UNIVERSITY FOR DEVELOPMENT STUDIES

PERFORMANCE EVALUATION OF SOLAR POWERED IRRIGATION SYSTEMS IN THE NORTHERN REGION OF GHANA

VEDASTE NIYOKWIZERWA

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BY

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(BSc. Irrigation and Drainage)

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A THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL ENGINEERING, SCHOOL OF ENGINEERING, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN IRRIGATION AND DRAINAGE ENGINEERING

2022

DECLARATION

DECLARATION BY CANDIDATE

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this University or elsewhere. The work of others which served as sources of information for this study, has been duly acknowledged in the form of references.

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DECLARATION BY SUPERVISORS

I hereby declare that the preparation and presentation of the thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the University for Development Studies.

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ABSTRACT

Performance of a solar powered irrigation systems in the Northern Ghana was evaluated in this study. Solar powered water application systems (drip, spray tube and sprinkler irrigation systems) were evaluated using performance indicators. Coefficient of variation (CV), emission uniformity (EU), emitter flow variation (Qvar) and mean application rate (MAR) were evaluated for the drip irrigation system for different water levels in the tank. Uniformity Coefficient of (CU), Distribution Uniformity (DU), Mean Application Rate (MAR) were evaluated for the spray tube and sprinkler irrigation systems. Pressures in the submain line of the drip irrigation system (DIS) were 4.7 psi, 5.3 psi and 6.4 psi at tank water levels of 3.3 m, 3.75 m and 4.5 m high, respectively. Results of irrigation efficiencies were high with drip, spray tube and sprinkler systems recording 87 %, 80.30 % and 73.70 % respectively. The EU for the DIS ranged from 87 - 88.1 %; Qvar ranged from 17.1- 18.7 %; CV ranged from 0.05 - 0.058 and MAR ranged from 0.60 -0.9683 l/h. The CU, DU and MAR were found to be 83.1 %, 80.5 % and 15.5 mm/h respectively for the spray tube irrigation system (STIS) and 82.5 %, 73.7 % and 4.1 mm/h respectively for the sprinkler irrigation system (SIS). The life cycle of the solar powered irrigation was estimated to be 25 years. The life cycle costs (LCC) for the drip, spray tube and sprinkler irrigation systems were estimated to be 165,259.63 USD, 205,703.99 USD and 223,785.44 USD respectively. The drip irrigation system recorded high capital, operation, maintenance and repair cost, replacement cost; followed by the sprinkler irrigation and spray tube irrigation. It is suggested that the drip irrigation should be used when the water source is scarce since it saves water more than the sprinkler and spray tube irrigation systems. A flow meter should be installed on the drip irrigation system to measure the volume of water applied in the field, since mean application rate changes due to water level in the tank.

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DEDICATION

I dedicate this work to my parents Niyomukiza Daniel and Mukasangwa Marcianne for their relentless support.

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LIST OF ACRONYMS AND ABREVIATIONS

AC	Alternative Current
AGRA	Alliance for a Green Revolution in Africa
BOS	Balance of System
CTCN	UN Climate Technology Centre and Network
DC	Direct Current
DPB	Discounted Payback Period
ECw	Electrical conductivity of water
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
FDR	Frequency Domain Reflectometry
GDP	Gross Domestic Product
GIDA	Ghana Irrigation Development Authority
IR	Infiltration Rate
IWAD	Integrated Water and Agricultural Development Ghana
IWRM	Integrated Water Resources Management
Ks	Saturated Hydraulic Conductivity
LCC	Life-cycle Cost
NPV	Net Present Value
MCIP	Minimum compensating inlet pressure
NGOs	Non-Government Organisations
NGOs	Non-Government Organisations
PR	Precipitation Rate

PV	Photovoltaic
PWP	Permanent Wilting Point
ROI	Return on Investment
RSC	Residual Sodium Carbonate
SAR	Sodium Adsorption Ratio
SNV	Netherlands Development Organisation
SPIS	Solar Powered Irrigation
TCC	Total Ownership Cost
TDR	Time Domain Reflectometry
TDS	Total Dissolved Salts or Total Dissolved Solids
TI	Toxic Ions
USD	United States Dollar
UN	United Nations

CHAPTER ONE

INTRODUCTION

1.1 Background

Ghana is considered as an agriculture dependent nation although mechanized agriculture is on small scale. The agricultural sector is the major driver of Ghana's economy. The sector accounted for 23 % of the National Gross Domestic Product (GDP) in 2012, and since 2000 there has between 35.8 % and 37 % contribution to the GDP from agriculture (Bawa, 2019).

Farmers in the region will describe the rainy season as beginning in April, with rains stabilizing by May. This means that they would begin land preparation after the start of the rains in April and are ready to plant in May. But farmer's expectations of when the rains will stabilize have been changing. Over the past ten to fifteen years the onset of the wet season has been getting later. However, a more important change is that once the rains have started, wet days are separated by several, dry spells.

Irrigation is one of the agricultural technologies needed to increase yields. Irrigation has the potential to increase agricultural productivity by at least 50 % in Africa, but the continent's food production is nearly completely rainfed. Irrigated land accounts for just 6 % of total cultivated land, or considerably more than 13 million hectares (You and Wood-sichra, 2010). However, there is a huge opportunity to expand irrigation, particularly in Sub-Saharan Africa, boost yields and improve climate resilience (AGRA, 2019).

Northern Ghana has one seasonal rainfed agriculture and needs the development of small to large scale irrigation schemes (Clottey *et al.*, 2009). Agriculture in Ghana is dominated by small-scale farms – about 3 million smallholder farmers, with an average farm size between 0.5 and 2 hectares. They currently produce 95 % of the country's food crops. Ghana's potential irrigable land is estimated to be 1.9 million hectares. This potential, on the other hand, is mostly untapped. Only 1.6 % of the land or 31 000 hectares is irrigated entirely and this is one of the lowest percentages in Africa (FAO, 2014).

Productivity of developed agriculture land in the country is currently poor and variable due to dependency on rain, especially in the drought-prone and flood-prone northern regions. Ghana, with its extensive cultivable area and substantial water supplies, provides considerable opportunity for agricultural production increase through irrigation development, but as previously noted, relatively little irrigable land is developed and existing irrigation schemes, particularly those established by the government have usually poor performance and productivity (FAO, 2014).

Two (2) types of irrigation systems observed in Ghana are the conventional irrigation systems, which are primarily initiated and established by the Ghanaian government or various non-governmental Organisations (NGOs), and the emerging irrigation systems, which are primarily initiated and developed by private entrepreneurs and farmers. Emerging systems are poorly understood, but they are rapidly growing, fueled mostly by access to very inexpensive pumping technologies and export markets for horticulture products (Namara *et al*., 2011).

Water pumps can be operated by different source of energy but most common are fuel, grid connection and solar pumps. Ghana's grid network is covering less than 50 % of the rural population, is underdeveloped in the rural and remote areas. Even those having access find it unreliable and expensive for irrigation (Gebrezgabher *et al*., 2021).

Solar-Powered Irrigation Systems (SPIS) have the potential to increase agricultural output, create jobs, enhance incomes, and provide resilience to climate change. Evidence from early systems deployed in Ghana and elsewhere has shown that the benefits are enormous, resulting in higher yields, more income for farmers, and an overall improvement in food security. SPIS also puts the agriculture sector on a greener road by displacing polluting solutions like diesel/petrol pumps and, in some cases, grid-powered irrigation pumps (SNV, 2021).

Solar energy has proven to be one of the most essential renewable sources due to its environmental friendliness and cheap operating costs, particularly for overcoming the projected energy crises of this millennium. Solar energy is rapidly becoming the most important renewable energy source, and it is being used to address global energy shortages (Zaman *et al*., 2018). Figure 1.1 presents the global price history of silicon PV cells from 1977 to 2020.

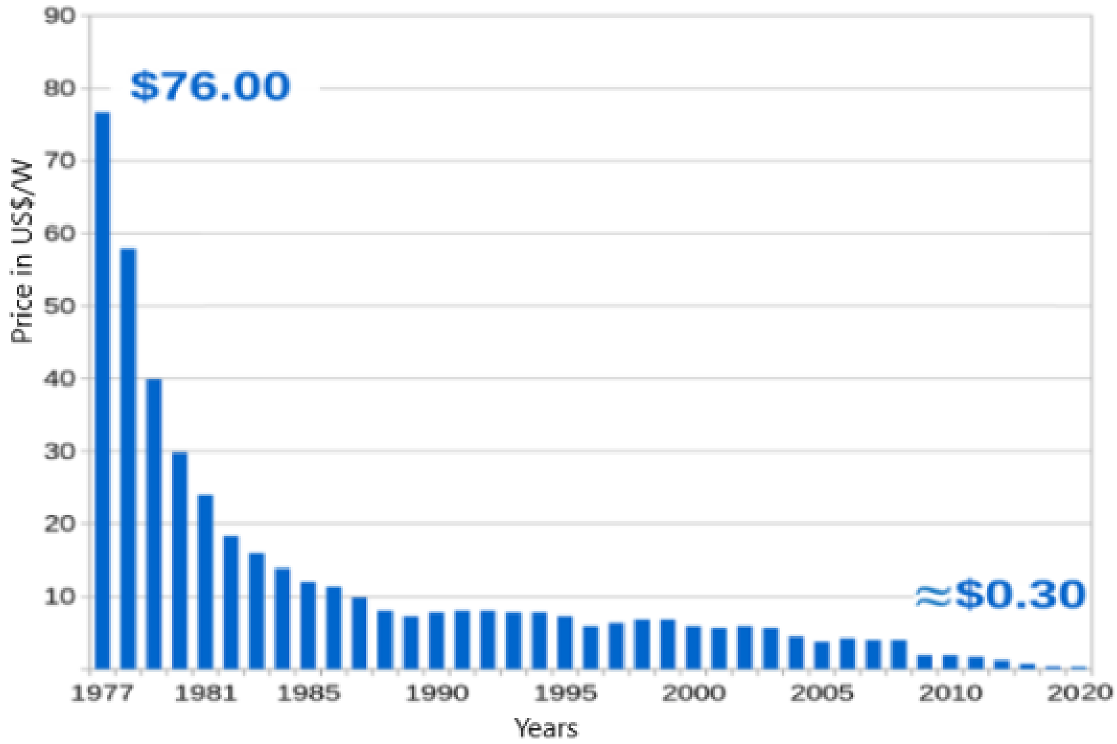


Figure 1.1: Global Price History of Silicon PV Cells

Source: Zaman *et al*., 2018.

As solar energy improves, so does solar PV prices as shown in the Figure 1.1. Ramez Naam is a climate Tech investor and clean energy advocate, and proposed Figure 1.2. which presents estimated cost of solar PV from 2020 to 2050 (Naam, 2020).

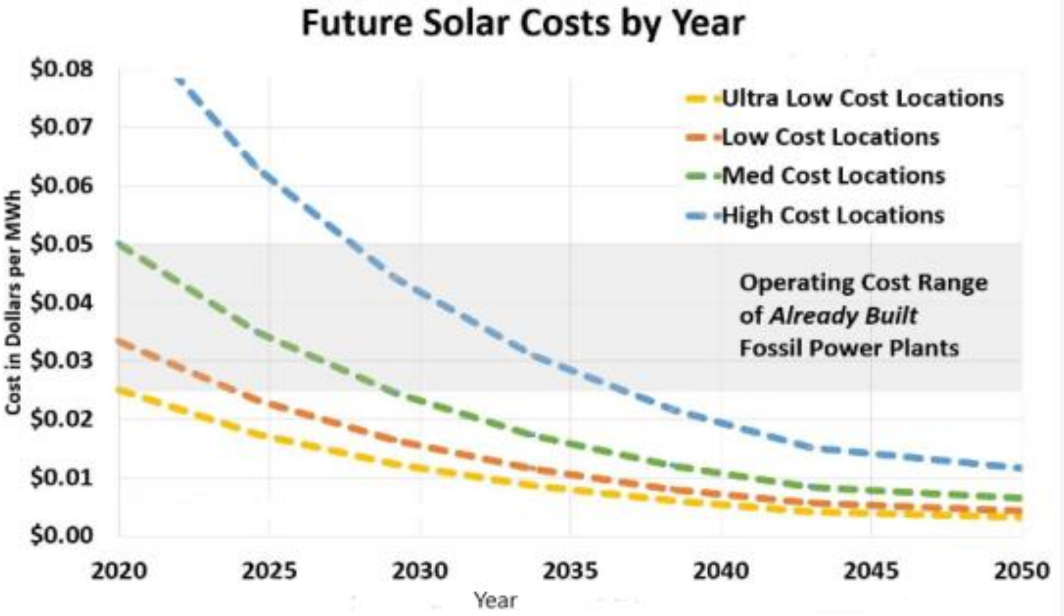


Figure 1.2: Projected Solar Cost from 2020 to 2050

Source: Naam, 2020.

Most efficient application methods must be employed for sustainable water pumping using photovoltaic solar energy, especially in reference to water consumption control (Zaman *et al*., 2018). Drip, sprinkler and spray tubes irrigation systems are well known irrigation systems that can be coupled with solar PV, and they differ in water use efficiency, installation cost, working pressure and operation and maintenance cost.

1.2 Problem Statement and Justification

Climate change is having a devastating impact in Sub-Saharan Africa, with far-reaching effects for millions of smallholder farmers. Farmers are finding it more difficult to cultivate crops and meet basic necessities as temperatures rise and rainfall becomes more irregular (Gadeberg, 2020). Statistics estimate 5 % of Ghanaian populace are food insecure and about 2 million Ghanaians are vulnerable to become food insecure (Bawa, 2019).

Small-scale irrigation expansion is becoming a part of the solution, where farmers can enhance productivity by supplementing their rainfed crops with irrigation and generating an additional harvest during the dry season when they take irrigation into their own hands. Small-scale irrigation has numerous advantages, including improved nutrition, increased revenue, and increased climatic resilience (Gadeberg, 2020).

Petrol and diesel pumps have helped to reduce the labour and time needed for irrigation, but they are expensive to run and also contribute to environmental pollution. With the abundance of sunshine in the northern regions of Ghana, solar pumps offer a promising alternative for small farmers if they can afford the initial investment. In fact, solar systems are becoming cheaper, while the cost of traditional fuels is rising. Nowadays, there are features that make the solar pump easy for farmers to install and eliminates the need for frequent visits from solar technology experts (Abena *et al*., 2021). Poor water assessment while designing, lead solar system to be unviable economically, due to under-utilization of its capacity, for example the case of Datoyili Cooperative in Tamale, where the system was designed to irrigate 5 ha and only 2 ha are irrigated due to water scarcity (Gebrezgabher *et al*., 2021).

This study was carried out to evaluate the performance of a solar powered irrigation system installed in the WACWISA demonstration farm in the Northern Region of Ghana, and perform lifecycle analysis of the system.

1.3 Objectives of the Study

1.3.1 Main Objective

The main objective of the study was to evaluate the performance of a solar powered irrigation system in the WACWISA demonstration farm at the Nyankpala Campus, Tolon District of Northern Region of Ghana.

1.3.2 Specific Objectives

The specific objectives of the study were:

i. To determine the soil characteristics in the irrigable area and the crop water requirement of tomato crop cultivated using the solar powered irrigation system.

ii. To evaluate the installed solar photovoltaic (PV) system and pump characteristics.

iii. To evaluate the technical performance of the drip, sprinkler and spray tube irrigation systems operating under the solar system.

iv. To evaluate the life-cycle cost of the solar powered irrigation systems.

1.4 Structure of the Thesis

The thesis is organised into five (5) main chapters. Chapter One (1) presents an introduction to the study which comprises; background to the study, problem statement and justification, objectives of the study and hypotheses of the study. Chapter Two (2) provides a review of the relevant literature relating to solar powered irrigation systems, pump sizing, pressurized irrigation systems, performance indicators for solar powered irrigation systems, irrigation water quality, irrigation scheduling, etc. Chapter Three

(3) outlines the materials and methods used in the study; description of study areas, data collection methods and performance evaluation indicators used in the study. The fourth (4th) Chapter presents the results and discussions and finally the fifth (5th) Chapter presents the conclusions and recommendations of the study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Solar Powered Irrigation

The primary user of water globally is the agriculture sector, which uses 90 % of the water in semi-arid and arid regions and 70 % of all water use worldwide. Water for irrigation will rapidly increase as population and household income increase in order to fulfill the need for food production, which is predicted to double between 1995 and 2025. As a result, it is expected that by 2030, irrigated lands would cover about 300 million hectares, with the increase of 14 % in developing countries and additional irrigation area of 45 million ha (Abdul-Ganiyu *et al.*, 2013).

Irrigation is critical to global food security, but it suffers water scarcity due to inefficient irrigation systems and increased competition from municipal and industrial water requirements (Kumari *et al.*, 2020). The need for a lot of water for irrigation requires a lot of energy to deliver water from the source to the field. It is estimated that about 70 % of the water abstracted for irrigation is lost through conveyance losses and poor water allocation methods (UN, 2021). This means that a lot of water is presently used to produce a unit of food. Improving water use efficiency in irrigation systems requires intelligent irrigation monitoring and control systems to ensure that no water is wasted and precise water application is achieved (Bwambale *et al.*, 2022).

Water can be conveyed from the source to the field by gravity or pumped by different types of energy. Gravity fed irrigation does not use any source of power but is possible only where irrigated field is downstream to the water source. Grid tied irrigation is done for most large-scale irrigation in Ghana but is limited for remote areas. Diesel pumps are often used in isolated rural regions where access to electricity is not available. Yet, the system has a number of issues, including fuel availability, technical expertise, and of course running costs (Mokeddem *et al*., 2011). A study carried out in Egypt by El-Gafy and El-Bably (2016) showed that the average CO_2 emission per cubic meter of water by non-improved pumps is 1.11 $kgCO_2/m^3$, 0.87 $kgCO_2/m^3$ for improved pumps and 0.02 $kgCO_2/m^3$ for electrical pumps. The same study showed that CO_2 emission per ha served 7.16 tCO_2/ha for non-improved pumps, 5.95 tCO_2/ha for improved pumps and 0.17 tCO_2/ha for electrical pumps.

When solar water pumps replace either diesel generated electricity or grid-based electricity, there are certain climate related benefits. A diesel generator emits CO_2 during operation and grid-based electricity is usually generated with either coal, oil or natural gas which also emits considerable quantities of CO_2. In contrast, a solar based water pump system does not result in greenhouse gas emissions. Extensive use of solar water pumps would therefore lead to substantial greenhouse gas emission reductions (CTCN, 2016). Another source of energy may be wind, bio-mass and geothermal. Solar energy (photovoltaic) is one of the major focuses as a renewable energy source in the world (Mongat *et al*., 2015).

In the last two decades, PV water pumping has become a widely adopted solar energy technology and PV water pumping system has been taken as attractive resource of supplying water in distant locations since the majority of global rural population lives in sunny tropical or sub-tropical regions. PV systems were particularly useful in areas, which were not near to extend electricity grid but even in places where connection could be made to a grid, experience have found it more feasible to use PV pumps than to extend and maintain the electric grid (Mongat *et al*., 2015).

Photovoltaic (PV) is a technology in which sun energy is directly converted to the electric power with the PV cells. Photovoltaic (PV) and thermal technologies are frequently used to capture solar energy as heat and power (Abdul-Ganiyu *et al*., 2020). A set of cells in the form of PV Panels are reliable energy source with about 20 - 25 years life span in weather conditions. The photovoltaic (PV) pumping system is naturally matched with solar radiations as usually water requirements increased during summer when solar radiation is in its peak (Mongat *et al*., 2015). Table 2.1 presents availability of solar resources in Ghana.

Table 2.1: Monthly Averages of Solar Radiation (kWh/m^2/day) at 19 Synoptic Stations in Ghana

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Kumasi	4.8	5.3	5.3	5.4	4.7	4	4	3.8	4	4.7	5	4.6	4.6
Accra	4.7	5.2	5.3	5.7	5.4	4.6	4.2	4.5	5.1	5.6	5.5	4.9	5.1
Axim	4.9	5.4	5.6	5.6	5.1	3.9	4.2	4.2	4.4	5.2	5.5	5	4.9
Navrongo	5.4	5.4	5.8	6	5.9	5.7	5.3	5.1	5.3	5.7	5.6	4.8	5.5
Saltpond	4.9	5.6	5.5	5.7	5.4	4.4	4.7	4.5	5	5.7	5.7	5.2	5.2
Ada	5	5.4	5.6	5.9	5.6	5	5.1	5.1	5.5	5.9	5.5	5.4	5.4
Koforidua	4.7	5.1	5.3	5.4	5.3	4.6	4.1	3.8	4.4	5.2	5.2	4.9	4.8
Wenchi	5.2	5.5	5.5	5.7	5.5	5	4.4	4.1	4.4	4.9	5.1	4.9	5
Tamale	5.1	5.5	5.6	5.9	5.9	5.5	5	4.8	5	5.5	5.7	5.2	5.4
Bekwai	4.7	5.1	5.3	5.5	5.3	4.6	4.1	3.8	4.1	5	5	4.4	4.7
Ho	4.9	5.2	5.5	5.7	5.6	4.9	4.6	4.2	4.7	5.5	5.6	5.1	5.1
Wa	5.5	5.8	5.8	5.9	5.9	5.6	5.1	4.9	5.1	5.6	5.6	5.4	5.5
Akim Oda	4.5	4.8	4.9	5.2	4.9	4.3	4	3.8	4.2	4.8	4.9	4.5	4.6
Krachi	5.1	5.4	5.7	6	5.9	5.2	4.7	4.5	4.8	5.3	5.7	5.1	5.3
Yendi	5.2	5.5	5.6	5.9	5.9	5.4	5	4.6	5	5.6	5.7	5.2	5.4
Takoradi	4.8	5.4	5.5	5.7	5.2	4.4	4.4	4.2	4.6	5.5	5.6	5	5
Bole	5.4	5.8	5.8	5.8	5.7	5.1	4.6	4.5	4.8	5.5	5.5	5.3	5.3

Abetifi	5	5.5	5.6	5.6	5.4	4.8	4.8	4.6	4.7	5.2	5.6	5.1	5.2
Akuse	4.6	5.1	5.2	5	5.3	4.6	4.3	4.1	4.7	5.3	4.8	4.8	4.8
Average	5	5.4	5.5	5.6	5.5	4.8	4.6	4.4	4.7	5.4	5.4	5	5.1

Source: Asumadu-Sarkodie *et al*., 2016.

Photovoltaic (PV) powered water pumping system is an alternative to diesel pumps, and around the world, several solar systems have been designed and tested, and their performance has been evaluated under a variety of climate and isolation situations. These systems use AC or DC power, are directly connected or battery-powered, and use a variety of pumps to function in a variety of climates (Gurung and Qiao, 2018). PV systems are becoming increasingly popular, particularly in isolated places where grid electricity is unavailable or prohibitively expensive to install. Additionally, advancement in the global photovoltaics market highlights the maturity of investments made, ensures the sustainability of the technology used, and makes it competitive for a number of applications to satisfy energy demands (Mokeddem *et al*., 2011).

The high initial capital costs of the PV array are the major barriers to high penetration rates of the use of solar water pumps because the PV array is the most expensive part of the system. The size and capacity of the PV array considerably influence the up-front costs of the system. Therefore, it is important to use the smallest system size possible that still meets all the criteria of that particular location. Government or donor agency subsidies which cover the high initial capital costs are required in many locations to realize PV water pump systems. The high reliability of solar water pumps might offset its higher initial costs compared to diesel powered pump systems (CTCN, 2016).

Local weather conditions have an impact on the operation of PV pumping systems. It fluctuates depending on cloud cover, temperature, wind speed, and other factors. However, steady insolation is a key feature of potential solar application sites (Mokeddem *et al*., 2011). The performance of a photovoltaic system also is determined by the equipment employed, and the system layout. PV performance is defined as the ratio of actual solar PV system output to predicted values, with this measurement being critical for the correct operation and maintenance of solar PV facilities (Mokeddem *et al*., 2011). Figure 2.1 represent the layout of irrigation system powered by solar. There are PV array which is made by number of PV panels, solar pump which can be surface or submersible pump, elevated tank which is held in several meters above the ground depending on the operating pressure needed in the system, and irrigation system.

