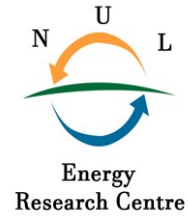**National University of Lesotho**

Economic Comparison of solar- and diesel-operated pumping systems for Irrigation applications in Lesotho

Mafa Tukula 200700116

A dissertation submitted in partial fulfilment

Of the requirements for the degree of

Master of Science in Sustainable Energy

Offered by the

Energy Research Centre

Faculty of Science & Technology

JUNE 2023

Acknowledgements

I would like to express my sincere gratitude to all who have assisted me throughout the course of this work. First and foremost, I would like to thank my supervisors **Dr. Molefe Makhele and Mr. Sebota Mokeke** for their invaluable guidance, support, and encouragement. Their expertise in the field of Sustainable Energy has been instrumental in shaping the direction of this thesis and ensuring its success. I would also like to thank the participants who volunteered their time and effort to take part in this study more especially **Engineer Tawanda Hove**. Their willingness to participate and provide valuable data has been essential in achieving the research goals. Furthermore, I would like to acknowledge the support and assistance provided by the **Energy Research Centre (ERC) staff**. Their expertise and technical support have been crucial in facilitating this project, and ensuring the accuracy of the results. I am also grateful to my family and friends for their unwavering support and encouragement throughout. Their belief in me has been a constant source of motivation and inspiration.

Lastly, I would like to thank all the relevant literature authors whose works were consulted in the course of this study. Their research has provided a strong foundation for this project and has helped in shaping the direction of the research.

Abstract

Access to electricity is improving in Lesotho although the use of energy for economic growth is still stagnant. Sustainable economic growth is essential for improving livelihoods; however, this is difficult to achieve in rural areas where agriculture is the main industry. Hence in this study, an innovative economic analysis of solar and diesel-operated pumping devices for irrigation application in Lesotho is put forth. The main objective of the study is to scrutinize the concepts related to the effective characteristics of irrigation pumps, their design, selection, installation, and possible diagnosis of their problems in order to assist farmers and stakeholders. Furthermore, the aim is to compare the economic costs of solar and diesel-pumping systems.

Several novel solar photovoltaic models and solutions have been proposed in an effort to circumvent some of the challenges. In addition, a recent intervention that serves as an example of the new study technique is discussed. A thorough technique for sizing and performance forecasting of photovoltaic (PV) solar pumps and a diesel generator is also given. The empirical data on the performance of the solar pump, the prescribed model of sizing, and the performance extrapolation approach made use of data on solar radiation and ambient temperature of the location. The empirical functions of the flow rate, as opposed to solar power, were similarly derived for different pipe size diameters of 63 *mm*, 75 *mm*, 90 *mm*, and 110 *mm*.

Additionally, depending on the pump, pipe diameter, and PV array size that resulted in the lowest pumping cost per unit of energy, the optimum solar pumping system was chosen. This method of designing solar pumping systems was advised because it produced significantly different and more accurate results than the frequently employed straightforward method, which ignored the fact that the total dynamic head (TDH) fluctuated as the solar irradiance deviated.

The simulation results drawn indicated that the best system configuration that resulted in the least unit cost of pumping is comprised of a 4 kW Lorentz PS2-4000-CS-F32-20-2 centrifugal solar surface pump, a 110 mm pipe size, and a 2110 watt PV array. As a stipulation, it is important to point out that solar photovoltaic (PV) seems to be a promising energy alternative to support irrigation development in Lesotho. In that matter, the unit cost of pumping for a solar PV-operated pump for irrigation application is 3.58 USD cents/ m^3 while for a diesel generator it is 16.1 USD cents/ m^3.

Based on the life cycle cost analysis (LCCA) of both systems, the annualized cost of solar PV at a 10% discount rate is $1263.00 and that of a diesel generator is $5517.00, with 35314 m³ of water pumped per annum. The cost of solar PV per watt, including installation at the initial stage is 0.42, $/watt, while for the diesel generator it is 0.41 $/watt. However, for a long run, solar PV is more cost effective as compared to diesel generator. The proposed system was also found to be not only cost-effective but similarly environmentally friendly, as it emits zero amounts of greenhouse gases (GHG). The amount of greenhouse gases to be emitted as per simulation when using a diesel generator for irrigation purposes is 32.3 tons of carbon dioxide (CO_2) per year.

Table of Contents

List of Figures

List of tables

Acronyms and abbreviations

CWR	Crop Water Requirement
UN	United Nations
SSA	Sub-Saharan Africa
SDGs	Sustainable Development Goals
PV	Photovoltaic
SAPP	South African Power Pool
EAPP	Eastern Africa Power Pool
GHG	Greenhouse Gases
GDP	Gross Domestic Product
IPC	Integrated Food Security Phase Classification
CO_2	Carbon dioxide
DHI	Diffuse Horizontal Irradiation
GHI	Global Horizontal Irradiation
PVGIS	Photovoltaic Geographical Information System
LCCA	Life Circle Cost Analysis
DC	Direct Current
AC	Alternating Current
STC	Standard Test Condition
MPPT	Maximum Power Point Tracker
TDT	Total Dynamic Head
EIA	Environmental Impact Assessment

EF   Emission Factor

EPA   Environmental Protection Agency

US   United States

ROIs   Return on Investment

PBP   Payback Period

IRR   Internal Rate of Return

NPV   Net Present Value

FAO   Food and Agriculture Organization

PVWP   Photovoltaic Water Pumping System

NOCT   Nominal Operating Cell Temperature

A_d Days of Autonomy

NWR   Net Irrigation Water Requirement

Chapter 1. Introduction

1.1 Background

Photovoltaic water pumping technology is used as an appropriate and economical solution to provide water for irrigation [1]. Hence, an applicable design needs to be considered based on the available solar radiation, crop water requirements (CWR), and water resources. However, the significant challenges faced by Sub-Saharan African (SSA) countries arise from intersecting with water problems [2]. Against this backdrop, it is obvious why providing widespread and

synergetic water energy access by 2030 is a top goal to help people who live in the rural areas of SSA to accomplish the United Nations' (UN) Sustainable Development Goals (SDGs) [3].

In our contemporary times, in this fourth industrial revolution era, the world views irrigation as a critical part of agriculture that plays a pivotal role in sustaining food production. For that reason, diesel fuel-based pumping units are incorporated as a means of irrigating farmlands [4]. Nevertheless, there has been a significant increase in the uptake of clean energy technologies recently. Today, renewable energy systems are considered a promising foundation for future sustainable energy, and, currently, hybrid renewable sources generate lucrative energy and have a negligible carbon footprint [5].

Power generation by solar photovoltaic (PV) from 2017 to 2030 is expected to grow by 17% globally [6]. Thus, to meet food and energy demands while considering the environmental impact reduction achieved by using fossil-based energy for irrigation, there is a need to power irrigation pumps with solar energy. It is also fundamental to meet the overall energy demand in the Eastern African Power Pool (EAPP) and the Southern African Power Pool (SAPP) by 2030 as per SDG7, where the goal's priority is to provide universal access to affordable and modern energy services [7].

Moreover, engaging solar irrigation for agricultural production benefits climate mitigation technology that contributes to reducing greenhouse gas (GHG) emissions [8]. However, modern irrigation systems require energy to lift water from wells, streams, or other sources to the fields where it will be used. The cost and efficiency of the energy technology used in irrigation systems are considered key determinants of the system's overall performance. Despite solar irrigation's potential for food production, small-scale farmers still have a problem of affording PV systems, and that forces them to use diesel-powered pumps for irrigation [8].

Several energy solutions are available for irrigation water pumping, such as on-grid electric pumps and manual treadle pumps [9]. In this study, the focus is on an economic comparison of solar- and diesel-operated pumping systems for irrigation applications in Lesotho, taking into account off-grid solutions to powering water-fed irrigation systems. Numerous studies on the matter have been carried out to compare the cost of solar-powered irrigation and diesel-powered

irrigation in Sub-Saharan African countries and to map the relative cost efficiency of such systems; hence, this study focuses on Lesotho.

Lesotho as a country is considered a small, mountainous, and landlocked kingdom, surrounded by its larger neighbour, South Africa. It is regarded by the World Bank as a developing country with a lower-middle-income level [10]. Most of its economy is driven by agriculture which accounts for nearly half of the country's gross domestic product (GDP). Rain-fed agriculture, which relies on rainfall, is the primary means of production in Lesotho, where only 47.4% of the population has access to electricity [11].

The reliance on rainfall for agriculture has caused Lesotho to be severely affected by droughts and other weather events which have led to the country facing social and economic hardships. Climate constraints in Lesotho are reported to hinder irrigated vegetables due to early and late frosts, high-intensity rainfall with thunderstorms, low rainfalls, snow, and untimely temperatures [12]. According to the Integrated Food Security Phase Classification (IPC), about 23% of the population of Lesotho residing in rural areas is projected to be in a food crisis and need humanitarian assistance to cover food gaps because of the lack of irrigation [13].

Furthermore, in fulfillment of the Paris Agreement for adaptation and efforts to limit global average temperature below two degrees (2°), Lesotho has adopted a mitigation strategy of deploying renewable energy sources in power generation to reduce over-reliance on fuel wood and diesel generator usage [14]. On the other hand, for irrigation purposes, the costs of solar irrigation pumps as compared to diesel irrigation pumps are considered to be higher at the initial stage of installation but have lower operation and maintenance costs in the long run [15].

In addition, photovoltaic irrigation water pumps are not only restrained to be more suitable for low and medium headwater pumping in off-grid locations but are also economical in operation during peak sunshine hours [6]. This has the potential to reduce the energy consumption of the irrigation systems and help to increase crop yields in areas where electricity is expensive or unavailable. Notwithstanding low capital costs, in his study, Abu-Aligah emphasized that the price increase of oil-based fuel hinders the margin to be gained by farmers if they use diesel and gasoline pumps for irrigation [16].

Hove and Mongufa [17], also point out that in the past decade, the photovoltaic (PV) module cost has reduced by 80% while the petroleum fuel module cost has increased by 250%. Furthermore, diesel-run pumping systems are considered environmentally unfriendly since they produce a huge amount of Carbon dioxide CO_2) and other toxic gases [18]. P.C. Pande et al. [19] emphasized that diesel generators commonly perform optimally for about 6 to 7 years, and as a result, about three replacements will be required in their 25-years life cycle.

