘BRRI Dhan 29’ are grown mainly. The rice is cultivated twice in a year and it takes about 90 days to mature. The main sources of income in Shibpur are Agriculture with a percentage of 54.55%, non-agricultural laborers with percentage of 2.08%, industry 3.16%, commerce 15.07%, transport and communication 4.77%, service 8.21%, construction 1.55%, religious service 0.22%, rent and remittance 2.41% and others 7.79%. [23]

Since Agriculture plays an important role for the people in Shibpur, they grow various crops like paddy, jute, ginger, turmeric, vegeTables. Rice is the most common and main crop grown here.

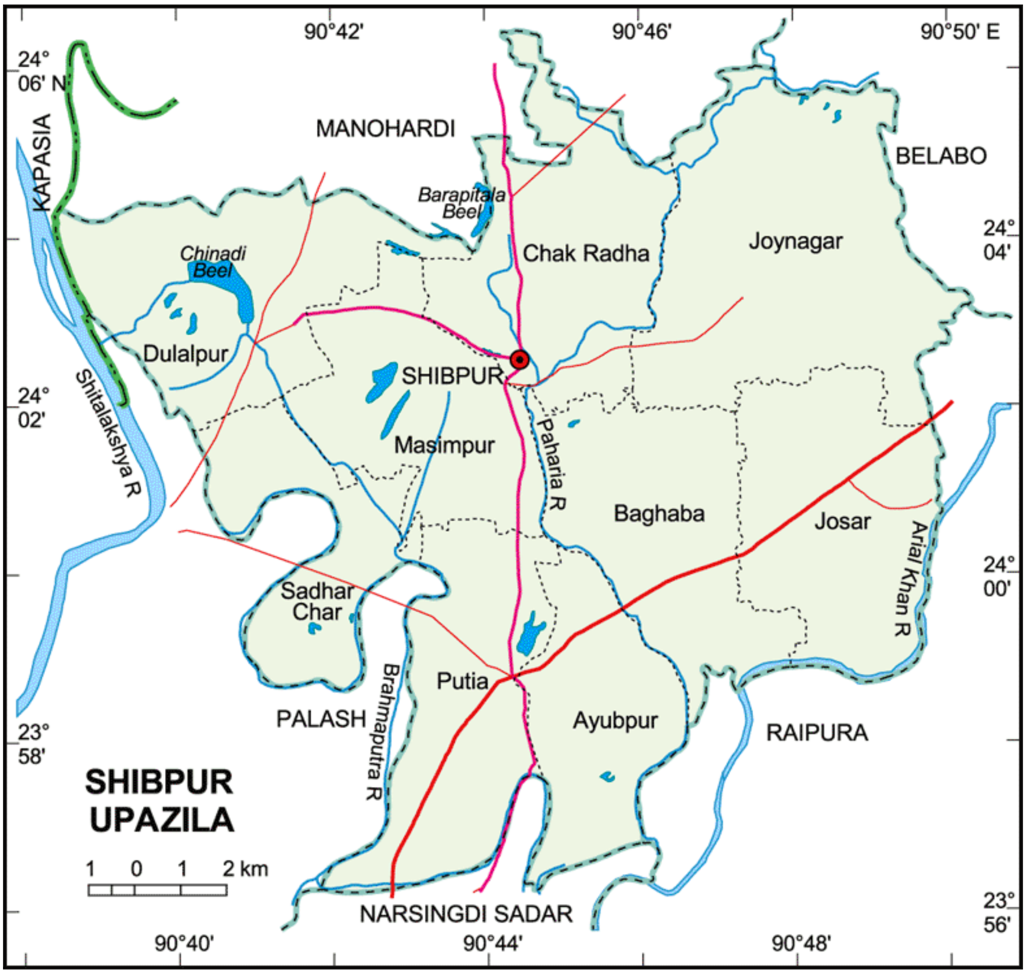

Figure 2.1: Location of Shibpur Upazila in the Narsingdi district, Bangladesh[23]

2.4.1 Climate of the Location

Shibpur Upazila is located under Narsingdi district (23º 29´ North latitude and 90º10´ East longitude). The climate of this area is in mild condition both in the summer and the winter season. The maximum average temperature and the minimum average temperatures during winter vary from 19ºC to 23.7ºC and in summer from 26ºC to 29ºC. The rainfall in Shibpur Upazila is generally heavy during the monsoon (July and August) and the average annual relative humidity is about 74%.[23]

2.4.2 Site Data

Initial work was to prepare an accurate site assessment, which is the critical part to successfully design solar pump. This will ensure that the system design and installation locations are site-specific; as a result the system delivers the required pumping outputs, with the least amount of energy which has wasted. For accurate site assessment we have to consider some requirements such as the land size, mainly the area of the land. Another requirement is what types of crops are grown in the particular location. Types of soil also have the significance for site assessment. What are the sources of water and the requirements of water are the important factors that have top consider for the assessment. How much water that can be delivered from the water sources, what types of pumps can be used for irrigation purposes to collect required amount of water also considered. Different types of crops have different types of cultivation period, during the assessment it can be considered as well.

The land which has chosen for this thesis work is a paddy field of 10 acres in size. The varieties of rice grown there they are, BRRI 28 and BRRI 29. These two types of rice are the most popular rice grown in Bangladesh. The soil named Doash Mati is available there. The water amount required by the crops is approximately 4, 41, 919.2 litres, which is supplied for 14 hours (from 8am to 10pm) for two days. So, the minimum average water required for one day is 2, 20,959.6 litres. The water required is supplied by using a centrifugal motor pump, which pulls up water from 80-85 feet below the ground. The motor runs on diesel where 2 litres is consumed per 3 hours.

The details of the pump and motor that is used in this study are given in Table 2.1:

Table 2.1: Details of pump and motor

Depth of water	80-85 feet
Pump type	Centrifugal Gazi Pump
Year of pump bought	2006
Motor type	Double Bird Diesel Engine
Pump costing	2500 Tk.
Motor costing	14000 Tk.
Fuel type	Diesel
Fuel consumption	2 litres/3hrs
Fuel Cost	70tk/litre

Generally, it takes almost three months for the crops to mature, from initial stage to harvest. The rice are cultivated twice yearly in summer season during the Bengali month Boishakh (April-May), and in winter during the Bengali month Poush (December-January).Due to the dry season the water level is below the ground in spring (February-April), they do not cultivate in this season.

Chapter 3

Solar Powered Water Pumping system

3.1 Types of Solar Powered Water Pumping system

Solar water pumping system mainly based on photovoltaic (PV) technology. This system operates on power, where. The PV array converts the solar energy to the electricity. This electricity is used for running the motor pump set. This pumping system draws water from the open well, bore well, stream, pond, canal etc. There are three types of solar powered pumping system-

1. Direct coupled System
2. Battery coupled System
3. Hybrid PV system

3.1.1 Direct coupled water pumping system

In direct-coupled pumping systems, electricity from the PV modules is sent directly to the pump, which in turn pumps water through a pipe to where it is needed Since the system is designed to pump water during the daytime, the amount of water mainly depends on the amount of sunlight which is laid on PV panels and the types of the pump. The amount of water pumped by the system changes with the amount of intensity of the sun and the angle at which it strikes to the PV panel throughout the day. For example during late morning to late afternoon pump operates at high efficiency with high amount of water on the other hand in early morning and late afternoon pump efficiency decrease due to low light condition. To achieve efficient water pumping system for these variable flow rate minimum mismatch should be occurred between the pump and PV modules. Without batteries, the PV pumping system is very simple. It consists of just three components: the solar array, a pump controller and the pump. Direct coupled systems are sized to store more water on sunny days so that it is available on cloudy days and at night also. Water can be stored at large stored tank than usual or separate storage tank. But it is economical not to use storage tanks.

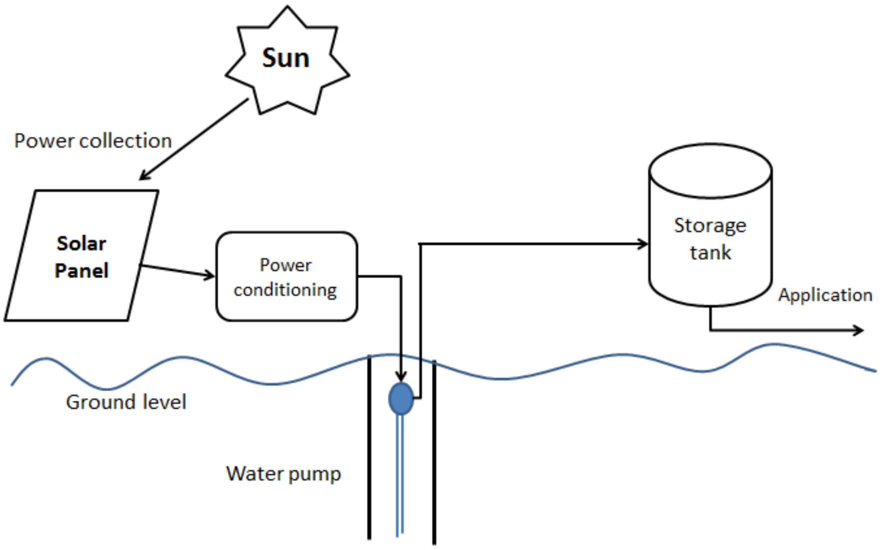

Figure 3.1: Direct coupled solar pumping system [25]

The main advantage of this direct coupled solar pumping system is low operating costs since the design is simple because it does not have battery or tanks. It does not require frequent maintenance. This system is Fuel free. It is environmental friendly and easy to transport.

Since the system lacks battery, therefore the system has no backup in case of shortage of power required to the pump. Moreover it drives less output during cloudy days.

Solar water pumps can be divided into two categories according to the motor used:

1. AC solar pump
2. DC solar pump

1. AC solar pump

AC solar pump is the modified version of the existing electric pump where some components have to be retrofitted. In general, the electric pumps are driven by AC supply but the power output from the solar panel is DC. To use the DC power to operate the AC system an additional inverter is required. Figure 3.2 has shown the block diagram of the AC solar pump, where an inverter has been used for DC to AC conversion. This AC power has been supplied to the AC motor then to the AC pump. From the pump the output has been delivered to the storage tank and other applications.

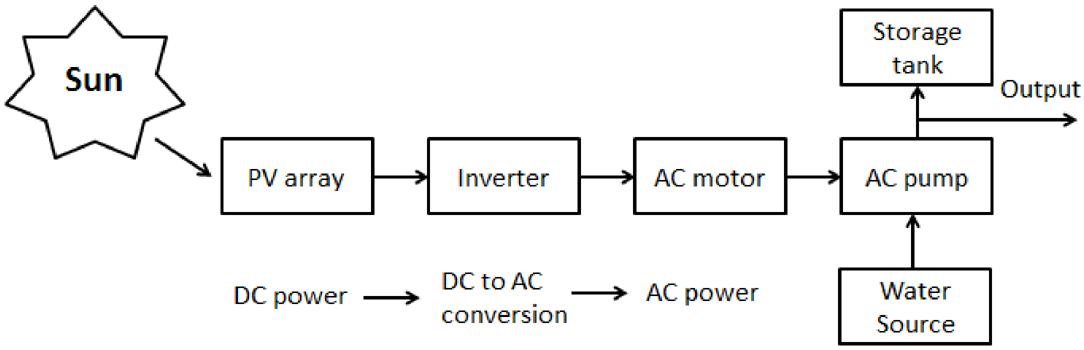

Figure 3.2: Block diagram of a direct coupled PV AC water pumping system

2. DC solar pump

Nowadays DC water pump is widely used all over the world for its simple mechanism. A DC pump is easy to maintain and can be operated by non-technical person in rural areas. Fig. 5 has shown the block diagram of the DC solar pump.

In Figure 3.3 a block diagram of direct coupled PV DC water pumping system has been shown. The main difference between the AC solar pumps and DC solar pumps is DC solar pump runs on a motor which is operated by direct current so no battery or inverter is needed.

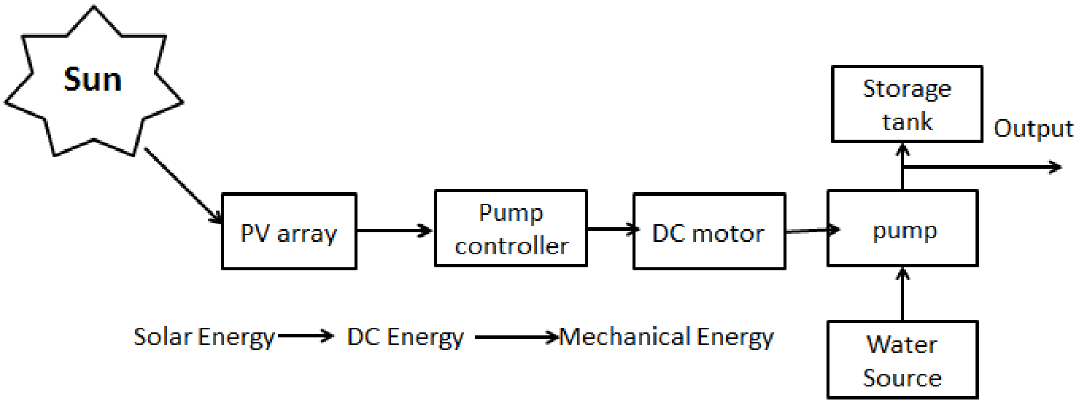

Figure 3.3: Block diagram of a direct coupled PV DC water pumping system

One of the features of the DC pumps is a direct DC power supply from solar panel runs the system. In DC water pumping system no inverter is needed to convert DC supply to SAC supply of the solar panel. Another advantage of this pumping system is it can be operated without any operator. Small scale irrigation can be done throughout the day time when the sun light available. For this system no storage material is needed. However, the repair and maintenance of DC pumps are difficult in rural and remote areas due to lack of service centers in these areas.

Considering the aspects of our country, A DC direct coupled solar pump has been designed and then the performance of the designed system has been analyzed in this thesis.

3.1.2 Battery coupled water pumping system

There are two technologies for storing water one is using battery another is using water tank. Although most of the time people use water tank rather than battery because of costing and less complicated, but battery also has some importance. During the night and rainy days when the solar panel is not active due to absence of sunlight then some backup storage needed to make water available at that time. When we need extra pressure on water, we can use the energy which is stored in the batteries. Figure 3.4 has shown the block diagram for a Battery coupled water pumping system. As it is shown in the block diagram, the main components of the battery-coupled water pumping system are photovoltaic (PV) panels, charge control regulator, batteries, pump controller, pressure switch and tank and DC water pump . The electric current produced by PV panels during daylight hours charges the batteries, and the batteries in turn supply power to the pump anytime water is needed. The use of batteries spreads the pumping over a longer period of time by providing a steady operating voltage to the DC motor of the pump. Thus, during the night and low light periods, the system can still deliver a constant source of water.