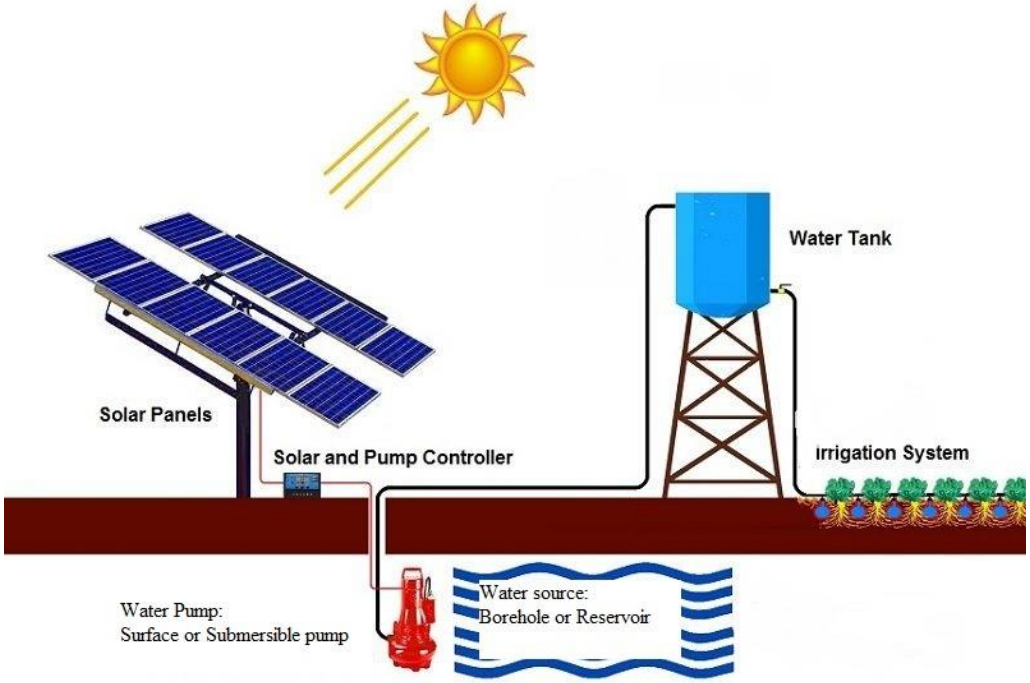


Figure 2.1: Layout of Drip Irrigation System Powered by Solar

Source: Sadhukhan, 2015**.**

2.1.1 Directly Coupled and Battery Coupled Solar Irrigation System

Alternating Current (AC) or Direct Current (DC) are the two (2) types of electrical connections that can be made between a solar array and a battery. When current runs rapidly forward and backward as it does in the power grid, it is called AC, and when current flows in only one direction, it is called DC. The majority of electronic circuits use DC, while solar panels and batteries both produce and store DC energy. The majority of electrical items, on the other hand, run on AC. This is why AC circuits are installed in every home and company. An inverter can convert DC to AC, however some energy is always lost during the process (Naam, 2020).

The most reliable and low-cost PV system is a directly-coupled PV pumping system. In the case of sunshine fluctuation, the DC motor-pump, on the other hand, is not running at its optimum. A battery buffered PV pumping system connects the PV array to the DC motor-pump group to ensure that the motor-pump is running at its best. The size of the battery storage is determined by the capital of the project. If the battery is fully charged when solar radiation is available, the battery will deplete while the PV array is turned off. As a result, there is a power loss. A switched mode PV pumping system is presented to overcome the aforementioned challenge (Gebrezgabher *et al*., 2021).

The battery is unplugged and the DC motor-pump is directly attached to the PV array when solar radiation is available and the battery is fully charged (Chahartaghi and Hedayatpour, 2019). To keep the motor from overheating, a portion of the PV array is turned off to lower the voltage. As a result, there is a significant reduction in energy loss. When compared to a traditional battery-buffered system, the discharged water increases by around 10 %, according to a detailed analysis of the suggested system (Shamim and Sarkar, 2015). The transient performance of the system soon after the switching moment reveals that it returns to a steady state in a short time (Anis *et al*., 1994).

2.1.2 Advantages and Disadvantages of Solar Powered Irrigation

Solar power is pollution-free, emitting no greenhouse gases after installation, and is a renewable source of clean energy that is available every day of the year. Solar energy reduces reliance on foreign oil and fossil fuels, provides a return on investment (unlike utility bills), and requires little maintenance as solar panels last over 30 years. Solar power supports the economy by creating jobs by employing solar panel manufacturers, solar installers, etc, and excess electricity can be sold back to the power company if grid connected (Riyo, 2020).

The ability to live off the grid if all electricity generated is sufficient for the home/building, and may be installed nearly anyplace from a field to a building, with batteries storing excess power for usage at night. Solar may be used to heat water, power homes and buildings, and is safer than regular electric current. Additionally, solar efficiency is constantly improving, so the same size solar available now will be more efficient tomorrow. To assist with the initial costs, federal grants, tax incentives and rebate programs are available (Riyo, 2020).

However, solar-powered irrigation has some limitations such as high initial material and installation costs as well as a long return on investment (ROI), and is not mass-produced due to a lack of material and technology to reduce the cost sufficiently to make it cheaper. Also, because there is no solar power at night and cloudy days do not provide much energy, as well as lower power output during the winter months, a large battery bank or huge night storage is required. Solar panels require a lot of area because their efficiency is not yet 100 %, and the size of solar panels vary depending on geographical location for the same electricity generation (Riyo, 2020).

2.1.3 Comparison of Solar Powered Irrigation and Other Irrigation Technologies

A stable power grid networks typically powers the pump in a standard water pumping system. The running speed of the pump in the system is stable and unchanged because the voltage amplitude and frequency of the power supply grid are fixed, and it has been working at the highest speed (50Hz) set by the system to ensure that the water output of the water lifting system is constant, which means the water output at each moment of the system is consistent and at the maximum value (Franklin, 2019).

Solar pumping systems are now widely used in various irrigation fields to perform daily water pumping and irrigation. The water pump in the solar water pumping system is powered by the solar panels and the power generated by solar panels and the intensity of sunshine have a proportionate relationship. The stronger the sunshine, the more power the panels generate, and the water output of the system will alter as the light intensity changes. As a result, the system's water output may fluctuate at any time. When the light intensity is at its highest, the system's water output is at its highest (CTCN, 2016). Table 2.2 presents different pumping technologies, their advantages and disadvantages.

Table 2.2: Comparison of Solar and other Remote Watering Options

Pumping Technology	Advantages	Disadvantages
Solar	Low maintenance	Potentially high initial costs
	No fuel costs or spills	Lower output in cloudy weather
	Easy to install	Must have good sun exposure between 9 am and 3 pm
	Simple and reliable	
	Unattended operation	
	System can be made to be mobile	
Diesel or gas	Moderate capital costs	Needs maintenance and replacement
	Can be portable	Maintenance often inadequate, reducing lifetime of system
	Extensive experience available	Fuel often expensive and supply intermittent
	Easy to install	Noise, dirt and fume problems
		Site visits necessary
Windmill	Potentially long lasting	High maintenance and costly repair
	Works well in windy site	Difficult to find parts
		Seasonal disadvantages
		Need special tools for installation
		Labour intensive
		No wind, no power
Gravity	Very low cost	Only feasible in a small number of places
	Low maintenance	
	No fuel costs or spills	
	Easy to install	
	Simple and reliable	
Ram	Very low cost	Requires moving water as an operational necessity
	Low maintenance	
	No fuel costs or spills	
	Easy to install	

Hauling	Simple and reliable	
	Lowest initial costs	Very labour intensive
	Excellent mobility	

Source: UN Climate Technology Center and Network, 2016.

The pump speed in a solar water pumping system must be adjusted in real time according to the intensity of radiation in order for the system to operate reliably and consistently. The major difference between the solar water pumping system and the traditional water pumping system is the variable frequency speed regulation control of the water pump based on light intensity (Solatech, 2013).

When the sunlight is strong, the battery panel generates a lot of electricity, the pump runs at 50Hz, and the water output reaches its maximum, which is the same as the power supply from the power grid; however, when the radiation becomes weak. the water pump's running frequency drops below 50Hz, and the water output drops accordingly (Solatech, 2013).

2.2 Estimation of Solar Energy Needed for Irrigation System

Since the initial capital of solar powered irrigation system is expensive, the design of solar irrigation requires following the procedure from the field to be irrigated to determine the power required (Sass and Hahn, 2020). It would be a loss if the solar system was bought beyond the capacity of the field to be irrigated or the system with less capacity was purchased. It is therefore important that, first of all, the water required in the field have to be determined, the efficiency of the water application system to be used, the efficiency of the water conveyance system, and the capacity of the pump will be used and its efficiency (Sass and Hahn, 2020).

2.2.1 Crop Water Requirement

Crop water requirements (CWR) can be defined as the amount of water (in millimeters) required to meet the water absorbed through evapotranspiration (ETc) by a disease-free crop growing in large fields under non-restricting soil conditions, including soil water and fertility, and achieving full production potential in the given growing environment (Pereira and Alves, 2004). CROPWAT is a computer programme that helps in calculation of crop water requirements and estimate irrigation water needed and possible schedules. This programme has been developed by FAO, and uses crop, soil and climate data (Sadick *et al*., 2015).

CROPWAT uses meteorological data to calculate crop evapotranspiration (ETc), rainfall data to calculate effective rainfall and soil data to calculate deep percolation losses. From this software, it is possible to estimate daily water need for field in millimeter (mm) and by known area of the farm we will be able to calculate the volume of water needed per day. Then pumping rate or discharge (Q) of solar pump is given by the daily water need divided by peak sun hours (PSH), and this is because water is pumped only in PSH where mostly considered as six hours per day (World Bank, 2018).

2.2.2 Estimation of Pump Capacity

The pumping system must be matched perfectly to the irrigation distribution system for proper irrigation system design. The pumping system can then efficiently produce the appropriate pressure and flow rate. The capacity of the pump must be measured while designing an irrigation system. Only by carefully measuring the flow rate and pressure of the pump can the irrigation system be appropriately built (Mahmood and Hussain, 2012).

Visual estimation of pump capacity or reliance on manufacturer's specifications to determine current pump capacity are insufficient. Visual estimations are rarely precise, and manufacturer's specifications typically ignore the effects of site-specific elements like well characteristics and suction and discharge pipe sizes. The effects of age and wear on pumping system performance are also not included in manufacturer's specifications. Pump capacity is determined by two (2) factors namely; pump discharge rate and discharge pressure. Gallons per minute (gpm) in English units or liters per second (lps) in metric units are commonly used to measure discharge rates. Normally, pressure is measured in pounds per square inch (psi) in English units or kilopascals (kPa) in metric values, however in pumping, pressure is converted to pressure head which is measured in meters (m) (Haman and Zazueta, 2017).

Sizing of pumping systems are difficult since the pumps must fit the pumping systems, as a result, it affects the installation, maintenance, and operations of centrifugal pumps and pumping systems (Ephrey and Vandi, 2020). The challenge of implementing proper maintenance plans for the pumping system affects the efficiency of the pump. The centrifugal pump efficiency can drop below 5 % of required operation duty point, consuming more energy and cost a company more than usual (Ephrey and Vandi, 2020).

Also, direct coupling of PV panels with the pump system has shown great potential with low cost for water pumping applications. Direct coupling of mechanical load with PV array requires a systematic study of load which might be cumbersome but eventually leads to a very simple and reliable design. Usually, the output of the PV array is time-dependent and also non-linear in nature which directly varies with solar insolation level and cell temperature. The proper matching of components is greatly essential in a direct coupling Pump-motor system (Shamim and Sarkar, 2015).

2.2.3 Estimation of PV Array Size

The size of the solar PV array can be calculated using a formula, where electrical energy consumption, peak sun-hours (PSH), and system derate factors are the variables. The first step is to figure out how many kilowatt-hours of solar PV energy are produced on a daily basis. This quantity will be calculated after estimation of the daily agricultural water demand and the head required to pump water from the source to a remote farm location. The highest point on the farm, the length to the farthest point on the farm, the type of pipe utilized, and the irrigation system's operating pressure are the variables for head calculation (Franklin, 2019).

The most advantageous of the numerous types of solar photovoltaic systems is a hybrid system or grid connected system that sends and receives power from a local utility, as the case of IWAD Ghana in Sisili-Kulpawn area irrigation scheme (IWAD Ghana, 2020). Figure 2.2 shows a grid-tied system (Hybrid) which sends excess energy to the local utility. The system pictured is a small-scale PV demonstration featuring all of the components including a PV array and combiner box mounted on a racking system, a DC disconnect switch, a string inverter (red and white unit), an AC disconnect switch, and an AC service panel.

Figure 2.2: Grid Tied Solar System (Hybrid)

Source: Franklin, 2019.

Direct Current (DC) electricity is generated in solar photovoltaic systems. Watts are the units of measurement for the total amount of power generated by a solar module (W). The power (measured in Watts) of a module is found by multiplying its voltage (V) by its current (I) (Franklin, 2019).

By connecting PV modules in series, voltage will be the summation of all the PV modules in the series and the current will still be the same. By connecting PV modules in parallel the current will be the summation of all currents of the PV modules in parallel while voltage will be the same (Franklin, 2019).

2.2.4 Pump Characteristic Curves

Pump performance is represented by a plotted curve that relates the total head produced in feet or meters of fluid to the flow of water in gallons per minute or cubic meters per hour. The manufacturer creates the pump curve under carefully monitored test conditions (Bell and Gosset, 2021). Figure 2.3 presents system curve representing pump output in m^3 per hour versus pump head (m).

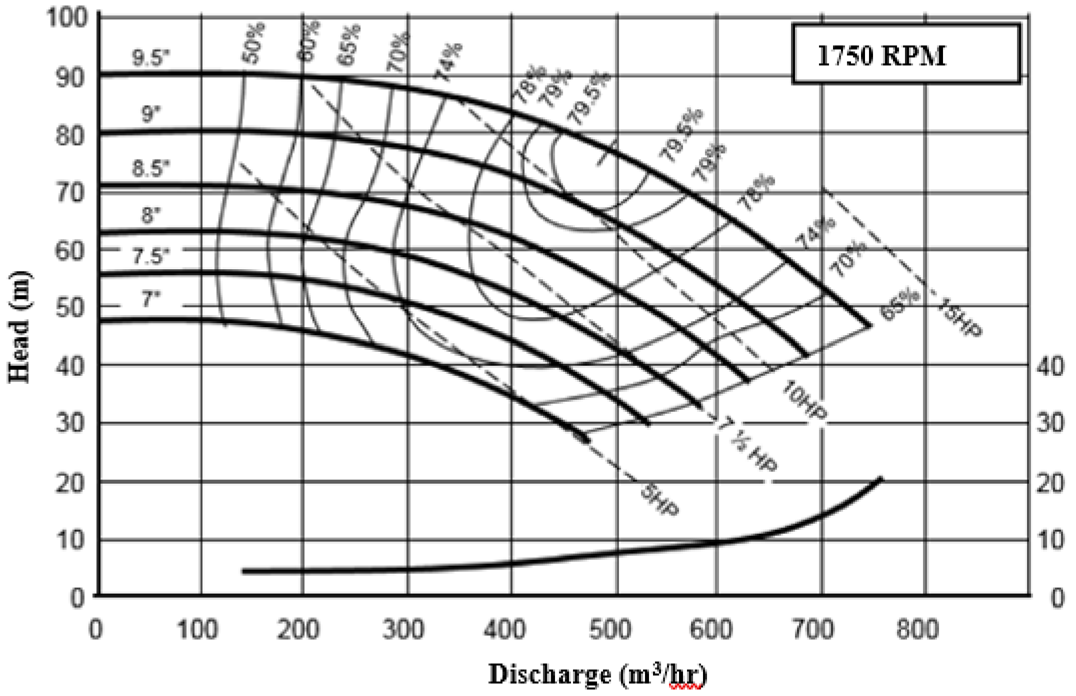


Figure 2.3: Pump System Characteristic Curves

Source: CSI, 2022.

System curve analysis methods provide means for determination of good pump application practice. System curve analysis will help define the operating relationships between the pump, control valves and piping circuitry. The analysis can be applied to permit engineered integration of operating variables. The system curve is simply a plot of the change in energy head resulting from a flow change in a fixed piping circuit.

System curve construction methods differ between open and closed piping circuits (Bell and Gosset, 2021).

Pump curves are categorized as "flat" or "steep" based on their shape. This refers to the general shape of the head capacity curve as shown in Figure 2.4 which presents two pump curves, steep and flat.

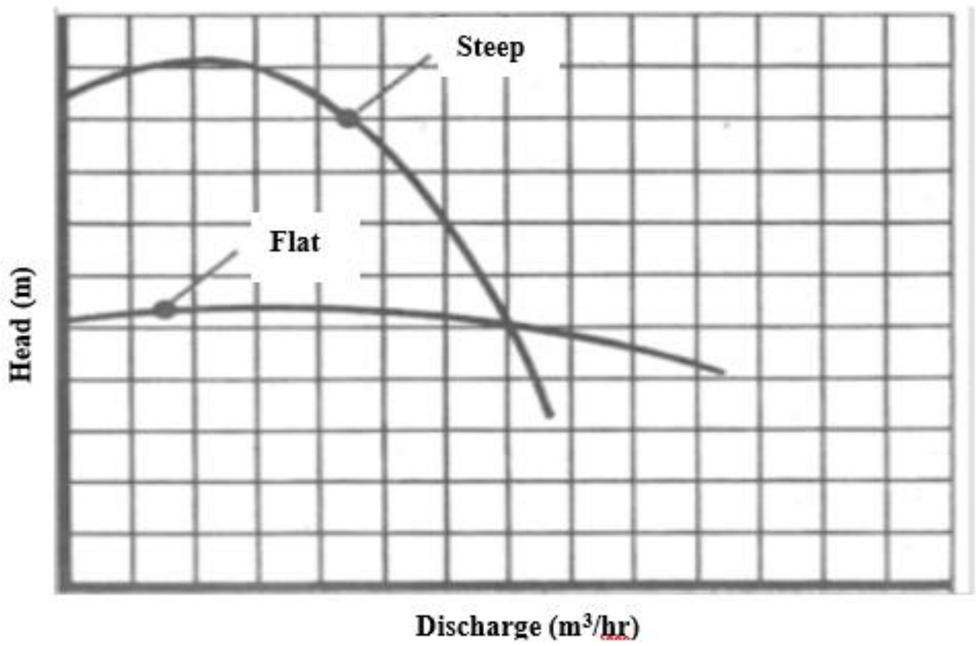


Figure 2.4: Flat versus Steep Pump Curve
Source: CSI, 2022

Due to the influence of the pump curve on the system operating components, flat-curve pumps are often preferred for closed circuit systems. With a slight change in head, large changes in capacity can be obtained. Pumps with flat curves should also be used in systems with valve control. The flat curve pump provides a more nearly constant pressure drop ratio across the valves as they close, reducing the possibility of control valve force open. The pump curve enables system curves to be used as a tool for pump selection analysis. The system curve can be utilized to gain a better understanding of how pump selection and operation affect overall system performance (Bell and Gosset, 2021).

2.3 Performance of Sprinkler Irrigation System

Sprinkler irrigation is the method of water application which resembles natural rain where water is given to the crop in the form of small droplets with a pre-calculated volume and appropriate discharge. To reduce water loss due to surface run-off, water reaches the earth's surface at a rate that is not greater than the rate of infiltration. With the industrial progress in the production of low weight and cheap pipes, the fields of application have expanded since the 1930s. Sprinklers have the advantage of not requiring ground to be leveled, which preserves the fertility of the top layer of soil around the root zone of the plant. If the system is effectively built and used, sprinkler irrigation can increase irrigation efficiency to 85 - 90 % by reducing surface runoff and deep percolation losses (Abdelmonem, 2020).

Sprinkler irrigation has some drawbacks, such as large evaporation losses, yet it is still preferable than surface irrigation. The operation and maintenance of this system require highly trained technical personnel. Sprinkler irrigation has limitations in clay, due to increased losses as the application rate exceeds the infiltration rate of the soil and the risk of high salinity, which requires periodic flooding to wash the field. High wind speeds will have a negative impact on sprinkler irrigation; it is not suggested to use if the wind speed is greater than 5 m/s. High wind speed will contribute to Reduced application efficiency due to water droplets drifted away target area, and it can contribute to uneven water distribution. It can also cause increased evaporation and water wastage. Sprinklers require energy to run since the system's operating pressure is high. Sprinklers have different types which operate within the range of pressures of 10 m to 80 m of head, thus discharge and sprayed circle diameter varies for each type (Abdelmonem, 2020).

There is a difference between sprinkler irrigation powered by battery coupled and direct coupled solar system. Since there is power fluctuation for directly coupled and constant pumping for battery coupled sprinkler irrigation. Cloudy days where solar radiations are not much power reduces and pumping pressure reduces too, this will affect uniformity of the system (Cavero *et al*., 2016).

Satisfactory hydraulic performance, which is mainly associated with the velocity distributions and droplet size, is the main purpose of sprinkler irrigation system. Droplet characterization affects the performance and efficiency of sprinkler irrigation system, in the form of evaporation losses due to the wind, and kinetic energy with which it hits the soil and crops. Studies revealed that night time wind drift and evaporation losses are lower as compared to daytime. They also revealed that the crop growth increased by day time irrigation as compared to night time irrigation because of day time sprinkler irrigation improve the crop canopy by modifying the microclimatic conditions. Studies revealed that lower water losses with more uniform irrigation at night time as compared to day time because of lower wind speed at night time (Cavero *et al*., 2016).

Hydraulic performance of sprinklers affected by droplets characteristics, such as droplet diameter, velocity and angle. Droplets characteristics vary with the type of sprinkler, nozzle size, and working pressure. Droplet diameter and velocity are vital to evaluate the performance of a sprinkler. To perform a sprinkler system well, it is also a necessity to have a good uniformity of its emitters and to achieve adequate hydraulic performance. Christiansen's Uniformity coefficient is mainly used for monitoring and evaluating the uniformity of irrigation (Zaman *et al*., 2018; Ferrarezi *et al*., 2020).

Table 2.3 represents classification of performance indicators of sprinkler irrigation, which are Christiansen Uniformity Coefficient and Distribution Uniformity as given by ASABE (1994).

Table 2.3: Classification of Performance Indicators for Sprinkler Irrigation

Performance Indicator Class	Christiansen Uniformity Coefficient (%)	Distribution Uniformity Coefficient (%)
Excellent	>90	>84
Good	80 - 90	68 - 84
Fair	70 - 80	52 - 68
Poor	60 - 70	36 - 52
Unacceptable	<60	<36

Source: ASABE, 1994

2.3.1 Water Quality for Sprinkler Irrigation

For sprinkler irrigation, using saline water or water with high boron concentrations can harm leaves. Boron, the same as sodium and chloride, can be absorbed by the leaves and can harm the plant if dangerous quantities develop. Table 2.4 presents toxic ions (TI) resulting in foliar injury and critical values for peanuts, corn, sorghum and cotton. The crop's sensitivity to harm is determined by how rapidly the leaves absorb these elements, which is determined by the plant's leaf qualities and the frequency with which it is watered, rather than the crop's tolerance to soil salinity. Plants having lengthy retention times, such as vines and tree crops, can accumulate significant quantities of certain elements even when their leaf absorption rates are minimal (Hanson *et al*., 2006).

Table 2.4: Toxic Ions Resulting in Foliar Injury of Crops

Measurements	Peanuts	Corn	Grain Sorghum	Cotton
Boron				
Parts per million (ppm)	0.75	2	3	3
Milligrams per liter (meq/L)	0.75	2	3	3
Milliequivalents per liter (meq/L)	0.075	0.2	0.3	0.3
Chloride				
Parts per million (ppm)	400 - 500	533	710	710
Milligrams per liter (meq/L)	400 - 500	533	710	710
Milliequivalents per liter (meq/L)	11 - 14	15	20	20
Sodium				
Parts per million (ppm)	400 - 500	533	710	710
Milligrams per liter (meq/L)	400 - 500	533	710	710
Milliequivalents per liter (meq/L)	17 - 21	23	31	31

Source: Mcfarland *et al*., 2018.

2.3.2 Catch-Can Test

A catch can test helps measure the health and performance of an irrigation system. The results of the test are important to analyze the performance of drip irrigation, sprinkler irrigation and spray tube irrigation system. Coefficient of variation, emission uniformity and emitter flow variation can be analyzed through this test and the distribution uniformity (DU) and a precipitation rate (PR) for sprinkler and spray tube can be determined too. The resulting DU indicates how uniformly water is distributed in that given area at a specific point in time. Catch cans are typically conical shaped devices placed in a holder which captures water from the sprinklers (Leder, 2019).