1.2 Problem Statement

The great bulk of Lesotho's topography is made up of rough hills and mountain ranges with sparsely populated rural communities, making it excessively expensive and unprofitable to link these isolated areas to the national electricity system. This low access to electricity in remote areas inhibits energy services that are critical to developing living circumstances, such as powered irrigation systems and electrified water pumps for a community supply.

Lesotho is water-rich and even supplies South Africa. The total arable land is projected at 325 000 hectares (10.7%) of the total area [20]. However, it is challenging to transport water from the source to the area where it is required, and that makes the irrigation of cultivated land problematic where electricity is not available. This also hinders the economic benefits of the country due to low production.

The use of photovoltaic energy is progressing exponentially, though the degree of acceptance of using photovoltaic solar-powered irrigation systems is very low in some areas. The wide-spread adoption of these techniques has been hampered by a number of problems which include the high initial cost, ignorance of relevant information and technological know-how, a lack of knowledge and technical proficiency, an inadequate understanding of the daily output of these systems, and a track record of failure.

In most remote areas where there is no electricity connection, farmers use diesel fuel generators to power irrigation pumps; this also influences greenhouse gases and toxic gases that pollute the environment. Apart from that, fuel prices are increasing daily, and the margin to be gained by farmers is negatively affected if they use diesel and gasoline pumps for irrigation.

1.3 Objectives

Water security in Lesotho depends on strong catchments in the major river basins. The renewable water resources of the country are estimated at 5.23 km³/yr, hence access to dynamic water for millions of Lesotho citizens, farmers, and businesses is protected [20]. However, the challenge of moving water from the point of supply to the point of demand still exists due to the lack of electricity, especially in the remote areas of the country.

Consequently, this research aims to familiarize the farmers and stakeholders with basic concepts related to the effective characteristics of irrigation pumps, their design, selection, installation, and diagnosis, with possible remedies in Lesotho. The research will aid in the implementation of a project to install rationally planned irrigation water pumping systems, considering a system that is more affordable, cost-effective, and environmentally friendly.

Most farmers in Lesotho depend on micro irrigation which uses high-pressure or sprinkler systems, center pivots, and drip kits. A number of these irrigation technologies are conventionally powered, while in some cases, a diesel generator is used. As a result, the study further aims to compare the economic costs of solar- and diesel-pumping systems in Lesotho, accounting for off-grid solutions to powering water-fed irrigation systems.

Lastly, the research intends to provide a general analysis of effective economic factors on the choice of type of energy for pumping systems from the user's perspective. To determine the overall cost of facility assets used, the life cycle cost analysis for both solar PV and diesel-operated pumping systems will be used. The unit cost of the pumping technique will also be employed.

1.4 Research Questions

This study aims to answer the following questions;

❏ Which is the most cost-effective way of moving water from the point of supply to the point where it is needed for irrigation?

❏ Between the diesel generator and solar-operated pumping system, which one is more reliable, affordable, and environmentally friendly?

1.5 Justification

Rainfall patterns due to climate fluctuation are posing a threat to crop production in Lesotho. As a result, this research will look into the details of cost-effective ways of uplifting water from the sources to the point of demand using cheaper, more reliable, and affordable energy solution for land irrigation. The study will also benefit stakeholders and enable them to make an informed decision between using solar-PV and diesel pumping systems for irrigation based on their socio-economic and environmental impacts in Lesotho.

1.6 Summary of Methodology

This study will first consider the crop water demand before optimization of irrigation components, and that will lead to the energy required for pumping water from the source. CROPWAT 8.0 computer software will be used to calculate the crop water and irrigation requirements of selected crops. This software was developed by the Food and Agriculture Organization of the United Nations to calculate irrigation schemes for varying crop patterns [21].

Topographical information of the study site, such as monthly solar radiation, diffuse horizontal irradiation (DHI), global horizontal irradiation (GHI), and ambient temperature will be downloaded from the photovoltaic geographical information system (PVGIS) data generator computer program [22]. Moreover, the study will also adopt Hove and Mungofa models [23] to size the solar pumping system apparatuses by employing derived power flow functions and meteorological data. The total dynamic head, total static head, friction head, flow rate, PV array size, diesel generator, pump, and storage will also be determined.

The life-cycle cost analysis (LCCA) for both solar- and diesel-operated pumping systems will be conducted to assess the total cost of facility possessions. In this regard, the unit cost of the pumping approach is going to be used. The life-cycle cost analysis will similarly help to estimate the overall costs of a project and its alternatives so that one can select a design which ensures a facility that will provide the lowest overall cost of ownership.

1.7 Research Report Structure

This research report is structured as follows: Chapter 1 is an introduction that outlines the problem statement, objectives, research questions, a summary of the methodology, and justification. A review of the economic and environmental impacts of solar and diesel-operated

pumps for irrigation applications is presented in Chapter 2. The methodology adopted in this study is discussed in Chapter 3. The results obtained are outlined and discussed in Chapter 4. Lastly, the conclusion is drawn, and recommendations for further work are elaborated on in Chapter 5.

Chapter 2: Literature review

2.1 Solar energy valuation

Understanding the isolation data for a certain region is a prerequisite to designing a solar energy conversion system and evaluating its potential. Yet, in many locations, horizontal surfaces are used to quantify solar radiation, including its global and diffuse components. Because of this, solar radiation values on an inclined surface are necessary for the design of both passive and active systems in order to determine the solar radiation falling upon its roof and various vertical walls [24].

Furthermore, solar radiation on the surface of the earth may typically be calculated in pure theoretical terms when there is a clear sky. Using environmental variables like the number of hours of intense sunshine, one can determine the long-term average of global irradiation on a horizontal surface in overcast or partially cloudy locations [25]. Based on measured quantities of global solar radiation, the coefficients in the correlations between isolation and the number of hours of bright sunshine can be calculated. And so, it is crucial to have access to the measured values of radiation.

The correlation model, therefore, was developed to determine the monthly-average daily diffuse irradiation on the horizontal plane. Based on the Maseru diffuse-ratio-clearness-index correlation in Lesotho, an estimation was made using the model represented by   (1 [26].

$$\overline{H_h}/\overline{H_d}=-20292+1.6118\,\overline{K}_h \tag{1}$$

Where $\overline{H}_h$ is the long-term monthly-average hemispherical irradiation on a horizontal plane (daily total), $\overline{H}_d$ is the long-term monthly-average diffuse irradiation on a horizontal surface, and $\overline{K}_h$ represents long-term monthly average clearness index. Another important parameter to

consider is the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface (R_b).

According to Kecili et al. [27], one way to determine the ratio of the average daily beam radiation on a slanted surface to that on a level surface is to assume that it has the value that would be attained if there was no atmosphere. Thus, in the southern hemisphere, the ratio of the average daily beam radiation on a sloped surface to that on a horizontal surface is given as:

$$R_b = \frac{\cos(\varphi+\beta)\cos\delta\sin\omega_s + (\pi/180)\,\omega_s\sin(\varphi+\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + \left(\dfrac{\pi}{180}\right)\omega_s\sin\varphi\sin\delta} \tag{2}$$

Where ω_s is the sunset hour angle for the tilted surface for the mean day of the month, φ is the latitude angle, β represents the surface slope from the horizontal, and δ denotes the declination angle. Nevertheless, surfaces with different orientations from true north are not covered by (2 [28].

2.2 System Overview

Designing a photovoltaic (PV) system is commonly based on the calculated solar irradiance level, motor power, and meteorological features at a certain geographical location [29]. Hence it is indispensable to simulate and optimize solar water pump size for irrigation purposes. Asif et al [30] argued that it is also important to know about irrigation's modern technologies so that it can be simple to direct the farmers to a more reliable, affordable, and cost-effective water-pumping irrigation system, taking into account a system that will benefit both the farmers and the ecology.

Water-pumping irrigation systems require energy for their operations. However, there is still a challenge as applications of renewable energy are limited by their intermittent nature, which requires energy storage systems [31]. These applications depend on various factors such as pumped hydro storage, batteries, and fuel cell technologies. According to Mansur A. et al [32], diesel-powered pumps seem to be the widely used pumps in farming and grassland irrigation, even though there is quite a situation of consistency and availability where fuel supply is unreliable and expensive, high maintenance cost, and short life anticipation.

Various studies and approaches have therefore been taken by previous researchers to determine diesel and solar energy costs assessment under irrigation systems and domestic water needs. In

Egypt, based on the diesel and solar energies costs assessment under the drip irrigation system, Abo-Habaga et al [33] presented solar photovoltaic panels as being a lower cost system compared to diesel generators.

In another study in the Philippines, Charmaine and Boongaling [34] investigated the socio-economic and environmental analyses of solar irrigation systems for sustainable agricultural production. Their results revealed that increasing the efficiency of irrigation systems as well as reducing the high operational costs associated with diesel pumping systems was made possible by the installation of solar PV. In Australia, investment analysis of solar energy in a hybrid diesel irrigation pumping system by Powell et al [35] found that by incorporating solar PV systems into off-grid scenarios, the solar installation drops emissions and costs, and further reduces exposure to future diesel fuel price variations.

Ben Richard et al. [36] also published a review of sustainable solar irrigation systems for Sub-Saharan Africa. The exploration focused on the research accomplished on solar photovoltaic and solar thermal innovations for pumping water generally for irrigation of remote farm geographic areas. Contrary to PV technology, there was a dearth of solar thermal technology, particularly for small scale enterprises. Thus, solar thermal water pumping systems were unable to overcome the drawback of PV technology. This has ultimately prevented the technology from being widely used for irrigation applications.

Likewise, in Sub-Saharan Africa, as a renewable and clean energy source, solar PV is reported to have attracted much consideration, hence there is a keen interest to invest in it to support the development of irrigation due to its cost-effectiveness [9]. In Morocco, where Fiona et al [37] investigated solar-powered drip irrigation as an optimal performance model that would lower the cost of drip irrigation systems for subsistence farmers, the results established huge opportunities for system cost reduction which will enable a good market for small hold farmers.