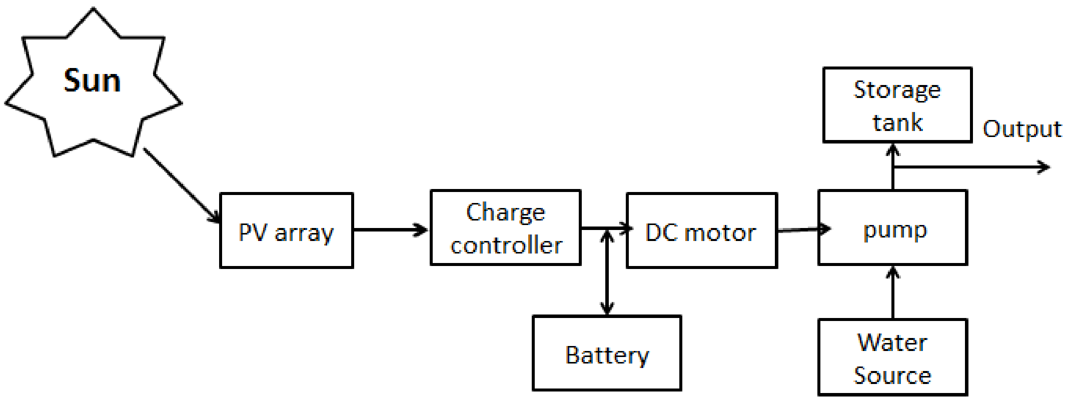

Figure 3.4: Block diagram of a Battery coupled water pumping system

In battery coupled water pumping system using batteries is another method of managing the solar power. This system maximizes self-consumption of solar power. It reduces network costs which control us when we use power and how much we pay for it. Battery coupled water pumping system is the backup plan for when the power goes out. It keeps the motor on, when the power is lost.

However there are some disadvantages of this system. Batteries are more expensive and less effective than the water tank. It reduces efficiency of the whole system. In this system batteries also require regular maintenance since it has no longer lasting warranty. It also increases maintenances cost. Battery coupled system is a complex system and is doesn’t have any backup during the outage.

3.1.3 Hybrid PV system

Hybrid solar PV system generate power as same as a common grid tie solar system do. It uses special types of hybrid inverters and batteries to store energy so that that can be used later in different applications. Most commonly the hybrid term used as two different sources have been used such as wind and solar, they are connected to the electricity grid. Battery ready system uses a hybrid inverter rather than typical inverter. Modern hybrid inverter has battery charger and connection built in itself.

A solar hybrid system stores excess energy and an also provide back-up power during load shedding.

This is preferable for home owners on the other hand common grid-feed solar system is preferable for the majority of businesses which operate during the daylight hours. It is a self –use or self-consumption system. It works as same as conventional one. The battery capacity is required less than the conventional one.[28] Figure 3.5 has shown the block diagram for the Hybrid PV system.

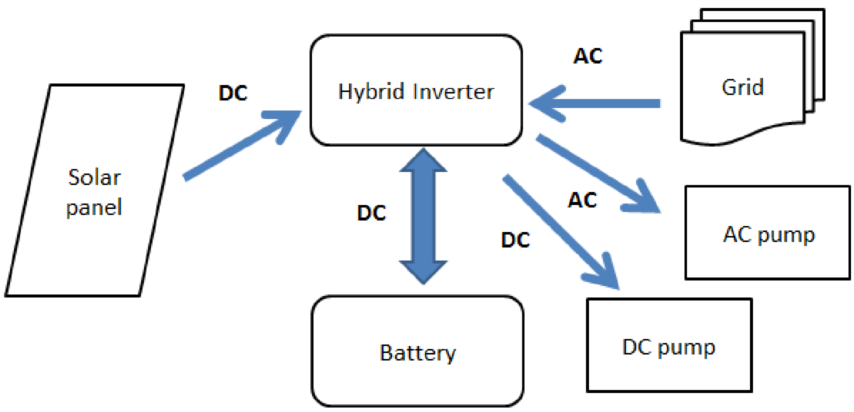

Figure 3.5: Block diagram of a Hybrid PV system

The features of this Hybrid PV system are: It allows storing excess amount of solar electricity. It can be allowed to use of stored solar energy during peak times at the evening. Most of the hybrid inverters have backup power capability. It reduces power consumption from the grid. It enables advanced energy management

In contrast the cost is high mainly due to the high cost of batteries. This system has longer payback time. Complex installation requires for more room and higher installs cost. The battery life of this system is about 7-15 years. Another problem of this system is backup power may limit the number of appliances who can run at the same time.

3.2 Proposed system and reasons behind choosing it

Different types of PV systems have already mentioned earlier. This proposed work will carry out using directly coupled water pumping system. Directly coupled water pumping system is a method where the equipment of this system are designed to collect and convert the solar radiation into direct current and then convert this electrical energy to mechanical energy. In this work the electricity from the PV modules is transferred directly to the pump to water through a pipe to the chosen location.

Directly coupled water pumping system is designed to pump water during the day hours. The amount of water pumped is dependent on the amount of sunlight hitting to the PV panels and the type of pump that is used for collecting water. Since the pump runs entire sunlight hours, the amount of water collection varies throughout the day. Pump runs at highest efficiency or the maximum amount of water can be collected when the sun is in highest position. During under low light condition such as during early morning and late afternoon when the sun is not in an optimal angle they the pump performance has been decreased and the amount of water collection is less than previous. The pump efficiency will also drop during cloudy days.

To compensate for variations in available sunlight, the incident energy for different tilt angles have been measured for three different seasons: February-April, September-November and September-April. Then the optimized values for each case have been considered for each.

The direct-coupled pumping system does not require any battery. The use of batteries reduce the efficiency of the overall system since the operating voltage is controlled by the batteries and not by the PV panels. The voltage supplied by batteries runs 1 to 4 times lower than the voltage supplied by the solar panels themselves under maximum sunlight. In addition, the use of battery will increase the price of the overall pump.

Another advantage of direct-coupled pumping systems is it can store extra water on sunny days as well as on cloudy days and at night. Water can be stored in a larger watering tank or in a separate storage tank. Later the water can be taken for other uses. Moreover, water-storage capacity is important for a solar pumping system. Following Figure 3.6 shows the block diagram of the proposed system.

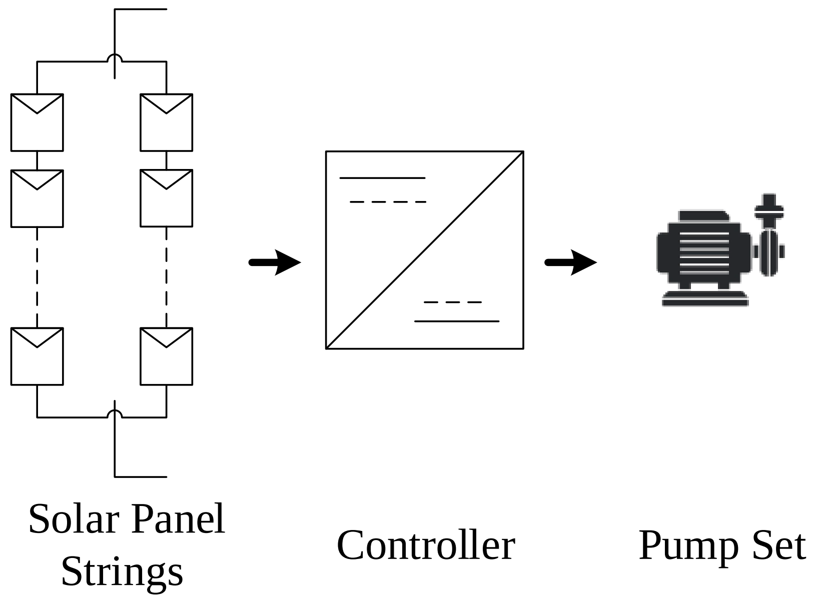

Figure 3.6: block diagram of the proposed system

On other hand the efficiency of this system is less than the efficiency of other PV water pumping systems. The system operates without batteries and it has simple electronic control which is not only cost effective compared to hybrid system but also maintenance, repairing and replacement cost can be saved. In addition, this system is environmental friendly as it will not be using or burning any fuels. It is not causing any harm to our surroundings.

Considering all the advantages and scenarios, for this proposed work direct-coupled pumping system has been chosen.

3.3 Components of Solar Powered Water Pumping system

A typical solar-powered water pumping system includes a solar array or solar panel, pump, storage tank (if needed) and controller.

3.3.1 Photovoltaic (PV) panel:

A solar-powered water pumping system mainly has two basic components. The first one is the power supply which is consisting of photovoltaic (PV) panels which is depicted in Figure 3.6. The smallest element of a PV panel is known as solar cell. Solar panel is rated based on its DC output power.

Each solar cell of PV panel has two or more specially prepared layers of semiconductor material that produce direct current (DC) electricity when exposed to light. This DC current is collected by the wiring in the panel. Then it is supplied either to a DC pump or stored in batteries for later use by the pump.

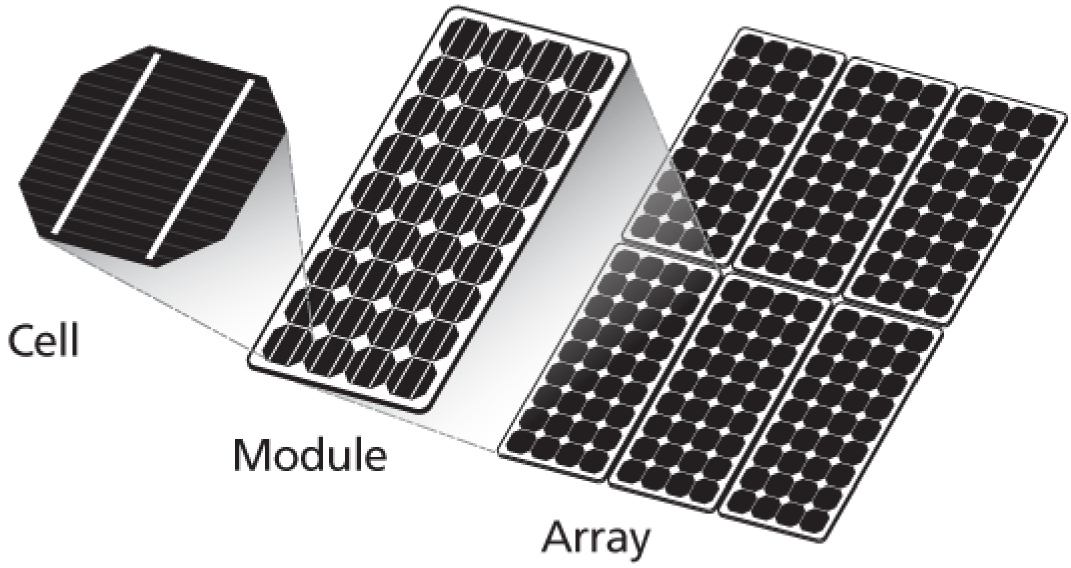

Figure 3.7: Solar cell, PV solar panel, and PV panel array

Manufacturers normally rate voltage (volts) and current (amps) output from PV panels under maximum power conditions. Maximum power (watts=volts x amps) is the power available from the PV panel at 1000 W/m² solar irradiance and a specified temperature, usually 25˚ C (77˚ F). The amount of DC current which is produced by a PV panel is much more sensitive to light intensity striking the panel than is voltage generated.

Solar cells that are made out of thin films, that might contain a variety of different metals, have efficiencies of approximately 8% to 11%. Crystalline solar cells are usually formed out of silicon and have an efficiency of 15% approximately. They are not as strong as silicon solar cells, but are less heavy and comparatively less expensive. PV panels are connected by wirings as they are arranged in arrays to deliver power the pump. PV panels must satisfy all NRCS required specifications, for both production and structural integrity.

To obtain the required voltage or current which is needed to run the pump, Individual PV panels can be wired in series or parallel. The output voltage from panels wired in series is the sum of all the voltages from the panels. The output current from these same panels wired in series is equal to the current output from an individual panel. The voltage and current output from panels wired in parallel is the exact opposite of series-wired panels. For parallel wired panels, the output current is the sum of all the currents from the panels and the voltage is equal to the voltage output from an individual panel.

3.3.1.1 PV Panel Orientation and Tracking

To be most effective, PV panels need to be continuously and directly faced incoming sunlight, which requires the use of one or more tracking mechanisms. A single-axis tracking system will rotate a PV panel about its vertical axis to follow the sun throughout the day. A double-axis mechanism will also control the panel tilt angle (the angle of the panel relative to horizontal where 0° is horizontal and 90° is vertical) to adjust for the raise of the sun in the sky throughout the year.

Single-axis tracking system can be very effective for increasing the amount of energy production throughout the year, by up to 50% during some months. Passive single trackers, which require no energy input, can be used. Passive single trackers use the heat from the sun to cause Freon or a substitute refrigerant to move between cylinders in the tracker assembly, which causes the panels to shift so that they maintain a constant 90-degree angle to the sun throughout the day. Single-axis trackers tend to be more appropriate for sites between ± 30 degrees latitude. Also, their benefits at higher altitudes tend to be less during the winter months when the sun is low on the horizon. Due to the complexity of tracking mechanisms and their associated controls, most installations for water pumps are stationary and oriented due south to take advantage of the maximum sunlight available in the middle of the day

The default tilt angle for a PV panel is equal to the latitude of the location. For a fixed array, this default angle will produce the maximum annual energy production.

A tilt angle of ± 15 degrees from latitude will increase energy amount for the winter or summer months, respectively. Most solar panels that are used for water pumping are set to collect the maximum amount of energy in the summer, when water demands are highest. However, to maximize energy for both summer and winter pumping, it is recommended that the tilt angle be adjusted at the spring and autumn equinoxes (March 21st and September 21st). In other words, the panel array tilt angle should be adjusted as follows:

• Summer tilt angle = latitude – 15° (when the sun is higher in the sky).

• Winter tilt angle = latitude + 15° (when the sun is lower in the sky).

If the array's tilt angle is adjusted seasonally, the site's solar insolation data that is used in the design of the solar-powered water pump system should be reflected.

PV panels and all associated components i.e. the mounting structure, power controller, and electrical connections are focused to a congregation of environmental pressures, such as high temperatures; dust; significant wind, snow, ice, or hail loading; etc. To tolerate such pressures, NRCS requires all components associated with powering a water pump to meet or exceed all current industry standards as specified.

3.3.1.2 PV Panel Characteristics

To explain the PV panel characteristics firstly need to explain the single diode model by followed by the I-V characteristics of the PV panel and lastly the associated parameters. We can explain this section in three sub section. The topics of these three subsections are: single diode model, IV characteristic of the PV panel and the parameters of PV panel.

Single diode model:

One most common use of equivalent circuit model is the Single Diode model. A practical solar cell equivalent circuit is shown below [30]:

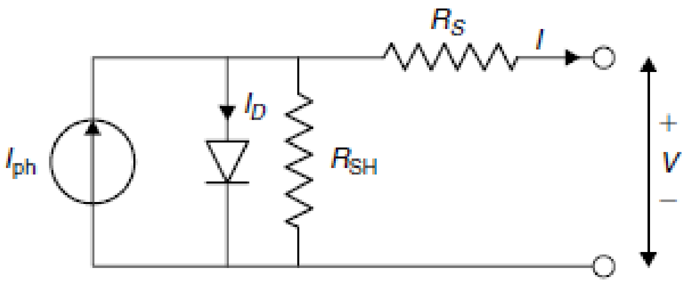

Figure 3.8: Single diode model

The I-V characteristics of a solar cell can be determined from the given operating conditions which can be observed from the equivalent circuit model. As we can see from the model in Figure 3.8, I_{ph} is the photocurrent, when electric conductors are attached with the negative and positive sides then electrical circuit is formed, there electric currents produce from the electron this current is known as photocurrent. When the solar cell is inactive then it acts as a diode. If this solar cell is connected with higher external voltage supply then the dark or diode current produces. This dark or diode current is denoted by I_D. This model consists of a current source I_{ph}, one diode, one series resistance Rs and an internal shunt resistance, R_{SH} of the diode.

The net current will be the difference between the photocurrent and the diode current [30],

$$I = I_{ph} - I_D \qquad (3.1)$$

$$I = I_{ph} - I_o\{exp^{\frac{q(V+IRs)}{KT_C}} - 1\} - \frac{V+IRs}{R_{SH}} \qquad (3.2)$$

In above equation, k is the Boltzmann's gas constant, T_C is the absolute temperature of the cell in kelvin, q is the electron charge, V is the voltage imposed across the cell in volt and Io is the dark saturation current in ampere.