When conducting a catch-can test, the collection devices must be spaced evenly in a grid pattern and not placed too close to the actual sprinklers. This helps avoid water knocking over the cans during the test. It also helps in capturing the water distributed out of the small and medium range nozzles. If can(s) is/are too close to the sprinkler, small holes can be cut into the soil and the cans lowered. The pattern can be rectangular, diamond or triangular. A sufficient run time should be used in order to collect at least 20 millimeters in a majority of the cans. Be careful to not run too many sprinklers on the same lateral at the same time or the results could be flawed due to low pressure on the laterals. For the assessment of distribution uniformity of drip irrigation, catch cans not less than 12 are needed and the number must be divisible by four (4) so that lowest quarter easily determined. Check that emitters are not blocked, choose the positions to place the catch cans. Mark the cans according to its position. Start the stopwatch and the irrigation system at the same time. The duration for the test will depend on the size of the catch can and the flow rate of the system. The test should be no less than 5 minutes (Leder, 2019).

2.3.3 Uniformity Coefficient

Christiansen’s uniformity coefficient (UC) is the most commonly used statistical method for evaluating sprinkler system uniformity. Due to variation of solar radiation pressure of the pump will vary and that variation will cause changes in the system, flow variation will decrease and uniformity coefficient will decrease (ASABE, 1999; Mangrio *et al.*, 2021).

Table 2.5: Classification of Coefficient of Variation

Coefficient of Variation, CV (%)	Classification
>90	Excellent
90-80	Good
80-70	Fair
70-60	Poor
<60	Unacceptable

Source: ASABE, 1999

2.3.4 Distribution Uniformity

Divide the average of the low quarter of the cans by the average of all cans used to get the DU. This means that the total number of cans should be a number divisible by 4. DU is measured in percentages. The DU is a measure of how efficient a system is. The higher the DU, the more efficient the system is. DU is influenced by a number of parameters, including the age of the system, worn nozzles, low or slanted heads, pressure, wind, sprinkler cycle periods, and pump efficiency (GIC, 2015). Table 2.6 presents the classification of distribution uniformity for sprinkler irrigation system.

Table 2.6: Classification of Distribution Uniformity

Classification	Distribution Uniformity (%)
Excellent	≥85
Very Good	80
Good	75
Fair	70
Poor	≤65

Source: GIC, 2015

2.4 Performance of Spray Tube Irrigation System

Spray tube or rain pipe is a simple lightweight, perforated lay flat irrigation hose that works under a low operating pressure from a water main or low pressure pumped system. The holes are made with laser punched technology to ensure uniform flow of water. Spray tube eliminates the need for expensive and complicated irrigation systems, yet it provides a fine, uniform irrigation pattern. Spray tubes minimizes runoff, maximizes ground saturation and very little maintenance required. It will not lose pressure at the end of the hose and more even watering pattern than circular sprinkling systems that makes it more uniform (Kathiriya *et al*., 2021).

Spray tube is applicable for liquid fertilizer and is suitable for irrigating vegetables, bananas, oil palms, corn, papayas, strawberries, tomatoes, potatoes, wheat, flowers and fruit trees. This is water-saving irrigation equipment that requires a slow working water pressure which saves both electricity and water. Up to 70 meters of spray tube can be laid. A pressure range of 0.5 to 1.5 kg/cm^2, or 7.12 to 21.3 psi, must be maintained (GREKKON, 2022).

It sprays uniformly, which improves seed germination and seedling survival rates. Following the application of solid fertilizer, spraying irrigation aids in the dissolution of the fertilizer, allowing it to effectively soak into the soil and reach the root without being washed away. Crops are planted in rows that are ideal for spray tubes that can cover an area ranging from 0.1 to 4 meters. It is the best irrigation equipment for sandy soil. Figure 2.5 illustrates the pattern of water movement from spray tube (GREKKON, 2022).

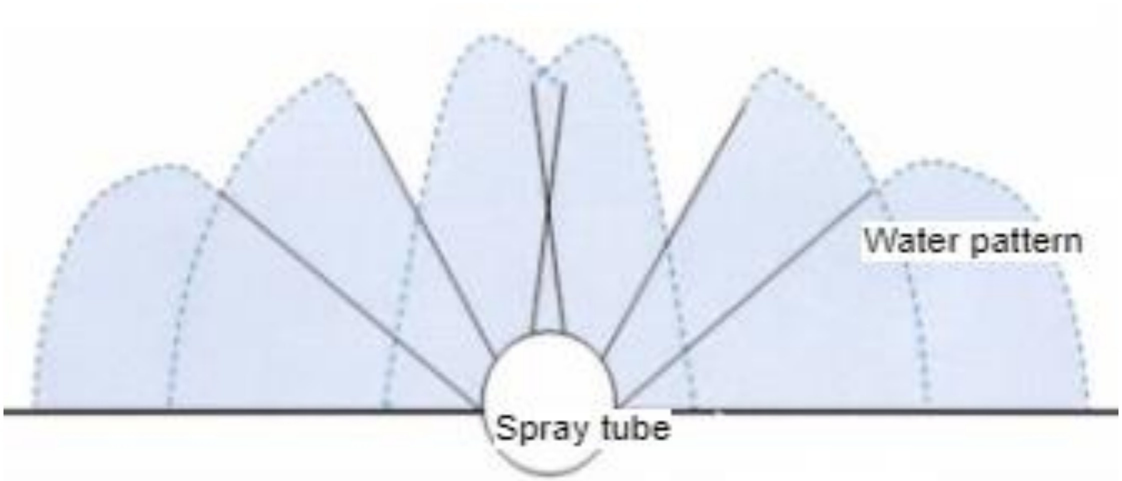


Figure 2.5: Pattern of Water from Spray Tube

Source: GREKKON, 2022

2.5 Performance of Drip irrigation system

Drip irrigation is a method of irrigation in which water is supplied to the soil surface in the form of drops or small streams through emitters. Single-outlet emitters have discharge rates of less than 2 gallons per hour (7.6 l/h) while line source emitters have discharge rates of 3 gallons per hour per 3.3 feet (11.4 l/h/m) (NRCS, 2013).

The goal of drip irrigation is to supply a steady readily available soil moisture required to meet transpiration demands. Drip irrigation provides distinct agronomic, agrotechnical, and economic benefits for water use efficiency. Salt buildup, sensitivity to clogging and poor soil moisture distribution are the primary drawbacks of drip irrigation systems (Keller and Karmeli, 1974). The important parts of drip irrigation are pumping station, filters, control head, main and submain lines, lateral lines, emitters, valves, fittings, and other essential equipment (Keller and Bliesner, 1990).

The flow rate at the emitters will decrease as the water level in the tank drops during the irrigation event. The volume calculations, on the other hand, assume that the flow rate at the emitters is constant (Megh, 2016). Pressure compensating (PC) emitters are preferred since with varied pressure within the lateral's emission will be almost the same because there will be change less than 7 %. Important thing is to maintain the minimum compensating inlet pressure (MCIP) which is pressure above which the emitter's flow rate is within 7 % of its nominal flow rate (Sokol *et al*., 2019). Figure 2.6 illustrates the characteristics of pressure compensating emitter before and after reaching MCIP point (Sokol *et al*., 2019).

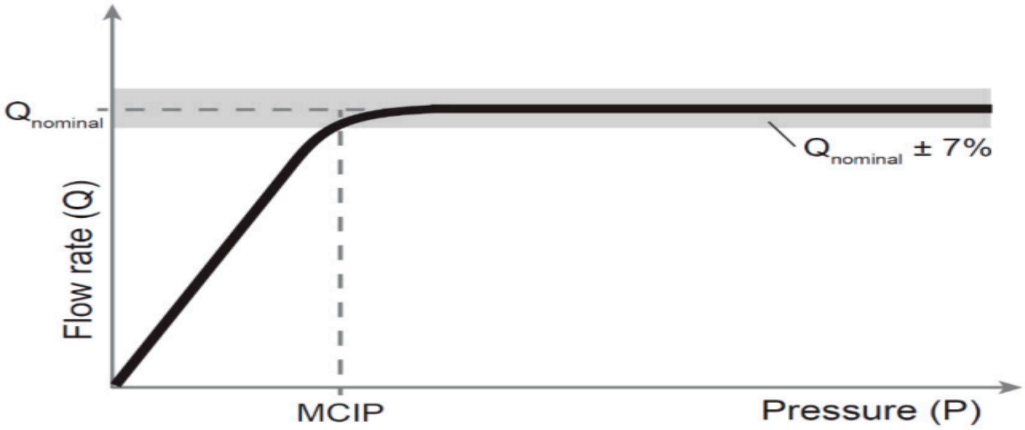


Figure 2.6: Characteristics of Pressure Compensating Emitter

Source: Sokol *et al*., 2019

2.5.1 Cost Saving Benefits of Drip Irrigation System

Because the crop absorbs nearly all of the water applied, drip irrigation can reduce water losses and operating expenses. Water evaporation from the plant and soil surface is limited to the portion of the soil surface wetted by the emitter. The soil surface is kept nearly dry at all times in a well-designed and operated sub-surface drip irrigation system. Drip irrigation also reduces weed growth and non-beneficial water usage, reducing the need for herbicides and weed control tillage. Minimum tillage is possible with sub-surface drip irrigation since drip irrigation laterals are not disturbed (NRCS, 2013).

2.5.2 Coefficient of Variation

When new emitters of the same type are operated at equal pressures and water temperatures, the manufacturing coefficient of variation (CV) is defined as the statistical coefficient of variation i.e., standard deviation divided by the mean discharge rate in emitter discharge rates. Variances in flow rates seen under these similar operating conditions are thought to be attributable to differences in emitter components. However, because manufacturing variance lowers the consistency of water application, use emitters with low CV values. When comparing emitters with identical flow parameters, the emitter with the smallest manufacturing variation will provide the best uniformity. The coefficient of variation is a measure of how variable emitter performance is as a result of minor differences in the manufacturing process and is calculated per ISO Standard 9261:2004 (ISO, 2004). Table 2.7 presents the classification of coefficient of variation for drip irrigation system (ISO, 2004).

Table 2.7: Classification of Coefficient of Variation for Drip Irrigation System

Emitter type	CV Range	Classification
Point source	<0.05	Excellent
	0.05 to 0.07	Average
	0.07 to 0.11	Marginal
	0.11 to 0.15	Poor
	>0.15	unacceptable
Line source	<0.1	Good
	0.1 to 0.2	Average
	>0.2	Marginal to unacceptable

Source: ISO, 2004

2.5.3 Emitter Flow Variation

Drip irrigation system emission device selection entails selecting an appropriate emission device based on the soil and crop requirements. The type of emission device used is determined by a variety of considerations, including the crop to be irrigated, filtration needs, the need for crop protection from frost, cost, and grower preference. Although closely spaced point source emitters, bubblers, and micro sprinklers can also be employed, line-source emitters are especially well suited for row crops. To attain a high level of system homogeneity, precise emitter fabrication is required. However, due to the complexity of emitters and their separate components, maintaining precision during manufacture is difficult. Changes in manufacturing temperature, mold damage, and non-uniform raw material mixing are all variables that impact emitter uniformity (Olorunwa *et al*., 2019).

In the manufacture of pressure compensating emitters, elastomeric materials are used to accomplish flushing action and pressure compensation. It is difficult to make these parts with uniform proportions. Variations in passage size, shape, and final finish will occur during the production process. Manufacturing differences occur as a result of the difficulty to maintain constant pressure and temperature during procedures like molding and welding, as well as irregularities in the materials employed. Any two emitters of the same kind from the same box, tested at the same temperature and pressure, can have different flow rates due to these manufacturing variations (Olorunwa *et al*., 2019).

Because the flow rate of trickle irrigation emitters is low, any change in the key dimensions of the emission devices might result in significant differences in relative flow rates. Despite the fact that the variation's absolute magnitude may be rather minor. As a result, the emitter's performance may have a significant impact on water application uniformity. Drip emitters control water flow by absorbing the flow's energy and dissipating it through frictional resistance. Laminar flow emitters control water flow by dissipating energy through friction with the water passage's walls. They use lengthy and narrow flow pathways; the smaller or longer the passage, the greater the flow's frictional resistance (Olorunwa *et al*., 2019).

Laminar flow emission devices include micro-tubes and spiral route emitters. Turbulent flow emitters control water flow by dissipating energy in friction against the water passage's walls as well as between the particles themselves during turbulent motion. Fully turbulent emitters include orifices, nozzle emitters, tortuous path emitters, and jets or sprayers. Drip tapes with orifices are turbulent flow devices as well. Emitter flow variation in the system will be given by the variation between the emitter that emits the most and the emitter that emits the least. Table 2.8 presents interpretation of emitter flow variation.

Table 2.8: Emitter Flow Variation Rating

Emitter Flow Variation (Qvar)	Interpretation
≤10 %	Desirable
10 – 20 %	Acceptable
≥25 %	Unacceptable

Source: Olorunwa *et al*., 2019.

2.5.4 Emission Uniformity

The single most significant indicator for measuring drip irrigation system performance is Emission Uniformity (EU), which is a measure of the uniformity of emitters discharge from all emitters in a drip irrigation system. The Emission Uniformity (EU) depicts the link between average and minimum discharge of emitters. EU is necessary for determining irrigation gross depth, irrigation interval, and system capacity. It is determined by the water temperature and the system's coefficient of variation specified by the manufacturer (Purohit *et al*., 2017). Table 2.9 presents emission uniformity rating for drip irrigation system.

Table 2.9: Classification of Emission Uniformity (EU)

Emission Uniformity (%)	Interpretation
90 – 100	Excellent
80 – 90	Good
70 – 80	Fair
< 70	Poor

Source: Purohit *et al*., 2017.

2.5.5 Gravity Fed Drip Irrigation

Irrigation with solar energy requires storing electricity in batteries or water in reservoirs so that irrigation can be possible when the sun is not there. To transport water from its source to its destination, all types of irrigation require pressure. Low pressure drip irrigation requires operating pressure between 0.5 and 2 bars. Raised tanks as water sources serves as water storage and pressure creation. The amount of pressure or push required is determined by a variety of factors, including the height at which water must be lifted, the length and size of the delivery pipe(s), the crop and size of the irrigated area, and the distance water must be moved from the source to the field (Nakashima, 2010).

The weight of water can also be employed to create pressure, and gravity-fed water delivery systems have been used for centuries in several regions of the world. When water is lifted 2.3 feet (0.7 m) above the surface of the area to be watered or irrigated, it creates pressure of 1 pound per square inch (1 psi or 0.0689 bar). Figure 2.7 illustrates that pressure is determined by the height of the water column rather than the tank's volume (Rowell and Jacobsen, 2018).

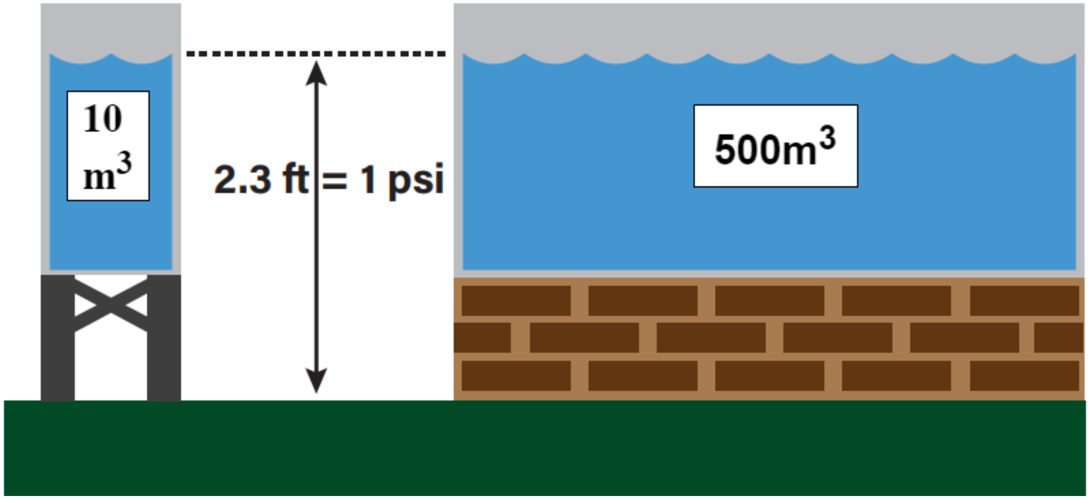


Figure 2.7: Large and Small Tanks for Gravity Fed Drip Irrigation
Source: Rowell and Jacobsen, 2018

2.5.6 Percentage Wetted Area

The percentage wetted area (Pw) is the average horizontal area wetted within the top 30 cm of the crop root zone depth in relation to the total cropped area. Most engineers agree on a minimum of 33 % and maximum of 67 % for spaced crops. Keller and Bliesner (1990) suggest that Pw often approaches 100 % for closely spaced less than 1.8 m apart.

2.6 Irrigation Scheduling

Irrigation scheduling is the process of determining the optimal amount and time of water application to achieve the desired crop production and quality while minimizing negative environmental consequences such as nutrient leaching below the plant root zone and maximizing water saving. Weather factors, soil type, crop type, management approaches, soil moisture content level, and water conveyance system all influence irrigation scheduling (Aziz *et al.*, 2022).

Water management and better water usage efficiency are important solutions for conserving water resources, especially in irrigated agriculture, which uses a lot of it. Improving irrigation efficiency could save a lot of water that could be put to better use irrigating a greater area. Irrigation efficiency might be improved if irrigation scheduling was implemented (Aziz *et al.*, 2022). Irrigation scheduling can help to reduce the amount of water that is applied to the farm. According to studies, monitoring soil water and estimating crop water use rates can save 1.5 - 2.0 inches of water. The goal is to reduce pumping by maximizing the utilization of stored soil water and precipitation (Martin *et al.*, 2011).

Evaporators have been used for irrigation scheduling (Goyal, 2016). An evaporator is an open container with vertical sides to ensure that the surface area for evaporation is constant regardless of the volume of water in the evaporator. A level line is marked on the inside of the container about 3 cm below the overflow level. Figure 2.8 represent an evaporator where the surface area for evaporation is approximately 0.1 m^2. Evaporator should be exposed to full sun so that the water in the evaporator can freely evaporate and any rain falling directly above the evaporator enters the evaporator. For drip irrigation, for each irrigation subunit, one of the emitters drips waters into the evaporator during the irrigation event and this emitter is called the control nozzle.

Figure 2.8: Evaporator for Irrigation Scheduling
Source: Megh, 2016.

Sensor based irrigation scheduling has recently been developed to address the challenges of high productivity while conserving resources. Sensor devices in irrigation assists in irrigation scheduling rationalization and lowers farmer drudgery. In this context, modern technology such as sensor-based precision irrigation to offer real-time watering scheduling is required. Many soil moisture sensors have been employed in precision irrigation to monitor and measure in-situ soil moisture, including Frequency Domain Reflectometry (FDR), tensiometers, granular matrix, resistance blocks, Time Domain Reflectometry (TDR), and watermarks (Kumari *et al*., 2020).

However, because of deep-rooted structure in orchards, determining soil moisture content with soil moisture sensors is quite challenging. Plant sensors are necessary to collect the water status because a plant is the best indication of its own water status. As a result, plant-based sensors such as sap flow meters, dendrometers, and infrared thermometers are preferred for monitoring plant water status (Kumari *et al*., 2020).

Irrigation scheduling also contributes to energy conservation. Although the solar gives energy at no extra cost, energy conservation will help to optimize the size of the field to be watered. Through irrigation scheduling, application efficiency, efficiency of the pumping plant, and the pumping pressure required for irrigation system energy will be conserved. Improving water application efficiency is one approach to save energy. The depth of water stored in the soil where it is available to the crop against the depth of water pumped is referred to as water application efficiency. Water can be lost from irrigation systems due to evaporation in the air or direct contact with plant foliage. Evaporation and runoff both lose water at the soil surface. Excessive irrigation and/or rainfall may also percolate through the root zone of the crop, resulting in deep percolation. Water is directed upward into the air using high-pressure impact sprinklers, allowing for more wind drift and in-air evaporation. In addition, high pressure impact sprinklers apply water to foliage for 20 - 40 minutes longer than low pressure spray heads mounted on drop tubes. The difference in application time results in less evaporation directly from the foliage for low pressure spray systems. Caution should be used so that surface runoff does not result with a sprinkler package. Good irrigation scheduling should minimize deep percolation (Kumari *et al*., 2020).

2.7 Soil Infiltration Rate

Infiltration is the downward movement of water from the surface of the soil into the soil. The rate of infiltration is measurement of the water depth that infiltrated into the soil from its surface per unit time (Mutasher and Al-Mohammed, 2019). Double ring infiltrometer is one of the methods used to determine soil infiltration rate. The double ring infiltrometer is a simple tool for determining the rate of water infiltration into the soil. The quantity of water per surface area and time unit that penetrates the soil determines the rate of infiltration (Mutasher and Al-Mohammed, 2019). In order to supply water to the root zone from the soil surface and reduce salinity through leaching, the infiltration rate, also known as the intake rate, is a crucial process. When infiltration rates are lowered in some unfavourable ways, issues associated to infiltration start to occur. Very little water is accessible to plant roots or remains on the soil's surface as a result of the low infiltration rate. This issue prevents plants from accessing essentials like water and nutrients. Beyond this case, there are many other variables that impact the water infiltration rate in soil, including soil structure, soil compaction, the availability of organic matter, water quality, and chemical composition (Bakhsh and Choudry, 2017). Figure 2.9 presents infiltration capacity, surface ponding and runoff, and rainfall intensity whilst Figure 2.10 illustrates double ring infiltrometer with its apparatus.

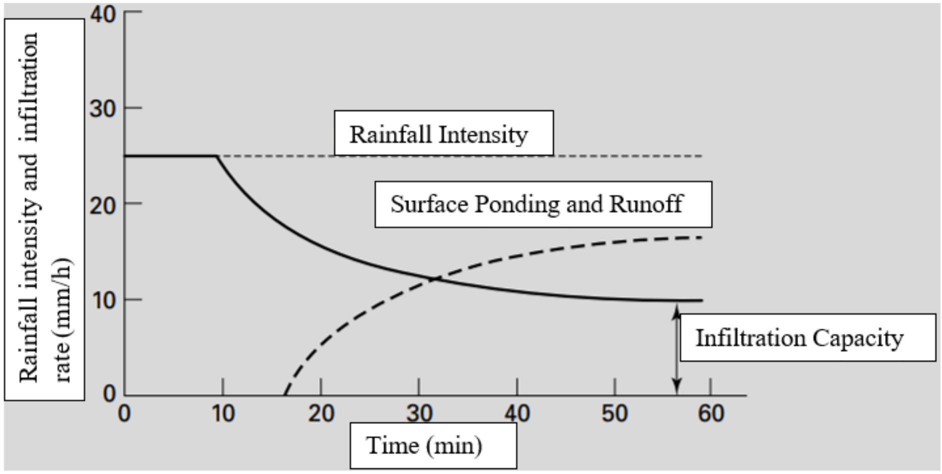


Figure 2.9: Infiltration Curve
Source: Mays, 2015.

Table 2.10: Classification of Infiltration Rate for Different Soil Types

Soil type	Constant Infiltration Rate (mm)
Sand	>30
Sandy loam	20-30
Loam	10-20
Clayey loam	05-10
Clay	<5

Source: Eijkelkamp, 2012

2.8 Field Capacity and Permanent Wilting Point

Field capacity is the moisture content in percentage of a soil on oven-dry basis when it has been completely saturated and downward movement of excess water has practically ceased at pressure of -1/3 bars. Such a stage is reached generally in 48 to 72 hours after saturation (Cong *et al*., 2014). After heavy rains, the soil will receive a lot of water almost at saturation, the next irrigation should be done based on the allowable moisture depletion of the crop grown in the field (USDA, 2008).

Permanent wilting point is defined as the soil water content at which the soil's matric potential equals or exceeds the maximum ability of plant roots to extract water from the soil and this happen at pressure of -15 bars. Available water content (AWC) of the soil is the amount of water that can be stored in the soil and is available for plant use between the field capacity and the permanent wilting point. It is an important soil characteristic that is critical for plant growth, as it determines the amount of water that can be stored in the soil for use by plants during periods of drought or water stress. The AWC of a soil is calculated as the difference between the water content at field capacity and the water content at permanent wilting point. The AWC can vary depending on the soil texture, structure, and organic matter content, with sandy soils typically having lower AWC than clay soils Enoviti (2012) classified soils and its corresponding field capacity and permanent wilting point.