Several renewable energy source water pumping systems such as solar thermal, wind energy, biomass, and hybrid renewable energy systems were reviewed by Gopal et al. [38]. A six-year payback period for technology was determined to be feasible for household use up to medium head requirements. It was shown that PV technologies perform better in drip irrigation applications, particularly in rural areas for the preservation of grassland and small-scale

irrigation applications. Throughout the course of the 25 years of operation, it was also anticipated that PV panels would be able to significantly decrease carbon dioxide emissions.

Comparing solar-PV water pumping technologies and wind driven water pumping systems, Campana et al. [39] discussed the technological and financial viability of renewable energy systems for irrigation and agricultural conservation in China. With the irrigation water requirement in mind, a model was built to determine the size of PV and wind powered systems based on the fluctuating solar irradiation and wind speed respectively. The PV system therefore resulted in 2.9 kWp whereas the wind turbine generated 2.6 kWp to power a 2.2 kW pump. According to the study's findings, wind powered systems and PV systems were found to compete depending on the site they are installed.

Moreover, Diop L. [40] point out that solar irrigation pumps are technically and economically feasible in many areas, with less environmental impact as compared to diesel irrigation pumps. On the contrary, the study conducted by Nitin B. [11] in India showed that even though solar pumps are economically viable, they need extraordinary initial investment. Besides, technically trained personnel are lacking in remote areas for PV solar maintenance and that hinders system lifetime and economic viability.

In the case of Lesotho, no studies have been carried out on solar and diesel-operated pumping systems for irrigation applications. Relebohile and Keregero [41] point out that most farmers in Lesotho rely on rain-fed agriculture. This indicates that they lack knowledge and access to the latest agricultural information. However, in a study carried out by Moholo. M. [42], optimization and evaluation of solar water pumping systems in Lesotho were presented, with the objective of an economical optimum combination of the system components that would meet the daily water demand at the least pumping cost for domestic purposes.

Based on the literature, most farmers in Lesotho depend on micro irrigation which uses a high-pressure or sprinkler system, center pivot, and drip kits irrigation technologies [20]. . Most of these irrigation schemes and technologies were subsidized by the government of Lesotho through donors. Needless to say, most of them have collapsed due to ruthless management. below shows irrigation technologies that are implemented in Lesotho and their energy requirement per location. Most of these irrigation schemes and technologies were subsidized by the government

of Lesotho through donors. Needless to say, most of them have collapsed due to ruthless management.

Table 1: Irrigation technologies and end users in Lesotho [20].

Location of irrigation	Type of technology	Source of technology	Source of and access to water	Energy requirement	Service provider	End User
Butha-Buthe-Hololo	High Pressure Sprinkler	imported	Hololo River	Electricity	Local agent and government	Community organization
Quthing-Seaka	High Pressure Sprinkler	Imported	Senqu River	Diesel	Local agent and government	Community organization
Maseru-Masianokeng	High Pressure Sprinkler	Imported	Phutiatsana	Electricity	Local agent and government	Community organization
Leribe-Tsikoane	High Pressure Sprinkler	Imported	Borehole	Electricity/Diesel	Local agent and government	Community organization
Berea-Linokong	Center pivot	imported	Mohokare	Diesel	Local agent and government	Community organization

2.3 Solar Energy Utilization

Solar energy, if used wisely, is likely to meet the requirement of energy for the survival of plants and human beings on planet Earth [43]. Lesotho as a country is lacking indigenous energy resources, but it has a significant amount of solar irradiation which is approximated between 5700 MJm^2 and 7700 MJm^2 per annum, where a large area of the country receives 6750 MJm^2 annually [44]. According to Taele et al. [45], Lesotho has more than 300 days of sunshine.

The sunshine period of Lesotho is reported to range from 10.2 to 13.8 hours per day for both the lowlands, and highlands [15]. For December, the annual daily mean global radiation ranges from 19.09 to 28.44 MJ/m²/day; although from June, the annual daily mean global radiation ranges from 10.30 to 13.48 MJ/m²/day. Because of these plentiful renewable resources, it is anticipated that Lesotho will achieve a national electrification rate of 54.2% by 2030, with 95% of urban households and 14% of rural households electrified [46].

The tilt angle of a solar energy system is one of the key variables for catching the maximum amount of solar radiation that strikes the solar panels. Therefore, it is crucial to take into account the tilt angle of a solar energy system when calculating how much solar energy will be consumed since it depends on the sun's course on a daily, monthly, and annual basis. Also, for the system

to produce the most amount of energy, the ideal tilt angle must be precisely determined for the area of interest [47].

Furthermore, to maximize the performance of solar panels, it is advised that they should be installed at an azimuth angle of zero degrees (0^0) oriented to the true south as shown in Figure 1. An azimuth angle is defined as the horizontal angle in degree with respect to the true north [47]. Another crucial angle is the solar elevation often known as the zenith. It is the angle formed by the sun disc and the horizon at the observation point or location of the solar panel, and it changes from zero degrees at sunrise and sunset to ninety degrees (90^0) at midday.
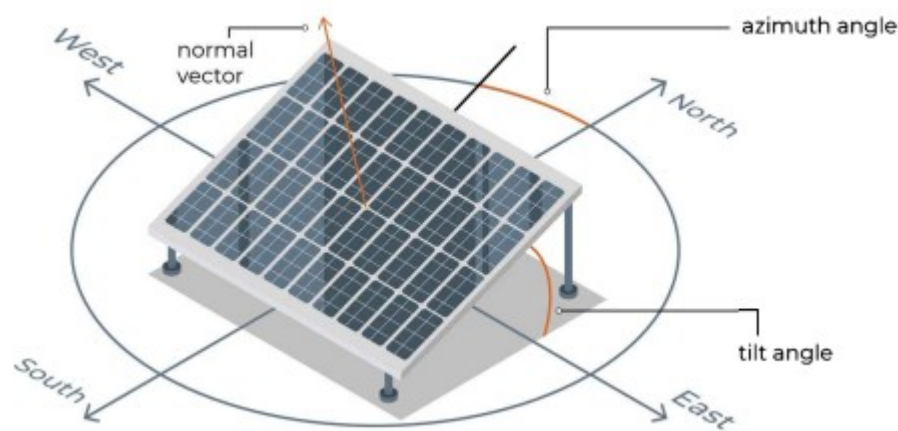
Figure 1: Solar panel orientation and positioning [47]

Manoranjan et al [48] also showed that solar energy is mostly utilized in the operation of solar pumping systems and other solar devices. They further underlined that solar irradiation is converted into electricity through the battery and the inverter where the battery is charged by the combination of the solar array and charge controller. The charge controller, in turn, plays a vital role in regulating the voltage and direct current (DC) coming from the solar panel to evade battery damage from overcharging.

The battery then sources the power to the inverter which permits the system to operate. Another important role of the battery is to store energy and use it in the days of autonomy. Apart from DC solar pumps, other solar irrigation pumps use alternating current (AC) where an inverter substitutes the charge controller [49]. Figure 2 below demonstrates a schematic diagram of a direct coupled PV DC water pumping system where the inverter and the battery storage are excluded.
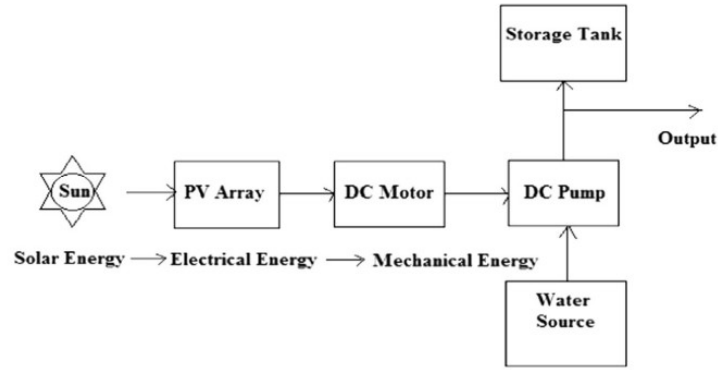
Figure 2: A direct coupled PV DC water pumping system [50].

2.4 Photovoltaic Generator

The photovoltaic generator is explained as a set of linked photovoltaic panels [40]. Their benefit is to generate energy without tracking the sun's position. Numerous numbers of PV panels are assured to generate 90% of their rated power for the first ten years and 80% of their rated power for up to 25 years. Their electrical energy source is also non-linear; hence they provide a variable voltage and current value based on the lighting and temperature conditions.

A PV panel's electrical output is rated according to industry Standard Test Conditions (STC) of 1000 Wm^2 incident solar radiation, at an operating cell temperature of 25°C, and under an absolute air mass of 1.5 [51]. Solar panels are normally made up of photovoltaic cells or solar cells. The solar cells are built up of two types of semiconductors called n-type and p-type silicon. The semiconductors are joined to make a P-N junction or solar cell as shown in Figure 3 [52].
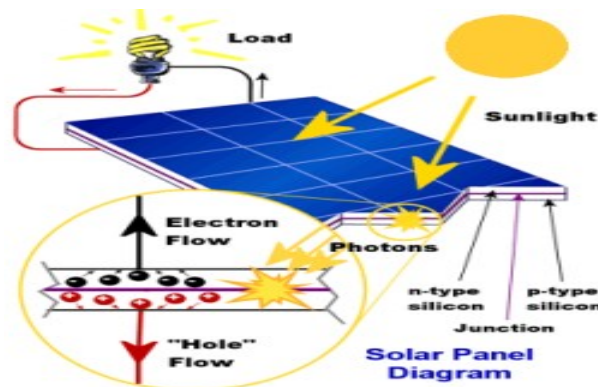
Figure 3: Schematic diagram of solar cell and current flow [52]

The cells are wired in series, wrapped between sheets of glass or plastic, and reinforced inside a metal frame. Solar cells are essential for producing direct current (DC) which is later converted into alternating current (AC) by a conventional inverter. Based on the power requirement of an appliance, multiple photovoltaic cells are electrically joined to make a solar module which is also coupled to form a PV array.