The I- V characteristics curve of a solar cell shown in the following for a certain irradiation at a constant cell temperature. PV cell current depends on the external applied voltage and the amount of the sunlight imposed on the cell. When the cell is in short circuit condition the maximum amount of current (Isc) obtained when the voltage across the cell is zero. When the PV cell is open circuit condition we obtain the maximum amount of voltage (open circuit voltage Voc) when the current is zero. The general I-V characteristics curve is shown in below:

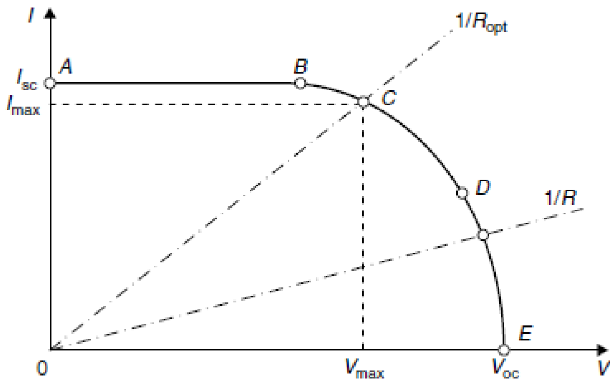

Figure 3.9: I-V characteristics curve for photovoltaic cell [31]

As we can see in the characteristics curve if the cell terminals are connected to a variable resistance R the operating point is determined by the intersection of the I-V characteristics of the PV cell with the load. For a resistive load the load line is a straight line with a slope of 1/R. If the load resistance is small the cell behaves as a constant current source. On the other hand if the load resistance value is large the cell behaves more constant voltage source which is equal to open circuit voltage.

3.4 Solar Powered Pumps

Solar water pumps are rated as per voltage supplied. For optimal function they require accessories like filters, float valves, switches, etc. Solar pumps are constructed from high quality low lead marine grade bronze and stainless steel and are designed for corrosion-free and maintenance-free service with long term performance and reliability.

Solar pumps are categorized into three types according to their applications: submersible, surface, and floating water pumps.

3.4.1 Submersible pump:

Submersible pump is a convenient and versatile device — useful for many different purposes. Submersible pumps are installed in underwater. It is a device consisting of a motor which is close-coupled to the pump body. The whole assembly is submerged in the fluid to be pumped. The shape of the submersible pump basically looks like a long cylinder that can fit inside the casing of any well. Submersible pumps are designed for medium flow application. The submersible pump has an in-built protection against dry run. However, A dry run of 15 minutes or more can cause considerable damage to a surface pump. Submersible pumps are easier to install and are better protected from the environment.

The main advantage of using these submersible pumps is the way it is designed. It is designed as a tightly contained unit, with watertight gaskets and seals that keep the liquid out of the housing and internal components which ensures that the pump don't leak or short out electricity when submerged. Another main advantage is how it pumps the water. It uses direct pressure through the pipe or hose to get the fluid out. This method is more effective than suction method because it covers more distance. In addition being self-primed is another advantage over a non-submersible. Priming is not required to start a submersible unit. The placement of the pumps has an additional advantage because it is placed inside the fluid. It helps them to pump out the fluid more efficiently.

In contrasts one potential problem would occur if a gasket were to rupture or lose its integrity. This would cause the pump to leak, eventually corroding the internal components and causing it to fail. In addition Non-submersible pumps cost lesser than these pumps.

3.4.2 Centrifugal pump:

Centrifugal pumps are used to transport fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. The rotational energy typically comes from an engine or electric motor. Common uses include water, sewage, agriculture, petroleum and petrochemical pumping. Centrifugal pumps are often chosen for their high flow rate capabilities, abrasive solution compatibility, mixing potential, as well as their relatively simple engineering. Like most pumps, a centrifugal pump converts rotational energy, often from a motor, to energy in a moving fluid. A portion of the energy goes into kinetic energy of the fluid. Fluid enters axially through eye of the casing, is caught up in the impeller blades, and is whirled tangentially and radially outward until it leaves through all circumferential parts of the impeller into the diffuser part of the casing. The fluid gains both velocity and pressure while passing through the impeller. The doughnut-shaped diffuser, or scroll, section of the casing decelerates the flow and further increases the pressure.

The main advantage of this pump is its simple construction. Power consumption of the centrifugal pump is low. Moreover there is no metal to metal fits and no valves involved in pump operation. Direct coupling to motors as a result it is easy to maintain and light weight.

However this pump is unable to handle highly viscous fluids efficiently. It cannot be operated at higher discharge pressure. This pump is unable to operate at high head value. Maximum efficiency holds for narrow ranges operating conditions.

Chapter 4

Calculation of Solar Irradiance and Optimization of Tilt Angle

4.1 Solar Irradiance and Incident Energy Calculation:

The amount of sunlight either absorbed or scattered depends on the length of path through the atmosphere. The solar constant for Earth is the irradiance received by the Earth from the sun at the top of the atmosphere, i.e., at AM0, and is equal to 1367 W/m^2. The intensity of sunlight can be obtained from the following equation [25]:

$$I = 1367(0.7)^{(AM)^{0.678}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

where, AM is the Air Mass which is defined as is the ratio of the path length, which beam radiation passes through the atmosphere, to the path it would pass through if the sun were at the zenith, directly at the overhead.[1]

$$AM = AM(90°)\csc(\alpha) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

In above equation, α is the solar altitude angle

The angle between the sun's ray and a horizontal plane is known as the solar altitude angle. The equation for the solar altitude angle is given by.

$$\varphi + \alpha = \frac{\pi}{2} = 90° \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

The mathematical expressions for the solar altitude angle is

$$sin(\alpha) = cos(\phi) = sin(L)\, sin(\delta) + cos(L)\, cos(\delta)\, cos(h) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.4)$$

In above equation, L is the latitude angle, α is the solar Altitude Angle and δ is the angle of Declination

Solar altitude angle is dependent on zenith angle, θ_Z . Zenith angle is defined as the angle between the sun and the zenith. The equation for zenith angle is given by,

$$\theta_Z = L - \delta \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.5)}$$

In this equation, L represents the latitude angle and δ is the angle of declination

In equation 4.3 Latitude is the angle measured at the center of the Earth, between the Equator plane and position of the object. It varies from 0° to 90°. Here the value of the latitude is 23.45°.

Declination is the angle of deviation of the sun from directly above the equator. [25]

$$\delta = 23.45° \, sin\left\{\frac{360}{365}\,(n + 284)\right\} \quad \ldots\ldots\ldots\ldots \text{(4.6)}$$

In above equation, *n* is the number day of the year

Declination angle varies with the season due to the tilt of the earth on its axis of rotation and the rotation of the earth around the sun.. On the same day the declination is equal everywhere on the earth. If the earth were not tilted on its axis of rotation, declination angle would always be 0°. The Declination varies between -23.45° ≤ δ ≤ 23.45 and is positive during summer and negative during winter.

To determine the location of the sun in the sky at any time of day at any time of year at any location on the planet, the declination is an important parameter. The earth is disposed of its polar axis by an angle of 23.45° to the plane of the earth's orbit about the sun as shown in Figure 4.1. This inclination is what affects the sun to be higher in the sky in the summer than in the winter. It is also the reason of shorter winter sunlight hours and longer summer sunlight hours.

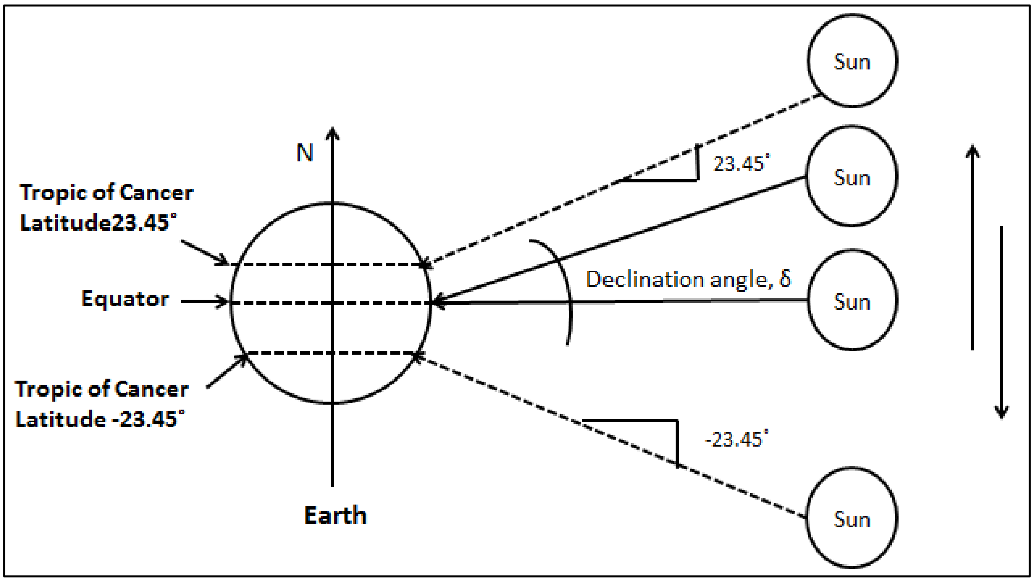

Figure 4.1: The orbit of the earth and the declination at different times of the year [25]

Hour angle is the difference between noon and the desired time of day in terms of a 360^{o} rotation in 24 hours. This time angle is negative if the solar time is less than 12 PM. This principle is used for characterization the rotation of the earth around its polar axis +15° per hour through the morning and −15° in the afternoon and it can be calculated [25] from

$$\omega = \frac{12-T}{24} \times 360° = 15(12-T)° \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.7)$$

Here, T is the time of day expressed with respect to solar midnight, on a 24hour clock.

The solar incidence angle, θ, is the angle between the sun's rays and the normal on a surface. For horizontal plane, the incidence angle, θ and the zenith angle, φ, are the same. The angles shown in the in the following Figure with the general expression for the angle of incidence [25]

$$cos(\theta) = sin(L)\, sin(\delta)\, cos(\beta) - cos(L)\, sin(\delta)\, sin(\beta)\, cos(Z_s)$$

$$+ cos(L)\, cos(\delta)\, cos(h)\, cos(\beta)$$

$$+ sin(L)\, cos(\delta)\, cos(h)\, sin(\beta)\, cos(Z_s) + cos(\delta)\, sin(h)\, sin(\beta)\, sin(Z_s) \;\ldots.(4.8)$$

In the equation, β is the surface tilt angle from the horizontal and Z_S is the surface azimuth angle, the angle between the normal to the surface from true south, westward is designated as positive

For a south-facing tilted surface,

$$\cos(\theta) = \sin(L-\beta)\sin(\delta) + \cos(L-\beta)\cos(\delta)\cos(h) \quad \text{(4.9)}$$

The effective area of the panel can be given as,

$$A_{eff} = A \times cos\,\delta \times cos\,\theta \quad \text{(4.10)}$$

Here, A is the area of the panel and θ is the angular position of sun at any time of the day and varies from 90˚ to 0˚ from sunrise to noon and then 0˚ to -90˚ from noon to sunset

The first work to implement the water pumping system is to determine the maximum amount of Incident Energy during the cultivation period (from February to April and from September to November) by optimizing the tilt angle. Firstly, single day of incident energy has been calculated, similar way incident energy has been calculated for one month after that for one year. The cumulative incident energy on the panel can be calculated using the following equation [25],

$$\text{Cumulative Incident Energy, E} = \int_{T_{SR}}^{T_{SS}} A_{eff}.I\,dt$$

$$= A\cos\delta \int_{T_{sR}}^{T_{SS}} I\,dt \quad \text{(4.11)}$$

Here, T_{SS} is the sun set time and T_{SR} is the sun rise time

The performance of a solar PV array is highly influenced by its tilt angle. The tilt angle, defined as the angle of PV arrays with respect to horizontal.

After determining the maximum (solar noon) daily light intensity (*I*) incident on the array for each of the design months, for both sunny days and typical cloudy days it is possible to find out the cumulative energy for one year.

Incident energy calculation considering Cloud Effect

After calculating the cumulative energy for one year it is needed to find out the energy for sunny and cloudy days to obtain the result for cloudy effects. Cloud cover is a significant cause of radiation attenuation and scattering. On a totally cloudy day, with no sunshine, most radiation reaching the earth's surface will be diffused.

After getting the insolation energy both for sunny and cloudy days, then using the following equations to find out the percentage of sunny and cloudy days [31],

$$R_{15} = X * S_{15} + Y * C_{15} \quad \text{.. (4.12)}$$

$$X + Y = 1 \quad \text{……………….………… (4.13)}$$

Here, R_{15} is the average cumulative incident energy for 15^{th} day of the month, S_{15} is the average cumulative energy for sunny day for 15^{th} day of the month, C_{15} is the average cumulative energy for cloudy day for 15^{th} day of the month, X and Y are the percentages of sunny and cloudy weather respectively.

Effective Incident Energy for sunny day, [31]

$$I_{eff_{forsunnyday}} = I cos\theta + 0.1I \quad \text{……………………… (4.14)}$$

Effective Incident Energy for cloudy day, [31]

$$I_{eff_{forcloudyday}} = 0.2I \quad \text{………………………… (4.15)}$$

4.2 Optimization of Tilt Angle

To optimize the tilt angle firstly we have to find out the total incident energy over the year for different tilt angles using the mentioned equation [4.1-4.11]. Total incident energy can be obtained from the following Table 1 without considering the cloud effect. Comparing the incident energy value during the cultivation period (February to April) and (September to November) it is observed that for which tilt angle it can get maximum amount of energy during cultivation period.

Tilt angles (λ) optimized for different time periods have been calculated using the following relation: [31]

$$\lambda = \varphi + |\delta \text{ (average)}| \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4.16)$$

In (4.16), δ (average) is the average declination angle and is calculated as by dividing the sum of declinations of all the days over a given time period by the total number of days during that time period.