Table 2.11: Soil Moisture Content in Inches of Water per Foot of Soil at Field Capacity and Permanent Wilting Point

Soil texture	Field Capacity (in/ft)	Permanent Wilting Point (in/ft)
Sand	1.2	0.5
Loamy Sand	1.9	0.8
Sandy Loam	2.5	1.1
Loam	3.2	1.4
Silt Loam	3.6	1.8
Sandy Clay Loam	3.5	2.2
Sandy Clay	3.4	1.8
Clay Loam	3.8	2.2
Silty Clay Loam	4.3	2.4
Silty Clay	4.8	2.4
Clay	4.8	2.6

Source: Enoviti, 2012.

2.9 Life Cycle Cost Analysis of a Solar Powered Irrigation System

The increase in productivity due to the technology used in agriculture does not always mean that the benefits that the farmer sees increase, as the technology used may be more expensive than the increased production. Irrigation is only economically viable if the expenditure of water can be covered by increased crop production revenue (Rentsch, 1982). Irrigation systems are infrastructures that last long time that can be predetermined or estimated and that period is known as lifecycle. After that period irrigation system will be redesigned or replaced and all economic analysis must be done within the limits of that time (Rentsch, 1982).

Life cycle costing provides a convenient method for comparing systems with differing cost streams throughout their lifetimes. All costs incurred during a system's lifetime are reduced to a single amount at the beginning of system operation. This amount is known as the life cycle cost (LCC) or present value of the system. The LCC may be thought of as the amount of money necessary in the first year of operation, which, if invested at a certain rate, would pay for the system throughout its lifetime. This rate is known as the discount rate, and is one of the parameters necessary to carry out the economic analysis (Lukens *et al*., 1977).

The life cycle cost assessment (LCCA) is a comprehensive economic assessment system that considers all expenses associated with owning, running, maintaining, and lastly disposing of a project (Ludin, 2019). Lifecycle cost analysis is very important on solar system because of its rate of decline which is said to vary between 0.3 – 1 % per year. So, within 25 – 30 years of operation, solar system will provide less than 75 % of its design capacity (Highnoonsolar, 2022).

All products or services can be affected by cost, performance, schedule, quality, risks, and tradeoffs. However, engineers devote the most of their formal education to performance and the majority of their working lives to thinking about resources and schedules. They focus too much on the technical performance to fulfill customer expectations, oblivious to the downstream expenses that contribute to the system's overall life cycle costs (LCC). Unfortunately, the LCC or total ownership costs (TOC) are frequently disregarded because either the total costs would render the project untenable, particularly for large government projects, or the additional acquisition costs required to lower the LCC would render the project unacceptable (Farr, 2011).

In the technologically advanced global economy, engineering has undergone significant transformation. Beyond technical process, success in modern engineering depends on a grasp of its economics or commercial components. Engineers must be involved in every step of developing new products in a field where network-centric of systems are typical. Among the abilities required for employment success include marketing, project management, leadership, and accounting. Engineers have an extensive array of economic techniques and tools at their disposal to predict and monitor costs and schedules, yet overruns are commonplace. They do not understand either the technical or non-technical aspects of LCC and the associated risks (Farr, 2011).

2.9.1 Life-Cycle Cost

The LCC method organizes and calculates the expenses of purchasing, owning, operating, maintaining, and eventually disposing of a system. To calculate the LCC, first calculate the present value of each cost that will be incurred during the study period using the discount rate, and then add these present values together to get the LCC. The computations can be done manually or with the help of a computer software (Fuller and Petersen, 1996).

The total estimated expenses incurred by a project or programme over the course of its life are known as life cycle costs. They represent the total of all expenses incurred or projected to be expended during the design, research and development (R&D), investment, operations, maintenance, retirement, and other support phases of the life cycle of a product i.e., its anticipated useful life span. Regardless of the financing source, business unit, managerial control, etc., all pertinent expenditures should be mentioned. Because the acquisition represents a tiny portion of the true or total costs related to owning and operating the systems, determining LCC is crucial for systems (Farr, 2011). Table 2.11 presents the comparison in financial requirements between five (5) PV systems and five (5) diesel pump systems of equivalent and sizes for small and large scale.

Table 2.12: Comparison in Financial Requirements between Five (5) PV Systems and Five (5) Diesel Pump Systems of Increasing Size

System Capacity	Total Capital Costs (USD)	Total Operating Costs (USD/year)	Total Costs Over a 10-year Period	Total Costs Over a 20-year Period
		Photovoltaic Pump		
4.5 kWp	27470	800	35470	43470
6.3 kWp	37398	900	46398	55398
10 kWp	56800	1400	70800	84800
15 kWp	82000	1600	98000	114000
		Diesel Pump		
4.5 KVA	4720	5864	63360	122000
6.3 KVA	6050	6029	66340	126630
10.0 KVA	8350	6307	71420	134490
15.0 KVA	10320	6593	76250	142180

Source: CTCN, 2016.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted in Tolon District in the Northern Region of Ghana, in a Research Demonstration Field of the West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies (UDS), Nyankpala Campus. It is located at latitude 9°24’39’’N and longitude 0°58’52’’W with an altitude of 161 meters above mean sea level. A new solar powered irrigation system was installed and it uses rain water harvested from rooftops stored in an underground reservoir of capacity 50 m^3. Figure 3.1 presents the location of the study area.

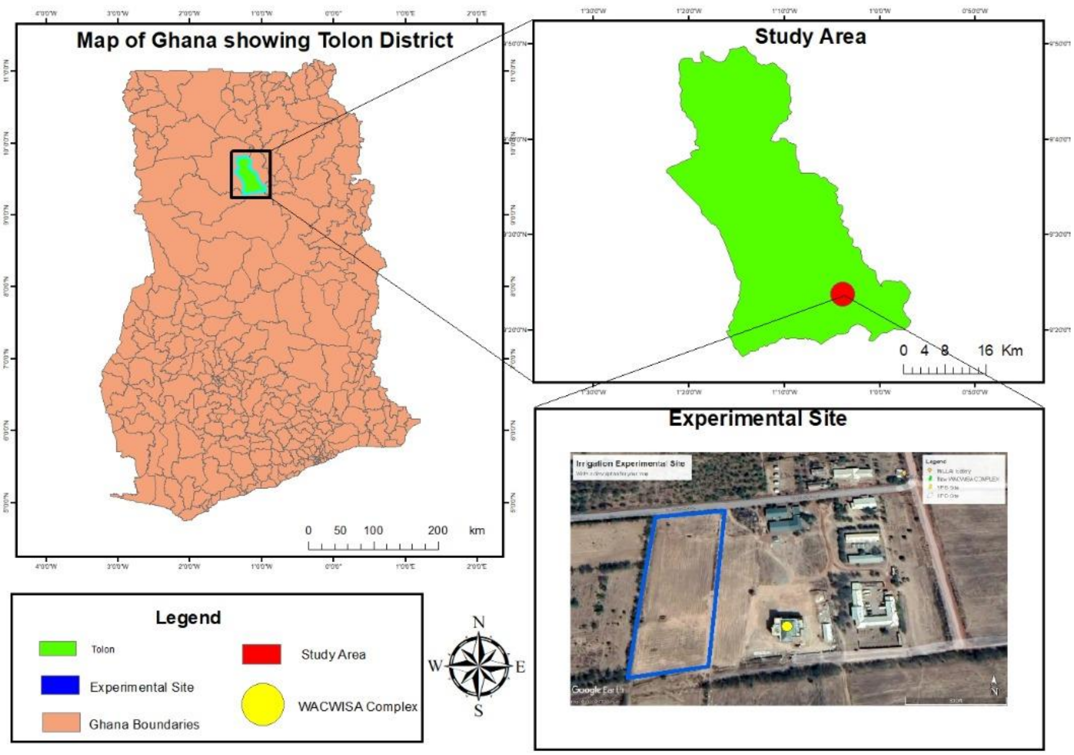


Figure 3.1: Map of Ghana Showing Tolon District and the Experimental Site

Source: Author, 2022

3.1.1 The Solar PV Characteristics

The PV array is made up of twelve (12) modules with four (4) connected in series and three (3) strings connected in parallel and each module has 72 cells. One PV module have 37.7 V and 8.76 A and the maximum power capacity of one PV panel is 330 W. The PV array is positioned in a permanent (fixed) frame facing North-South, at an angle of 15^o to the horizontal. A number of cables passed through the Solar Disconnect (SD) to the controller.

Table 3.1: Nominal Ratings of Installed Solar PV

Item	Symbol	Capacity
Maximum power (+3 %)	Pmax	330 W
Current Maximum power	Imp	8.76 A
Voltage Maximum power	Vmp	37.7 V
Short Circuit Current (±3 %)	Isc	9.20 A
Open Circuit Voltage (±3 %)	Voc	46.1 V

source: Author, 2022

The controller acts as brain of the system and it stops the system whenever any of the sensors detect any parameter which is out of range. Three (3) sensors namely; solar, water level and pressure sensors have been installed as safety devices. The solar sensor detects whether solar radiation is too low to start the pump, controller stop the pump automatically. When water level goes down in the reservoir so that suction pipe will never reach water level, water sensor will communicate to the controller to stop pump automatically so that there will be no empty pumping. The pressure sensor sends information to the controller about operating pressure, when pressure is out of range, automatically system will shut off. Water level in suction section also have sensor. There can be water in reservoir but when priming is not effective there will be no water in suction pipe, in that case the sensor will stop the pump. Solar sensor, water sensor, pressure sensor and system switch all are connected to the system controller. A submersible solar pump of 19 m^3/hour, 8 – 22 m of head have been installed to pump water to the field for irrigation. Figure 3.2 illustrates the flow chart of the solar system installed in the study area.

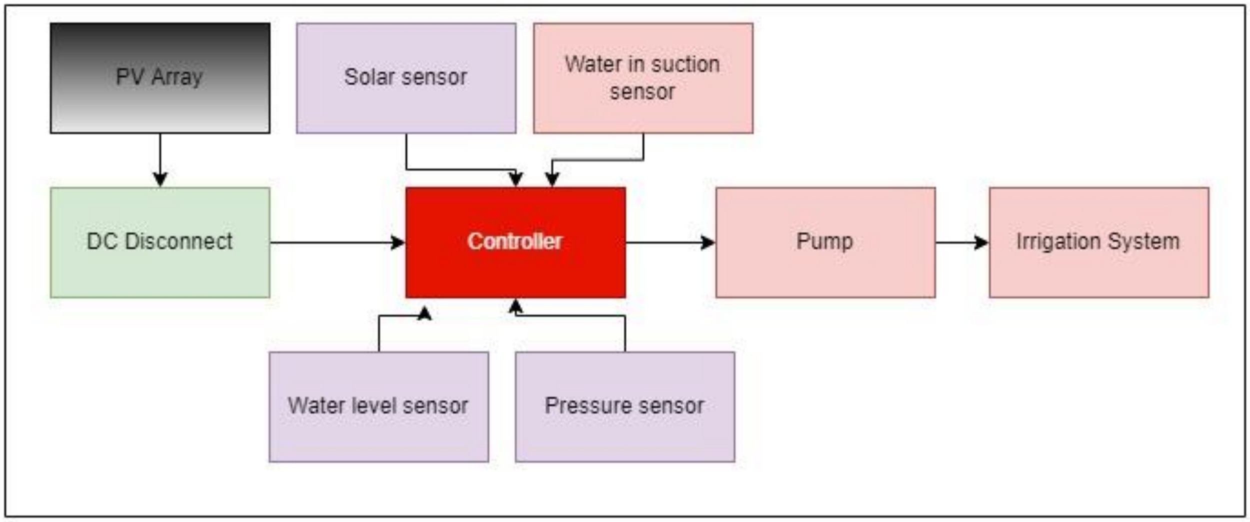


Figure 3.2: Flow Chart of the Installed Solar Powered Irrigation System in the WACWISA Research Demonstration Site

Source: Author, 2022

3.1.2 Water Source

Water used is harvested from building rooftop of 252 m^2 and stored in an underground reservoir with a capacity of 50 m^3.

3.1.3 Conveyance

Irrigation system is installed in the field of about one acre and consists of three (3) water application systems namely; spray tubes, sprinkler and drip irrigation systems. The spray tubes and sprinkler irrigation systems are directly coupled to the pump, that means irrigation is only done when solar energy is available, while the drip irrigation system is operated by two (2) elevated tanks with total storage capacity of 6 m^3. The tanks are mounted on a metallic stand of 3 m high.

The main line from the pump station to the submain line of the spray tube system is 38 m and elevation from the pump to the field is 2 m. The spray tube irrigation system consists of ten lines of 25 m each, spaced by 3 m apart from each other.

The main line from the pump to the submain of the sprinkler irrigation system is 69 m and the height of the riser pipes is 1 m. There are four (4) lines of sprinkler laterals with 3 sprinkler head per each lateral, giving a total sprinkler head of twelve (12). The spray tube and sprinkler irrigation systems share the same main line and each one has its submain line.

The main pipe from the pump station to the elevated tank is 108 m and height to the top of the tank is 4.5 m because tank is held at 3 m high and tank itself is 1.5 m. Drip irrigation system is divided into four (4) subunit and each of them works independently with a control valve. The water source for drip irrigation is the elevated tank. There is one main pipe of 32 mm diameter from the elevated tank and submain for every subunit. The first, second, third and fourth subunits are placed at 13 m, 25 m, 37 m and 50 m respectively from the elevated tank. Table 3.1 presents the specifications of materials used for the solar and irrigation systems whilst Figure 3.3 illustrates the layout of the irrigation system at the field.

Table 3.2: Materials Specifications of the Solar and Irrigation Systems

Item	Specification
Solar PV	
Technology	Polycrystalline
Power	330 Watts
Number of PV panels	12
Pump	
Head	8 - 22 m
Discharge	19 m^3/h
Sprinkler Irrigation System	
Sprinklers heads	MEGANET 550 l/h
Wetting diameter	17 m
Working pressure	2 bar – 3 bars (20.4 m – 30.6 m
Laterals and raisers	1/2-inch PVC pipe
Submain lines	3/4-inch PVC pipe
Main line	50 mm HDPE pipe
Spray Tube Irrigation System	
Submain	1.5-inch PVC pipe
Spray tubes	1.5 inch
Drip Irrigation System	
Drip lines	16 mm (0.63 inch)
Submain	32 mm HDPE Pipe
Main line	32 mm HDPE Pipe
Elevated Tank	2 Poly tank 6m3 each

Source: Author, 2022

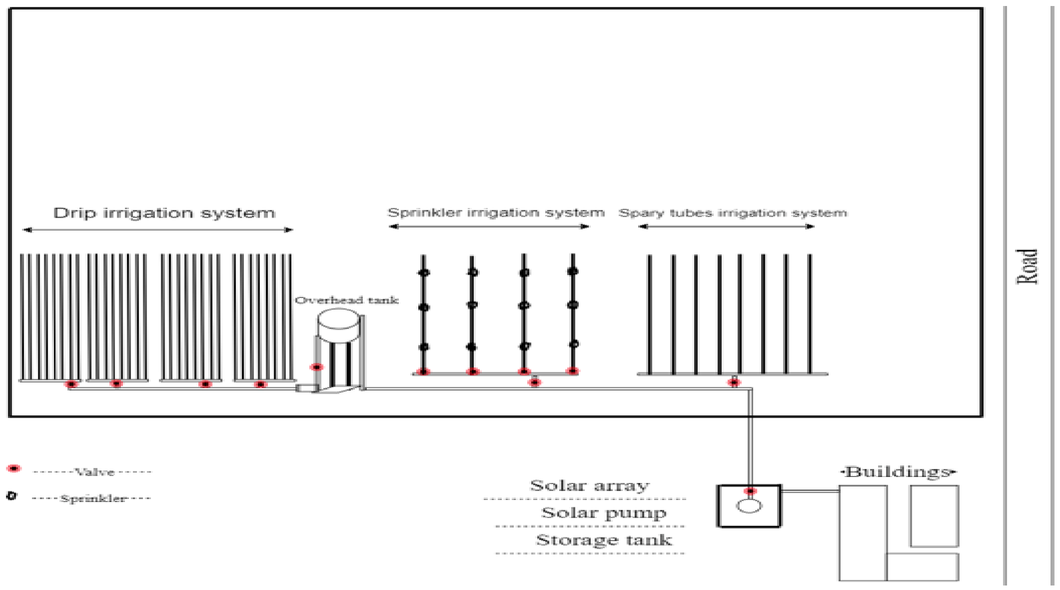


Figure 3.3: Schematic Drawings of the Layout of the Solar Powered Irrigation System

Source: Author, 2022

3.2 Determination of the Soil Characteristics of the Irrigable Area of the Solar Powered Irrigation System and the Crop Water Requirement for Tomato

3.2.1 Soil Infiltration Rate

Double ring infiltrometer was used for the determination of soil infiltration rate in the study area. The diameters of the inner and outer stainless-steel infiltration rings are 30 cm and 53 cm respectively, and 25 cm in height and has one cutting edge to enter the soil. The purpose of the outer ring was to act as a buffer zone for infiltrating water, preventing it from straining away sideways from the inner ring (Eijkelkamp, 2012). Plate 3.1 illustrates how the infiltration rate data was collected using the double ring infiltrometer.

Plate 3.1: Measuring Infiltration Rate Using Double Ring Infiltrometer at the WACWISA SPIS Field

Source: Author, 2022

After collecting the infiltration data using the double ring infiltromer, the infiltration model - Equation 3.1, established by Horton (1940) was used to determine the infiltration rate of the soil in the irrigable area of the solar powered irrigation system.

$$\mathbf{f}(\mathbf{t}) = \mathbf{f_c} + (\mathbf{f_o} - \mathbf{f_c})\mathbf{e}^{-\mathbf{Kt}} \quad \text{...} \text{ Eq. 3.1}$$

Where:

f(t) - Infiltration rate at time t in (cm/h),

Fc - Final constant infiltration rate (cm/h),

F0 - Infiltration rate at the start (cm/h),

K - The constant of Horton or Decay coefficient of exponential Decay curve (h^{-}), and

t - infiltration time (h).

3.2.2 Determination of Soil Dry Bulk Density

Dry bulk density of the soil was determined by the metal core sampler method as described by Blake and Hartge (1986). The dry bulk density for each sample was calculated using Equation 3.2 (Cresswell and Hamilton, 2002):

Dry bulk density (g/cm^3) = $\frac{M_2 - M_1}{V}$……………………………………….…. Eq 3.2.

Where:

M_1 - Mass of empty core sampler (g),

M_2 - Mass of core sampler + oven dried sediment (g),

V - Volume of core sampler ($\pi r^2 h$), cm^3

π - 3.142,

r – radius of core sampler (cm), and

h – height of core sampler (cm).

Plate 3.2: Measuring Soil Bulk Density at Laboratory
Source: Author, 2022

3.2.3 Water Content at Field Capacity (FC) and Permanent Wilting Point

A pressure plate was used to apply a suction of -1/3 atmosphere (- 0.3 bar) and (- 15 bars) to a saturated soil sample, which is the most frequent way of evaluating field capacity and permanent wilting point in the laboratory. The soil moisture in the sample is assessed gravimetrically and equated to field capacity and permanent wilting point when water is no longer leaving the sample. Plate 3.3 illustrates how the field capacity test was conducted using pressure plates in the laboratory.

Plate 3.3: Determination of Field Capacity using Pressure Plates
Source: Author, 2022

One field approach for determining field capacity is irrigating a test plot until the soil profile is saturated to a depth of roughly one meter. To prevent evaporation, the plot is then covered. Each 24 hours, the soil moisture content is measured until the fluctuations are very minimal, at which point the soil moisture content is said to be field capacity (FAO, 1989).

The moisture content corresponding to a pressure of -15 atmospheres from a pressure plate test is generally defined as the soil moisture coefficient at the permanent wilting point. Although actual wilting values can differ from - 10 to - 20 atm, soil moisture content is mostly constant throughout this range. As a result, the wilting point was estimated using the -15 atm moisture content (Equations 3.3 and 3.4) (FAO, 1989).

$$\boldsymbol{\theta_{fc}} = \frac{\boldsymbol{\rho_d * \theta g_{fc}}}{\boldsymbol{\gamma_w}} \quad \text{…………………………………………………………………… Eq 2.3.}$$

Where:

θ_{fc}- Volumetric water content at field capacity, (fraction),

ρ_d − Bulk density of the soil, (g/cm^3),

θg_{fc} - Gravimetric water content at field capacity, (fraction), and

γ_w - Specific weight of water, (g/cm^3).

$$\boldsymbol{\theta g_{fc}} = \frac{\boldsymbol{W_{fc} - W_s}}{\boldsymbol{W_s}} \quad \text{…………………………………………………………….……… Eq 3.3.}$$

Where:

W_{fc} - weight of soil at field capacity, and

W_s - weight of oven dried soil.

3.2.4 Soil Particle Size Distribution

Soil particle size distribution was analyzed using sieve analysis in laboratory and based on the U.S. Department of Agriculture (2016) size separates for soil classification.

Table 3.3: Soil Classification

Soil	Diameter (mm)
Gravel	> 2.0 mm
Very coarse sand	< 2.0 to > 1.0 mm

Medium sand	0.5 to > 0.25 mm
Very fine sand	0.10 to > 0.05 mm
Coarse silt	0.05 to > 0.02 mm
Fine silt	0.02 to > 0.002 mm
Coarse clay	0.002 to > 0.0002 mm
Fine clay	≤0.0002 mm

Source: USDA, 2016.

3.2.5 Determination of Crop Water Requirement

Crop characteristics such as agronomic performance, crop evapotranspiration (ETc), life cycle, etc. are important in irrigation especially for crop water need and irrigation scheduling. Crop water requirement for tomatoes was estimated using CROPWAT software. The main aim of calculating crop water requirement is to evaluate if the system will be able to provide water required for crops, prepare irrigation scheduling. For spray tube and sprinkler irrigation system field has to wet 100 % because water sprayed resembles natural rainfall. For drip irrigation system field has to partially wet according to the percentage wetted area. CROPWAT provides water that will be needed by the plant for the whole growing period and the schedule of every 10 days. CROPWAT calculates the water needed by the plant and deduct the effective rainfall and provides irrigation water requirement. All of this is based on long-term meteorological data, namely rainfall data, minimum and maximum temperatures, relative humidity, wind speed, and sunshine duration and sun radiation intensity.

The amount of water calculated by CROPWAT is an approximation based on climatic data obtained over the years. As a result, CROPWAT's results are supported by data collected on the field at the time of performing irrigation scheduling, the most important of which is soil moisture content and rainfall data which can be collected by rain gauge. Irrigation water requirement for localized irrigation was calculated using Equation 3.5 given by Keller and Bliesner (1990).

$$\mathbf{T_d = U_d * \left[0.1(P_d)^{0.5}\right]}$$ ……………………………………………………….Eq 3.4

Where:

Td – Estimated ETcrop at peak demand for localized irrigation (mm/day)

Ud – water requirement calculated for in CROPWAT model (mm/day)

Pd – percentage ground cover (%)

Percentage wetted area can vary depending on soil type and type of emission device used and it was measured on the field.

3.3 Study of the Solar PV and Pump Characteristics

The relationship of power generated by solar array and discharge of pump was examined at different sun radiation by using digital meter to measure voltage and current of the system. System was monitored in the morning when sun rises, at noon when sun is maximum and at evening when sun set. The system was also monitored on cloudy days. Water meter was used to measure flow rate and pressure gauge to measure operating pressure of the system. The power requirement of the pump was calculated using Equation 3.6 given by FAO (2001).

$$\mathbf{Power\ Requirement\ of\ Pump(Kw) = \frac{Q*H}{360*e}}$$ ……………………….. Eq 3.5.

Where:

Q - Discharge (m^3/h),

H - Total head (m), and

e - Pump efficiency (%).

3.3.1 Determination of Pump System Curve

The curve representing pump output versus system power is known as system curve. The power of the system was estimated using Equation 3.7.

$\mathbf{P = V \times I}$ …………………………………………………………………… Eq 3.6.

Where:

P - the power generated by the system (W)

V - the voltage (volt), and

I - the current (amp).

Power of the system was carefully recorded using digital multimeter. Pump output was recorded at the same time using water flow meter and this helped to draw system curve. Figure 3.4 presents system curve experimental design as described by Bell and Gosset (2021). First there is a pump followed by pressure gauge to measure operating pressure, then flow meter and regulating valve. By using regulating, pressure in the system can be adjusted by fully or partly closing the valve. A pump performance curve indicates how a pump will perform in regards to pressure head and flow. A curve is defined for a specific operating speed (rpm) and a specific inlet/outlet diameter. The curve also shows the shut off head or the head that the pump would generate if operating against a closed valve.