Once the pump has received the alternating current electricity, a pump can either start pumping water right away or store it for later use. In Figure 4, the schematic diagram of the photovoltaic generator and how it operates is presented.
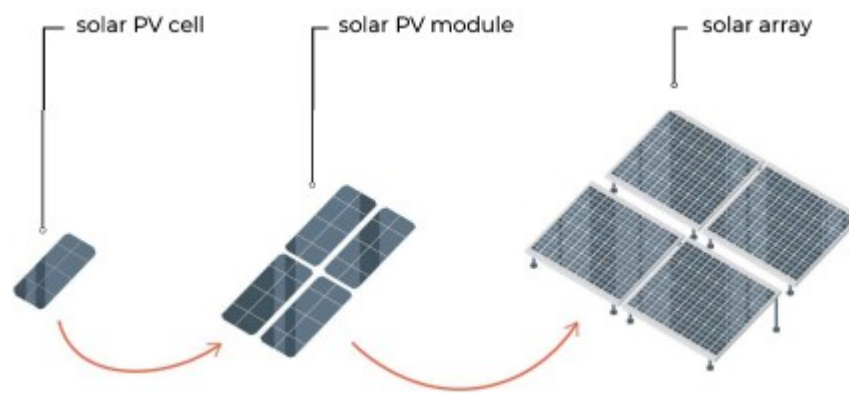
Figure 4: Photovoltaic generator [40]

2.5 Irrigation System Apparatuses

An irrigation system comprises of various components which include solar panels, a support structure with a tracking mechanism, pipes, battery storage, a pump controller, and the converter. In some circumstances, the storage tank can replace the batteries as they are more expensive and not easily attainable [4]. The volume of the storage tank is typically fixed based on the amount of water required to irrigate the crops for 2-5 days when there is no sunshine.

2.5.1 Battery Storage

Due to unpredictable weather, solar photovoltaic (PV) system performance degrades, thus making it difficult for it to integrate into the electrical grid. Integration of battery energy storage with a PV system may be a solution to reduce this challenge and power fluctuations at the load end [53]. Again, battery storage can hypothetically improve the security, consistency, quality, and accessibility of electricity supply from solar PV power systems.

Optimization of the battery bank is done based on the daily water consumption. However, its size can differ depending on the desire and length of the expected power outage [54]. For instance, the size of the battery bank for an off-grid standalone system is optimized to operate for at least one to three days when there is no sunshine. In the same manner, rated voltages that range between 16.5 V and 17.5 V are usually required for 12 V liquid-acid batteries [53]. The combination of battery backup and PV modules in a solar irrigation system is depicted in Figure 5 below.
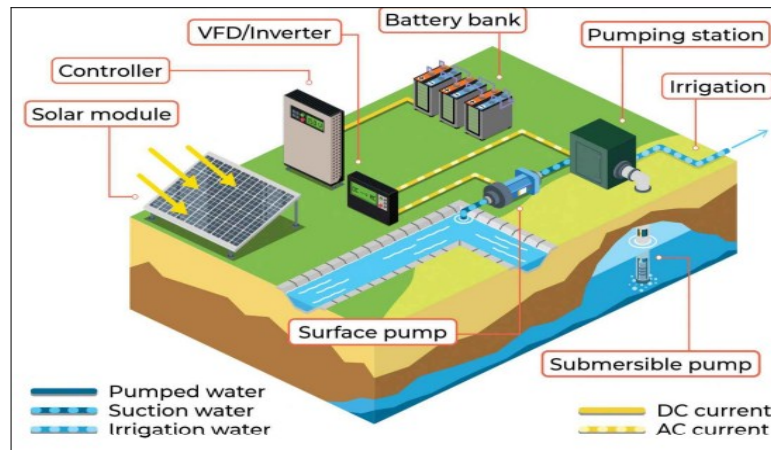
Figure 5: Integration of solar-PV modules and battery backup [54].

2.5.2 Pump controller and inverter

The inverter is considered an electronic component which transforms direct current electricity coming from the solar panels into alternating current electricity. For system reliability, the pump controller connects the motor pump to the solar modules which play a major role in adjusting the output frequency of PV modules and also control the direct current electric power input to the pump. Moreover, the pump controller equally plays a key role in protecting the system by turning it off in cases where the voltage is low or too high [54].

In a nutshell, the maximum power point tracker (MPPT) which is characterized in Figure 6 by curves can also play a pivotal role in converting the direct current power that is produced by the solar array to contest the voltage and current required for the operation of the solar pump. Another advantage of a maximum power point tracker is to ensure that the pump still functions at its maximum performance level regardless of days of no sunshine.

In the absence of a maximum power point tracker, the PV arrays would need to be enlarged to supply the motor's startup current, even though once the motor starts, the pump's startup current requirement decreases, and at that point, the array can then produce more power than is required [54].
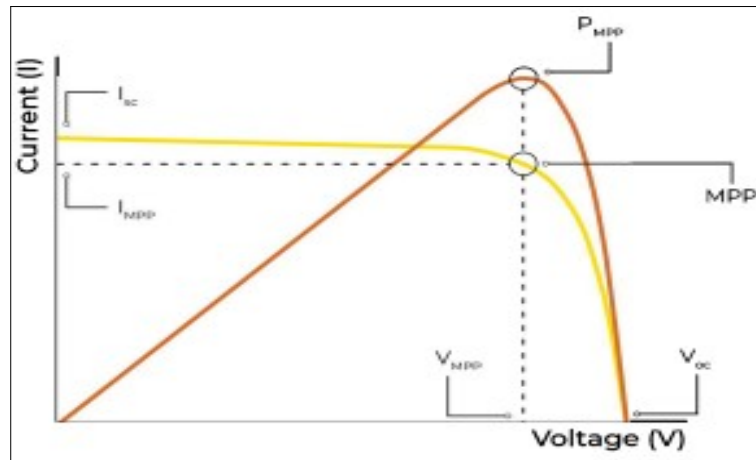
Figure 6: The maximum power point curve [54].

In recent years, the public's interest in solar PV pumps has grown along with a sharp decline in the cost of solar PV panels [55]. There are a number of alternative pumps which are available in the market with different capacities depending on the required water. Thus, in solar-PV water pumping systems, pumps are classified into three categories based on their applications such as submersible, centrifugal, and floating pump [56]. These pumps are designed in such a way that they can work under harsh environments with a long lifespan without corrosion.

Based on their installation, submersible pumps are mounted in the deep bore wells since they compromise high discharge rates and heads while centrifugal pumps mostly work on the surface ground to draw water from the narrow wells, rivers, ponds, and lakes. They also operate at low head and high discharge conditions, and their suction power is not thriving compared to submersible pumps. Floating pumps are used where the total dynamic head is high as it has relatively good suction power but a low discharge rate. Their advantage is that they can adjust their height with the level of water.

Based on their installation and configurations, solar pumps differ in that, in the submersible pump and floating pump, both motor and pump are adapted into a single unit. Whereas in the

centrifugal water pump, both motor and pump are selected separately according to the performance of the PV system laterally with the controller and the PV array [56]. The schematic diagram as portrayed in Figure 7 illustrates the generalized representation of a solar-powered pump.
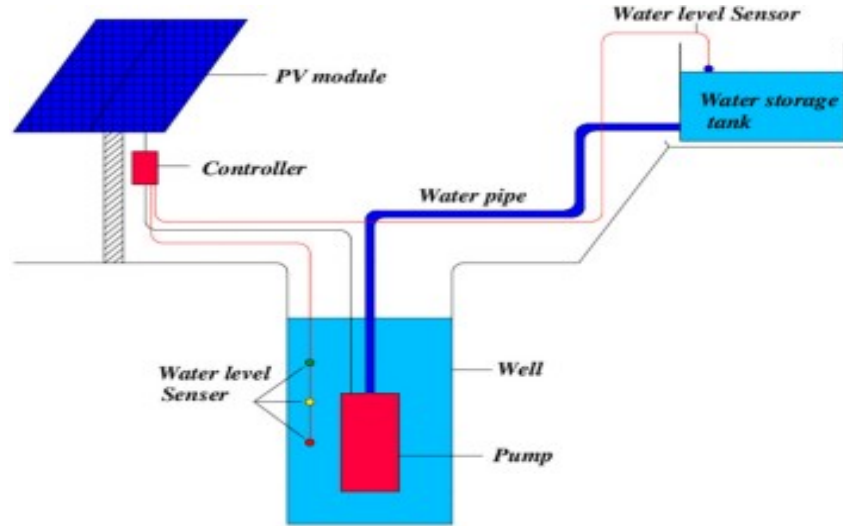
Figure 7: Schematic diagram of irrigation system components [56]

2.6 Solar modules

The solar panels are the main elements which are responsible for driving the solar irrigation-operated pump. They are interconnected in arrays and produce direct current (DC) electricity. This connection of solar panels is made up of using series or parallel arrangements to attain the preferred voltage and power for the pump [51]. The variables in e   (3 illustrate how solar panels generate power from the sun [57].

$$P_{pv} = C_{pv} D_{pv} = \frac{G_T}{G_{T,STC}} [1 + \propto_p (T_C - T_{C,STC})] \qquad \textbf{(3)}$$

Where C_{pv}(kW) is the graded capacity of the PV array under STC, D_{pv}(%) is the degrading factor, G_T(kW/m²) is mentioned as the solar radiation incidence on the PV array while $G_{T,STC}$ is considered as the incidence radiation beneath standard test conditions (1 kW/m²) and, $\propto_p$

(%/°C) is the temperature coefficient of power. T_C and T_{CSTC} are the temperature of the PV cell (°C) and the temperature of the PV cell below standard test conditions (25°C) in that order. The overall irradiation on an inclined surface $\dot{G}(\beta)$ is elaborated as the sum of direct or beam $\dot{B}(\beta)$, diffused $\dot{D}(\beta)$, and the reflected irradiation $\dot{R}(\beta)$ as shown in (4 [57].

$$\dot{G}(\beta)=\dot{B}(\beta)+\dot{D}(\beta)+\dot{R}(\beta) \qquad \textbf{(4)}$$

The direct or beam component of the global tilted irradiation can be determined from the horizontal radiation through *equation* 5 (5.

$$B(\beta)=\frac{G_{g,h}-G_{d,h}}{\cos(90-\alpha)}\cos(\Theta) \qquad \textbf{(5)}$$