The Table 4.1 shows the list of optimized tilt angles those are considered in this study

Table 4.1 List of optimized tilt angles considered in this study

Optimization Period	Tilt Angles (λ)
September-November	33.29°
February-April	25.83°
September-April	38.70°
Whole year	23.45°
December	46.54°

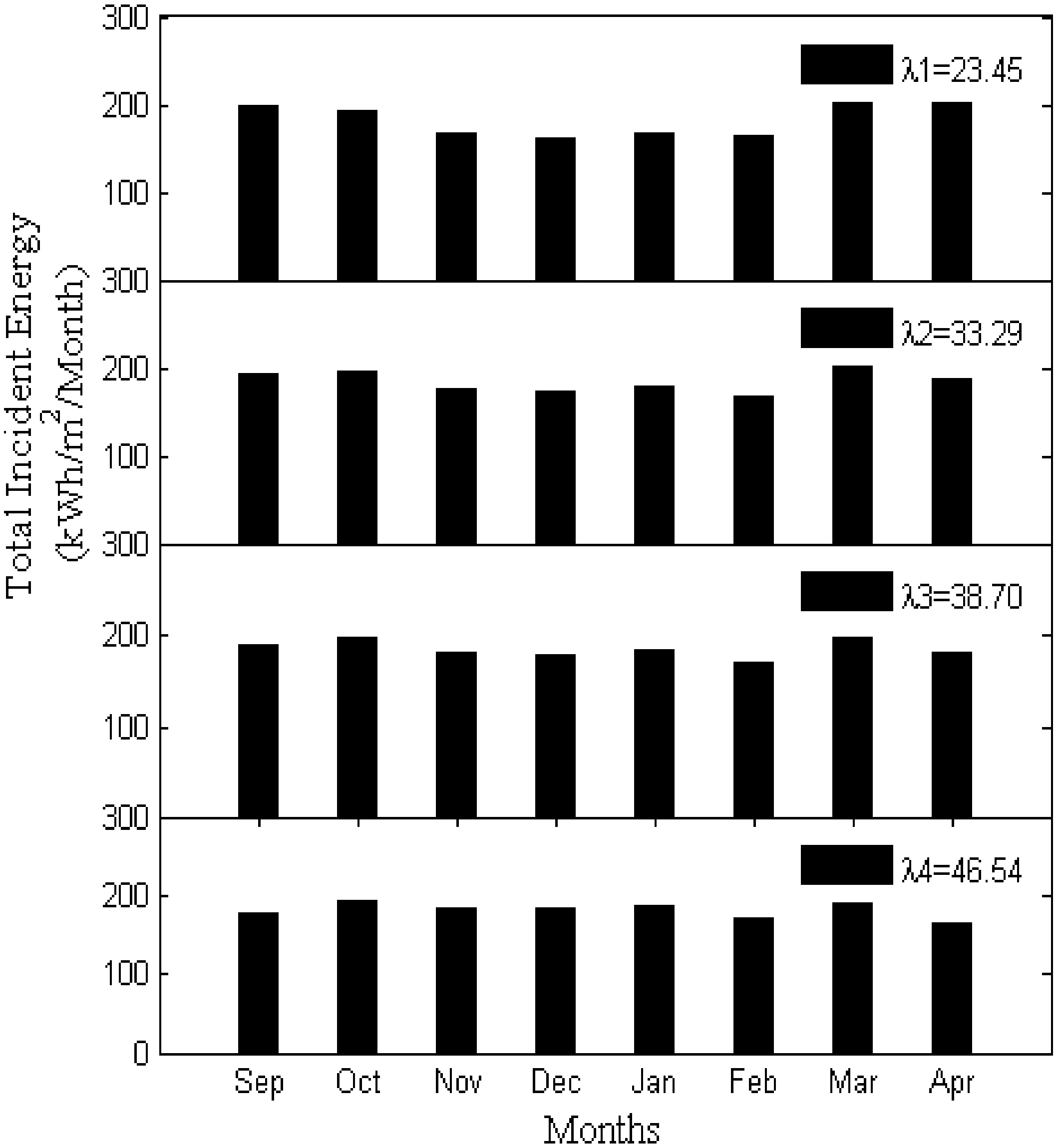

Figure 4.2: Total Incident energy (kWh/m^2/month) for different months from September to April, calculated using tilt angles, (top) λ1 = 23.45°, optimized for the whole year; (second) λ2 = 33.29° (September – November; (third) λ3 = 38.7082° optimized for Sep- Apr; and (bottom) λ4 = 46.54° optimized for December.

Figure 4.2, shows the total incident energy for the different optimized tilt angle from the month of September to April. Here, λ1 is the optimized tilt angle for the whole year and the value of λ1 is 23.45°. Similarly λ2, λ3 and λ4 are the optimized tilt angle for September – November, September-April and December respectively. The values of λ2, λ3 and λ4 are 33.29°, 38.7082° and 46.54° respectively. From the Figure it is shown that for tilt angle 23.45° (= latitude) total incident energy value of the month of December is the lowest. For tilt angle 33.29, it shows that the lowest energy is accumulated in the month of February. It is clear that the month of March has the highest energy accumulation for latitude tilt angle. The total incident energy for the month of March is always high for the entire optimized tilt angles. For the month of February is it shown that the value of energy increases by 4.61% for the optimized tilt angle value of 38.7082° than the value for 23.45°. Among these eight months it is observed that the incident energy value for February and November month are quite low than the other months during cultivation period. Since the number of days of February is less than the month of November. Daily incident energy value for the month of November lowest than other months. So for pump designing purposes November month can be considered as a critical month.

4.2.1 Incident energy calculation considering cloud effect:

As it is known that the solar energy is the most abundant energy of the earth. Amount of sunlight is not always the same all over the year due to cloud impact and other atmospheric and seasonal variations. Cloud plays a vital role in the transfer of energy through the atmosphere.

Total incident energy for the cloudy days and sunny days can be calculated from the previous mentioned equations (4.12-4.15). For this purpose the number of sunny days and cloudy days for each of the month has to be calculated. Energy of sunny days' refer to the energy that is received on a pure shiny day while having the sun directly overhead and cloudy days' energy refers to 20% of the energy on sunny day. Then multiplication of the percentage of the sunny and cloudy portion with the amount of energy will give the value of total incident energy for the individual sunny and cloudy days for each of the month. Using the equations number of sunny days and cloudy days can be found out. The Table 4.2 shows the number of sunny and cloudy days for the months of September to April:

Table 4.2: Number of Sunny and Cloudy days.

Months	**Number of sunny days**	**Number of cloudy days**
September	13	17
October	21	10
November	25	5
December	26	5
January	28	3
February	23	5
March	25	6
April	20	10

From Table 4.2 it is observed that September is mainly the cloudy season where the number of cloudy days is higher than other months. In this month rainfall data is also higher. Among the months of cultivation period November is mostly dry season. Similarly, in the month of December and January the number of sunny days is higher and therefore water collection from rainfall is less.

The next step is to calculate the amount of actual energy after the cloud effect is considered. Then the total value of energy of both total sunny and cloudy days obtained, and then added them up to find the energy of a whole month. The whole procedure has been repeated to sum up the energy received for all the months of a particular year.

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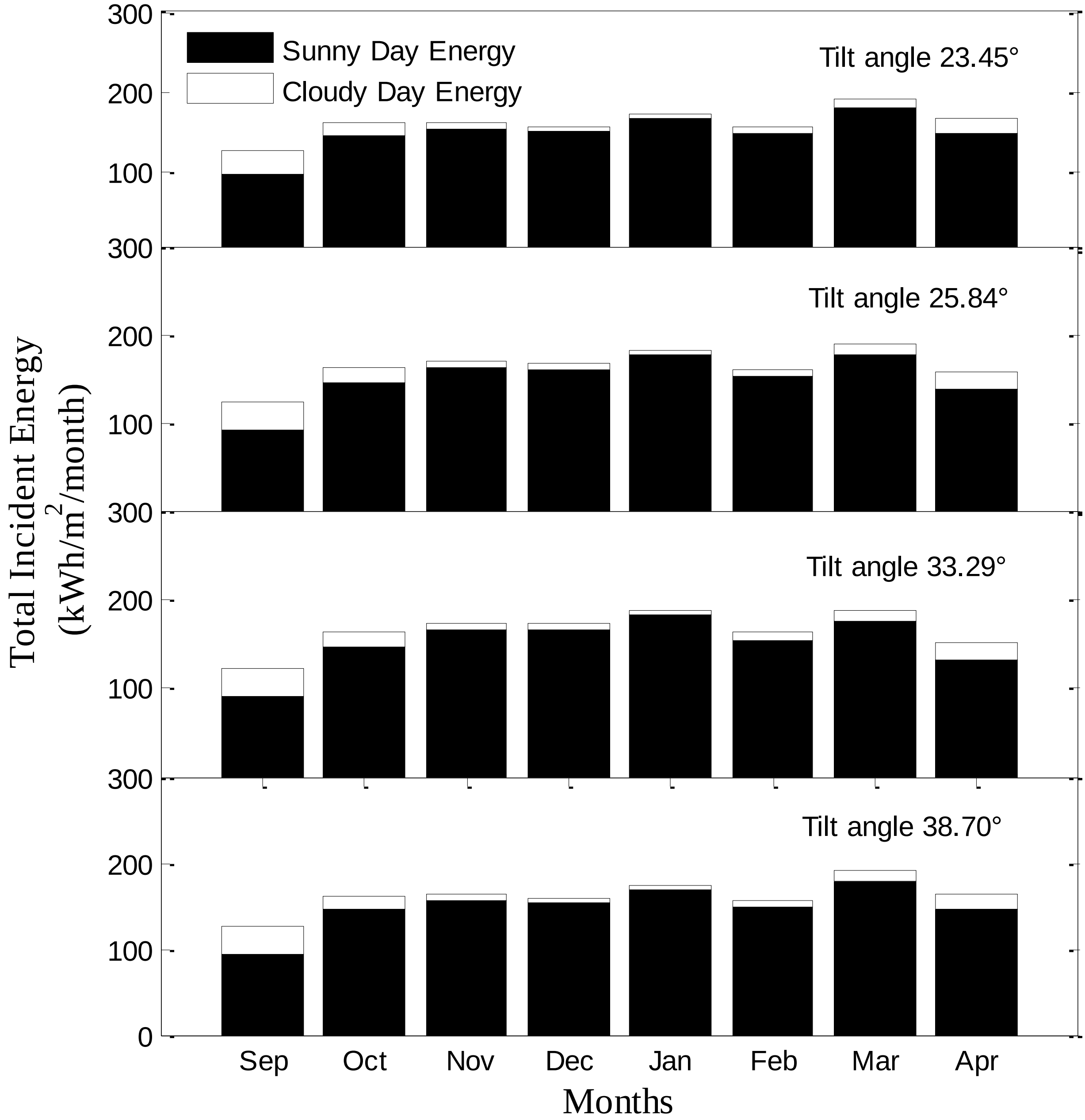


Figure 4.3: Total Incident energy (kWh/m^2/month) for different months from September to April, calculated using tilt angles, (top) λ1 = 23.45°, optimized for the whole year; (second) λ2 = 25.83° (February – April); (third) λ2 = 33.83° (September – November) optimized for Sep- Apr; and (bottom) λ4 = 38.70° (September – April) optimized for Sep- Apr considering cloud effect.

Figure 4.3 show the total Incident energy (kWh/m^2/month) for different months from September to April. These are calculated using tilt angles, (top) λ1 = 23.45°, optimized for the whole year; (second) λ2 = 25.83° (February – April); (third) λ2 = 33.83° (September – November) optimized for Sep- Apr; and (bottom) λ4 = 38.70° (September – April) optimized for Sep- Apr considering cloud effect. It shows the energy accumulation by the sunny days (black) and the cloudy days (white) separately for each of the months. Considering cloud effect after analyzing the data set, it is seen that the value of total incident energy decrease. As the cloudy percentage data is larger for the months of September, it shows that the energy value of September decreases by 35%. Both for tilt angle 23.45° and 38.70° total incident energy for October, November and January the values are slightly changed. However the total incident energy during cultivation period is highest for the optimized tilt angle value of 38.70°.

Both for without cloud effect and with cloud effect result shows that for 38.70° total incident energy value increases for the month of September to April and the increment is linear for these 8 months. So 38.70° can be considered as the optimized tilt angle.

Chapter 5

Pump Selection and Panel Sizing

For the pump selection and panel sizing process, at first the minimum amount of water requirement has been calculated. Then the amount of water that can be collected from rainfall has been calculated. The rest amount of water will be supplied by the pump. The amount of power that is required for driving the pump will be supplied by the PV module.

5.1 Water collection from rainfall

During cultivation period the water requirement for irrigation collet from the water from rainfall then the rest amount of water collect from the water pumping system. In this study the rainfall data for ten years (2001-2010) is used. From the data it is calculated the average rainfall data in litres. The Figure 5.1 shows the average amount of rainfall for each of the month. Also the results are depicted in Figure. 5.1.

Figure 5.1 presents that the July has the highest average rainfall. During the dry season the rainfall is very low for the month of November-March. Among the two cultivation period of February-April and September-November, November and February show the lowest rainfall. In the month of December, January also have the lowest rainfall as well. The average rainfall for the month of May and September are also high then the month of December and January. Since the rainfall for the month of September is higher during the cultivation period, therefore maximum amount of requirement water has been fulfilled by the rainfall water.

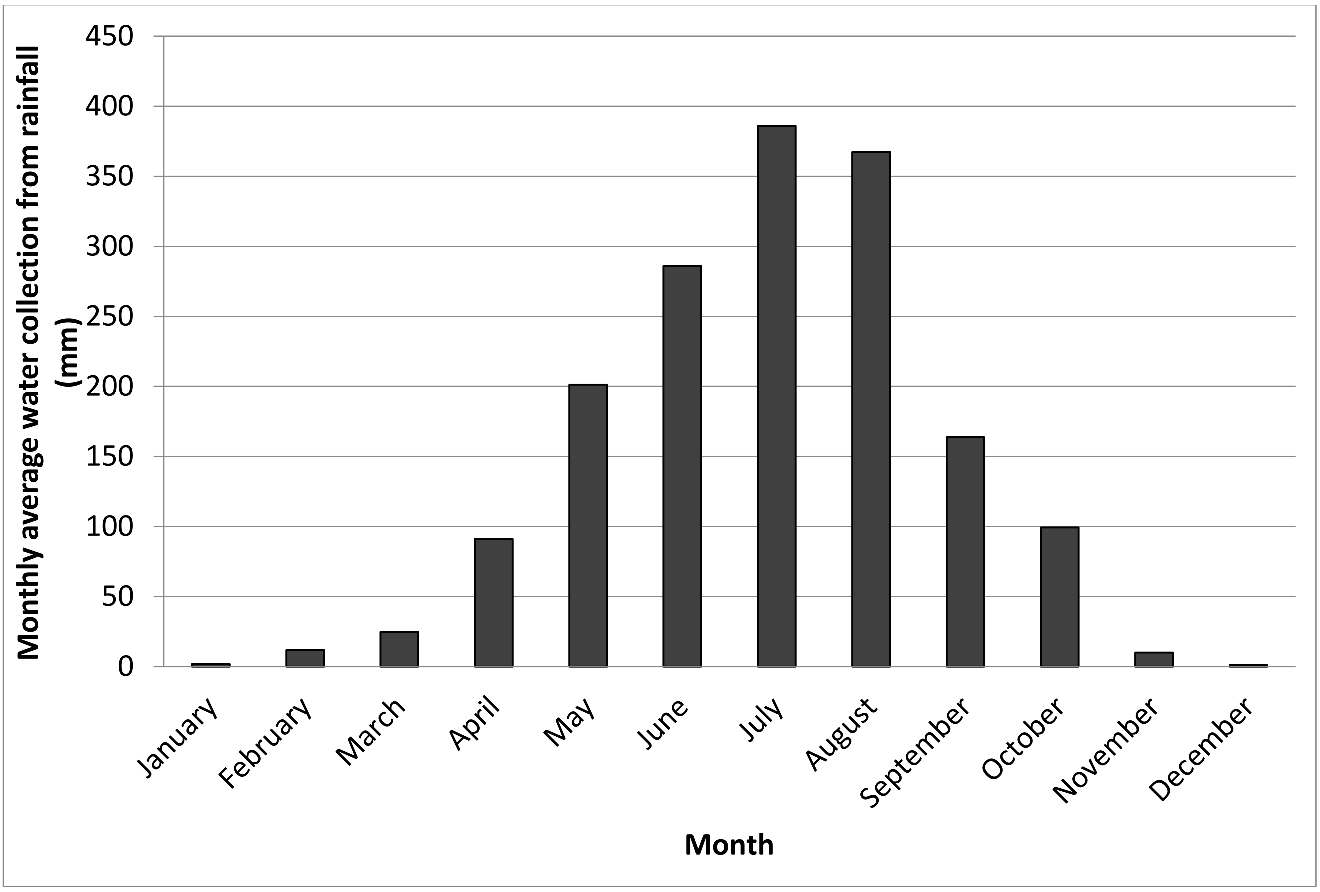


Figure 5.1. Monthly average rainfall for a whole year

Shibpur is an Upazila of Narsingdi District of Dhaka total area of 206.89 Km^2 (=206890000 m^2). The area of the considered paddy field 10 acres (40468.6 m^2). Considering the area and the average rainfall, water from collection from the rainfall is calculated and shown in Table 5.2. As discussed in Chapter 2, the minimum daily water requirement for one day is 220959.6 liters.