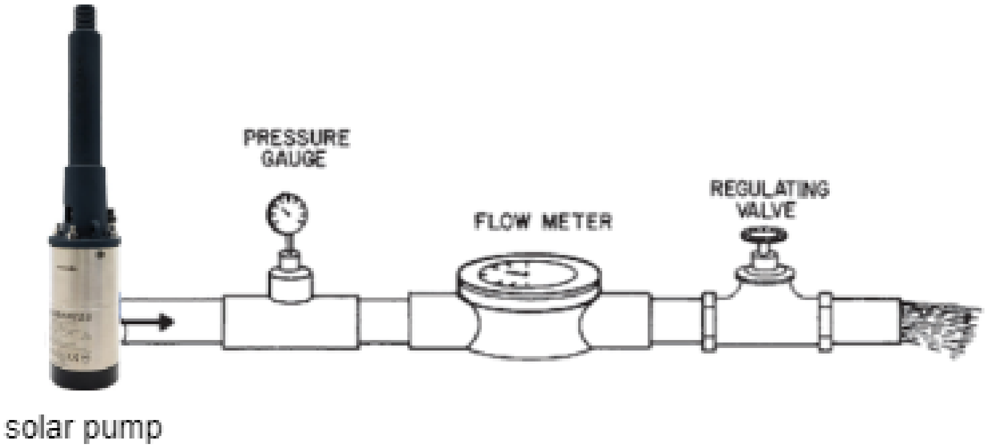


Figure 3.4: Setup of Pump Curve Test at the WACWISA Solar Pump Station
Source: Author, 2022

3.3.2 Measuring Head-Discharge Curves

For centrifugal and turbine irrigation pumps, the discharge rate depends on the pressure that the pump operates against. If the pressure is high, the discharge rate will be low, and conversely, if the pressure is low, the discharge rate will be high. The relationship between pressure and discharge rate is known as the head-discharge curve for the pump. The head-discharge curve may be different for each pump because of the pump characteristics and many site-specific factors (Haman and Zazueta, 2017).

Curve representing head of irrigation system versus output of the pump is called pump curve. There are three (3) irrigation system which work under different pressures. The system head was carefully analyzed by using pressure gauge and the flow rate was recorded using water flow meter. The discharge rate of centrifugal and turbine irrigation pumps is determined by the pressure against which they operate. When the pressure is high, the discharge rate is low, and when the pressure is low, the discharge rate is high.

The head-discharge curve for the pump is the relationship between pressure and discharge rate. However, because of pump features and several site-specific considerations, the head-discharge curve for each pump may be different (Haman and Zazueta, 2017). For this study, the pump was operated at the peak sun hour (PSH) and the pressure and flow rate were recorded using pressure gauge and water flow meter.

3.4 Determination of the Technical Performance of Drip Irrigation System

After building a new irrigation system, performance evaluation is the most important thing to do. A well-designed system evaluation helps to determine if its performance is within the acceptable range or whether it is low. Performance evaluation helps to find out where the problem is to be corrected.

When irrigating using solar energy, irrigation is only done when the sun is there, so it would not be good to do direct pumping on drip irrigation where full control of irrigation water is needed, because irrigation is not possible in the night or cloudy days where there is no sun. Some of the simplest option is elevated tanks because drip irrigation requires less operating pressure, which can be provided by elevated tank. Unlike a spray tube or sprinkler where the operating pressure is high which makes using an elevated tank require setting it to the highest height which would make it expensive to construct. As the water level changes in the tank, so does the pressure in the submain. This also causes the mean application rate of the emitter to change. This allows the water level in the tank to be involved in irrigation scheduling. This means that if we are going to irrigate 5 mm when the tank is full it will take a few minutes, but if the water is low, it will take longer.

3.4.1 Coefficient of Variation for the Drip Irrigation System

The coefficient of variation for the drip irrigation system was calculated using Equation 3.8 given by Keller and Bliesner (1990).

$$\mathbf{cv} = \frac{\sqrt{\sum_{i=1}^{n}(q_i - q_a)^2}}{q_a\sqrt{n-1}} \quad \text{……………………………………………………..…Eq 3.7.}$$

Where:

cv - coefficient of variation

qi – observations (ml)

qa - average value of all observations (ml), and

n - number of observations.

Plate 3.4: Catch Can Test for Drip Irrigation System at the WACWISA SPIS Site
Source: Author, 2022

3.4.2 Determination of Emission Uniformity of the Drip Irrigation System

To estimate the design emission uniformity, the Equation (3.9) developed by Keller and Karmeli (1974) was used.

$$\mathbf{EU} = \left[\mathbf{1.0 - 1.27}\frac{\mathbf{Cv}}{\sqrt{\mathbf{N}}}\right]\frac{\mathbf{q_{min}}}{\mathbf{q_a}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 3.8}$$

Where:

EU - Design emission uniformity of a subunit (%),

v - Emitter coefficient of manufacturing variation from the manufacturer,

N - Number of emitters per plant,

Q_{min} - Minimum emitter discharge rate, L/h (gph), and

qa - Average or design emission rate, L/h (gph).

3.4.3 Emitter Flow Variation

Equation 3.10 was used to calculate emitter flow variation (Olorunwa *et al.*, 2019)

$$\mathbf{Q_{var} = 100} * \left[\mathbf{1} - \frac{\mathbf{Q_{min}}}{\mathbf{Q_{max}}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 3.9}$$

Where:

Qvar - Emitter flow variation (%),

Qmin - Minimum emitter rate in the system (l/h), and

Qmax - Average or design emitter discharge rate (l/h).

3.5 Determination of Technical Performance of Sprinkler and Spray Tube Irrigation Systems

The sprinkler and spray tube irrigation systems provide water to the fields that resembles the natural rainfall, but they are different regarding working pressure because the spray tubes use less pressure than sprinklers. Spray tubes irrigation has proven to have better distribution uniformity than that of sprinkler irrigation. The performance indicators of these systems are almost the same except for spray tube discharge per meter has to be measured. Three (3) performance indicators namely; uniformity coefficient (UC), distribution uniformity (DU), and mean application rate (MAR) were evaluated for the two (2) application systems.

3.5.1 Coefficient of Uniformity

Uniformity coefficient (UC) of the drip irrigation system was determined using Christiansen's coefficient of uniformity as given in Equations 3.12, 3.13 and 3.14.

$$\mathbf{UC} = \left(\mathbf{1} - \frac{D}{M}\right) * \mathbf{100} \text{ ……………………………………….…………… Eq 3.10}$$

$$\mathbf{D} = \frac{\mathbf{1}}{\mathbf{n}}\sum_{\mathbf{i=1}}^{\mathbf{n}}|\mathbf{X_i} - \mathbf{M}| \text{ …………………………………………………..… Eq 3.11}$$

$$\mathbf{M} = \frac{\mathbf{1}}{\mathbf{n}}\sum_{\mathbf{i=1}}^{\mathbf{n}}\mathbf{X_i} \text{ ...……………………………………………………………. Eq 3.12}$$

Where:

UC - Coefficient of uniformity (%),

D - Average of the absolute values of the deviation from the mean discharge,

M - Average of water in the catch can values (mm),

Xi – Water in the catch can (mm), and

n - Number of waters in the catch can values.

3.5.2 Distribution Uniformity

Merriam and Keller (1978) established a methodology for assessing water application uniformity for irrigation systems in the field and derived the following formulas. The distribution uniformity was determined using Equation 3.15 as given by Merriam and Keller (1978).

$$\mathbf{D_u} = \frac{\mathbf{q_{1/4}}}{\mathbf{q_a}} * \mathbf{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 3.13}$$

Where:

DU – Distribution uniformity (%), and

$q_{1/4}$- Average of water in the catch can for low quarter.

3.5.3 Determination of Mean Application Rate

The emitter flow is controlled by the hydrostatic pressure at the emitter. This means whenever there is a pressure variation in the drip irrigation line there will be an emitter flow variation along the irrigation line (Omofunmi *et al*., 2019). The mean application rate (MAR) for the sprinkler and spray tube irrigation systems was determined using Equation 3.16 given by Kathiriya *et al.* (2021). Drip lines used are pressure compensating 16 mm diameter, 30 cm spacing between emitters and can emit up to 2 l/h application rate depending on operating pressure.

$$\mathbf{MAR} = \frac{\frac{1}{n}\sum_{i=1}^{n} X_i}{t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 3.14}$$

Where:

MAR - Mean application rate (mm),

Xi - Water collected in the catch can (mm),

t - Time (h), and

n - Number of catch cans.

3.5.4 Determination of Irrigation Width Covered by One Spray Tube

The width of irrigation covered by one spray tube was measured using measuring tape for different operating pressures.

3.6 Life Cycle Cost Analysis of the Solar Powered Irrigation System

3.6.1 Determination of the Total Life Cycle Cost of the Solar Powered Irrigation System

The total life cycle cost (LCC) of the installed solar powered irrigation system was determined using Equations 3.17 and 3.18 given by Fuller and Petersen (1996).

$$\mathbf{TLCC} = \sum_{\mathbf{t=0}}^{\mathbf{N}} \frac{\mathbf{C_t}}{(\mathbf{1+d})^{\mathbf{t}}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{Eq 3.}\mathbf{15}$$

Where:

TLCC - Total life cycle cost in present value,

C_t - Sum of all relevant cost, including initial and future costs; less any positive cash flows, occurring in year t,

N - Number of years in the study period, and

d - Discount rate used to adjust cash flows to present value.

$$\mathbf{TLCC} = \mathbf{C_I} + \mathbf{C_{OMR}} + \mathbf{C_{rep}} + \mathbf{C_O} - \mathbf{C_{res}} \dots\dots\dots\dots\dots\dots \text{Eq 3.16}$$

Where:

TLCC – Total life cycle cost

CI - Investment cost

C_{OMR} - Operating cost, maintenance and repair

C_{REP} - Replacement cost

C_O - Other costs, and

C_{RES} - Residual value.

Residual value of solar system is 20 % (APEC Energy Working Group, 2019)

3.6.2 Net Present Value

The net present value (NPV) of the installed solar powered irrigation system was determined using Equation 3.19 given by Fuller and Petersen (1996)

$$\mathbf{NPV} = \frac{\mathbf{R_t}}{\mathbf{(1+i)^t}} \text{ ....Eq 3.17}$$

Where:

NPV – Net Present Value, and

Rt – Net Cash Flow

3.6.3 Estimation of Operation, Maintenance and Repair Cost for System Lifespan

For estimation of anual operation, maintenance and repair cost ($C_{OM\&R}$) of system hardware, 2 % of capital cost was adapted and this is standing value given by GIZ (Sass and Hahn, 2020), (Lukens *et al*., 1977) and (William *et al*., 1967).

3.6.4 Replacement Cost Estimation

Replacement cost was estimated according to the lifespan of every component of the system and the references were mentioned. Net present value (NPV) of every item was applied to calculate the current value of a future value and was found using Equation 3.19. Lifespan of solar pump was found in pump manual (GPD, 2019) and GIZ paper about Solar Powered Irrigation Systems (SPIS) Technology, Economy, Impacts (Sass and Hahn, 2020), and that of sprinkler head and spray tubes and drip lines was found in Shiksha (2014) and DIN (2021).

3.6.5 Other Costs

Other costs include all the costs in tomato farming/production including land, fertilizers, chemicals, labour costs and cost of water. Labor costs was estimated to 13 % of other farm inputs. Cost of water was estimated according to the price of water in the community.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Soil Characteristics of the Irrigable Area and Crop Water Requirements of Tomato Crop

4.1.1 Infiltration Rate

The double ring infiltrometer was used to conduct the infiltration test at the irrigable area and the results are presented in Table 4.1 and Figure 4.1. Constant infiltration was found to be 1.2 cm/h and according to Bouwer (2018), the soils of this infiltration rate are classified as sandy loam soils. These soils are suitable for irrigating a wide variety of crops especially vegetable crops. The results agreed with the findings of the study carried out by Salifu *et al*. (2021) which evaluated the parameters of infiltration models in selected irrigation fields of northern Ghana.

Table 4.1: Infiltration Rate of the Soil in the Irrigable Area of the Solar Powered Irrigation System

Run time (min)	Time Interval (min)	Infiltration Depth (mm)	Cumulative Infiltration Depth (mm)	Infiltration Capacity (cm/h)
0	0	0	0	0
5	5	7	7	8.4
10	5	4	11	4.8
15	5	3	14	3.6
25	10	4	18	2.4
35	10	3	21	1.8
45	10	4	25	2.4
60	15	5	30	2
80	20	5	35	1.5
100	20	5	40	1.5
120	20	5	45	1.5
150	30	6	51	1.2
180	30	6	57	1.2

Source: Author, 2022

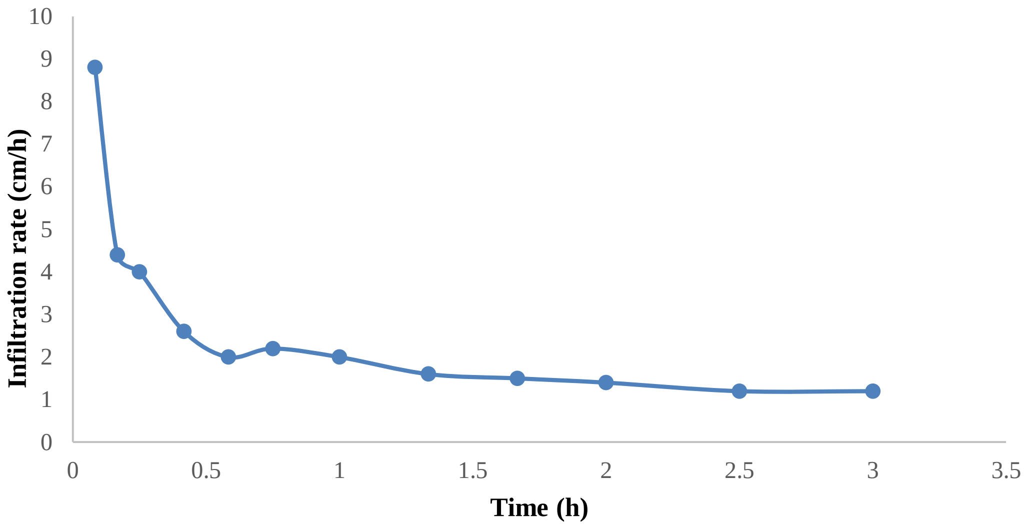


Figure 4.1: Infiltration Rate Curve of the Soil in the Irrigable Area
Source: Author, 2022

As presented in Figure 4.2, the initial infiltration rate (fo) and constant infiltration (fc) were found to be 9.2 cm/h and 1.2 cm/h respectively, whilst the value for Horton K was found to be 2.08. Salifu *et al.* (2021) asserted that when the field is dry, infiltration rate is very high and when field is saturated, infiltration rate is low and constant. The field results and those of the Horton equation showed the same trend as the infiltration rate was noted to be decreasing exponentially with time.

The infiltration curve in Figure 4.2 was plotted using result of Horton equation and compared to direct field measurements. From the curve of infiltration capacity, there is a positive correlation between the Horton equation and the field measured infiltration. These findings are similar to Mutasher and Al-Mohammed (2019) who also recorded similar trend in three (3) locations in AL-Jadwal Al-Gharbi District, Karbala, Iraq. When comparing the infiltration values obtained from the field (Figure 4.1) to those determined by the Horton equation (Figure 4.2), the correlation coefficient (R^2) was 79.51 % and 74.96 % respectively. According to Champatiray (2014), the values of

(R^2) between 70 % and 100 % are regarded to be solid bonds. This implies that the Horton's model provided a good correlation for the results of the field infiltrations in this study.

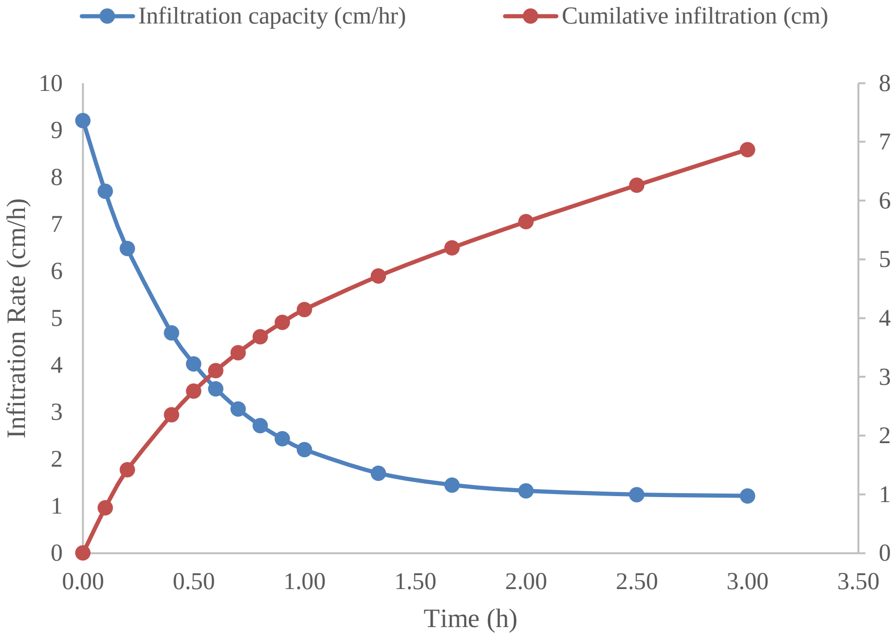


Figure 4.2: Infiltration Rate Curve after Applying Horton Model
Source: Author, 2022

4.1.2 Dry Bulk Density and Water Content at Field Capacity

The dry bulk density of the soil was found to be 1.37 g/cm^3 and according to Yu *et al.* (2014), soils with bulk density of this range are classified as sandy loam. The water content at field capacity and permanent wilting point were found to be 24.26 % and 9 % respectively. According to Enoviti (2012), soil texture classification of this field capacity and permanent wilting point can be classified as sandy loam.

4.1.3 Soil Particle Size Distribution

Sieve analysis test was carried out and the percentage of soil particles were found to be 55 %, 38 % and 7 % for sand, silt and clay, respectively. By using the soil textural triangle, the soil texture was found to be sandy loam. The results agreed with that of Tetteh *et al*. (2016) who conducted the same test in Northern, Upper East and Upper West Regions of Ghana and with results indicating that most of the soils of northern Ghana are sandy loam. Sandy loam soils are suitable for maize, okra, radishes, eggplant, carrots, pole beans, spinach and in general vegetables do well in sandy loam soil.

4.1.4 Crop Water Requirement of Tomato under Different Irrigation Systems

CROPWAT computer program was used to determine the water requirement for tomatoes which is the predominate crop cultivated in the irrigable area of the solar powered irrigation system. As presented in Table 4.2, the net water requirement for tomatoes was found to be 198.4 mm/season for both spray tube and sprinkler irrigation systems. Irrigation efficiency of 80.5 % was recorded for the spray tube whilst 73.7 % was recorded for sprinkler irrigation system. However, for the drip irrigation system, a higher irrigation efficiency of 87 % was recorded given a net water requirement of 166 mm/season. It can be seen that less water was applied in the drip system to slowly wet only rootzone of the crop, unlike the other water application systems which require wetting the whole field that leads to higher losses.

Table 4.2: Estimated Irrigation Water Requirement for Tomato under Different Irrigation Systems

Application System	Net Irrigation Requirement (mm/season)	Irrigation Efficiency (%)	Gross Irrigation Requirement (mm/season)	Volume of Water Needed per Hectare (m^3/ha)
Drip irrigation	166	87	190.8046	1908.046
Spray tube irrigation	198.4	80.5	246.4596	2464.596
Sprinkler irrigation	198.4	73.7	269.1995	2691.995

Source: Author, 2022

4.2 Characteristics of the Installed Solar PV and Water Pump Characteristics

4.2.1 Effect of Power Change on Pump Discharge Due to Diurnal Solar Radiation Variation

The diurnal variation of power and discharge of pump due to solar radiation at different operating pressures during the day in May and June 2022 was measured and presented in the Figures 4.3a, 4.3b and 4.3c. It can be seen in the figures that averagely, the peak of daily power of the solar PV panels is generated at around 1:00 pm (afternoon), which starts to decline gradually until 5:00 pm (evening). It was observed that the discharge of the pump follows the trend of power change during the day. The results indicated that for clear days by 11:00 am to 3:00 pm the pump is working at its maximum capacity. Results obtained in this study are in agreement with that of Kathiriya *et al*. (2021) who also conducted a similar study in Junagadh, India.

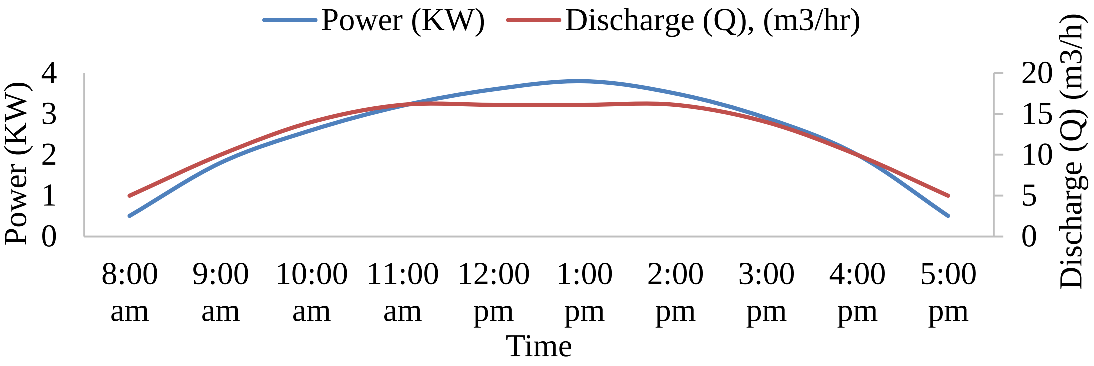


Figure 4.3 a: Discharge Variation Due to Solar Radiation for Spray Tube Irrigation (11.25 m Head)

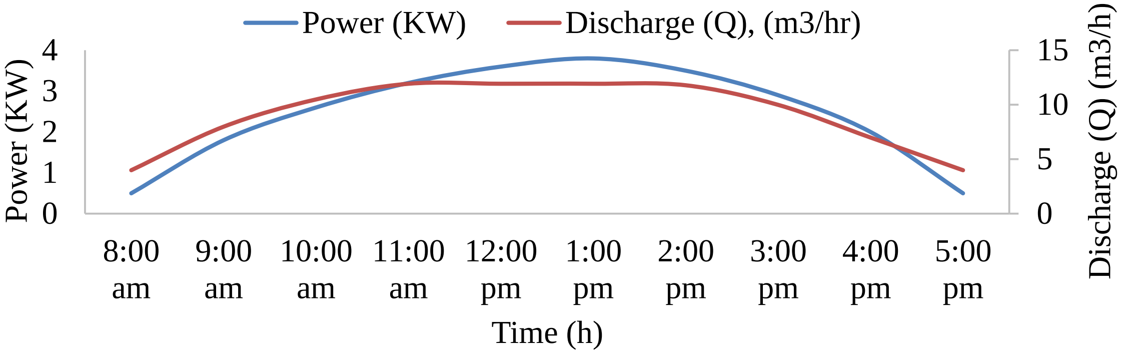


Figure 4.3 b: Discharge Variation Due to Solar Radiation for Elevated Tank (21.1 m Head)

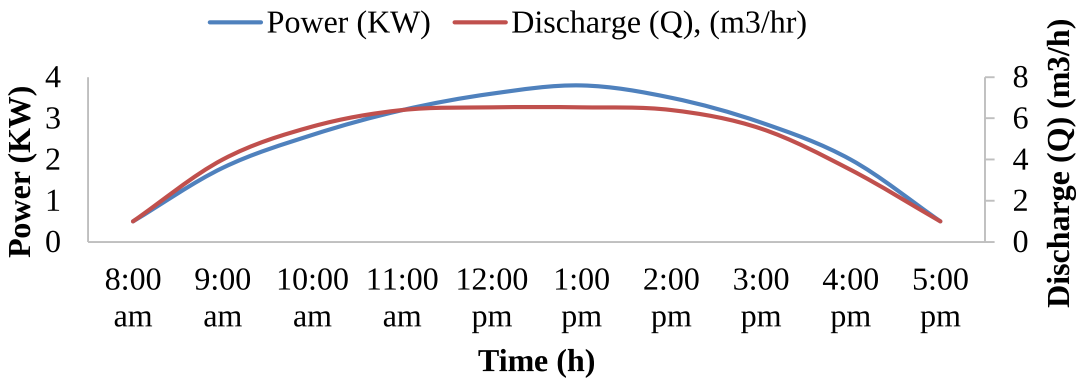


Figure 4.3 c: Discharge Variation Due to Solar Radiation for Sprinkler Irrigation System (28.13 m Head)

Source: Author, 2022

4.2.2 Pump Characteristic Curves of the Installed System

The system discharge was recorded for sprinkler irrigation, spray tube irrigation and drip irrigation system, under different operating pressures. In Figure 4.4, the spray tube, sprinkler and elevated tank for drip irrigation system were found to be operating efficiently at a head of 11.2 m, 28.13 m and 21.1 m respectively. When the pump is working at its peak, the highest discharge recorded is 16.1 m^3/h for the spray tube irrigation system which is operated at 11.2 m head, whilst the smallest discharge of 6.53 m^3 was recorded for the sprinkler irrigation system which is operated at 28.13 m head. The results agree with the working principle of centrifugal pump as presented by Bell and Gosset (2021), which indicate that as the head increases, discharge reduces. As seen in Figure 4.4, as the solar radiation increases, the pump discharge also increases until it reaches its peak capacity. It was also noted that as the solar radiation decreases, discharge decreases until it reaches the minimum possible solar radiation to operate the pump and the controller switch off the pump automatically. Solar generator can generate up to 3.8 KW as maximum capacity.