Where $G_{g,h}$ is the global horizontal radiation (W/m²), $G_{d,h}$ is the diffused horizontal radiation (W/m²), α is the solar altitude (°) and Θ is expressed as the angle of incidence (°) [1]. The diffused components can be computed as follows:

$$D(\beta)=G_{d,h}\frac{1+\cos(\beta)}{2} \qquad \textbf{(6)}$$

The reflected radiation, therefore, can be articulated by *equation* 7 (7: where ρ_g is the ground reflectance [1].

$$R(\beta)=\rho_g G_{d,h}\frac{1-\cos(\beta)}{2} \qquad \textbf{(7)}$$

2.6 Applications of solar-PV system

Solar panels are increasingly utilized to meet a variety of energy needs such as powering homes, providing irrigation, supporting communication, and lighting streets [58]. As evidence of this trend, the global installation of solar energy has surpassed 945.4 GW as illustrated in Figure 8. The yearly PV installation, total module PV production, and total module production capacity worldwide also lean towards exponential progress [59].
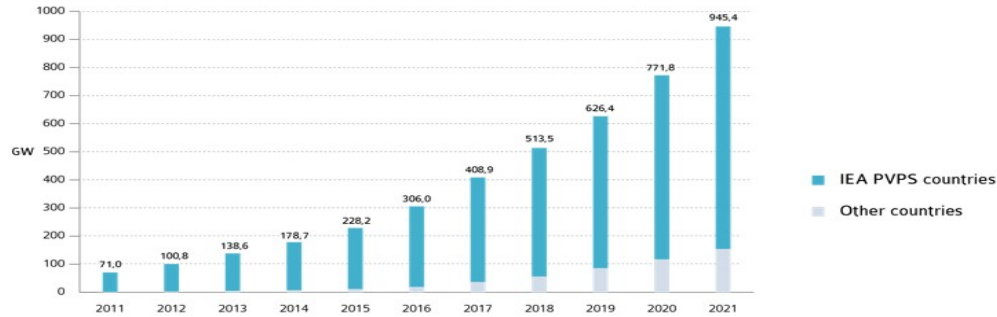
Figure 8: The global installed capacity trends of the PV system [59].

David F. et al [60] also emphasized that out of 55 GW that have been installed in China in 2021, solar contributed 30% to the new generation capacity while in 2022, China installed 13.2 GW of solar-PV which add to 945.4 GW cumulative worldwide.

The application of solar PV for irrigation was also done in Jordan where the study was conducted to investigate whether the application of a PV-Thermal array for pumping water as an alternative to PV would solve the energy demand [61]. The results revealed the average monthly electricity output of the PV and PV-Thermal as 12.7% and 10.86% respectively. In Morocco, solar application in agriculture has as well emerged as a cutting-edge and environmentally benign method of water conservation for the agricultural sector [62].

Moreover, around 6000 solar pumps with a capacity of 2000 Wp and 3000 Wp have been built in India due to the abundance of solar irradiation which is available, with an average irradiance of 6 kWh/ m²/day [63]. Currently, 21.2 million electrified pumps and 4.9 million diesel pumps are used to irrigate 50% of the world's agricultural land, and out of 18% of the total electricity used, 3.3 % of diesel consumption is used in irrigation pumps [55].

2.8 Diesel Generator

Despite all the improvements in renewable energy technologies, numerous remote sites and applications are still dependent on diesel generators and fossil fuels to produce electricity. Diesel generators are still commonly used to provide electricity in isolated communities as renewable energies are unpredictable, intermittent, and the storage capacity is limited [64]. In addition, diesel generators are frequently utilized in power plants as the main source of energy generation in countries with frequent electric outages, both in the residential and commercial sectors. Some

benefits of diesel generators for energy generation are stability, dependability, and ease of production.

In the case where solar panels are not generating electricity for irrigation systems, some farmers make use of diesel generators to power irrigation pumps even though the incomplete combustion of diesel results in the emission of carbon dioxide¿) and other pollutant particulates [65]. Lukuyu et al [66] argued that reliance on diesel generators is unsustainable in that it is expensive and detrimental to human health and the environment.

The performance of a diesel generator, in that case, is characterized by how much fuel it consumes at any time interval [57]. Moreover, other two crucial factors which have a significant impact on the diesel generator performance are the electric load and the instantaneous generation from renewable sources [64]. Therefore, the price of diesel generator fuel differs geographically based on subsidies and taxes. For that reason, the lifetime diesel fuel cost for a system is given by [67]:

$$C_{diesel\,fuel} = U_{NPV\,diesel} * V_{hour} * H_d \qquad \textbf{(8)}$$

In equation 8, $C_{diesel\,fuel}$ is the lifetime diesel fuel cost, $U_{NPV\,fuel}$ is referred to as the net present value of the price of diesel fuel per litre, V_{hour} represents the amount of fuel the diesel generator consumes per hour, and H_d is the annual operating hours expressed as:

$$H_d = G_d H_P \qquad \textbf{(9)}$$

Where G_d is the number of days in the growing season and H_p represents the hours per day the pump runs. The required rating power $P_{gen,rated}$ of the diesel generator that would be competent to drive the pump is represented in   (10, where P_p is the power required by the pump, and η_p is the pump efficiency.

$$P_{gen,rated} = \frac{P_p}{\eta_p} \qquad \textbf{(10)}$$

2.9 Water pump operating principle

The operation and ability of an irrigation water pump are associated with three major variables, the flow rate, pressure, and pump power [40]. In the case where the water pump is powered by

PV panels, the electricity produced by the arrays is transformed into mechanical energy that in turn converts into hydraulic energy within the pump. Thus, before choosing an irrigation pump, the source of water, the total suction head as well as the total dynamic head (TDH) need to be taken into consideration.

Besides, when selecting a solar-PV pump for a particular application, it needs to be compatible to transfer the appropriate volume of water from the source over the necessary distance and static head (delivery point). In addition to that, the selection of the pump should start with reading the pump curve, which depicts the correlation between the pump flow rate and the pressure head or total dynamic head as illustrated in Figure 9 [54].
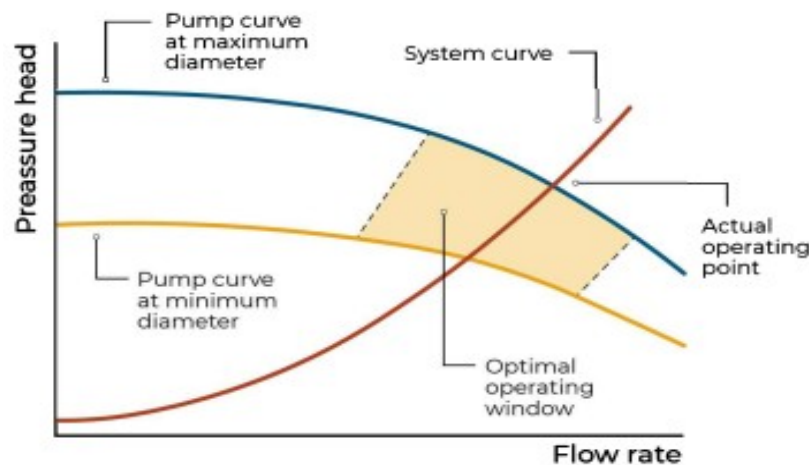
Figure 9: Overlaid generic pump curve and system curve [54].

The pump head plays a critical role in assessing the overall efficiency of the solar-PV-operated pumping system. The performance of the pump depends on the head or the discharge head; if the pump head is greater, it mainly leads to greater pressure. This simply implies that the flow rate is influenced by the pumping head and solar radiation level [68]. In Figure 9, the system curve is also presented, and where it intersects with the pump curve it indicates the actual operating point for the specific user application.

Figure 10 congruently demonstrates the total dynamic head, the suction head, and the static head involved in the system design together with the solar array, the DC motor, the pump, and the storage tank. As previously mentioned, the pumping head should carefully be selected because if the total pumping head is too high, it may not be possible to pump water at one stage.
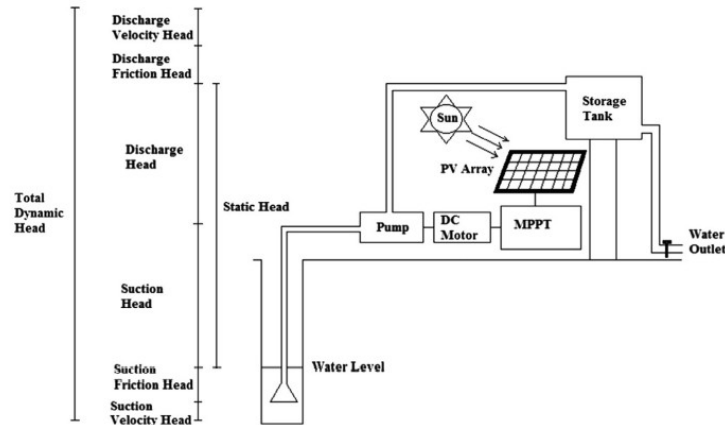
Figure 10: Irrigation schematic diagram setup with total dynamic head [69].

2.10 Effects of pumping head

Arunendra et al. [70] analyzed the impact of the head (10 m and 50 m) and PV array configuration on a solar water pumping system. It was concluded that the maximum discharge rate of 300 L/min was at 10 m head while the maximum discharge for 50 m head was 50 L/min when solar radiation is maximum. Further evidence showed that the outflow from various heads is insignificant in the early morning and late in the afternoon. While the discharge variation is very minimal for upper heads, it is significant for lower heads.

Moreover, Arunendra et al. [71] in another study evaluated six different pumping heads (10 m, 20 m, 30 m, 40 m, 50 m, and 60 m) to examine the effectiveness of the solar powered submersible pump and how well it performed under bright, sunny conditions. The head of 60 m has been shown to have the highest system efficiency and is advised for submersible pumps with deep heads.

Odeh et al. [72] established the scenario in PV water pumping as being distinct. The primary variables that have a significant impact on the design, optimization, and rating of PV pumping systems are the diurnal variability of isolation, the nonlinear behaviour of efficiencies and flow rate with isolation, and the sensitivity of system performance to a well pumping head and array size.

In the study conducted by Elias et al. [73], several pumping heads (50 m, 60 m, and 70 m) and 8S * 3P array configuration were considered when examining a submersible type variable speed DC water pump system. According to the research and simulation results, a lower pump head produced a higher flow rate regardless of the changes in solar irradiation levels.