Figure 5.2 depicts the Water collection from the rainfall from the month of September to April. As it can be seen the maximum amount of water (almost 100%) accumulates in the September month. 58% and 55.65% of the total water requirement can be obtained from the rainfall for the month of October and April respectively. In the harvesting period in February and November month it doesn't get sufficient amount of water. Comparing the data of November and February, it is observed that the water collection per day in February is 5.23% higher than the Month of November.

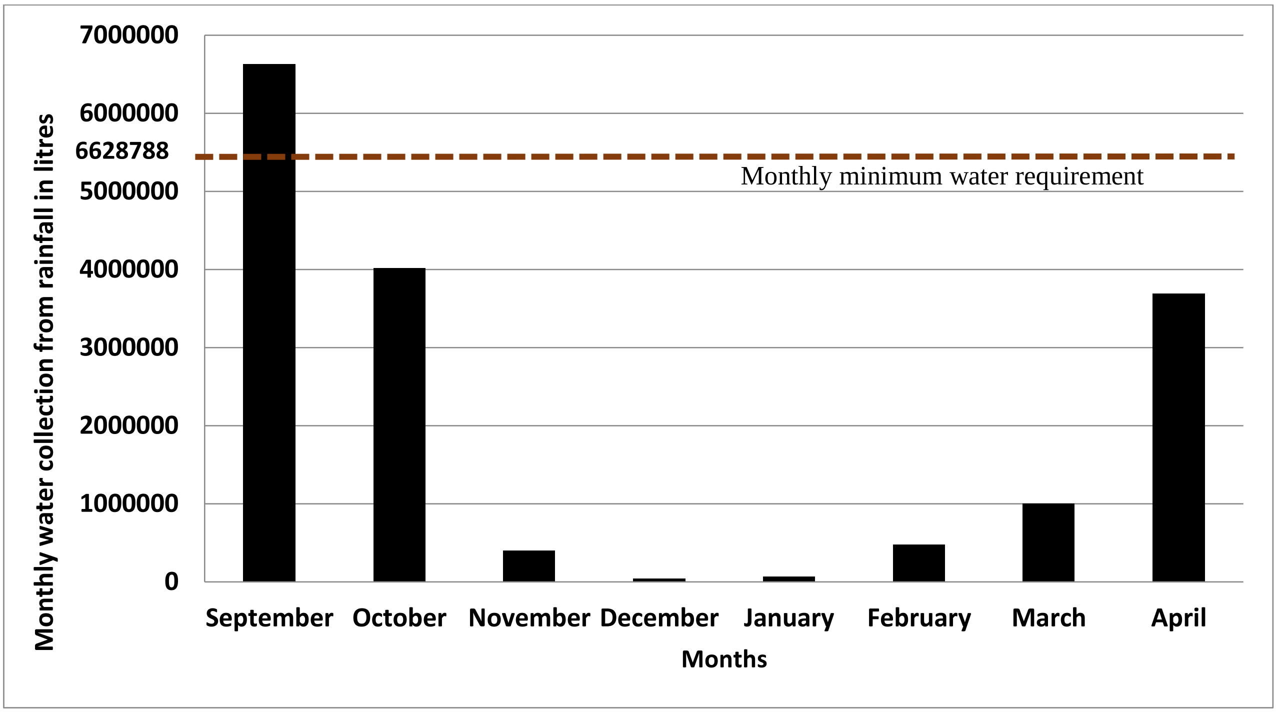


Figure 5.2. Monthly water collection data from rainfall in litres from September to April

The Figure shows the monthly water collection from the rainfall from the month of September to April. Here the average data have been calculated from the collected data of rainfall for last ten years that has been collected from the website. The monthly average data then multiplied with the area of our selected location to determine the amount of water collection from the rainfall in litres. As it is shown in the Figure that the maximum amount of water can be collected from the rainfall for the month of September. But during cultivation period particularly in November and February month the water collection is lesser than other months. In this Figure the monthly water requirement has been shown.

In terms of Solar Irradiance data, the value for total incident energy per day for February month is 0.10% higher than November total incident energy. Moreover, considering rainfall water collection per day in February month is 5.23% higher than the month of November. Considering all the values of the factor, it is decided to design the pump for the month of November.

5.2 Solar Insolation and required flow rate calculation

Solar Irradiation means the total amount of solar radiation energy received on a given particular horizontal surface per unit time per unit area. The solar radiation depends on a place depends on the time of the year and the place's latitude and longitude. The pump is designed based on flow rate which is based on the sun peak hours for the chosen designed month and the daily requirement.

Solar insolation can be calculated from the data of solar irradiation. After that minimum and maximum value of flow rate can be calculated from the solar insolation value.

5.2.1 Solar Insolation

The maximum amount of solar insolation on a surface at a particular tilt angle can be calculated as a function of latitude and day of the year. This value can be calculated from the value of sunshine hours. It is important to know the value of insolation for certain values of optimized tilt angle to determine the size and output of solar powered water pumping system. Insolation values also can help to determine the expected output for solar panels.

Solar insolation can be calculated by:

$$Solar\ Insolation = \frac{Total\ Energy\ (kWh)}{1\ kW} \quad \text{(5.1)}$$

Table 5.1 shows the solar insolation values for the different optimized tilt angles values. As we can see in September month for different tilt angle solar insolation value is quite low compared to other months. In the month of March the maximum value of solar insolation can be obtained in the Table for all the values of optimized tilt angle. Here the solar insolation values in hours have been determined by dividing the value of total incident energy by 1KWh. With the help of the insolation value, the flow rate of a day can be obtained.

From the Table 5.1 it is seen the daily average solar obtained for different optimized tilt angle.

Table 5.1. Daily average solar insolation obtained for different optimized tilt angle

Months	**Solar insolation (hr.)**			
	Tilt angle 23.45 (latitude)	**Tilt angle 33.2985 (Sept.-Nov)**	**Tilt angle 38.7082 (Sept.-Apr)**	**Tilt angle 43.0024 (November)**
September	3.2	3.1	3.0	2.9
October	4.6	4.7	4.7	4.7
November	5.1	5.4	5.5	5.6
December	4.8	5.2	5.3	5.4
January	5.4	5.7	5.9	6.0
February	5.3	5.5	5.5	5.5
March	5.8	5.8	5.7	5.6
April	4.9	4.6	4.4	4.2

5.2.2 Required flow rate in litres/min

Required flow rate in litres/min can be calculated from the value of solar insolation. It is necessary to obtain the maximum and minimum values of required flow rate for the different values of tilt angle. If the values of the required flow rate can be obtained then we can compare this set of values with the value of the flow rate that can be obtained from the pump operating characteristics curve. Then we can decide whether the pump can fulfil the requirement or not.

The required flowrate can be calculated as such:

$$Flow\ Rate = \frac{Total\ Water}{Solar\ Insolation} \quad \text{.............................} \quad (5.2)$$

Table 5.2: Daily required flow rate of water for different optimized tilt angle

Months	Required flow Rate (litres/min)(220959.6litres/(solar insolation*60))			
	Tilt angle 23.45 (Sept.-Nov)	**Tilt angle 33.2985 (Sept.-Nov)**	**Tilt angle 38.7082 (Sept.-Apr)**	**Tilt angle 43.0024 (November)**
September	1164	1193	1225	1259
October	793	775	775	780
November	719	678	665	659
December	764	708	689	679
January	685	640	625	618
February	698	672	667	667
March	636	638	647	659
April	750	794	831	868

It is clear from the Table 5.2 that minimum required flow rate can be obtained for the month of November. For the optimum tilt angle value of 38.7082, it shows the flow rate value about 665.1879 litres/min. By comparing the data for the February and November it is observed that water collection for February month is much higher than November month. Therefore to design the pump the month of November has been chosen. Here the flow rate for March is much less than the other month for the optimized tilt angle of November. On the other hand solar irradiance value for the March month is higher than some of the other months as can be seen from Table 5.3. Considering Solar irradiance, water collection from rainfall and Flow rate November month is chosen as a critical month. Therefore the solar powered water pump will be designed considering the month of November.

5.3 Pump selection:

The head value of our selected site has been calculated and the value of the head is 26m. Maximum and Minimum value of flow rate for cultivation period has been calculated. A pump has been selected from manufacturer's details that can achieve the required flow. In this study, it is chosen the Shakti pump 42.5 DCSSP 6750 pump motor that can fulfill the requirements. The curve for the head of 30m is used and according to that the input variable power will change with solar intensity and our flow rate will vary as shown in the Table in Appendix B. Pump and motor specifications has been shown in the following Table:

Table 5.3: Specifications of pump and motor of Shakti pump 42.5 DCSSP 6750

Pump	
Pump type	SOLAR SUBMERSIBLE PUMP
Flow (m3/h)	42.5
Head(m)	22-30
Pump Efficiency (%)	70
Motor	
Motor Type	PERMANENT MAGNET SOLAR MOTOR
Motor Power (KW)	5.5
Rated Voltage (V)	244
Rated Current (A)	14.6
Motor rated efficiency at duty point (%)	88
Pump Controller	
Controller type	SHAKTI SUD 3P, 20A, 450Vdc, 7.5HP
Power of drive (kW)	5.5
Maximum input voltage at solar array (vdc)	450
Rated output voltage	180-415
Rated Output current	20

5.4 Panel Sizing Calculation

To calculate the total water obtained and the panel design, three optimizations are considered.

- September to November
- September-April
- November

For the three scenarios, this study considers the month of November to design the whole system. This is because for the month of November, it can get the lowest solar intensity and hence the lowest energy obtained. If the system can fulfill the demand for November, it will be able to do it for the other months. This study considers the September-April period and September to November which include the cultivation time of the location.

Output panel power

As the pump has the rated power of 6750 W, the photovoltaic panel should be arranged in such a way that it can provide minimum 6750 W power after considering different losses. For that purpose PV module of 340 watt has been chosen. The main purpose of choosing that high watt module is to get the necessary power from less number of modules.

Table 5.3 presents the panel specifications which are used in this study.

Table 5.4 Specifications of the solar panel

Cell specification (Standard condition, 1000W/m2 and 25˚C)	
Maximum Power , Pmax	340W
Maximum power point voltage, Vmpp	38V
Maximum Power point current, Impp	9.01A
Open circuit voltage, Voc	47.6V
Short Circuit Current, Isc	9.69A
Module Efficiency, ɳ	17.04%
Cells per module	72

Current and voltage requirement

To calculate the panel output power, current and voltage need to be calculated after considering the voltage and current losses. Panel voltage drop can be determined from the equation (5.3)

Panel voltage dropped,

$$Vdrop = V_{diode} \times V_{temp} \times \Delta T \qquad (5.3)$$

Here, ΔT is the change of temperature

Total loss considering temperature effect and line loss =

$$Vdrop + LL \qquad (5.4)$$

It is necessary to find out the value of panel output voltage from the equation (5.5). The rated voltage of the motor can be known from the pump specification.

Motor rated voltage,

$$V_{mr} = [100 - (Vdrop + LL)] \times V_{panel} \qquad (5.5)$$

Total loss considering De rating factor, ηD and edging factor, $\eta e = \eta D + \eta e$

Similarly from equation (5.6), panel output current can be determined.

Motor rated current,

$$I_{mr} = [100 - (\eta D + \eta e)] \times I_{panel} \qquad (5.6)$$

$Here, V_{panel} = panel\ output\ voltage$ And $I_{panel} = panel\ output\ current$

$Panel\ output\ power,$

$$P_{panel} = V_{panel} \times I_{panel} \qquad (5.7)$$

Panel sizing can be determined from the total energy required for the pump specification.

$$\text{Number of panels needed for this study} = \frac{P_{panel}}{power\ of\ a\ single\ module} \quad (5.8)$$

To find the size of the solar panel required, we need the new parameters for the losses for both voltage and current.

Table 5.5: list of parameters for determining the panel output power

Parameters	Values
Silicon solar cell voltage, V_{diode}	0.6V
Standard condition temperature	25˚C
average cell temperature	45˚C
Voltage drop due to temperature drop, V_{temp}	$2mV/℃$
Line loss, LL	2%
De rating factor, ηD	10%
edging factor, ηe	10%

For every 1˚ C temperature change 2mV voltage will be dropped from the voltage that we get from the solar panel. Here, Silicon solar cell voltage is 0.6V. Standard condition temperature is 25˚C. On average cell temperature is 45˚C. So the voltage dropped from the panel voltage, 6.67%. Therefore due to temperature increment panel output voltage decreased by 6.67%.

Considering, Line loss 2%. Total loss considering temperature effect and line is 8.67%. Considering line loss and temperature effect the rated voltage will be the (100%-8.67%) or 91.47% of the output voltage. Here, Motor rated voltage is 244V, therefore the panel output voltage is 266.75 Volt. Here, Solar panel maximum power point voltage, V_{mpp} = 38V, Considering De rating factor, ηD = 10% and edging factor, ηe = 10% using the equations we can get the value of 20%. From the motor specification motor rated current is 27.66, using the equation panel output current will be 80% motor rated current. So panel motor current will be

34.575A. Solar panel maximum power point current, I_{mpp} = 9.01A and the maximum power will be 9222.88W

The maximum output power of the selected module is 340 W

Number of panel requirement for the panel arrangement = $\frac{P_{panel}}{340W} = \frac{9222.88W}{340W}$ = 27.12 = 8 (approx.)

Here, the Table 5.4 shows obtaining output current, voltage and power of the PV panel using the equation (5.3-5.8)

Table 5.6: List of panel output voltage, current and power

Output	**Values**
voltage dropped from the panel , $Vdrop$	6.67%
Total voltage loss, $Vdrop + LL$	8.67%
panel output voltage, $Vpanel$	244V
Total current loss, $\eta D + \eta e$	20%
Panel output current , $Ipanel$	34.575A
Total output panel power, P_{panel}	9222.88W
Number of 340W solar panels	28

Panel arrangement

Firstly the number of PV modules in series connection has to be determined. Each of the PV module has an operating output current and voltage. Series connected modules increases the value of total voltage to fulfil the required pump motor voltage. Equation 5.10 illustrates this, and Equation 5.8 illustrates how the PV strings can be connected in parallel to increase the total amount of current and this will fulfil the required pump's power.

Number of Panels required for Series connection = $\frac{Estimated\ output\ voltage}{Voltage\ at\ maximum\ power\ point}$ (5.9)

Which gives that the panel's required for the series connection is 7 approximately.

To get the number of panel's requirement for parallel set up, equation 5.8 can be used.

Number of solar panels required for parallel connection = $\frac{Estimated\ output\ current}{Maximum\ power\ point\ current}$ (5.10)

Calculation shows it requires approximately 4 panels.

To arrange the panel, 28 modules are required. There will be 4 parallel strings. Each string has 7 modules. Figure 5.3 shows the possible orientation of the photovoltaic modules. It shows that the arrangement gives 9 kW output power considering no loss. After considering loss it will provide the power as the pump required. The output of the panel is considered as the input of the pump.