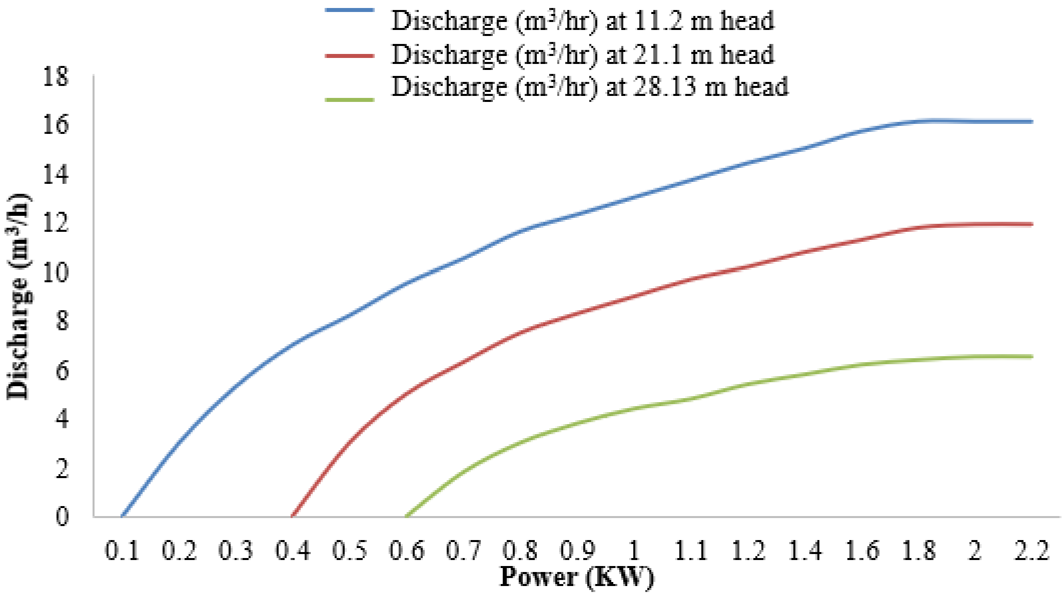


Figure 4.4: System Curves under Different Operating Pressures
Source: Author, 2022

As presented in Figure 4.5, the pump curve can be classified as flat, and this means that the performance of the installed pump is good. For flat curve, large changes of discharge can be achieved with a small change in head as described by Bell and Gosset (2021).

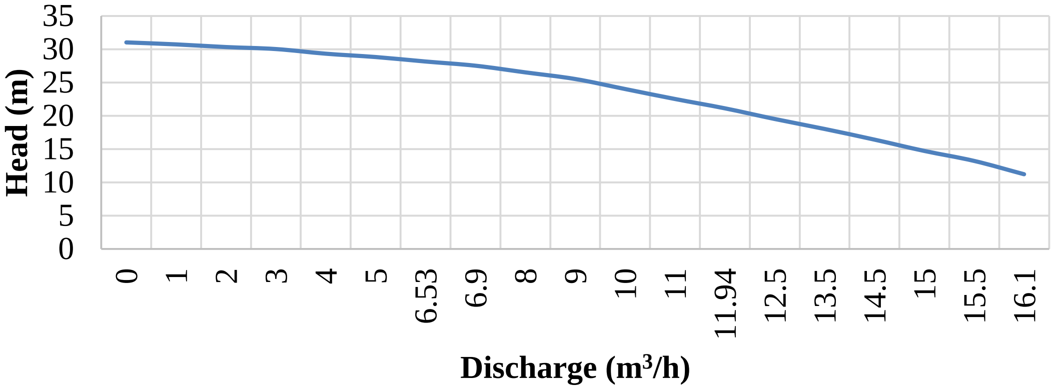


Figure 4.5: Pump Curve Indicating Pump Discharge Versus Head
Source: Author, 2022

4.3 Technical Performance of Drip Irrigation System

Pressures in the submain line of the drip irrigation system were carefully recorded at different water levels in the elevated tank to determined performance indicators such as emission uniformity (EU), emitter flow variation (Qvar), coefficient of variation (CV) and mean application rate (MAR). Results of the measured performance indicators are presented in the Table 4.3.

Table 4.3: Measured Performance Indicators for Drip Irrigation System

Water Level in the Tank (m)	Pressure in sub-main, (psi)	Emission Uniformity (EU), (%)	Emitter Flow Variation (Qvar), (%)	Coefficient of Variation (CV)	Mean Application Rate (MAR), (l/h)
3.30	4.70	87.0	17.1	0.050	0.6008
3.75	5.33	87.2	17.6	0.057	0.7754
4.50	6.40	88.1	18.7	0.058	0.9683

Source: Author, 2022

4.3.1 Effect of Water Level in the Tank on Pressure in Submain Line

The elevated tank is held at 3 m above the ground and the height of the tank is 1.5 m. This means that the water level is at 4.5 m high when the tank is full, and when the water level in the tank is very low at 0.3 m, the water level decreased to 3.3 m which is the dead storage depth. Pressure in the submain line was monitored following the changes in water levels in the tank at full capacity, half full and water at dead storage capacity. Table 4.3 presents the pressures in the submain line for water level at 4.5 m, 3.75 m and 3.3 m were 6.4 psi, 5.33 psi and 4.7 psi respectively which resulted in significant change in water flow. Results obtained in this study are similar to Rowell and Jacobsen (2018) who presented the relationship of the pressure change due to water level in elevated tank, and showed that an increase in water level to 0.7 m which corresponded to an increase in pressure of 1 psi.

4.3.2 Effect of Pressure Change in Submain Line on Emission Uniformity

As presented in Table 4.3, the emission uniformities (EU) of the drip irrigation system were found to be 88.2 %, 87.2 % and 87.0 % for pressures of 6.4 psi, 5.33 psi and 4.7 psi, respectively in the submain line. The emission uniformities obtained in this study are classified as good as reported by Purohit *et al.* (2017) and Jamrey and Nigam (2017). As shown in Figure 4.6, change in pressure of 13.4 % and 36 % caused a change in EU by 0.23 % and 1.26 % in the submain line, which are not significant and are good for the irrigation system because large change in pressure does not lead to change in EU of the system.

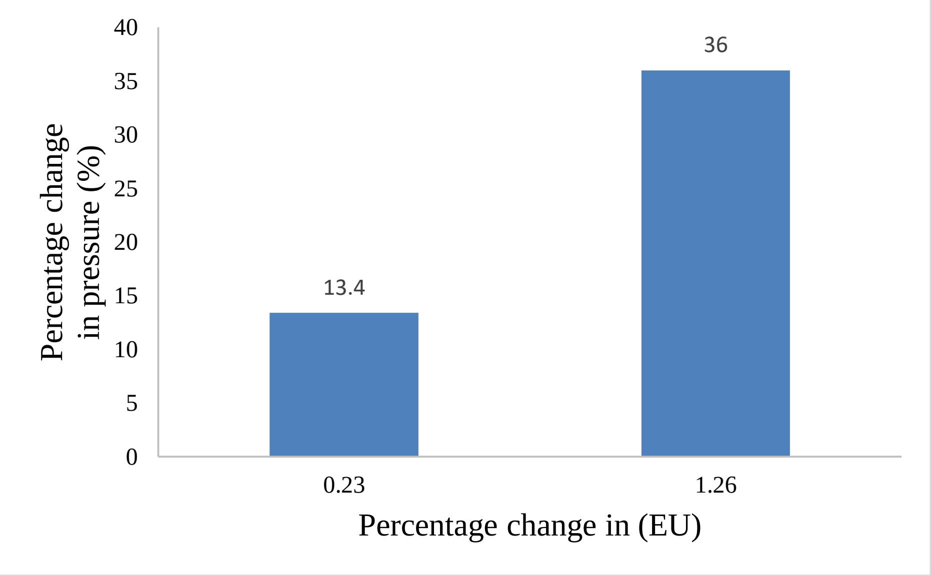


Figure 4.6: Percentage Change in Emission Uniformity Due to Pressure Changes
Source: Author, 2022

4.3.3 Effect of Pressure Change in Submain Line on Emitter Flow Variation

As presented in Table 4.3, the emitter flow variations (Qvar) of the drip irrigation system were found to be 18.7 %, 17.6 % and 17.1 % for pressures of 6.4 psi, 5.33 psi respectively in the submain line and these are classified as acceptable according to ASAE (1990) and Olorunwa *et al*., (2019). Figure 4.7 presents the percentage change in emitter flow variation due to change in pressure in the submain line. It was clear that, 13 % and 36 % change of pressure in submain resulted in 2.92 % and 9.35% change in emitter flow variation which are not significant.

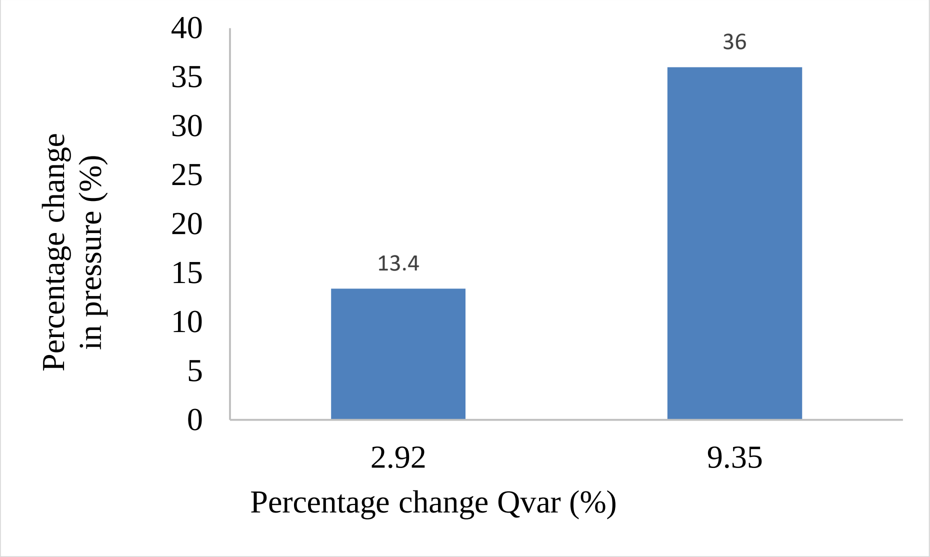


Figure 4.7: Percentage Change in Emitter Flow Variation Due to Pressure Change in Submain Line
Source: Author, 2022

4.3.4 Effect of Pressure Change in Submain Line on Mean Application Rate

Table 4.8 shows the mean application rates (MAR) of the drip irrigation system were found to be 0.9683 l/h, 0.7754 l/h and 0.6008 l/h for pressures of 6.4 psi, 5.33 psi and 4.7 psi, respectively. It was clearly noted that only a change of 13.4 % of pressure in submain line resulted in a 29.06 % change in mean application rate and a change of 36 % of pressure in the submain, resulting in 61.16 % change of mean application rate. These changes noted in the system are significant. Sokol *et al*. (2019) described minimum compensating inlet pressure (MCIP) which is the pressure above which the emitter's flow rate is within ±7 % change of its nominal flow rate. Based on the description of Sokol *et al*. (2019), the results of this study showed that the emitter flow rate change is out of this range of ±7 % of nominal flow rate, and this implies that the pressure in submain lines does not reach the MCIP.

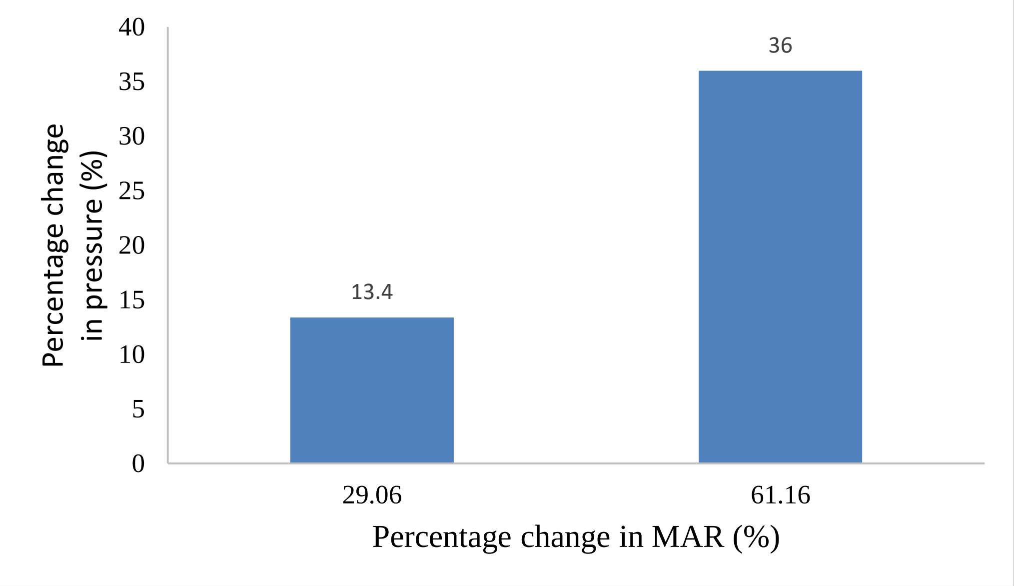


Figure 4.8: Percentage Change in Mean Application Rate of the Drip Irrigation System
Source: Author, 2022

4.4 Performance of Spray Tube Irrigation System

Uniformity coefficient (CU), mean application rate (MAR) and distribution uniformity (DU) of the spray tube irrigation were determined for pressures of 2 psi, 7 psi, 10 psi, 15 psi and 17 psi and the results are presented in Table 4.4 and Figure 4.9. Results revealed that as the system pressure increases, the measured performance of the spray tube irrigation system in terms of CU, MAR and DU also increases.

Table 4.4: Measured Performance Indicators for the Spray Tube Irrigation System

Pressure in the System (PSI)	Mean Application Rate (mm/h)	Uniformity Coefficient (%)	Distribution Uniformity (%)	Covered Width (m)
2	4.2	33.5	2.5	0.3
7	8.6	67.3	44.3	1.5
10	11.7	74.7	65.9	2
15	14.5	81.7	76.7	2.8
17	15.5	83.1	80.5	3.1

Source: Author, 2022

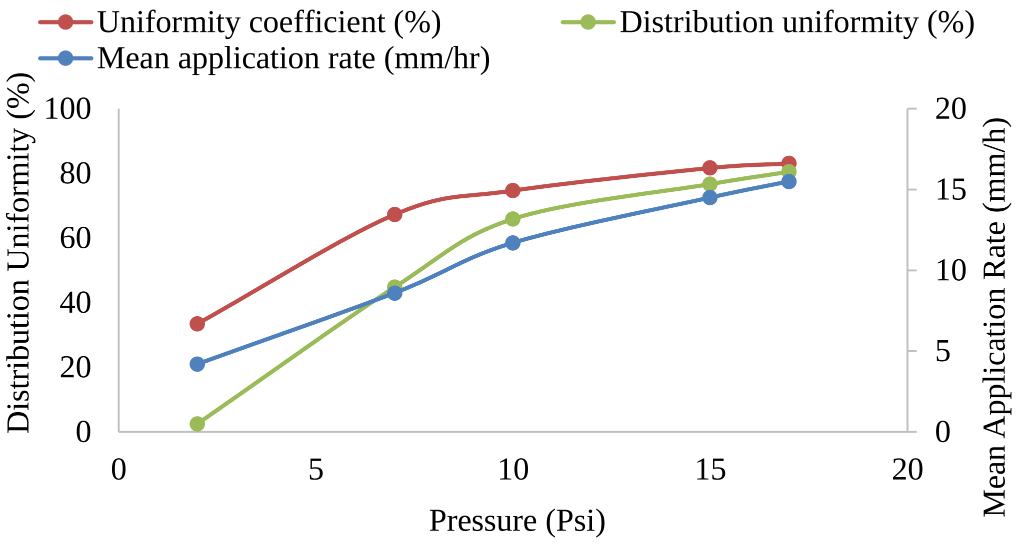


Figure 4.9: Effect of Pressure Change on Uniformity Coefficient, Distribution Uniformity and Mean Application Rate Due to Solar Radiation
Source: Author, 2022

4.4.1 Variation in Discharge Due to Power Change Caused by Solar Radiation

The power generated by the solar PV generator was recorded under different conditions from morning at sunrise up to evening at sunset. It was noted that, as the power changes, the water horse power of the pump also changes causing the discharge to change. It was also observed that when solar radiation increases, water horse power also increases, but if the solar radiation decreases, water horse power also decreases. When the solar radiation goes below the minimum, it is not possible for the pump to operate, thus the system shuts down automatically. The system controller receives a signal from the solar sensor that solar radiation is no longer enough to operate the pump. This happens between 5:00 pm and 5:30 pm as can be observed from Figure 4.3a. It was noted that the highest discharge of 16.41 m^3/h was recorded at a pressure of 17 psi and the lowest discharge value of 1 m^3/h at a pressure equal to 2 psi.

4.4.2 Effect of Operating Pressure on Distribution Uniformity of Spray Tube Irrigation

The distribution uniformity (DU) was found to be increasing as the system pressure increases. Results as presented in Table 4.5 showed that the highest distribution uniformity of 80.5 % was recorded for a pressure of 17 psi and lowest distribution uniformity of 2.5 % was recorded for a pressure of 2 psi.

The results showed that there was a significant change in distribution uniformity due to change in pressure in the system. The study revealed that the change in distribution uniformity was due to the reduction in width covered by one spray tube. The results obtained from this study are in agreements with those of GREKKON (2022) which recorded similar findings in a study on spray tube irrigation system in Kenya and concluded that the system pressure must be maintained within the range of 7.12 to 21.3 psi for the spray tubes of 70 m length.

Figure 4.10 presents the width covered by a spray tube at system pressure of 2 psi and it showed no overlap of water from two adjacent spray tubes. Figure 4.11 presents the width covered by as pray tube at system pressure of 10 psi and it showed partial overlap of water pattern from two adjacent spray tubes. Figure 4.12 presents the width covered by a spray tube at system pressure of 17 psi and it showed 100 % overlap of water pattern from two adjacent spray tubes. A low system pressure was found in the morning where the sun was still low and in the evening at sunset and it was also noted on cloudy days. Results obtained in this study are similar to Kathiriya *et al*. (2021) who studied performance of spray tube irrigation system under solar photovoltaic pump in Junagadh, India.

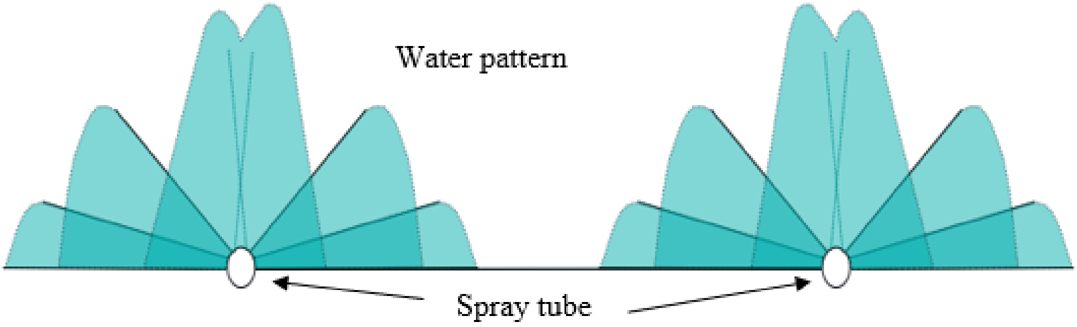


Figure 4.10: Water Pattern for Minimum Pressure (2 psi) for the Spray Tube Irrigation System

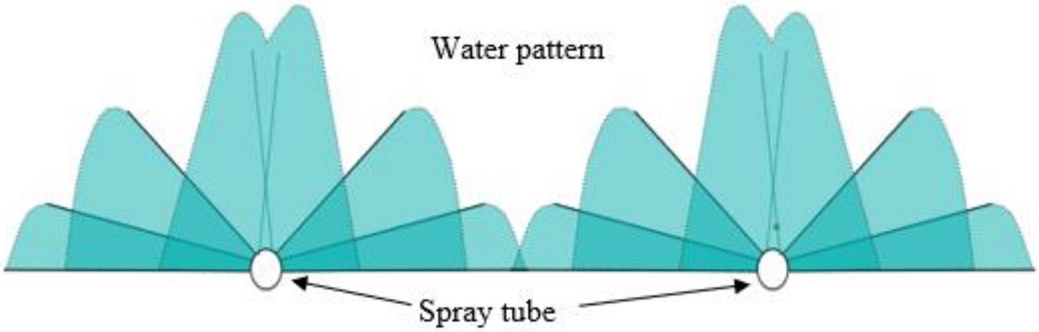


Figure 4.11: Water Pattern for Medium Pressure (10 psi) for the Spray Tube Irrigation System

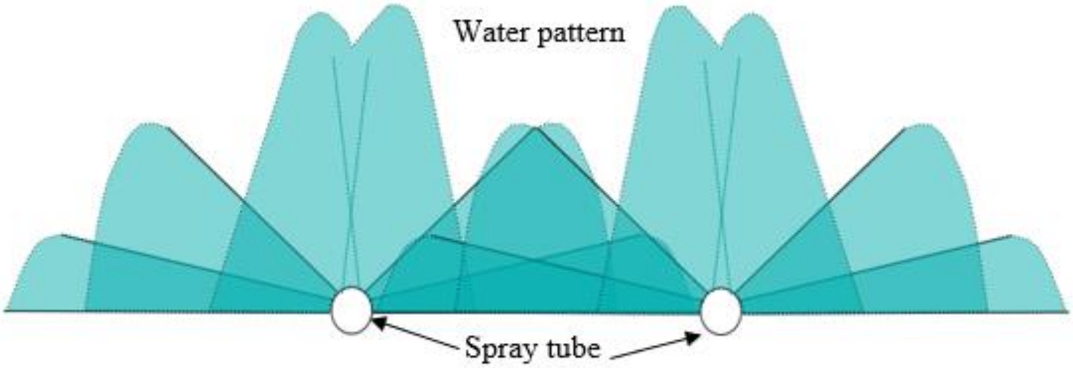


Figure 4.12: Water Pattern for High Pressure (17 psi) for the Spray Tube Irrigation System
Source: Author, 2022

4.4.3 Effect of Operating Pressure on Uniformity Coefficient of the Spray Tube Irrigation

The uniformity coefficients (UC) of the spray tube system were found to be 83.1 %, 81.7 %, 74.7 %, 67.3 %, and 33.5 % for pressures of 17 psi, 15 psi, 10 psi and 2 psi respectively (Table 4.3). Based on the classification of UC as given by ASABE (1999) and Mangrio *et al*. (2021), the recorded UC of 83.1 % and 81.7 % can classified as good, 74.7 % as fair, 67.3 % as poor and 33.5 % as unacceptable.

4.4.4 Effect of Operating Pressure on Mean Application Rate of the Spray Tube Irrigation

Table 4.4, the mean application rates (MAR) of the spray tube irrigation system were found to be 4.2 mm/h, 8.6 mm/h, 11.7 mm/h, 14.5 mm/h and 15.5 mm/h for pressures of 2 psi, 7 psi, 10 psi, 15 psi and 17 psi respectively. The results showed that, the mean application rate of the spray tube irrigation system is highly affected by pressure change in the system. These results of the study are in agreement with that of Kathiriya *et al*. (2021) who did similar study on spray tube irrigation system under solar photovoltaic pump in Junagadh, India.