On the techno-economic design of a PV-pump system for groundwater irrigation of crop production in Nigeria, Okakwu et al. [74] studied the impacts of the total system head and solar radiation. The results showed that the PV-pump system underperformed at higher system heads but worked effectively at higher solar radiation, providing insight into the impacts of altering the system head and the solar radiation. This was brought on by a drop in the discharge rate and an increase in power output correspondingly.

2.11 Environmental Analysis

Recent years have seen a rise in the use of solar-PV pumping systems for irrigation because of their environmental friendliness and desire to lessen reliance on fossil fuel-based energy sources. According to the Paris Agreement's target, 90% of the reduction of carbon dioxide (CO_2) emissions in the roadmap to 2050 can be provided by renewable energy sources combined with improvements in energy efficiency [75].

In a study conducted by Ali H. A. et al [76] for the optimum design and evaluation of solar water pumping system, the study found photovoltaic water pumping system having zero carbon emissions as compared to diesel generator with 144.64 kg CO_2 over the lifetime of the system. In Bangladesh, a 1.5 Horsepower (hp) capacity solar irrigation pump was tested to investigate its economic feasibility. It was discovered that although the solar irrigation system involves higher initial cost, it is economically viable and environmentally friendly [77].

The International Energy Agency [59] also pointed out that in 2021, about 1060 million tons of CO_2 have been saved globally. As per the study carried out by Charmaine S. et al [78], for socio-economic and environmental analyses of solar irrigation systems for sustainable agriculture production in the Philippines, it was discovered that solar irrigation has a positive environmental impact in terms of the reduction of greenhouse gas emissions by up to 26.5 tons CO_2eq/ha/year.

At this juncture, it is very fundamental to mention that environmental impact assessment (EIA) should be one of the steps in carrying out project evaluations. Environmental impact assessment

is described as a process to predict the environmental significance of a project's development and lessen or mitigate the negative impact of the human kind's footprints and maximize positive ones [78]. In terms of greenhouse gas emissions, the amount of greenhouse gases emitted can be calculated by using *equation* (11.

$$GHG = FC \times EF \tag{11}$$

Where *FC* is denoted as the average litres of diesel used for irrigation in the growing cycle of crops in a year. The emission factor (EF) is obtainable from Greenhouse Gas Inventories which is affirmed by the US Environmental Protection Agency (EPA) [79].

2.12 Economic Feasibility

The economic feasibility of the pumping system is related to system size optimization to express the reasonable price of power produced. The common economic approach that is mostly used to assess the system size and viability is the life cycle cost (LCC) analysis. The life cycle cost entails capital costs, maintenance costs, operational costs, fuel costs, and equipment salvage value [80]. The life cycle cost can be expressed by (12, where L_{CC} is the initial investment and the long-term (after *n* years) expense of owning and operating the irrigation pump, T_{RC} is all annual costs while T_{cap} is the initial costs that include equipment, and installation costs [6].

$$L_{CC} = T_{Rc} + T_{cap} \tag{12}$$

However, other researchers adopted traditional valuation approaches such as return on investments (ROIs), the payback period (PBP), the internal rate of return (IRR), and net present value (NPV) [8]. To determine the ROIs the following *equation* (13 is used where the investment return of the project is divided by the cost of the investment.

$$ROI = \frac{\sum_{t=1}^{T} R_t - I}{I} \tag{13}$$

In *equation* (13, *R* represents the annual net cash flow, *t* is the valuation period, *T* shows the technical lifetime of solar PV, and *I* is the investment cost for the solar irrigation system. Moreover, the other economic tool as mentioned earlier is the payback period. It is obtained by

calculating the time required to recover investment in the project and it is expressed by *equation* (14 below [8].

$$PBP = \frac{I}{R_t}$$ (14)

The net present value is also imperative for the system evaluation in that, a positive net present value indicates the improved financial position of the investor while a negative net present value implies a financial loss in the project. The zero or null net present value shows that the present value of the benefits over the valuable lifetime of the project is the same as the present value of all costs [8]. The net present value, therefore, can be described in *equation* (15.

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} - I$$ (15)

In *equation* (15, the net present value (NPV) of the project is the value of all future cash flows over the entire life (T) of solar PV irrigation pump's operation discounted to the present period at a discount of (r). Another economic tool is the internal rate of return; it is defined as the annualized effective compounded return rate earned on the invested capital. It is considered as the discount rate of interest which makes the NPV equal to zero [49]. It can be expressed as follows:

$$0 = CF_0 + \frac{CF_1}{(1+IRR)} + \frac{CF_2}{(1+IRR)^2} + \ldots + \frac{CF_n}{(1+IRR)^n}$$

$$0 = NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n}$$ (16)

Where CF_0 is the initial investment, CF_1, CF_2… CF_n represent the cash flow of the project, *n* means each period, and *N* is the holding period of the entire project [49].

Chapter 3: Methodology

3.1 Anticipated procedure

The procedure of the life cycle cost analysis of solar and diesel-operated pumping systems planned for irrigation application in Lesotho is depicted in Figure 11. The list of important input parameters and variables is also illustrated. The rationale of conveying single-site economic analysis on solar and diesel water pumping systems will be used as well. Nonetheless, the choice of the evaluation method employed in each step of estimation in this study has implications due to the very wide spatial scale of the investigation. Also, the implementation specifics of the life cycle cost estimating approach will be analyzed. For a diesel generator simulation, the cost of

fuel to be used will be based on the present price of fuel which amounted to 1.4 USD per litre in Lesotho.
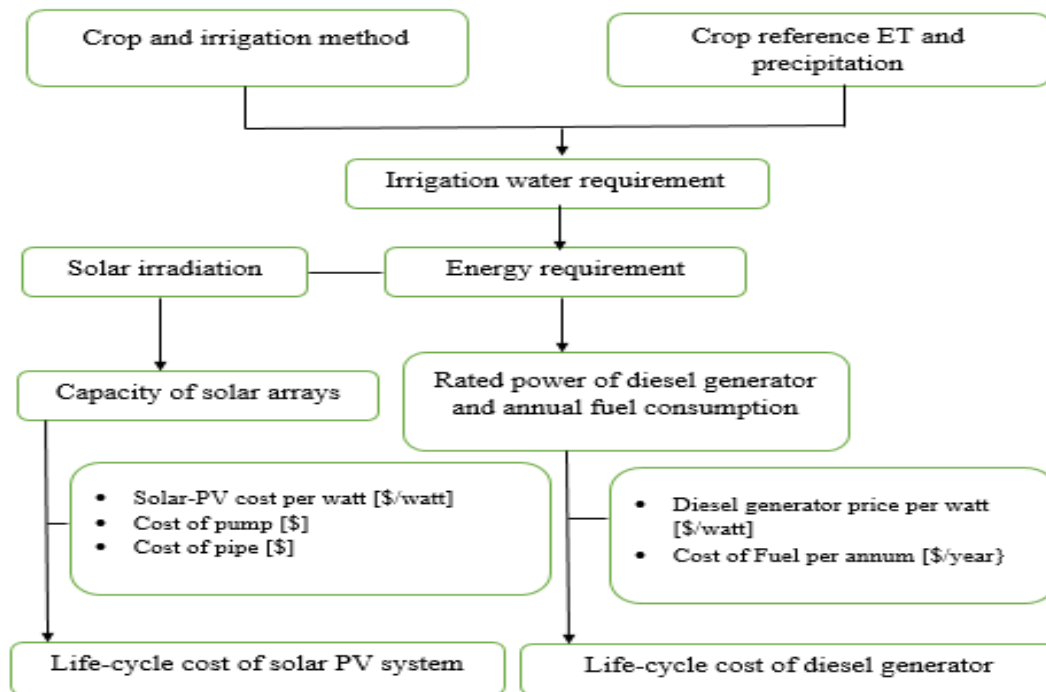
Figure 11: An estimation procedure of life cycle cost of solar and diesel operated pumping systems for irrigation application.

3.2 Study Area

Masowe is located in the peri-urban area of the Maseru district at the following coordinates: -29.377483° (latitude) and 27.492832° (longitude) as shown in Figure 12. The total utilized arable land for the study area is four hectares. The topography of the land is flat, with black loam soil that has intermediate water-holding capacity due to its texture and structure. This type of soil also dries quickly in the face of Lesotho's scorching radiation. However, it is fertile and rich in nutrients, necessitating irrigation to improve the long moisture content. The water source from this location is the Phuthiatsana River and the means of energy used for powering the irrigation pump is a diesel generator.

Figure 12: Geographical landscape of the study area

The annual precipitation received by the lowland parts of Lesotho, including the reference area, is 300 mm [20]. Based on Sharon [4], Solar PV water pumps are extremely recommended for regions with at least 300 mm to 400 mm precipitation per annum because their operation pumping units can reduce the payback period meaningfully. The meteorological data of the location for the year 2005 to 2020 would also be collected using PVGIS computer software which provides data about solar radiation and PV system enactment for any location. The average Global Horizontal Irradiation (GHI) in MJ/m²/day will be determined using an Excel program.

The rainfall pattern of Masowe is uneven and mostly falls outside the main farming season from October to April [20]. In , a brief description of values that need to be determined for the study area are presented, and the volume of water expected for irrigation per hectare is assessed. The static head H_o which is the elevation difference from the point of water supply to the point of discharge and the pumping distance *(Y)* will be taken into consideration. Pumping mains such as PVC pipes with different diameters will also be used to optimize the pipe which yields the least unit cost of pumping.