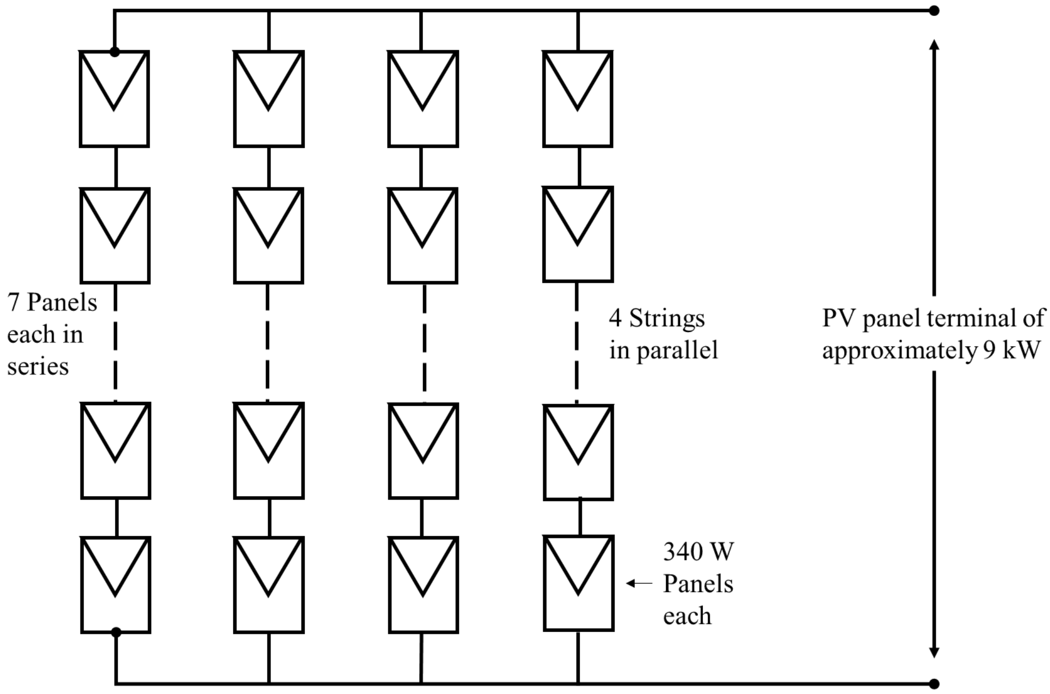


Figure 5.3: PV module orientation in series and parallel connection

Chapter 6
Validation

6.1 Calculation of output energy of the PV panels

In section 3.3.3 the single diode model of a solar cell discussed already, This section the parameters of the single diode model or PV panel have been discussed.

the net current of the cell can be written as[30]

Net current, $I = I_{ph} - I_d - I_{Rp}$

$$= I_{ph} - I_o \left[exp\left(\frac{q(V/N_S+IR_S)}{nKT}\right) - 1\right] - \left(\frac{V/N_S+IR_S}{R_{SH}}\right) \qquad \text{--------------------- (6.1)}$$

In above equation, k is the Boltzman constant, q is the charge of electron, I_{ph} is Photo current , n is the ideality factor, V is the voltage across the diode, I_o is Reverse saturation current, T is the operating temperature, Rs is Series resistance, R_{SH} is the Shunt resistance and Ns is the number of series connected cell

Short circuit current can be obtained from the I-V characteristics curve. The short circuit current *Isc* is the maximum amount of current generated by the cell when the voltage across the solar cell is zero. For an ideal solar cell short circuit current value is equal to I_{ph}. This current depends on the generation and and collection of the light generated carriers.

The ideality factor of a diode is a measure of how closely the diode follows the ideal diode equation. It is denoted by n and indicates the recombination mechanisms ruling inside the diode. The derivation of the simple diode equation uses certain assumption about the cell. The value of n is in between 1 and 2. [30]

The equation for the ideality factor is:

$$n = \frac{(V_{OC1} - V_{OC2}) \times q}{k * T * N_S * \ln\left(\frac{I_{SC1}}{I_{SC2}}\right)} \text{.................................(6.2)}$$

In above equation, *Ns* is the number of cells connected in series in the panel, V_{oc1} & V_{oc2} are the open-circuit voltages at the same temperature with different solar irradiance, I_{sc1} & I_{sc2} are the short circuit currents at the same temperature with different solar irradiance.

For this study, the open-circuit voltage and short circuit current have been measured almost the same temperature but with different solar irradiance the ideality factor has been measured using the above equation. For our solar module, the ideality factor is 1.3.

Reverse saturation current in a PN junction diode, is due to the flow of minority electrons from the p-side to the n-side and the minority holes from the n-side to the p-side. The reverse saturation current denoted as *I0* and the equation for the reverse saturation current is [30]:

$$I_o = \frac{I_{sc}}{exp\left(\frac{V_{oc}}{n * V_T * N_S}\right) - 1} \text{...(6.3)}$$

In this equation, q is the charge of an electron, k is the Boltzmann's constant, n is the ideality factor, *Ns* is the number of cells connected in series in the panel , V_T is the thermal voltage , I_{sc} is the short circuit current and V_{oc} is the open circuit voltage

Temperature dependant reverse saturation current[30],

$$I_o = I_{on} \left(\frac{T}{T_n}\right)^3 \exp\left[\frac{qE_g}{nK}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \text{-----------------------------(6.4)}$$

In above equation, I_{on} is the nominal (at 1000W/m^2) reverse saturation current in Ampere, *Tn* is nominal (at 1000W/m^2) temperature in Kelvin, T = operating temperature in Kelvin, E_g is the energy band gap in eV, n is the ideality factor

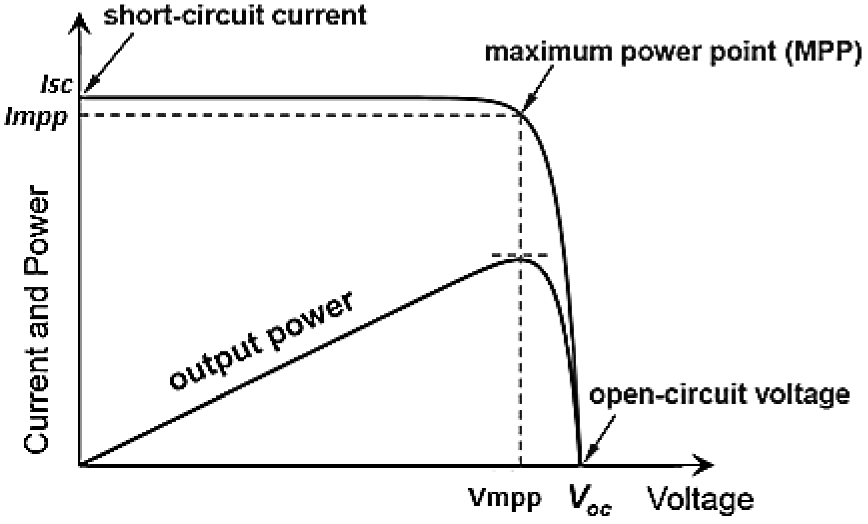


Figure 6.1: IV and PV characteristic curve of a solar module [29]

The equation that is used for Thermal volatge is,

$$V_{Tn} = \frac{N_s KT}{q} \qquad \text{------------------------------(6.5)}$$

The open circuit voltage is obtained when the current is transverse and the generated current value is 0. During night the equation we can obtain [30],

$$V_{OC} = \frac{KT_C}{q} \ln\left(\frac{I_{SC}}{I_o} + 1\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(6.6)$$

In above equation, V_{OC} is the open circuit voltage in volt and I_{SC} is the short circuit current in ampere. In above equation it is shown that the value of V_{OC} depends on the light generated photo current and short circuit current. Reverse saturation current depends on the recombination process in solar cell. The measurement of the recombination in a cell is the open circuit voltage. In Figure 3.11 V_{oc} has been shown for a particular solar cell.

Open circuit voltage also can be written as ,

$$V_{OC} = \frac{akTN_s}{q} ln\left(\frac{I_{SC}}{I_{on}}\right) \qquad \text{------------------------------ (6.7)}$$

The power can be calculated by the product term of voltage and current. At maximum power point the load resistance value is optimum R_{opt} and the resistive load power is maximum. Maximum power point is the operating point where P_{max}, I_{mpp}, V_{mpp} values are obtained. Here in Figure 3.11 maximum power can be calculated by the rectangular area under the I-V characteristic curve of the PV module. The point where the rectangular region cuts the I-V characteristic curve is the maximum voltage (V_{mpp}) and maximum current (I_{mpp}).The equation for the maximum power is given by [30],

$$P_{max} = I_{mpp}V_{mpp} \quad \text{……………….………….(6.8)}$$

In this equation, V_{mpp} is the maximum voltage at maximum power point and I_{mpp} is the amount of maximum current at maximum power point

Fill Factor, FF can be calculated from the maximum voltage (V_{mpp}), current (I_{mpp}), Open circuit voltage (V_{oc}) and short circuit current (I_{sc}). It is the ratio of the maximum power deliver to the cell and the product term of V_{oc} and I_{sc} For a good solar cell this value will be greater than 0.7.

Fill factor value decreases with the increment of cell temperature. Equation for the FF is given by,

$$FF = \frac{I_{mpp}V_{mpp}}{I_{SC}V_{OC}} \quad \text{………………………………….(6.9)}$$

Graphically, the FF is a measure of the area of the largest rectangle which will fit in the I-V curve of a solar cell. It shows the influence of the serial resistance on efficiency of solar cell. The value of large voltage has larger value of FF. The variation in values of FF can be significant for solar cells made for different materials

Efficiency is defined as the ratio of output energy from the solar cell to the input energy from the sun and it is the commonly used parameter to compare the performance of the one solar cell to another solar cell. In addition, the value of efficiency depends on the spectrum and intensity of the incident sunlight and temperature of the solar cell. Efficiency can be determined by [30],

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}} \qquad (6.10)$$

In above equation, FF is the Fill factor and Pin is the input power, I_{sc} is the short circuit current and V_{oc} is the open circuit voltage

Figure 6.2 and 6.3 plots show the Current and power change according to the applied voltage for different values of solar irradiation for the month of November considering the optimized angle 38.7^o. These two graphs are plotted considering the daily intensity data for the 15th day of the November month. Here solar irradiation varying with the time during sunrise to sunset. Here time has been considered from 7.00am to 5.00pm. Here it is observed that higher irradiation value gives the higher current and the maximum power with the change of voltage. With the change of solar irradiation short circuit current and open circuit voltage changes significantly. As shown in graph here the short circuit current change is directly proportional but not the open circuit voltage. From the maximum value of point which is known as maximum power point, V_{mpp} and I_{mpp} have been determined from the graph. These two maximum values give the maximum output of the PV panel. The daily intensity is calculated theoretically for different time staring from the sunrise to sunset. The plot of P-V curve gives the maximum power output for different intensity.

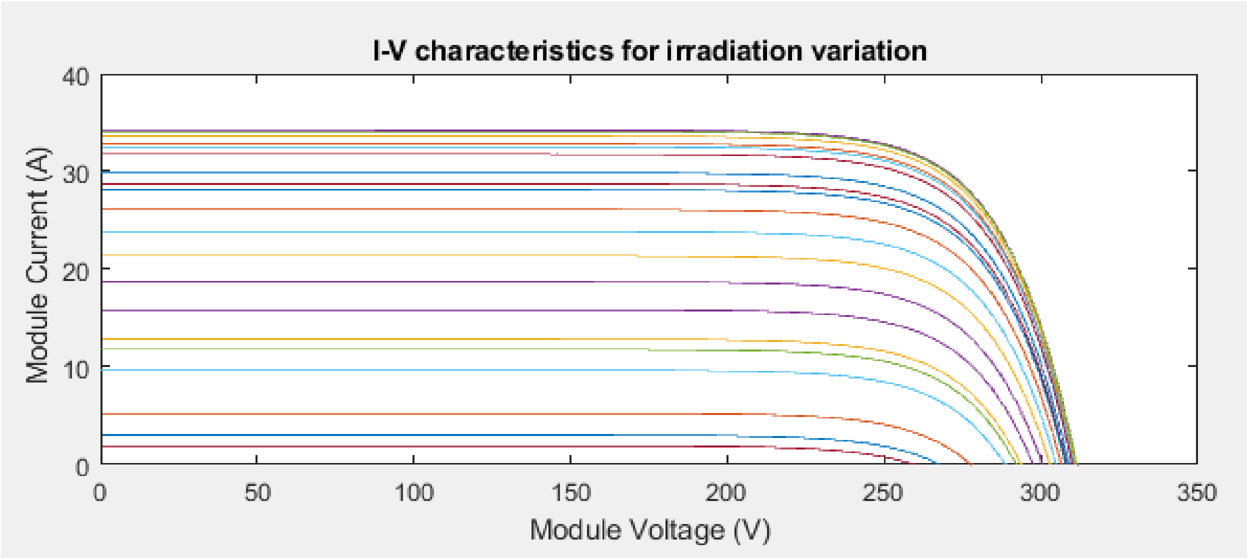


Figure 6.2. Plots of I-V characteristics curves of the PV panels, for varying solar irradiance from sunrise to sunset, calculated for the 15th day of the November month, considering the optimized tilt angle of 38.7˚

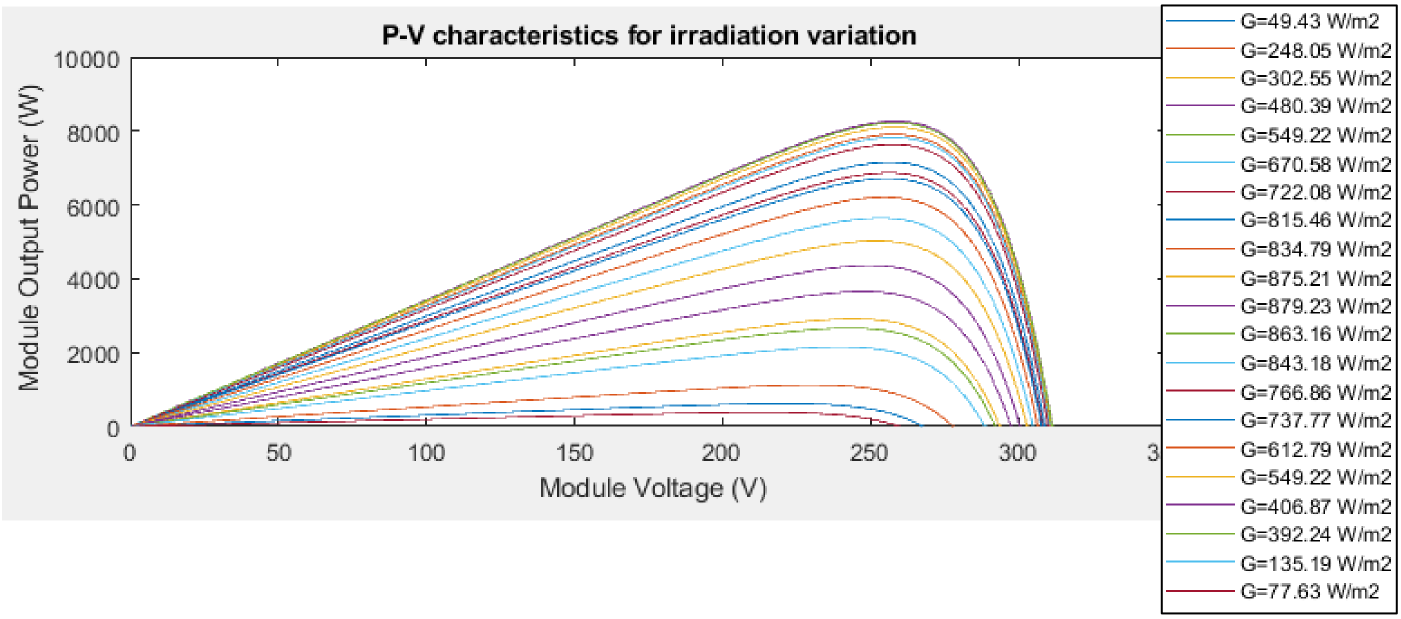


Figure 6.3. Plots of P-V characteristics curves of the PV panels, for varying solar irradiance from sunrise to sunset, calculated for the 15th day of the November month, considering the optimized tilt angle of 38.7˚

6.2 Calculation of flow rate

Pump input power can be detemined from the maximum output of the PV module. As we can see in equation 6.6, Output power of the PV module is the driving input power to the pump. Here considering all the volatge and current losses Volatge will be the 98% of the V_{mpp} and Current will be the 80% of the I_{mpp}. Multiplying these two voltage and current, input power of the pump has been calculated.