4.4.5 Effect of Operating Pressure on Width Coverage of the Spray Tube Irrigation System

The width covered by one spray tube on one side for system pressures of 2 psi, 7 psi, 10 psi 15 psi and 17 psi were 0.3 m, 1.5 m, 2 m, 2.8 m and 3.1 m respectively (Table 4.4. Results indicated that, the width covered by one spray tube is highly dependent on the pressure in the spray tube and that there is 100 % overlap when there is maximum system pressure, and 0 % overlap when system pressure is minimum.

4.4.6 Effect of Crop Canopy on Distribution Uniformity for the Spray Tube Irrigation System

When crops are planted too close to the spray tube and they grow, their canopy cover the spray tubes as they are lying on the ground. This results in poor spray of water from the tubes. It was observed from the study that, crops that were planted 30 cm away from the spray tube do not impede the spray water from the tubes, however the leaves of the crops which are planted less than 30 cm away from the tube intercept water from spray tube, thereby, impeding uniform distribution of water to the crops.

4.5 Performance of the Sprinkler Irrigation System

The sprinkler irrigation system used in this study had the highest operating pressure of 28.13 m. Hence, when the solar radiations are not enough, the system does not work properly. For example, some of the sprinklers will rotate with very low speed. As presented in Table 4.5, the measured uniformity coefficients (UC) for the sprinkler irrigation system were found to be 38.4 %, 66.1 %, and 82.5 % for operating pressures of 20 psi, 30 psi, and 40 psi respectively. The distribution uniformities (DU) were found to be 8.7 %, 49.5 % and 73.1 % for operating pressures of 20 psi, 30 psi and 40 psi respectively, whereas the mean application rate (MAR) were noted to be 1.8 mm/h, 3.0 mm/h and 4.1 mm/h for operating pressures of 20 psi, 30 psi and 40 psi respectively. Based on the classification of ASABE (1994), the performance of the installed sprinkler irrigation system can be described as good for the corresponding pressures.

Table 4.5: Measured Performance Indicators for the Spray Tube Irrigation System

Pressure (psi)	Uniformity Coefficient (%)	Distribution Uniformity (%)	Mean Application Rate (mm/h)
40	82.4	73.1	4.1
30	66.1	42.9	3
20	38.4	8.7	1.8

Source: Author, 2022

4.6 Life-Cycle Cost Analysis of the Solar Powered Irrigation System

4.6.1 Capital Cost of the System

The capital cost for the solar pumping system including reservoir was7,540.70 USD and that of the drip, sprinkler and spray tube irrigation systems were estimated to be 3,738.00 USD, 3,273.00 USD and 2,997.00 USD, respectively per hectare as presented in Table 4.6. The drip irrigation system showed high capital cost, followed by sprinkler irrigation and then spray tube irrigation system which had the lowest capital cost. The initial investment cost of the irrigation systems is similar to the findings of Smith (2015) who conducted research on low cost drip irrigation in Haiti and the results showed that the cost of drip irrigation installation per hectare was between 1,200.00 USD and 3,000.00 USD. RMCG (2018) did comparative studies between irrigation systems costs and results showed that sprinkler system installation is between 3,740.00 USD and 6,557.00 USD per hectare which are within the range of this study.

Table 4.6: Initial Investment Cost of the Solar Powered Irrigation System

Item	Cost (USD)
Solar pumping station	7,540.70/ha
Drip irrigation system	3,738.00/ha
Sprinkler irrigation system	3,273.00/ha
Spray tube irrigation system	2,997.00/ha

Source: Author, 2022

4.6.2 Estimated Cost for Operation, Maintenance and Repair of the Solar Powered Irrigation System

As presented in Table 4.7, the cost for operation, maintenance and repair of the solar powered irrigation system were estimated to be 1,927.86 USD, 955.68 USD, 836.79 USD, and 766.23USD for the solar pumping station, drip irrigation system, sprinkler irrigation system, and spray tube irrigation system respectively.

Table 4.7: Estimated Cost for Operation, Maintenance and Repair of Solar Powered Irrigation System

Item	Cost (USD)
Solar system	1927.86
Drip irrigation system	955.68
Sprinkler irrigation system	836.79
Spray tube irrigation system	766.23

Source: Author, 2022

4.6.3 Estimated Replacement Cost of the System

The replacement costs were estimated according to the lifespan of every component of system and the results are presented in Table 4.8. The replacement cost was estimated to be 2,923.9 USD, 591.07 USD, 242.4 USD, and 1,703.4 USD for the solar pumping station, sprinkler irrigation system, spray tube irrigation system and drip irrigation system.

Table 4.8: Estimated Replacement Cost of the System

Item	Lifespan (years)	Capital Cost (USD)	Replacement cost (USD)
Solar system			
Solar Pump	7	1908	2,522.724
Water sensor	3	83	308.681
Pressure sensor	7	70	92.552
Sprinkler irrigation system			
Sprinkler heads	10	720	591.078

Spray tube irrigation system			
Spray tubes	15	616	242.486
Drip irrigation system			
Drip lines	8	1424	1703.476

Source: Author, 2022

4.6.4 Income and Savings from Energy Production

The solar powered irrigation system did not generate any income from the energy produced. This is because the system is not hybrid or any regulation for selling the energy that has been produced. The system is only for self-consumption for the installed irrigation systems, thus, help to save money from paying utility bill that would have been incurred by the energy authority company for irrigation.

Income generation is the production of crop grown in the field. For this study tomato (*Solanum lycopersicum* L.) Pectomech variety was used as a test crop for the calculation of income generation and these can be grown in two seasons per year. Table 4.9 presents the production and the price of tomatoes per year. Income generation was estimated to be 22,746.80 USD per year per ha. By applying NPV for the lifespan of the system of 25 years, a total income of 290,780.4 USD will be generated.

Table 4.9: Income Generation Using SPIS for Crop Production

Crop Grown	Yield (t/ha)	Price per 1 Tonne (USD)	Income per Year (USD)
Tomato (Pectomech variety)	13.8	824.16	22746.8

Source: Author, 2022

4.6.5 Other Costs

Table 4.10 and Table 4.11 presents other costs incurred on the project and cost of water for every water application system. NPV was applied for the estimation of present value of future cash flows.

Table 4.10: Other Costs Incured on the Tomato Production

Item	Cost (USD)/Season
Fertilizers	1104.1
Chemicals	95.6
Land	40
Labour cost	156
Total	**1395.7**

Source: Author, 2022

Table 4.11: Cost of Water for the Various Irrigation Systems

Irrigation System	Cost of Water (USD)/Season
Drip irrigation	146,347.4
Spray tube irrigation	189,034.9
Sprinkler irrigation	206,476.4

Source: Author, 2022

4.6.6 Residual Values for the Solar Powered Irrigation System

The residual values of the solar powered irrigation system were estimated for the solar pumping station, sprinkler, spray tube and drip irrigation systems and they were found to be 1,374.8 USD, 654 USD, 599.4 USD and 747.6 USD respectively as presented in Table 4.12. This is the estimated value of the system at the end of 25 years and was estimated as 20 % of capital cost as recommended by APEC Energy Working Group, (2019).

Table 4.12: Residual Values of the Solar Powered Irrigation System

Item	**Capital Cost (USD)**	**Residual Value (USD)**
Solar system	6,874	1,374.8
Sprinkler irrigation system	3,273	654.6
Spray tube irrigation system	2,997	599.4
Drip irrigation system	3,738	747.6

Source: Author, 2022

4.6.7 Life Cycle Cost of the Irrigation System

The life cycle costs (LCC) were estimated for the drip, spray tube and sprinkler irrigation systems and were found to be 165,259.63 USD, 205,703.99 USD and 223,785.44 USD respectively (Table 4.13). It was noted that, the drip irrigation system recorded high capital, operation, maintenance and repair cost, and replacement cost; followed by sprinkler irrigation and the spray tube irrigation recorded low investment cost. The drip irrigation was noted to use less water compared to sprinkler and spray tube irrigation systems. The results showed that drip irrigation is the best system in places where water resource is scarce. The spray tube irrigation has shown good performance over sprinkler irrigation. The spray tube was also observed to have good distribution uniformity and low operating pressure than the sprinkler irrigation system. In addition, the spray tube system showed low capital, operation, maintenance, repair and replacement cost over drip and sprinkler irrigation.

Table 4.13: Life Cycle Cost of the Irrigation System

Application System	**Capital Cost (USD)**	**OM and Repair Cost (USD)**	**Replacement Cost (USD)**	**Other Cost (USD)**	**Residual Value (USD)**	**LCC (USD)**
Drip irrigation	10,612	2,883.54	4,627.4	147,703.1	2,255.74	165,259.63
Spray tube irrigation	9,871	2,694.09	3,166.4	190,390.6	2,107.54	205,703.99
Sprinkler irrigation	10,147	2,764.65	3,515.1	207,832.1	2,162.74	223,785.44

Source: Author, 2022

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study showed that:

- The soils in the irrigable area of the solar powered irrigation system are sandy loam with infiltration rate of 1.2 cm/h and dry bulk density of 1.37 g/cm^3, which are suitable for cultivation of a wide variety of crops, especially vegetables.
- The net irrigation requirement for tomato was 190.80 mm/season (under drip irrigation system), 246.46 mm/season (under spray tube irrigation system), and 269.20 mm/season (under sprinkler irrigation system).
- The installed solar pump with a maximum head of 70 m can provide the required operating pressure with a maximum discharge of 16 m^3/h to the installed irrigation systems. In clear days, peak sun hours (PSH) can be obtained between 09:00 am to 04:00 pm thus providing enough energy to power the installed irrigation systems.
- Irrigation efficiencies of the installed irrigation systems were high with drip, spray tube and sprinkler systems recording 87 %, 80.30 % and 73.70 % respectively.
- For the drip irrigation system, the water levels in the tank at heights of 4.5 m, 3.75 m and 3.3 m recorded pressures of 6.4 psi, 5.33 psi and 4.7 psi respectively in the submain line and at these pressures, a significant change in water flow was observed.

- The emission uniformities (EU) for the drip irrigation system were high and were found to be 88.2 %, 87.2 % and 87.0 % for pressures of 6.4 psi, 5.33 psi and 4.7 psi respectively in the submain line.
- The emitter flow variations (Qvar) for the drip irrigation system were low and were found to be 18.7 %, 17.6 % and 17.1 % for pressures of 6.4 psi, 5.33 psi respectively in the submain line and these are classified as acceptable levels of emitter flow variations.
- The mean application rate (MAR) for the drip irrigation system ranged from 0.60 - 0.97 l/h, 4.2 - 15.5 mm/h for the spray tube irrigation system and 1.8 - 4.1 mm/h for sprinkler irrigation system.
- The uniformity coefficients (UC) and distribution uniformities (DU) of the spray tube and sprinkler irrigation systems were high and within the acceptable range with the spray tube irrigation system recording CU of 81.7% and DU of 80.5 % whilst the sprinkler irrigation system recorded 82.5 % CU and 73.7 % DU.
- The life cycle of the solar powered irrigation was estimated to be 25 years and the life cycle costs (LCC) for the drip, spray tube and sprinkler irrigation systems were estimated to be 164,908.1 USD, 202,428.4 USD and 220,509.8 USD respectively.
- The drip irrigation system recorded high capital, operation, maintenance and repair cost, and replacement cost, followed by sprinkler irrigation and the spray tube irrigation recorded low investment cost.

5.2 Recommendations

Based on the findings of the study, the following recommendations are made:

- The drip irrigation should be used when the water source is scarce as it saves water more than the sprinkler and spray tube irrigation systems.
- A flow meter should be installed on the drip irrigation system to measure the volume of water applied in the field, since mean application rate changes with water level in the tank.
- Crops should be planted 30 cm away from the spray tubes to avoid the canopy of the crops from impeding the uniform distribution of water to the crops.
- More area should be cultivated as the installed solar and pump has the capacity to irrigate up to 4 acres without encountering any inefficiencies.

REFERENCES

1. Abdelmonem, Y. (2020). Sprinkler Irrigation. Yehia kamal Abdelmonem. May. https://doi.org/10.13140/RG.2.2.31017.42080
2. Abdul-Ganiyu, S., Quansah, D. A., Ramde, E. W., Seidu, R. and Adaramola, M. S. (2020). Investigation of Solar Photovoltaic-thermal (PVT) and Solar Photovoltaic (PV) Performance: A Case Study in Ghana. *Energies*, *13*(11). https://doi.org/10.3390/en13112701
3. Abdul-Ganiyu, S., Mfum, S.Y. and Adongo, T. A. (2013). Assessing the Performance of Subinja Irrigation Scheme in the Wenchi Municipality of the Brong Ahafo Region of Ghana. *International Journal of Agriculture Innovations and Research*, *1*(6), 2319–1473.
4. Abena, O., Osman, S. K. and Thai, T. M. (2021). Building a Better Solar Irrigation Market in Ghana | *Agrilinks*. https://agrilinks.org/post/building-better-solar-irrigation-market-ghana.
5. Alliance for a Green Revolution in Africa (AGRA) (2019). Irrigation doubles African food production - AGRA. https://agra.org/irrigation-doubles-african-food-production/
6. Anis, W. R., Abdul-Sadek N., M. (1994). Switching Model Photovoltaic Pumping System. *JPS*, *47*(1), 35–43. https://doi.org/10.1016/0378-7753(94)80048-0
7. ASABE (1994). Microirrigation Equipment for Okra Cultivation in the U.S. Virgin Islands. *ASABE Standard Engineering Practices Data, St. Joseph, MI.*
8. ASABE (1999). Field Evaluation of Microirrigation Systems. 7.

https://global.ihs.com/doc_detail.cfm?document_name=ASABE EP458&item_s_key=00576509

9. Asia Pacific Economic Cooperation (APEC) Energy Working Group (2019). Life Cycle Cost Assessment of Photovoltaic Systems in the APEC Region (Issue April).
10. Asumadu-Sarkodie, S., Owusu, P. A. (2016). A Review of Ghana's Solar Energy Potential. *AIMS Energy 2016 5:675*, *4*(5), 675–696. https://doi.org/10.3934/ENERGY.2016.5.675
11. Aziz, M., Khan, M., Anjum, N., Sultan, M., Shamshiri, R. R., Ibrahim, S. M., Balasundram, S. K. and Aleem, M. (2022). Scientific Irrigation Scheduling for Sustainable Production in Olive Groves.
12. Bakhsh, A., and Choudry, M. R. (2017). Applied Irrigation Engineering Book.
13. Bawa, A. (2019). Agriculture and Food Security in Northern Ghana. *Asian Journal of Agricultural Extension, Economics & Sociology*, *September*, 1–7. https://doi.org/10.9734/ajaees/2019/v31i230127
14. Bell and Gosset (2021). Pump and System Curve Data for Centrifugal Pump Selection and Application. https://documentlibrary.xylemappliedwater.com/wp-content/blogs.dir/22/files/2013/02/TEH-375A.pdf
15. Bouwer, H. (2018). Intake Rate: Cylinder Infiltrometer. Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 825–844. https://doi.org/10.2136/SSSABOOKSER5.1.2ED.C32
16. Bwambale, E., Abagale, F. K., and Anornu, G. K. (2022). Smart Irrigation

Monitoring and Control Strategies for Improving Water Use Efficiency in Precision Agriculture: A Review. *Agricultural Water Management*, *260*(October 2021), 107324. https://doi.org/10.1016/j.agwat.2021.107324

17. Cavero, J., Faci, J. M., and Martínez-Cob, A. (2016). Relevance of Sprinkler Irrigation Time of the Day on Alfalfa Forage Production. *Agricultural Water Management*, *178*, 304–313. https://doi.org/10.1016/J.AGWAT.2016.10.008
18. Chahartaghi, M., and Hedayatpour J. M. (2019). Mathematical Modeling of Direct-coupled Photovoltaic Solar Pump System for Small-scale Irrigation. *Https://Doi.Org/10.1080/15567036.2019.1685025*. https://doi.org/10.1080/15567036.2019.1685025
19. Clottey, V., Karbo, N., and Gyasi, K. (2009). The Tomato Industry in Northern Ghana: Production Constraints and Strategies to Improve Competitiveness. *African Journal of Food, Agriculture, Nutrition and Development*, *9*(6). https://doi.org/10.4314/ajfand.v9i6.46265
20. Cong, Z. T., Lü, H. F., and Ni, G. H. (2014). A Simplified Dynamic Method for Field Capacity Estimation and its Parameter Analysis. *Water Science and Engineering*, *7*(4), 351–362. https://doi.org/10.3882/j.issn.1674-2370.2014.04.001
21. CSI (2022). How to Read a Pump Curve: Complete Guide. https://www.csidesigns.com/blog/articles/how-to-read-a-pump-curve
22. Eijkelkamp (2012). Double Ring Infiltrometer: Operating Instructions. 1–9.
23. El-Gafy, I. K. E. D., and El-Bably, W. F. (2016). Assessing Greenhouse Gasses Emitted from On-farm Irrigation Pumps: Case Studies from Egypt. *Ain Shams*

Engineering Journal, *7*(3), 939–951. https://doi.org/10.1016/j.asej.2015.07.001

24. Enoviti. (2012). *Soil Texture and Water Holding Capacity---Part 1*. https://enoviti-hanumangirl.blogspot.com/2012/06/soil-texture-and-water-holding-capacity.html
25. Ephrey, M. M., and Vandi, D. K. V. (2020). Optimization of the Pumping Capacity of Centrifugal Pumps Based on System Analysis. *12th South African Conference on Computational and Applied Mechanics, SACAM 2020, 00024*. https://doi.org/10.1051/matecconf/202134700024
26. Omofunmi, E. O., Ayodele I., O., and Orisabinone, T. (2019). Performance Evaluation of Hydraulic Parameters of a Developed Drip Irrigation System. *Malaysian Journal of Civil Engineering*, *31*(2). https://doi.org/10.11113/mjce.v31n2.556
27. Farr, J. V. (2011). Systems Life Cycle Costing: Economic Analysis, Estimation, and Management (T. G. Kotnour & W. Karwowski (eds.)). CRC Prss Taylor & Francis Group.
28. Ferrarezi, R. S., Geiger, T. C., Greenidge, J., Dennery, S., Weiss, S. A., and Vieira, G. H. S. (2020). Microirrigation Equipment for Okra Cultivation in the U.S. Virgin Islands. *American Society for Horiticulutre Science*. https://journals.ashs.org/hortsci/view/journals/hortsci/55/7/article-p1045.xml
29. Food and Agriculture Organisation (FAO) (1989). Guidelines for Designing and Evaluating Surface Irrigation Systems: *FAO Irrigation and Drainage paper 45. Rome: FAO*.

30. Food and Agriculture Organisation (FAO) (2001). Irrigation Manual. In *Planning, Development Monitoring and Evaluation of Irrigated Agriculture with Farmer Participation: Vol. III*.

31. Food and Agriculture Organisation (FAO) (2014). Ghana: Irrigation Market Brief. *FAO Investment Centre, Rome*. https://www.fao.org/3/i4158e/i4158e.pdf

32. Franklin, E. (2019). Calculations for a Grid-Connected Solar Energy System. *The University of Arizona Cooperative Extension*, *June*, 1–8. https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1782-2019.pdf

33. Fuller, S. K., and Petersen, S. R. (1996). Life-cycle Costing Manual for the Federal Energy Management Program. In *National Institute of Standards and Technology Handbook 135, 1996 edition*.

34. Gadeberg, M. (2020). Solar-Powered Irrigation Could Boost Climate Resilience for Millions | *Agrilinks*. https://agrilinks.org/post/solar-powered-irrigation-could-boost-climate-resilience-millions

35. Gebrezgabher, S., Leh, M., Merrey, D. J., Kodua, T. T., and Schmitter, P. (2021). Solar Photovoltaic Technology for Small-scale Irrigation in ghana: Suitability Mapping and Business Models. In *IWMI Research Report* (Vol. 178). https://doi.org/10.5337/2021.209

36. Golf Irrigation Consultants (GIC) (2015). Water Audit | Catch Can Test -. Water Audit. http://golfirrigationconsultants.com/catch-can-test

37. GREKKON (2022). Rain Hose Irrigation. Grekkon Limited. https://grekkon.com/rain-hose-irrigation/

38. Groenendyk, D. G., Ferré, T. P. A., Thorp, K. R., and Rice, A. K. (2015). Hydrologic-Process-Based Soil Texture Classifications for Improved Visualization of Landscape Function. *PLoS ONE*, *10*(6). https://doi.org/10.1371/JOURNAL.PONE.0131299

39. Gurung, A., and Qiao, Q. (2018). Solar Charging Batteries: Advances, Challenges, and Opportunities. *Joule*, *2*(7), 1217–1230. https://doi.org/10.1016/j.joule.2018.04.006

40. Haman, D. Z., and Zazueta, F. S. (2017). Measuring Pump Capacity for Irrigation System Measuring Head-Discharge Curves. 2–5.

41. Hanson, B., Gratta, S., and Fulton, A. (2006). Agricultural Irrigation and Drainage. *Water Management Series*, *3375*(5), 298–300.

42. HIGHNOONSOLAR (2022). How long do Residential Solar Panels last? - High Noon Solar. https://highnoonsolar.com/how-long-do-residential-solar-panels-last/

43. Horton, R. E. (1940). An Approach Toward a Physical Interpretation of Infiltration-Capacity. *Soil Science Society of America Journal*, *5*(C), 399–417. https://doi.org/10.2136/SSSAJ1941.036159950005000C0075X

44. Integrated Water and Agricultural Development Ghana Limited (IWAD) (2020). *IRRIGATION – IWADGHANA*. https://iwadghana.com/irrigation/

45. ISO (Internationational Organization for Standardization) (2004). *ISO - ISO 9261:2004 - Agricultural irrigation equipment — Emitters and emitting pipe — Specification and test methods*. https://www.iso.org/standard/28459.html

46. Merriam, J.L., Jack, K. (1978). Farm Irrigation System Evaluation : A Guide

for Management. Third Edition. https://pdf.usaid.gov/pdf_docs/PNAAG745.pdf

47. Kathiriya, G. R., Prajapati, G. V, Paghdal, A. M., Rank, H. D., and Kelaiya, S. V. (2021). Performance Evaluation of Rain Pipe Irrigation under Solar Photovoltaic Pump. 10(4), 587–591.
48. Keller, J., and Karmeli, D. (1974). Trickle Irrigation Design Parameters. *Transactions of the American Society of Agricultural Engineers*, *17*(4), 678–684. https://doi.org/10.13031/2013.36936
49. Kumari, A., Subha, K., Koley, T. K., and Ahmad, A. (2020). Recent Advances in Irrigation Scheduling to enhance Agricultural Water Productivity. *1*(September), 8–10.
50. Leder, S. (2019). Improving water use for dry season agriculture by marginal and tenant farmers in the Eastern Gangetic Plains, Final Report. November, 114.
51. Ludin, N. A. (2019). Life Cycle Cost Assessment of Photovoltaic Systems in the APEC Region. In *Ewg 06 2017a* (Issue April). www.apec.org
52. Lukens, L. L., Perino, A. M., and Vandevender, S. G. (1977). Preliminary Economic Analysis of Solar Irrigation Systems (SIS) for Selected Locations.
53. Mahmood, K., and Hussain, T. (2012). Irrigation Pumping Systems. *Energy Efficiency Measurement & Verification Practices*, 185–196.
54. Mangrio, A. G., Asif, M., Ahmed, E., Sabir, M. W., Khan, T., and Jahangir, I. (2021). Hydraulic performance evaluation of pressure compensating (pc) hydraulic performance evaluation of pressure compensating (pc) emitters and

micro-tubing for drip irrigation system. March.