Table 2: description of the study area

Item	Description
Location	Masowe, Maseru Lesotho Lat. -29.4, Lon. 27.5
Average daily water demand	To be determined (m³/day)
Static Head	H_o (m)
Pumping distance	**Y (m)**
Pumping mains	PVC diameter range 63 mm; 75 mm, 90 mm and 110 mm
Pump Type	To be determined
Irrigation Technology	Flood irrigation

3.3 Irrigation water requirements

The capacity flow rate of water required for irrigation purposes will be determined based on crop evapotranspiration which is defined as the total amount of water lost due to transpiration from plants and the evaporation of water content in soil [4]. It will be calculated by using (17, where K_c is the crop coefficient, which will be extracted from the FAO crop data base, and ET_o is the reference evapotranspiration.

$$ET_c = ET_o K_c \qquad\qquad\qquad (17)$$

The amount of water lost during evaporation will be provided to the plants by irrigation or rainfall to enable the effective growth of the plant. It is also fundamental to evaluate crop water requirements since it guarantees sustainable and efficient management of water resources. The amount of water required for the entire crop cycle is firmly constrained by the climatic conditions of the specific site such as air humidity, ambient temperature, solar radiation, wind speed, and yearly amount of rainfall for the location [1]

The daily amount of water required by the crop will consequently be determined by the use of CROPWAT 8.0 computer software, which will determine crop water and irrigation requirements of selected crops (peas, beans, and maize) based on their growing seasons. CROPWAT 8.0 is the program developed by the Food and Agriculture Organization (FAO) of the United Nations to analyse the scheme of water supply for varying crop patterns [21]. As a result, the daily and

hourly evaluation of crop water demand will be determined by employing the FAO Penman-Monteith technique given by   (18 below [1].

$$ET_o = \frac{0.408\,\Delta\left(R_n - G\right) + \gamma\,\dfrac{900}{T_a + 273}\,u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34\,u_2\right)}$$

(18)

Where R_n is the net radiation at the grass surface (MJ/m²), G is the soil heat flux density (MJ/m² h), T_a is the mean hourly air temperature (°C), Δ is the saturation slope of the vapor pressure curve at T_a (kPa/°C), γ is the psychrometric constant expressed (kPa/°C), e_s is saturation vapor pressure   (kPa), e_a is the average hourly actual vapor pressure (kPa), and u_2 is the average hourly wind speed (m/s), while 900 is the conversion factor. The irrigation requirement (IR) will then be determined from [77].

$$IR = \sum\left(ET_c - P_{effective}\right)$$

(19)

Where $P_{effective}$ is the effective rain which is the total annual or seasonal precipitation that is directly or indirectly useful for crop production [77]. The effective annual rainfall will be considered using equation and   (21 below, where P is the monthly precipitation.

$$P_{effective} = ¿¿$$

(20)

$$P_{effective} = 0.1\,P\ for\ P > 250\,mm$$

(21)

3.4 Water pumping system Modelling

The dynamic model of the photovoltaic water pumping (PVWP) system needs the simulations of the photovoltaic array, crop water requirement, and the water pump [1]. Several studies have been carried out using different software such as MATLAB [81], LABVIEW [82], HOMER [83], SAM [84], PVSYS [85], TRANSYS [86], and Mathematical model [87] to optimize and evaluate the photovoltaic water pumping system. In this study, a method for optimal sizing and performance prediction of an irrigation solar pump would be done by adopting the Hove and Mungofa model [23].

The model was originally developed and used by Hove and Mungofa [23] for the optimal sizing of the solar-powered pump-pipe storage system. The advantage of the model is that it is precise and efficient in terms of sizing and extrapolation. It uses Microsoft Excel computer software

with simple equations for optimizing and sizing pumping mains, storage capacity, solar, and cost of pumping using the metric system approach of the unit cost of pumping. In addition, unlike other software, the model is capable of optimizing the solar-PV arrays, pump-pipe, and storage capacity even though in this study the ordinary storage calculation is used.

Moreover, the model uses an integrated approach to size the pumping mains and the water storage tank. It also develops a flow power function which systematically takes into account the time-step variation of solar irradiance and its effect on the pump system flow rate and the total dynamic head (TDH) which is given by *equation*   (22 below.

$$TDH = H_o + h_L \tag{22}$$

Where H_o is the static head and h_L is the friction and abrupt losses. For a long pipeline, the unexpected losses tend to be minor and may be disregarded. The friction loss h_L will be expediently determined for each flow rate by implementing the Hazen-William formula exemplified in *equation*   (23 [17]. The flow velocity V [m/s] is also given by *equation*   (23, where D [m] is the pipe diameter of the pumping main, C is the Hazen-William coefficient, Q [m³/s] is the volumetric flow rate, and S (h_L) is the slope which is the ratio of frictional loss to the length of the pumping main.

$$V = 0.85 C \left(\frac{D}{4}\right)^{0.63} S^{0.54} \tag{23}$$

Furthermore, in this model, the flow power function prompts the flow output of the solar pumping system as a function of the time-step variation of the PV array power output for a specified pump and pipe size. In that regard, based on the relative precise costs of PV arrays and pipe, an economically optimum combination of system components that conveys the desired daily amount of water required for irrigation at the least cost of pumping will be determined [17].

Most solar pump manufacturers offer laboratory-measured performance characteristics of the pump. These features of the solar pump reflect the variation of the pump flow rate (Q) in response to the discrepancy of power supplied by the photovoltaic array for a given persistent total dynamic head (TDH) [17]. Hence, an empirically driven method will be needed to predict pump performance, given that the PV power differs with the time of the day and causes the flow

rate to fluctuate. On the other hand, the variation of flow rate can influence total dynamic head to change based on the material, diameter, and length of the pipe.

So, the irrigation pumping system which is required is the one that will pump the required amount of water per hectare which will be determined from GROPWAT 8.0 using the Penman-Monteith technique developed by FAO. Hence, a rough selection performance table from a local Lorentz partner with the design flow rate calculated by dividing the daily water requirement by the peak sunshine hours and the total dynamic head will be used to select the required pump. The performance chart that will be utilized to select the pump is shown in Figure 13.
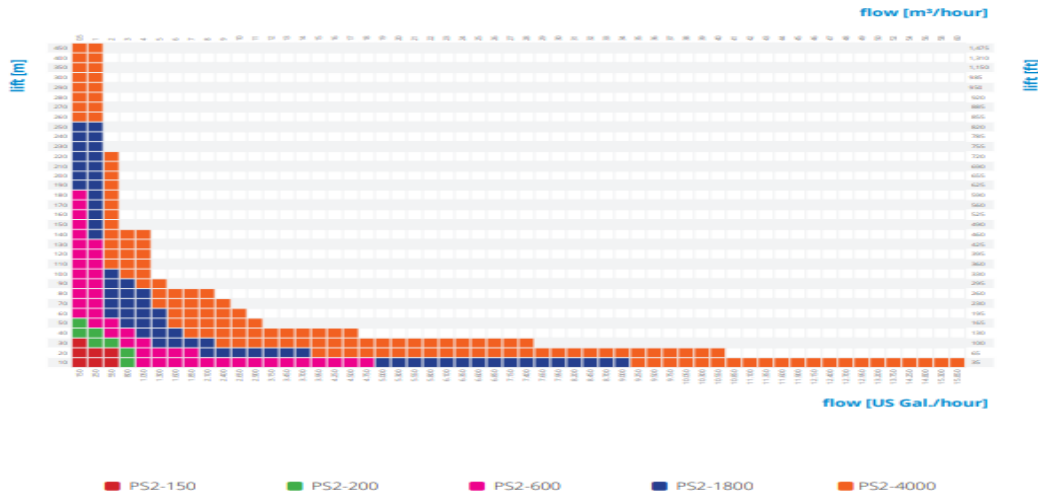
Figure 13: Pump performance selection table [88]

3.5 The PV Power Output Modelling

The shortfall in electricity and high diesel costs that are increasing daily affects the pumping necessities of water supply for irrigation purposes and community water supply. Therefore, solar water pumping technology which depends on PV that converts solar energy into electrical energy to track a DC or AC motor-based water pump is incorporated [50]. The solar pump performance output is required by the PV power output which in turn relies on the radiation collected on the plane of the PV array [17]. The PV output power P_{PV} of the PV modules under subjective atmosphere conditions are expressed as:

$$P_{PV} = \frac{\frac{\eta_{PV}}{\eta_{STC}} * G_T}{G_{STC}} * P_{STC} \qquad (24)$$

Where η_{PV} is the operating efficiency, G_T is the irradiance measured on a tilted plane, and G_{STC} represents the reference irradiance while P_{STC} is the rated power of the PV array at Standard Test Conditions (STC). In addition, the operating efficiency is considered as the function of temperature. It is also interrelated to other constants such as the matching factor F_m which is described as a ratio of the power output of the PV array under operation conditions to its power output at the maximum point. It can be described as [17]:

$$\eta_{pv} = F_m [1 - \beta (T_{cell} - 25)] \eta_{STC} \tag{25}$$

Where T_{cell} is the cell temperature and β is the cell efficiency temperature coefficient. Here, different matching factors will be examined, together with the 0.9 matching factor which is commonly acknowledged in a PV system [17]. Other parameters will be obtained from manufacturers' product data sheets because cell temperature is hard to monitor under field operation. As a result, the standard formula to engage cell temperature with ambient and in-plane solar radiation ignoring the effect of wind speed on cell temperature can be expressed in this form:

$$T_{cell} = T_a + \frac{G_T}{G_{T,NOCT}} (T_{C,NOCT} - T_{a,NOCT}) \tag{26}$$

The symbol $T_{C,NOCT}$ in   (26 represents the nominal operating cell temperature (NOCT), $T_{a,NOCT}$ is ambient temperature at NOCT, and G_T is the irradiance incident on the plane of the PV array.

3.6 Solar Pump Flow-Power Function

The solar pump flow-power function is explained as the flow output of the solar pumping system and it relies on the active variation of the PV array power output for a given pump and pipe dimension [17]. So, for the study that was conducted by Hove and Mongufa of sizing and performance prediction of solar-powered pump-pipe systems using empirical solar radiation and pump characteristic data, it was discovered that as the power supply level fluctuates, the speed of the solar pump also differs.

Therefore, for each particular PV power supply level, a pump head-flow (H-Q) can be described and read from the matching pairs of H and Q values, fitting the best curve that relates head and

flows. On the other side, the curve fitting techniques will be used to find the best fitting curve to calculate the regression coefficient of the pump. The head-flow correspondence can then be expressed as:

$$H_{pump} = p_2 Q^2 + p_1 Q + p_0 \tag{27}$$

Where H_{pump} is the pump head at a flow rate [m³/hr] and p_0, p_1, and p_2 are the pump-specific regression coefficients as presented in . The operating flow rate is delineated by the intersection of the H_{pump} and total dynamic head curves for the pump when connected to the pipeline diameters.