Pump input power can be calculated,

$$P_{pump} = (0.98V_{mpp})*(0.8I_{mpp}) = 0.784V_{mpp}I_{mpp} = 0.784P_{max} \text{----------} (6.11)$$

By using the equation 6.11, input power for the pump is determined. After getting the input power, the pump curve is used to determine the flow rate.

It can be determined the flow rate (m^3/hr.) from the given curve of input power (Watt) vs flow rate (m^3/hr.) of the selected pump. From the curve the flow rate according to the solar irradiation can be calculated. Here Maximum output power of the PV panel has been calculated from the equation of ($P_{max} = V_{mpp}*I_{mpp}$) where V_{mpp} and I_{mpp} are the maximum power point output voltage and maximum power point output current of the PV module of 28 solar panels where 7 solar panels are in series and 4 parallel branch aligned with it respectively. The input power of the pump will be 78.4% of the output power of the PV module considering voltage and current losses. After that the value of flow rate from the curve of the pump can be calculated.

The list of the parameters and values of the parameters have been shown in Table 6.1

Table 6.1 List os the parameters along with their corresponding values

Parameters	symbol	values	Unit
Boltzman constant	k	1.38065×10^{23}	J/K;
charge of electron	q	1.602×10^{-19}	C
nominal (at $1000W/m^2$) short circuit current	Iscn	9.69	A
nominal(at $1000W/m^2$) open circuit voltage	Vocn	47.6	V
Temperature current constant	K1	0.0023	
number of series connected cell	Ns	72	
operating temperature	T	(45+273)	K
nominal (at $1000W/m^2$) temperature	Tn	(25+273)	K
nominal irradiance,	Gn	1000	W/m^2
diode ideality constant	n	1.3	
band gap of Silicon at 25 degree celcius	Eg	1.12	eV
actual irradiance	G	variable	W/m^2
Series resistance	Rs	0.001	ohm/cell
Shunt resistance	Rp	10000	ohm/cell

Considering all the parameters and the equation, the daily variation of maximum power for different irradiation can be calculated.

Table 6.2 shows the detailed calculation of the pump input power for a particular day. Firstly Maximum output power has been calculated from the maximum power point current and voltage value. Here the 15^{th} day of November has been considered. Then the input power of the pump has been calculated. From the pump characteristics curve the flow rate have been determined according to the pump input power.

Table 6.2 Flow rate calculation from the daily intensity of a specific day of November 15 with the optimized tilt angle 38.7082^{o}

Time	Daily intensity for tilt angle 38.7082	Maximum Output power Pmax (watt)	Pump input power =0.784Pmax	Flow rate m3/hr
7.00	77.63	617.09	483.80	0.00
7.30	135.19	1122.20	879.80	0.00
8.00	329.24	2913.50	2284.18	200.00
8.30	406.87	3651.40	2862.70	330.00
9.00	549.22	5023.50	3938.42	500.00
9.30	612.79	5642.30	4423.56	570.00
10.00	737.77	6867.20	5383.88	610.00
10.30	766.86	7153.70	5608.50	620.00
11.00	843.18	7907.30	6199.32	630.00
11.30	863.16	8104.90	6354.24	635.00
12.00	879.23	8264.10	6479.05	650.00
12.30	875.21	8224.10	6447.69	645.00
13.00	834.79	7824.30	6134.25	640.00
13.30	815.46	7633.30	5984.51	625.00
14.00	722.08	6712.90	5262.91	600.00
14.30	670.58	6207.50	4866.68	580.00
15.00	549.22	5023.50	3938.42	500.00
15.30	480.39	4357.40	3416.20	400.00
16.00	302.55	2661.90	2086.93	180.00
16.30	248.05	2152.50	1687.56	40.00
17.00	49.43	378.63	296.84	0.00
				8955.00
Daily water collection				268650.00
Number of Sunny days				25.00
Entire month water collection from the pump				6716250.00

Figure 6.4 shows the plot of daily incident solar power and the flow rate with respect to time of the day in a single plot. For 15th November, the time duration from 7.00am morning to 5.00pm evening is considered to plot it. Here it is seen that the maximum solar irradiation shows the value at 12.00 noon. From the graph after determining the flow rate for each of the time duration, the total water collection value for a day is calculated. Here for the month of November it meets the daily water requirement and it can get 2, 68,650 litres of water for an entire day from 7.00am to 5.00pm duration. The required per hour minimum requirement of the water for this month is

368.26 L/min. That means for this particular day of 15th November, the collected water is 17.75 % higher than the minimum requirement of the water. This can be fetched from the pump by using the calculated panel sizing and selected pump.

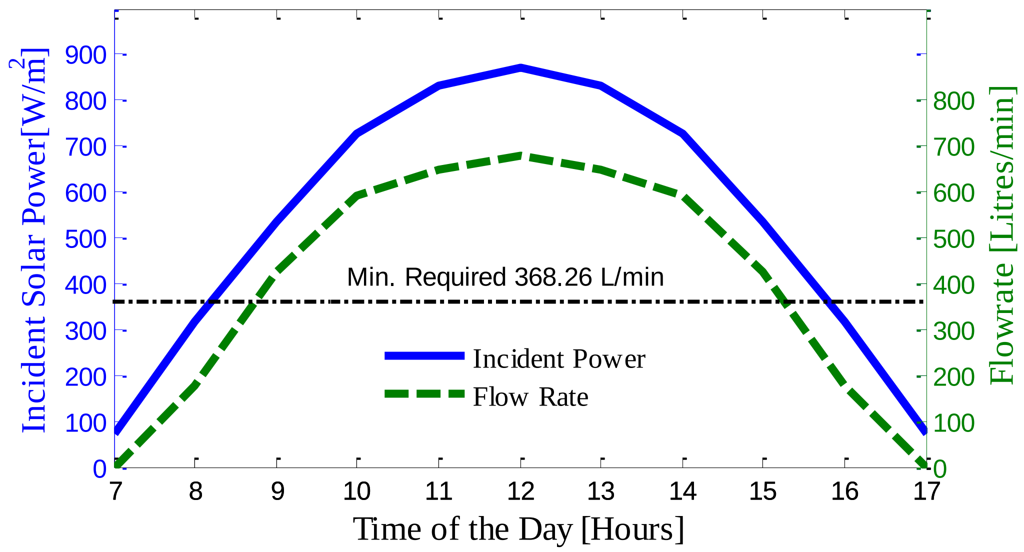


Figure 6.4. Plots of incident solar irradiance (solid line) and the water flow rate of the pump (dotted line), calculated for November 15, with the tilt angle set at 38.7082°.

6.3 Validation

To validate, it is required to observe whether the total water collection from PV module and rainfall can fulfil the total water requirement or not. Firstly, monthly water collections have been calculated both from PV module and from rainfall. Here the water collection from PV module has been calculated considering the sunny days of a month, since the pump can deliver water during sunny days and in cloudy days it is not possible to fulfil the minimum water requirement. So the monthly water collection has been calculated water collection from PV module per day multiplied by the number of sunny days in a month. This calculation gives the water collection per month data. We have already calculated monthly water collection from rainfall in previous section. The summation of these two collections gives the total amount of water collection in a month. The daily water requirement multiplied the number of days in a month gives the value of water required in a month.

TABLE 6.3 Table of Monthly collected water and required water (in thousand litres)

Month	Water collected using solar energy (W_{Sun})			Water collected per month from rain (W_{Rain})	Total water collected per month (W_{Sun} +W_{Rain})	Water Required per month (W_{Req}/day) ×Number of days in a month
	Water collected per day (W_{Sun}/day)	Number of sunny days (N_{Sun})	Water collected per month (W_{Sun} = W_{Sun}/day ×N_{Sun})			
Sep	251	13	3263	6630.323	9893.323	6628.788
Oct	264	21	5544	4018.531	9562.531	6849.747
Nov	268	25	6700	399.464	7099.464	6628.788
Feb	273	23	6279	475.179	6754.179	6186.868
Mar	260	25	6500	1004.357	7504.357	6849.747
Apr	236	20	4720	3689.169	8409.169	6628.788

Table 6.3 shows the values of the monthly water collection and monthly water requirement. Figure shows that the water collection from the PV module per day for the cultivation period (September to November and February to April). Then from the per day calculation, monthly water collection have been calculated. Water that can be collected in one whole month from the PV module and rainfall and the required amount of water in one whole month are shown in this Table. It is shown that all the months during cultivation period fulfil the minimum requirement of water in every month of the cultivation period.

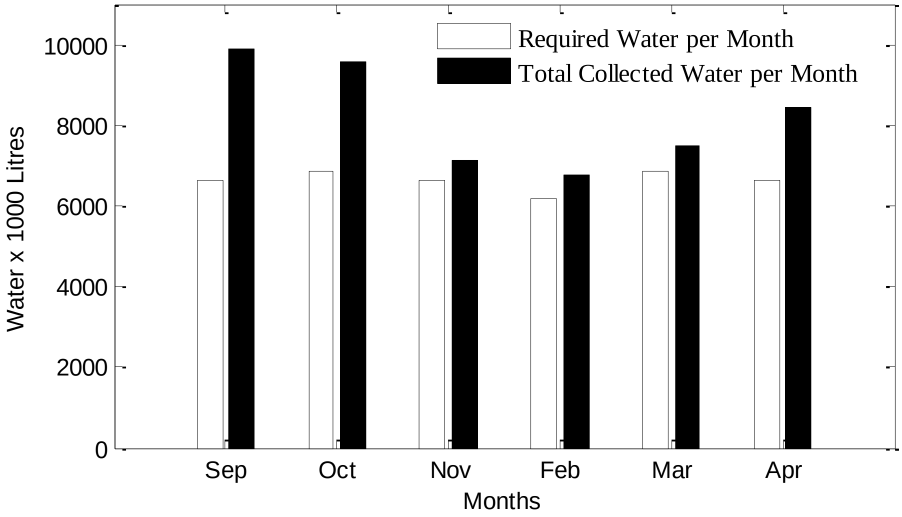


Figure 6.5: Bar chart of total collected water and required water per month

Figure 6.5 shows that the water collection from the PV module per day for the cultivation period (September to November and February to April). It is shown that all the months during cultivation period fulfil the minimum requirement of water in every month of the cultivation period. It is also shown that the highest amount of water can be collected in the month of September.

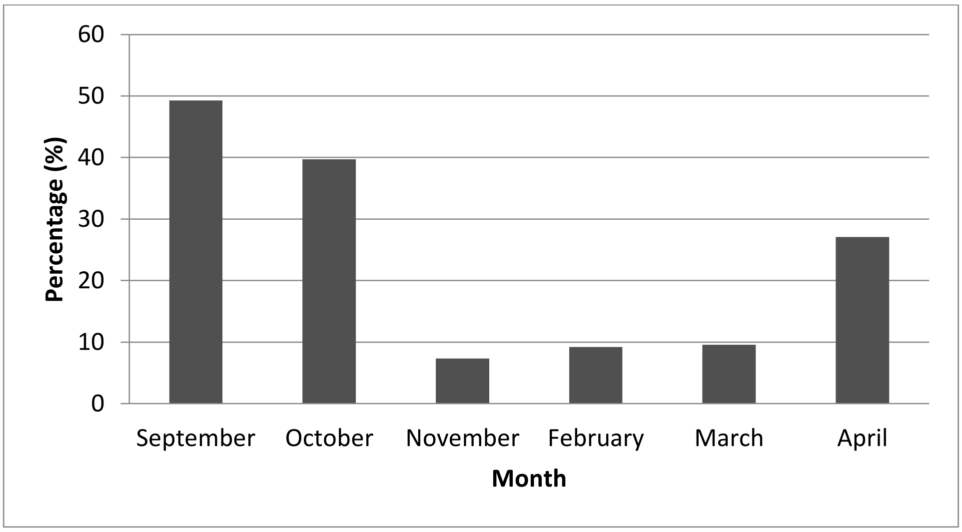


Figure 6.6 Percentage difference of the total water collection with respect to the required water per month

Figure 6.6 shows that how much of excess amount of water can be collected monthly compared to monthly water requirement. It is shown in Figure that in the month of September the water collection is very high than rest of the month. Since the rainfall rate is very high in the month September, it almost exceeds by 50% from the monthly requirement water. In November, February and March month rainfall is not much as a result the exceed amount of water percentage is almost 7-9% on average from the required amount of water. In addition, since November month is considered as critical month and the pump design and panel orientation are based on the month of November. From the Table 6.3 and Figure 6.5 it is shown that, it fulfil the minimum amount of monthly water requirement. As a result, rests of the month are also satisfy the requirement of monthly water which is need for irrigation.

Chapter Summary:

From the previous chapter as the month of November is already considered as a critical month during cultivation period. As in this month the total amount of water collection from rainfall is critically low as well as the value of total incident energy also low for this month. Considering the value of minimum and maximum of flow rate and also considering the water head of the selected location, Shakti pump 42.5 DCSSP 6750 has been selected for irrigation purposes. Daile solar irradiance for the 15^{th} day of the November month has been shown in the Table. The I-V and P-V characteristics curve have been plotted by the 15^{th} day of the November month daily irradiation data. From this two characteristics curve voltage and current of the maximum power point can be determined. The maximum output power of the PV module has been calculated by multiplying the voltage and current value. The product term gives the value of maximum output power of the module. 78.4% of the output power of the module gives the input power of the pump here all the voltage and current losses have been considered. Once the input power has been calculated, from the Input power Vs Flow rate curve of the selected pump flow rate has been determined according to the pump input power values. The summation of all the flow rate values during the duration from sunrise to sunset multiplied by 30 gives the amount of total water collected from the PV module. From the Table as it is seen that the value of total water collection from PV module fulfilled the total daily water requirement for the irrigation of the selected site. Similarly the procedure has been repeated for the rest of the months of the cultivation period and it has been shown that daily water requirement for all of the months have been fulfilled by using 42.5 DCSSP 6750 pump and 28 solar panel PV module for irrigation.

6.4 Limitations

1. Initial investment for solar system is high. It includes the costing of solar panel, wiring, installation etc.

2. Since the solar energy can be collected from the rainy and cloudy days, the efficiency of the solar energy can be decreased. Solar panels depend on sunlight, therefore the performance decrease during rainy and cloudy days.

3. More solar panels are required to produce more electricity. More space required for installing more solar panels.

Chapter 7

Conclusion

In this study, design of an optimized and cost-effective solar powered water pumping system for irrigation purposes using the directly coupled PV that does not use batteries or generators has been presented. This work focuses on the water requirement for irrigation mainly during two cultivation periods, one from February to April and the other from September to November, as during these two periods weather remains mostly dry and demand for ground water for irrigation is high. Directly coupled PV system has been chosen to power the pump because of its simplicity, minimum maintenance and almost zero running cost and zero carbon emission. These features will make the system economically affordable and technologically feasible for the farmers in village areas where skilled maintenance person is not always available.