55. Martin, D. L., Dorn, T. W., Melvin, S. R., Corr, A. J., and Kranz, W. L. (2011). Evaluating Energy Use for Pumping Irrigation Water Energy Use in Irrigation. *Proceedings of the 23rd Annual Central Plains Irrigation Conference*, 104–116. https://www.ksre.k-state.edu/irrigate/oow/p11/Kranz11a.pdf
56. Mays, L. W. (2015). Water Resources Engineering. Second Edition (Vol. 7, Issue 1). John Ziley and Sons, Inc. https://www.researchgate.net/publication/269107473_What_is_governance/link/548173090cf22525dcb61443/download%0Ahttp://www.econ.upf.edu/~reynal/Civil wars_12December2010.pdf%0Ahttps://think-asia.org/handle/11540/8282%0Ahttps://www.jstor.org/stable/41857625
57. Mcfarland, M., Lemon, R., and Stichler, C. (2018). Critical Values for Salts in Irrigation Water for Major Crops. *Texas A & M Agrilife Extension*.
58. Megh, R. and Goyal, M. K. G. (2016). Potential Use of Solar Energy and Emerging Technologies in Micro Irrigation. In *Potential Use of Solar Energy and Emerging Technologies in Micro Irrigation*. https://doi.org/10.1201/9781315366272
59. Mokeddem, A., Midoun, A., Kadri, D., Hiadsi, S., and Raja, I. A. (2011). Performance of a directly-coupled PV water pumping system. *Energy Conversion and Management*, *52*(10), 3089–3095. https://doi.org/10.1016/j.enconman.2011.04.024
60. Mongat, A. S., Arshad, M., Bakhsh, A., Shakoor, A., Anjum, L., Hameed, A., and Shamim, F. (2015). Design , Installation and Evaluation of Solar Drip

Irrigation System at Mini Dam Command Area. 52(2), 481–488.

61. Naam, R. (2020). Solar's Future is Insanely Cheap. https://rameznaam.com/2020/05/14/solars-future-is-insanely-cheap-2020/
62. Nakashima, M. (2010). Design Recommendation for Storage Tanks and their Supports. 179.
63. Namara, R. E., Horowitz, L., Nyamadi, B., and Barry, B. (2011). Irrigation Development in Ghana: Past experiences, emerging opportunities, and future directions. *Ghana Strategy Support Program (GSSP) GSSP Working Paper No. 0027*, 41. http://agriskmanagementforum.org/sites/agriskmanagementforum.org/files/Documents/IFPRI - Irrigation in Ghana.pdf
64. Natural Resources Conservation Services (NRCS) (2013). Part 623 Irrigation National Engineering Handbook Chapter 7 Microirrigation (Issue October).
65. Netherlands Development Organisation (SNV). (2021). Solar-powered Irrigation Systems for Smallholder Farmers in Ghana | SNV World. https://snv.org/update/solar-powered-irrigation-systems-smallholder-farmers-ghana
66. Pereira, L. S., and Alves, I. (2004). Crop Water Requirements. *Encyclopedia of Soils in the Environment*, *4*, 322–334. https://doi.org/10.1016/B0-12-348530-4/00255-1
67. Purohit, R.C. C. K. A., Singh, L. K. D. P.K., and Kothari, M. (2017). Performance Evaluation of Drip Irrigation Systems. *International Journal of Current Microbiology and Applied Sciences*, *6*(4), 2287–2292.

https://doi.org/10.20546/ijcmas.2017.604.266

68. Rentsch, U. (1982). Microfiche Reference Library. *Swiss Center for Appropriate Technology (SKAT) , Switzerland*.
69. Riyo. (2020). *The Advantages and Disadvantages of Solar Powered Irrigation - 1001 Artificial Plants*. https://www.1001artificialplants.com/2020/03/12/the-advantages-and-disadvantages-of-solar-powered-irrigation/
70. Rowell, B., and Jacobsen, K. (2018). Off the Grid : Ultra-low Pressure Drip Irrigation and Rainwater Catchment for Small Plots and High Tunnels. http://www2.ca.uky.edu/agcomm/pubs/HO/HO120/HO120.pdf
71. Sadick, A., Ansah, I. O., Badu, A. O., Nketia, K. A., Asamoah, E., Asaana, J., and Amfo-Otu, R. (2015). Estimation of Potential Evapotranspiration at Botanga Irrigation Scheme in the Northern Region of Ghana. *Environmental Research, Engineering and Management*, *70*(4), 5–13. https://doi.org/10.5755/j01.erem.70.4.7752
72. Sass, J., and Hahn, A. (2020). Solar Powered Irrigation Systems (SPIS): Technology, Economy, Impacts. www.giz.de/hera
73. Shamim R, S. M., and Sarkar, N. I. M. (2015). Design and Performance Analysis of a Directly-coupled Solar Photovoltaic Irrigation Pump System at Gaibandha, Bangladesh. *2015 International Conference on Green Energy and Technology, ICGET 2015*, *3*(2). https://doi.org/10.1109/ICGET.2015.7315116
74. Sokol, J., Amrose, S., Nangia, V., Talozi, S., Brownell, E., Montanaro, G., Naser, K. A., Mustafa, K. B., Bahri, A., Bouazzama, B., Bouizgaren, A., Mazahrih, N., Moussadek, R., Sikaoui, L., and Winter, A. G. (2019). Energy

Reduction and Uniformity of Low-pressure Online Drip Irrigation Emitters in Field Tests. *Water (Switzerland)*, *11*(6). https://doi.org/10.3390/w11061195

75. SOLATECH (2013). *The Difference between Grid Power Supply and Solar Power Supply|Solartech*. https://www.solartech.cn/service/the-difference-between-grid-power-supply-and-solar-power-supply_14.html
76. Trax Ghana (2017). *How Climate Change is Affecting Crops in Northern Ghanao Title*. https://traxghana.com/2017/05/11/how-climate-change-is-affecting-crops-in-northern-ghana/#:~:text=It's mid-May so traditionally,be planted in mid-May.
77. UN Climate Technology Center and Network (2016). Solar Water Pumps. https://www.ctc-n.org/technologies/solar-water-pumps
78. White, R. E. (2006). Principles and Practice of Soil Science. The Soil as a Natural Resource. Fourth Edition. In *Blackwell Publishing* (Vol. 55, Issue 1). https://doi.org/10.5357/koubyou.55.153
79. William, G. S., Wicks, E. M., and Koelling, C. P. (1967). Engineering Economy. *Gastronomía Ecuatoriana y Turismo Local.*, *1*(69), 5–24.
80. World Bank (2018). Solar Pumping, The Basics. *International Bank for Reconstruction and Development/ The World Bank*.
81. You, L., and Wood-sichra, U. (2010). What is the Irrigation Potential for Africa ? A Combined Biophysical and Socioeconomic Approach. June. https://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/2205/filename/2206.pdf
82. Zaman, M., Yuan, S., Junping, L., Minggao, T., Jien, X., and Xiao, T. (2018).

Quantifying the Irrigation Performance of Newly Developed Solar Sprinkler Irrigation System. *ACM International Conference Proceeding Series, September 2018*, 90–95. https://doi.org/10.1145/3285957.3285995

APPENDICES

Appendix 1 Infiltration Rate Test Data Sheet

Date: Location: Remarks:								
A	B		C	D	E	F	G	H
Time	Water Level		Cumulative time	Time interval	Infiltration	Infiltration capacity	Infiltration capacity	Cumulative infiltration
Hour:min:sec	Before filling (mm)	After filling (mm)	Determine from A (min)	Determine from A (min)	Determine from B (mm)	Calculate from D & E (mm/min)	Calculate from F (../..)	Determine from E mm
			Start = 0					

Appendix 2: Collected Catch Cans Data for Spray tubes for Pressure Equal to 2psi for 20min

No	xi (ml)	Xi (mm/h)	no	xi (ml)	Xi (mm/h)
1	2	1.29	13	6	3.87
2	12	7.73	14	0	0.00
3	8	5.15	15	9	5.80
4	10	6.44	16	15	9.66
5	14	9.02	17	6	3.87
6	0	0.00	18	3	1.93
7	14	9.02	19	11	7.09
8	6	3.87	20	0	0.00
9	0	0.00	21	13	8.38
10	0	0.00	22	2	1.29
11	7	4.51	23	1	0.64
12	7	4.51	24	9	5.80

Appendix 3: Collected Catch Cans Data for Spray Tubes for Pressure Equal to 7psi for 20min

No	xi (ml)	Xi (mm/h)	No	xi (ml)	Xi (mm/h)
1	9	5.80	13	20	12.88
2	19	12.24	14	13	8.38
3	1	0.64	15	14	9.02
4	19	12.24	16	13	8.38
5	5	3.22	17	11	7.09
6	13	8.38	18	12	7.73
7	5	3.22	19	11	7.09
8	10	6.44	20	18	11.60
9	12	7.73	21	20	12.88
10	15	9.66	22	20	12.88
11	17	10.95	23	21	13.53
12	12	7.73	24	0	0.00

Appendix 4: Collected Catch Cans Data for Spray tubes for Pressure Equal to 10psi for 20min

No	xi (ml)	xi (mm/h)	No	xi (ml)	xi (mm/h)
1	15	9.66	13	10	6.44
2	15	9.66	14	21	13.53
3	16	10.31	15	27	17.39
4	12	7.73	16	13	8.38
5	17	10.95	17	17	10.95
6	25	16.11	18	30	19.33
7	25	16.11	19	21	13.53
8	15	9.66	20	18	11.60
9	21	13.53	21	17	10.95
10	25	16.11	22	13	8.38
11	14	9.02	23	24	15.46
12	10	6.44	24	16	10.31

Appendix 5: Collected Catch Cans Data for Spray Tubes for Pressure Equal to 15psi for 20min

No	xi (ml)	xi (mm/h)	No	xi (ml)	xi (mm/h)
1	20	12.88	13	27	17.39
2	15	9.66	14	21	13.53
3	25	16.11	15	18	11.60
4	21	13.53	16	24	15.46
5	18	11.60	17	23	14.82
6	38	24.48	18	26	16.75
7	20	12.88	19	19	12.24
8	25	16.11	20	27	17.39
9	17	10.95	21	19	12.24
10	32	20.62	22	26	16.75
11	25	16.11	23	17	10.95
12	19	12.24	24	20	12.88

Appendix 6: Collected Catch Cans Data for Spray Tubes for Pressure Equal to 17psi for 20min

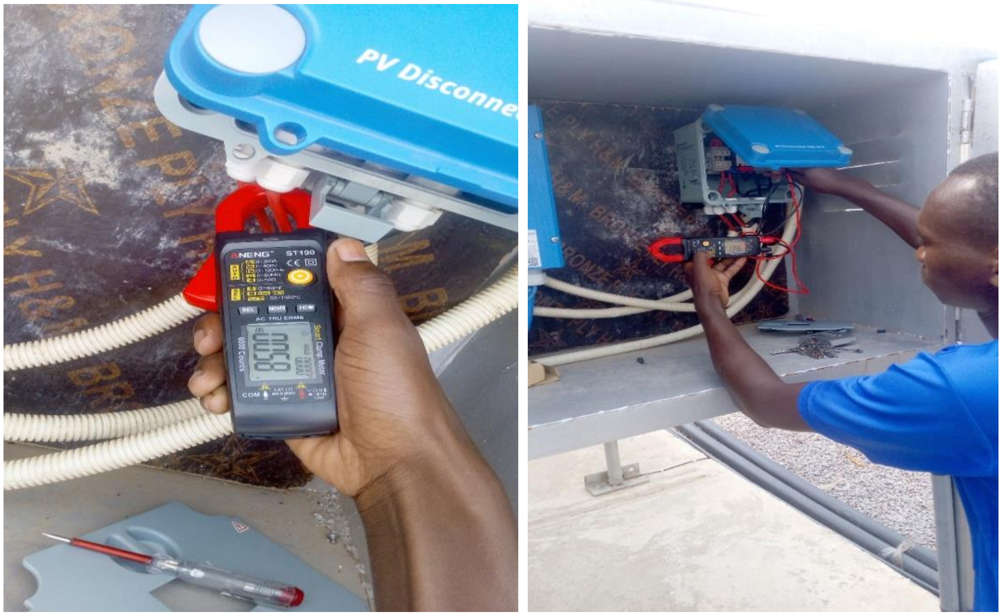
No	xi (ml)	xi (mm/h)	No	xi (ml)	xi (mm/h)
1	20	60	13	27	81
2	18	54	14	21	63
3	25	75	15	19	57
4	21	63	16	24	72
5	19	57	17	23	69
6	38	114	18	26	78
7	20	60	19	19	57
8	25	75	20	27	81
9	20	60	21	19	57
10	38	114	22	26	78
11	25	75	23	19	57
12	22	66	24	20	60

Appendix 7: Head Loss in Meter per Meter of Pipe

	Internal Diameter PVC Pipe (in mm)			
Flow (m^3/h)	0,75 inch (20 mm ID)	1 inch (25 mm ID)	1,10 inch (28 mm ID)	1,25 inch (32 mm ID)
0.5	0.014	0.005	0.003	0.001
1	0.049	0.016	0.01	0.005
1.5	0.103	0.035	0.02	0.011
2	0.176	0.059	0.034	0.018
2.5	0.266	0.09	0.052	0.027
3	0.373	0.126	0.073	0.038
3.5	0.496	0.167	0.096	0.05
4	0.635	0.214	0.124	0.064
4.5	0.789	0.267	0.154	0.08
5	0.959	0.324	0.187	0.097
5.5	1.144	0.386	0.223	0.116
6	1.344	0.454	0.262	0.137
6.5	1.559	0.526	0.303	0.158
7	1.788	0.604	0.348	0.182
7.5	2.031	0.686	0.395	0.206
8	2.289	0.773	0.445	0.233
8.5	2.56	0.865	0.498	0.26
9	2.846	0.961	0.554	0.289
9.5	3.145	1.062	0.612	0.32
10	3.459	1.168	0.673	0.351
10.5	3.785	1.278	0.736	0.385
11	4.125	1.393	0.803	0.419
11.5	4.479	1.512	0.871	0.455
12	4.846	1.636	0.943	0.492
12.5	5.226	1.765	1.017	0.531
13	5.619	1.897	1.093	0.571
13.5	6.026	2.035	1.172	0.612
14	6.445	2.176	1.254	0.655
14.5	6.877	2.322	1.338	0.699
15	7.323	2.473	1.425	0.744

Appendix 8: Monitoring Water Level in the Overhead Tank for Drip Irrigation

Appendix 9: Using Digital multimeter to Measure Voltage and Current of the System



Appendix 10: Power and Discharge Change due to Diurnal Variation of Solar for 11.25 m Head

Time	Power (KW)	Discharge (Q), (m3/h)
8:00 am	0.5	5
9:00 am	1.8	10
10:00 am	2.6	14
11:00 am	3.2	16.1
12:00 pm	3.6	16.1
1:00 pm	3.8	16.1
2:00 pm	3.5	16.1
3:00 pm	2.9	14
4:00 pm	2	10
5:00 pm	0.5	5

Appendix 11: Power and Discharge Change due to Diurnal Variation of Solar for 21.1 m Head

Time	Power (KW)	Discharge (Q), (m3/h)
8:00 am	0.5	4
9:00 am	1.8	8
10:00 am	2.6	10.5
11:00 am	3.2	11.94
12:00 pm	3.6	11.94
1:00 pm	3.8	11.94
2:00 pm	3.5	11.8
3:00 pm	2.9	10
4:00 pm	2	7
5:00 pm	0.5	4

Appendix 12: Power and Discharge Change due to Diurnal Variation of Solar for 28.13 m Head

Time	Power (KW)	Discharge (Q), (m3/h)
8:00 am	0.5	1
9:00 am	1.8	4
10:00 am	2.6	5.6
11:00 am	3.2	6.4
12:00 pm	3.6	6.53

1:00 pm	3.8	6.53
2:00 pm	3.5	6.4
3:00 pm	2.9	5.5
4:00 pm	2	3.5
5:00 pm	0.5	1

Appendix 13: Catch Cans Collected data for 0.3 m Water Level in the Tank

No	Collected water in catch can (l/h)	no	Collected water in catch can (l/h)	no	Collected water in catch can (l/h)
1	0.6	9	0.64	17	0.6
2	0.63	10	0.63	18	0.6
3	0.55	11	0.55	19	0.63
4	0.6	12	0.53	20	0.58
5	0.61	13	0.6	21	0.62
6	0.63	14	0.64	22	0.61
7	0.61	15	0.62	23	0.62
8	0.56	16	0.57	24	0.59

Appendix 14: Catch Cans Collected Data for 0.75 m Water Level in the Tank

No	Collected water in catch can (l/h)	no	Collected water in catch can (l/h)	no	Collected water in catch can (l/h)
1	0.7831	9	0.78667	17	0.79333
2	0.8067	10	0.78667	18	0.70667
3	0.8333	11	0.82667	19	0.73333
4	0.7933	12	0.83333	20	0.74667
5	0.7467	13	0.80667	21	0.68667
6	0.7933	14	0.82	22	0.81333
7	0.7867	15	0.76667	23	0.71333
8	0.8133	16	0.7	24	0.73333

Appendix 15: Catch Cans Collected Data for 1.5 m Water Level in the Tank

No	Collected water in catch can (l/h)	no	Collected water in catch can (l/h)	no	Collected water in catch can (l/h)
1	0.92	9	1.00667	17	0.98
2	1.0133	10	0.96	18	1.06
3	0.94	11	0.90667	19	0.86667
4	1.0667	12	0.91333	20	1.00667

5	1.0267	13	0.96667	21	0.94667
6	1	14	0.96667	22	0.98667
7	0.9	15	0.89333	23	1
8	1.02	16	1.01333	24	0.88

Appendix 16: Detailed Capital Cost for Solar System

No	Item	Quantity	Unit	Unit price GHC	Total
1	panels	3960	watt	5	19800
2	wires	30	meter	29	870
3	PV disconnect	1	Piece	2502	2502
4	stand	3960	watt	2	7920
5	Water sensor	1	Piece	623	623
6	Pressure sensor	1	Piece	525	525
7	Water storage	1		5000	5000
8	50mm Foot valve	1	Piece	50	50
9	Motor + Controller + Solar sensor	1	Pieces	14310	14310
10	Pressure gauge	1	Piece	170	170
11	Water meter	1	Piece	400	400
	Total				**52170**

1USD = 7.5 by March 2022

Appendix 17: Detailed Capital Cost for Drip Irrigation

No	Item	Quantity	Unit	Unit price GHC	Total
1	HDPE Pipe 50mm Main line	111	Meter	32	3552
2	Submain	50	Meter	22	1100
3	Drip tape with emitters	1900	Piece	0.7	1330
4	Screen filter	1	Piece	100	100
5	32 mm HDPE compression Tee	4	Piece	69	276
6	50 mm HDPE compression Tee	2	Piece	150	300
7	HDPE 32 mm compression end cap	7	Piece	20	140
8	3/4-inch ball valve	3	Piece	50	150
9	50 mm HDPE compression coupler	9	Piece	75	675
10	16 mm drip offtake Valve	76	Piece	5.5	418

11	Overhead tank	2	Piece	2400	4800
	Total				**12841**

Appendix 18: Detailed Capital Cost for Sprinkler Irrigation

No	Item	Quantity	Unit	Unit price GHC	Total
1	Submain, 3/4-inch PVC, 6 meters	5	Piece	18	90
2	Laterals, 1/2-inch PVC, 6 meters	16	Piece	16	256
3	Raisers, 1/2-inch PVC, 6 meters	2	Piece	16	32
4	3/4-inch PVC Tee	4	Piece	20	80
5	3/4-inch PVC valve	6	Piece	45	270
6	3/4-inch PVC elbow	1	Piece	30	30
7	50mm Foot valve	1	Piece	50	50
8	50mm Ball valve	2	Piece	150	300
9	50mm Non return valve	1	Piece	350	350
10	50mm HDPE compression elbow	4	Piece	40	160
11	Sprinkles head	12	Piece	45	540
12	HDPE Pipe 50mm Main line	69	Meter	32	2208
	Total				**4366**

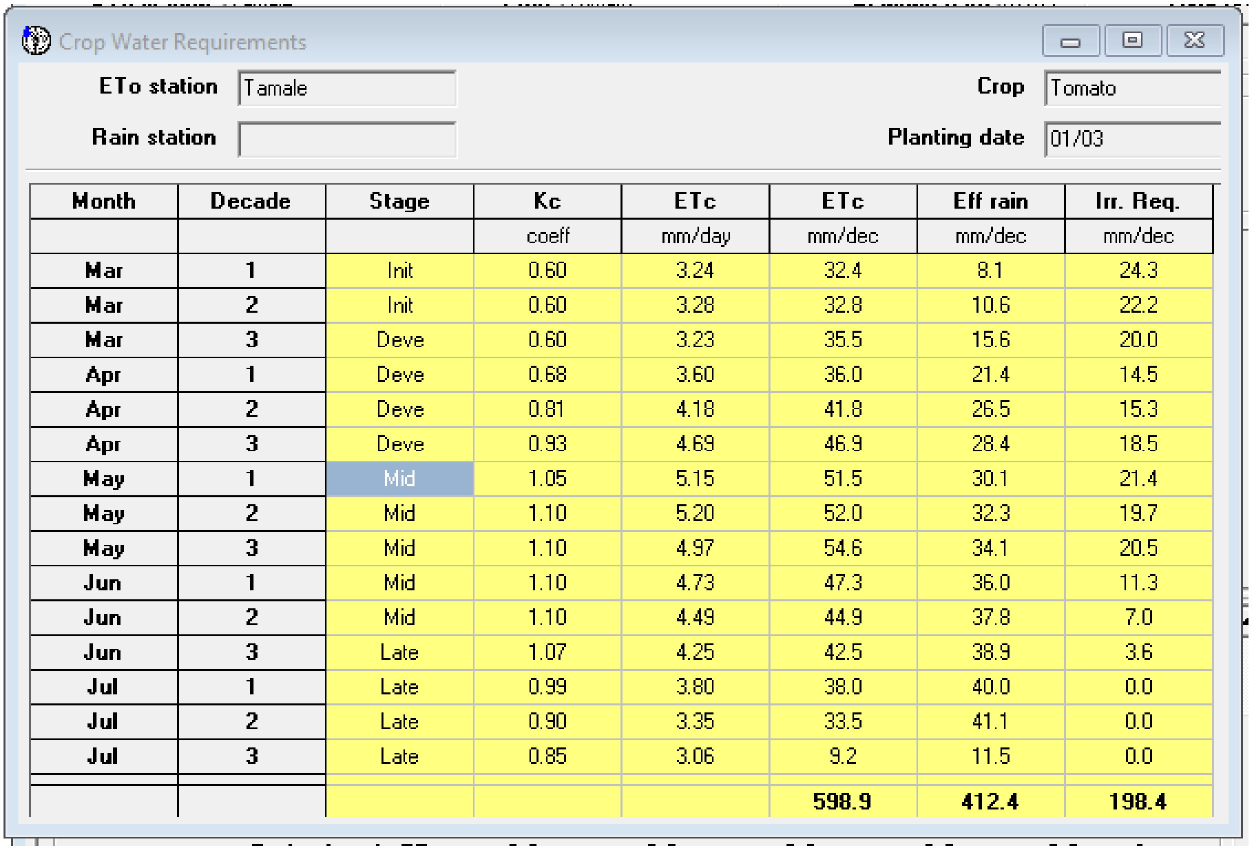
1USD = 7.5 by March 2022

Appendix 19: Detailed Capital Cost for Spray Tubes Irrigation

No	Item	Quantity	Unit	Unit price GHC	Total
1	submain, 1.5-inch PVC, 6 meters	5	Piece	80	400
2	spray tubes	250	meters	1.6	400
3	1.5-inch PVC valve	11	Piece	45	495
4	1.5-inch PVC end cap	1	Piece	3	3
5	HDPE Pipe 50mm Main line	38	meter	32	1216
6	50mm Foot valve	1	Piece	50	50
7	50mm Ball valve	2	Piece	150	300
8	50mm Non return valve	1	Piece	350	350
	50mm HDPE compression elbow	4	Piece	40	160
	Total				**3374**

1USD = 7.5 by March 2022

Appendix 20: CROPWAT Results



ETo station: Tamale

Rain station:

Crop: Tomato

Planting date: 01/03

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Mar	1	Init	0.60	3.24	32.4	8.1	24.3
Mar	2	Init	0.60	3.28	32.8	10.6	22.2
Mar	3	Deve	0.60	3.23	35.5	15.6	20.0
Apr	1	Deve	0.68	3.60	36.0	21.4	14.5
Apr	2	Deve	0.81	4.18	41.8	26.5	15.3
Apr	3	Deve	0.93	4.69	46.9	28.4	18.5
May	1	Mid	1.05	5.15	51.5	30.1	21.4
May	2	Mid	1.10	5.20	52.0	32.3	19.7
May	3	Mid	1.10	4.97	54.6	34.1	20.5
Jun	1	Mid	1.10	4.73	47.3	36.0	11.3
Jun	2	Mid	1.10	4.49	44.9	37.8	7.0
Jun	3	Late	1.07	4.25	42.5	38.9	3.6
Jul	1	Late	0.99	3.80	38.0	40.0	0.0
Jul	2	Late	0.90	3.35	33.5	41.1	0.0
Jul	3	Late	0.85	3.06	9.2	11.5	0.0
					598.9	**412.4**	**198.4**