In order to design the system, first an optimum tilt angle for the panel has been determined that will require minimum panel size that can supply the required amount of water for irrigation during the cultivation period considered. Detailed calculations show that a tilt angle of 38.7° would require minimum panel size of 4 strings with 7 series connected modules at each string. Result shows that the proposed system can meet the minimum daily water requirement. It shows 17.75% extra collection than the daily requirement for the 15^{th} of November. The designed system has a limitation that it will not be able to supply enough water during prolonged period of cloudy days. This limitation can be partly offset by using a slightly oversized system and storing the excess water in a water tank which can be supplied during the cloudy period. Future work can be directed towards designing a smart water pump system that is responsive to the fluctuating weather. For other cultivation area can be considered to design the pump for irrigation. In addition, Grid tied water pumping system can be designed for prolong period.

References

[1] *Official website of Bangladesh Power Development Board, Energybangla and Ministry of Power. Available at: http://www.bpdb.gov.bd/bpdb/ ; http://www.powerdivision.gov.bd/ and http://www.energybangla.com.*

[2] *A. H. Zenan, S. Ahmed, M. K. Rhaman and M. M. Rahman, 'A Multilevel Solar Panel System for Urban Areas', Proc. of 39th IEEE PV Spec. Conf., June 2013, Tampa, Florida, USA, pp. 1526-1530.*

[3] *Ismail, C. Soh, L. Cronin, M. Lisewski, N. Jo & R. Vagani , "Solar Water Pump System, Tsavo East National Park Kenya: Feasibility Study Report", Tech. Report, Imperial College London, Feb. 2012.*

[4] *Hamidat A., Benyoucef B. and Hartani T., Small-scale irrigation with photovoltaic water pumping system in Sahara regions. Renewable Energy, Vol. 28, pp. 1081-1096, 2003.*

[5] *Daud A.K. and Mahmoud M.M., Solar powered induction motor-driven water pump operating on a desert well, simulation and field tests. Renewable Energy, Vol. 30, pp. 701-714, 2005.*

[6] *Haque M.M., "Photovoltaic water pumping system for irrigation,"4th International Conference on Mechanical Engineering, December 26-28, Dhaka, Bangladesh: , pp.21-26, 2001.*

[7] *Harishankar S., Sathish Kumar R., Sudharsan K.P., Vignesh U. and Viveknath T., Solar Powered Smart Irrigation System. Advance in Electronic and Electric Engineering, Vol. 4(4), pp.341-346, 2014.*

[8] *A. Bekraoui, M. Yaichi, M. Allali, A. Taybi and A. Boutadara, "Performance of Photovoltaic Water Pumping System in Adrar, Algeria," 2018 6th International Renewable and Sustainable Energy Conference (IRSEC), Rabat, Morocco, 2018, pp. 1-5,*

[9] *K. A. Sado, L. H. Hassan and M. Moghavvemi, "Design of a PV-powered DC water pump system for irrigation: a case study," 2018 53rd International Universities Power Engineering Conference (UPEC), Glasgow, 2018, pp. 1-6, doi: 10.1109/UPEC.2018.8542072.*

[10] *M. Saputra, A. Syuhada and R. Sary, "Study of Solar and Wind Energy Using as Water Pump Drive-Land for Agricultural Irrigation," 2018 4th International Conference on Science and Technology (ICST), Yogyakarta, 2018, pp. 1-4, doi: 10.1109/ICSTC.2018.8528643.*

[11] *Mansur Aliyu, Ghassan Hassan, Syed A. Said, Muhammad U. Siddiqui, Ali T. Alawami, Ibrahim M. Elamin, A review of solar-powered water pumping systems, Renewable and Sustainable Energy Reviews,vol. 87, 2018, Pages 61-76,*

[12] *Pushpendra Kumar Singh Rathore, Shyam Sunder Das, Durg Singh Chauhan, Perspectives of solar photovoltaic water pumping for irrigation in India, Energy Strategy Reviews, Volume 22, 2018, Pages 385-395*

[13] *M.N. Sarkar, H.R. Ghosh, Techno-economic analysis and challenges of solar powered pumps dissemination in Bangladesh, Sustain. Energy Technol. Assess. Vol. 20 (Apr 1, 2017) pp. 33–46.*

[14] *M. T. A. Khan, M. R. Ahmed, S. I. Ahmed and S. I. Khan, "Design and performance analysis of water pumping using solar PV," 2nd International Conference on the Developments in Renewable Energy Technology (ICDRET 2012), Dhaka, 2012, pp. 1-4.*

[15] *Shahidul I. Khan1, Md. Mizanur R. Sarkar and Md. Quamrul Islam, Design And Analysis Of A Low Cost Solar Water Pump For Irrigation In Bangladesh, Journal of Mechanical Engineering, Vol. ME 43, No. 2, December 2013*

[16] *M. Nadim, M. R. H. Rashed, A. Muhury and S. M. Mominuzzaman, "Estimation of optimum tilt angle for PV cell: A study in perspective of Bangladesh," 2016 9th International Conference on Electrical and Computer Engineering (ICECE), Dhaka, 2016, pp. 271-274, doi: 10.1109/ICECE.2016.7853908.*

[17] *Productivity and Profitability of Jackfruit-Eggplant Agroforestry System in the Terrace Ecosystem of Bangladesh - Scientific Figure on Research Gate. Available from: https://www.researchgate.net/Figure/Location-of-the-study-area-in-Shibpur-Upazila-under-Narsingdi-district-terrace-ecosystem_Figure1_323432992 [accessed 5 Dec, 2020]*

[18] *M. R. Khan and Edward D. Brown, "DC Nanogrids: A Low Cost PV Based Solution for Livelihood Enhancement for Rural Bangladesh", Proc. of 3rd Int. Conf. on the Devlop. in Renewable Energy Tech., ICDRET 2014, May 2014, Dhaka, Bangladesh*.

[19] *S. Ahmed, A. H. Zenan, N. Tasneem and M. M. Rahman, 'Design of a Solar Powered LED Street Light: Effect of Panel's Mounting Angle', Proc. 2013 IEEE Conf. Sust. Utilization and Develop. in Eng.& Tech. (2013 IEEE CSUDET), May 2013 Selangor, Malaysia, pp. 74-79.*

[20] *The Crops Of Bangladesh. (n.d.). Retrieved from http://en.banglapedia.org/index.php?title=Crop*

[21] *The Climate Of Bangladesh. (n.d.). Retrieved from http://www.geography-site.co.uk/pages/countries/climate/bangladesh_climate.html*

[22] *The irrigation Of Bangladesh. Retrieved from http://en.banglapedia.org/index.php?title=Irrigation*

[23] *ShibpurUpazila. (n.d.). Retrieved from http://en.banglapedia.org/index.php?title=Shibpur_Upazila*

[24] *S. R. Wenham, M. A. Green, M. E. Watt, and R. Corkish, 'Applied Photovoltaics', 2nd Ed., 2007, Earthscan Publications Ltd., London, UK.*

[25] *R. A. Messenger, and J. Ventre, 'Photovoltaic Systems Engineering', 2nd Ed., CRC Press, 2005, Boca Raton, Florida*

[26] *S.S. Chandel, M. Nagaraju Naik, Rahul Chandel, "Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies, Renewable and Sustainable Energy Reviews",Volume 49,2015, Pages 1084-1099*

[27] *Solar Water Pump. (2017, March 31). Retrieved August 18, 2017, from https://highlandsolar.wordpress.com/solar-water-pump/*

[28] *"Hybrid PV system" Retrieved from https://www.cleanenergyreviews.info/blog/2014/8/14/what-is-hybrid-solar*

[29] *"I-V characteristics curve" Retrieved from*

Mohammed S, Sheik & Devaraj, D. (2015). Simulation and Analysis of Stand-alone Photovoltaic System with Boost Converter using MATLAB/Simulink

[30] *M. Islam, M. M. Hasan Shawon, S. Akter, A. Chowdhury, S. I. Khan and M. M. Rahman, "Performance Investigation of Poly Si and Mono Si PV Modules: A Comparative Study," 2019 International Conference on Energy and Power Engineering (ICEPE), Dhaka, Bangladesh, 2019, pp. 1-5, doi: 10.1109/CEPE.2019.8726598.*

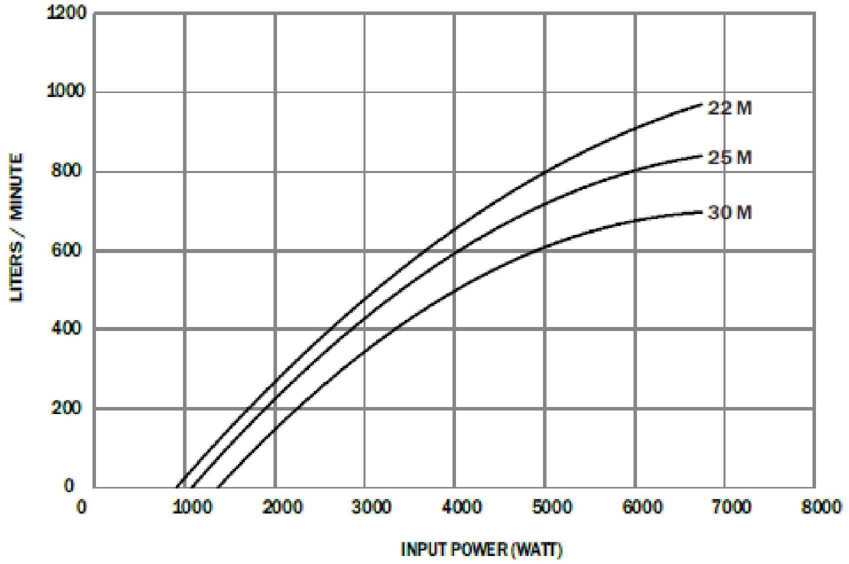
[31] *"Applied Photovoltaic"- 2nd edition by S.R. Wenham, M.A. Green, M.E. Watt and R. Corkish*

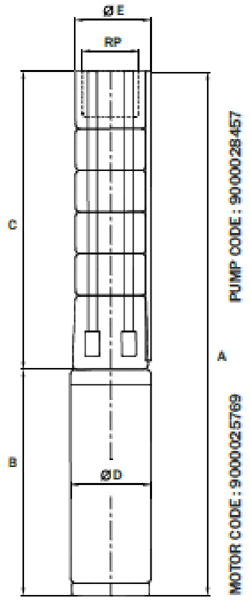
Appendix A

SOLAR PUMPING SYSTEM

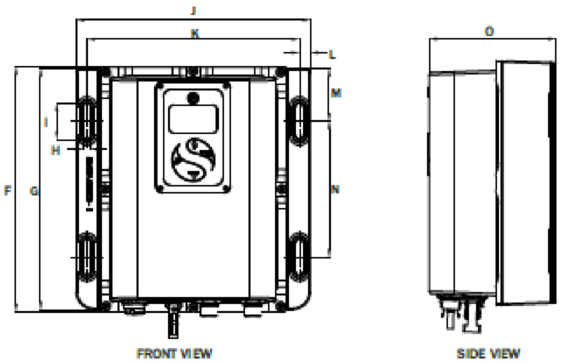
SOLAR 42.5 DCSSP 6750
BSP 75 mm (6X6)

PUMPSET CODE	9500000620
DISCHARGE (LPD)	307702
DUTY HEAD	30 METER





	INPUT POWER (WATT)						
	6750	5200	3700	2100	1500	1250	700
HEAD (m)	FLOW IN LPM						
30	708	600	460	212	0		
25	850	720	552	254	150	0	
22	965	818	627	289	170	0	0



CONTROLLER CODE : 9600000021

Appendix B

Sunmodule®

SW 340-350 XL MONO (33mm frame)

SOLARWORLD REAL VALUE

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

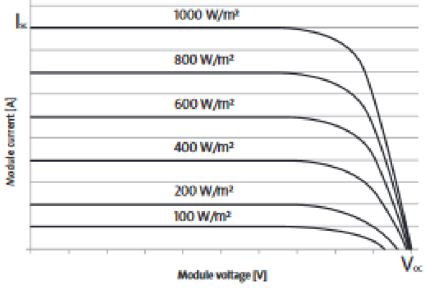
		SW 340	SW 345	SW 350
Maximum power	P_{max}	340 Wp	345 Wp	350 Wp
Open circuit voltage	V_{oc}	47.6 V	47.8 V	48.0 V
Maximum power point voltage	V_{mpp}	38.0 V	38.2 V	38.4 V
Short circuit current	I_{sc}	9.69 A	9.75 A	9.82 A
Maximum power point current	I_{mpp}	9.01 A	9.10 A	9.17 A
Module efficiency	η_m	17.04 %	17.29 %	17.54 %

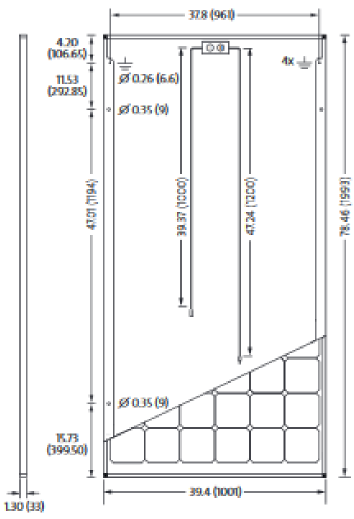
*STC: 1000W/m², 25°C, AM 1.5

PERFORMANCE AT 800 W/M², NOCT, AM 1.5

		SW 340	SW 345	SW 350
Maximum power	P_{max}	259.3 Wp	263.8 Wp	267.2 Wp
Open circuit voltage	V_{oc}	41.5 V	41.8 V	42.0 V
Maximum power point voltage	V_{mpp}	34.9 V	35.2 V	35.4 V
Short circuit current	I_{sc}	8.05 A	8.10 A	8.16 A
Maximum power point current	I_{mpp}	7.42 A	7.50 A	7.56 A

Minor reduction in efficiency under partial load conditions at 25° C: at 200 W/m², 100% of the STC efficiency (1000 W/m²) is achieved.





COMPONENT MATERIALS

Cells per module	72	*Front*	Low-iron tempered glass with ARC (EN 12150)
Cell type	Mono crystalline	*Frame*	Clear anodized aluminum
Cell dimensions	6.17 in x 6.17 in (156.75 x 156.75 mm)	*Weight*	47.6 lbs (21.6 kg)

THERMAL CHARACTERISTICS

NOCT	46°C
TCI_{sc}	0.042 %/K
TCV_{oc}	-0.304 %/K
TCP_{mpp}	-0.43 %/K
Operating temp	-40° C to +85° C

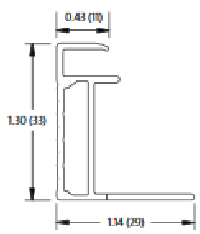
ADDITIONAL DATA

Power sorting	-0 Wp/+5 Wp
J-Box	IP65
Connector	PV wire per UL4703 with H4 connectors
Module fire performance	(UL 1703) Type 1

PARAMETERS FOR OPTIMAL SYSTEM INTEGRATION

Maximum system voltage SC II / NEC		1000 V
Maximum reverse current		25 A
Number of bypass diodes		3
*Design loads**	*Two rail system*	113 psf downward, 64 psf upward
*Design loads**	*Edge mounting*	178 psf downward, 23 psf upward

*Please refer to the Sunmodule installation instructions for the details associated with these load cases.



- Compatible with both "Top-Down" and "Bottom" mounting methods
- ⏚ Grounding Locations:
  - 4 locations along the length of the module in the extended flange.

All units provided are imperial. SI units provided in parentheses.
SolarWorld AG reserves the right to make specification changes without notice.

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