Table 3: H-Q regression coefficients for Lorentz PS2-4000-CS-F32-20-2

PV Power (kW)	1.2	1.8	2.4	2.8
p_2 [hr².m^{-5}]	0	0.014	0.003	0.011
p_1 [hr².m^{-2}]	-1.15	-1.45	-1.101	-1.72
p_0 [m]	32.3	42.7	48.6	64

3.7 PV Array Modelling

The size of the photovoltaic array will be attained by iteratively changing the PV power and by using for (28 for (28 to determine the hourly PV power. In this equation, P_{OFF} is the minimum PV power that can make the pump operate.

$$Q_{op} = q_1 \in (P_{PV}) - q_0 \qquad \textbf{for } P_{PV} \geq P_{OFF} \tag{28}$$

$$Q_{op} = 0 \qquad \qquad \textbf{for } P_{PV} < P_{OFF}$$

Where Q_{op} is the operating flow rate, the flow power function will be used to calculate the flow rate for each hour using for (28 which results in the daily water volume provided by the pump when unified numerically over time. The PV array size will be modeled when the solar

pump is linked with a selected pipe diameter. The photovoltaic power will then be changed in small steps until the required daily pumped volume of required water is gained. The designed month will formerly be selected based on the month that requires more water per amount of radiation received.

3. 8 Storage Capacity

It is very important to optimize the water storage capacity of the irrigation system to store the water that will be used during the days of no sunshine. The storage capacity refers to the volume of water that must be stored to maintain a balanced supply of water for irrigation purposes. According to Miran et al [29], based on the location and usage patterns, storage tanks classically have a capacity of 3 to 10 days storage. Thus, if the daily water requirement is *X* Litres, the storage capacity should be at least 3*X* Litres, and in high cases, it can be as much as 30*X* Litres.

Abu-Aligah [15] showed that instead of storing energy in batteries, it is economically viable to store water in the reservoirs as it reduces about 1/3 of the system cost and most of the system maintenance. Pande et al [19] also emphasized that the utilization of available runoff water through surface storage systems followed by pumping may be a potential solution to achieve the set goal of the 'crop per drop' mission. However, this method of storing water has a disadvantage in that the high evaporation loss of water and easy accumulation of fragments and sediments as well as algae growth can persist.

As a result, the method that will be applied in this study is the ordinary method of determining the storage capacity requirement for irrigation by multiplying the average daily water demand per hectare by the days of autonomy (A_d) which usually range between 2 to 5 days here in Lesotho to cater for a long cloudy period. The electric load demand for filling the storage will then be determined by the multiplication of operation hours and pump power.

3.9 Greenhouse Gases determination

The use of diesel generators can result in the emission of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). For the purpose of managing land use, addressing global warming, and conducting climate research, accurate quantifications are required because both storage and emission capacity may be greater [89]. So, in terms of greenhouse gas emissions, the amount of GHG to be emitted by diesel generators will be

calculated by using *equation*   (11. The emission factor (EF) of 10.21 kgCO_2 for 2022 is obtainable from Greenhouse Gas Inventories which is declared by the US Environmental Protection Agency (EPA) [79].

3.10 Economic Feasibility of Pump for Irrigation

The economic feasibility of pump irrigation is the most important factor that inspires the expansion of large-scale pump irrigation systems. It is also considered a vital indicator which mostly concerns stakeholders [40]. Various factors are employed to evaluate the economic feasibility of pumping irrigation and these factors are associated with the investment cost, the Net Present Value (NPV), the Internal Rate of Return, the Payback Period (PBP), and the Life Cycle Cost Analysis (LCCA) [40].

Consequently, in this study, the life-cycle cost analysis (LCCA) for both solar- and diesel-operated pumping systems will be affianced to assess the total cost of facility possessions engaged. In this respect, the unit cost of the pumping approach will be used. The life-cycle cost analysis will help to estimate the overall costs of a project and its alternatives to select the design that ensures the facility that will provide the lowest overall cost of ownership [6].

It is very important to elaborate that for the selection of pipe diameter, the comparison matric of the unit cost of pumping will be employed. So, the unit cost of pumping is determined as the annualized cost of the sum of capital costs of the solar PV array, pipeline, pump motor controller unit, and the annual maintenance costs which are all divided by the annual amount of water pumped as expressed by   (29 [17].

$$C_{pumping} = \frac{C_{capex} * r}{1 - (1+r) - ¿^n + C_M ¿} \qquad \textbf{(29)}$$

Where r is the discount rate and n is the project's life span. C_M is the maintenance cost while C_{capex} represent the capital cost of the asset and $C_{pumping}$ is the cost of pumping.

An optimized pump, key components, and a diesel generator's cost requirements and manufacturing technical parameters will be required for analysis to determine each system's life cycle cost. For irrigation applications, it is estimated that the solar-PV and diesel-operated pumping systems have usable lifetimes of 25 years and 10 years, respectively.

Chapter 4: Results and discussions

The results obtained in this study unveil the values of several key transitional variables such as the irrigation water requirement, the size of solar photovoltaic power system, the size of the required pipe diameter, the diesel fuel consumption, and the amount of greenhouse gas emissions. An optimized solar pump and the power of an optimized diesel generator are also presented. In addition, the results are also illustrated through tables, graphs, and figures for easy interpretation. Flood irrigation adopted in this study with an efficiency of 0.6 is also stated. Lastly, the storage capacity and the economic comparison between diesel-operated systems and solar-operated systems for irrigation are discussed.

4.1 Geographical Location Information

The monthly meteorological data for the study area from 2005 to 2020 has been extracted from the photovoltaic geographical information system (PVGIS) computer software which provides data about solar radiation and PV system portrayal for any location [22]. The Global Horizontal Irradiation (GHI) in MJ/m²/day was then determined using an Excel program. The maximum temperature (T_{max}), minimum temperature (T_{min}), humidity, precipitation, and wind speed of the location which were obtained from Maseru, Lesotho using the climate and monthly weather forecast are characterized in [90].

The study area's topography is flat, with black loam soil that has intermediate water-holding capacity. Due to its texture and structure, this type of soil dries quickly in the face of Lesotho's burning radiation. Nevertheless, it is fertile and rich in nutrients, enabling irrigation to improve the long moisture content. For this study area, December is considered the month with the highest GHI of 26.31 MJ/m²/day and June is the lowest with 12.79 MJ/m²/day. This suggests that the area receives plenty of sunshine throughout the year which will help solar PV technology produce more electricity.

Table 4: meteorological data of study area.

Month	GHI(kWh/m²/day)	GHI(MJ/m²/day)	Tmax	Tmin	Humidity (%)	Rainfall (mm)	Wind speed (km/h)	Wind speed (km/day)
Jan	6.97	25.10	26.1	14.8	54	65	9	216
Feb	6.46	23.27	25	13.3	59	51	8	192
Mar	5.69	20.47	23.8	11.3	58	42	8.1	194.4
Apr	4.60	16.55	19.6	7.9	58	37	7.6	182.4
May	3.96	14.26	17.1	5.2	56	8	7	168
Jun	3.55	12.79	13.6	2.1	55	12	7.6	182.4
Jul	3.89	13.99	13.8	2.2	51	7	7.4	177.6
Aug	4.63	16.68	17.1	4.2	41	7	9.1	218.4
Sep	5.81	20.91	21.2	7.7	35	9	10.4	249.6
Oct	6.46	23.25	23.1	10.6	40	33	10.7	256.8
Nov	7.21	25.95	24.2	11.6	45	45	11.1	266.4
Dec	7.31	26.31	25.5	13.8	51	71	10	240

4.2 Preliminary Findings

The qualitative analysis of gathering data was used to find the costs and fuel consumption of five small-scale farmers using diesel irrigation systems. Some data was also collected from the Ministry of Agriculture's department of irrigation. The thematic analysis which is considered a foundational method of all qualitative analysis was employed to describe data familiarization after the interviews with different farmers [91]. According to the department of irrigation's analysis, 95% of Lesotho's farmers still rely on gravity-fed irrigation and rain-fed agriculture.

The summary of the costs of fuel, operation, and maintenance is presented in for the farmers who use diesel generators for an estimated 200 days of the irrigation schedule and growing cycle of crops per year. Four of the farmers interviewed use drip irrigation kits to irrigate under greenhouses covering an area of $15\,m \times 30\,m \approx 450\text{m}^2$ and a 5000-liters tank for storage. Based on the findings, the initial capital cost of a diesel generator used by these farmers is USD 811.47 and it can fill two 5000-litre tanks, with 10 litres of fuel consumption per day, using a 50 mm pipe diameter in 4 hours.

Pressure from an elevated tank is used to supply drip kits which takes a long time and costs a lot of money to refill two tanks a day which do not even achieve the total amount of water demanded by the crops. According to the farmers, the operation and maintenance costs of the diesel generator amount to 5% of the initial cost per annum whereas the fuel cost is estimated to be $2,834.88 per year based on the current price of diesel in Lesotho. It was also discovered that

for some farmers, the amount of water pumped per day does not cover a specified area to be irrigated.

Table 5: Summary of costs from different interviewed diesel irrigation users

Item	Parameter	Unit	Costs
1	Investment cost (diesel gen)	$/ha	811.47
2	Diesel Consumption	L/ m^2/yr	2,000.00
3	Fuel cost	$/ m^2/yr	2,834.88
4	Operation and Maintenance	$/ m^2/yr	40.57

Table 6 also indicates the technical manufacturer's characteristics and economic parameters of the self-driven diesel generator that is operated at the study site. The generator was provided as a subsidy by the government of Lesotho and the farmer only paid $ 520.72 as capital cost for a 6-cylinder diesel generator. Irrigation technologies used in this study area include flood and micro-sprinkler.

The Phuthiatsana River is used as the main source of water for irrigation. For the economic aspects, the diesel generator operates for 5 hours per day and consumes 20 litres of fuel, which is approximately $5660.87 per annum for 200 days of operation in a year for one hectare. The maintenance of the generator is done once after a growing season, with the amount approximated to be $ 115.63. The calculated unit cost of pumping was found to be 22.74 USD cents/ m³.

Table *6*: Parameters of a Diesel Generator on the Study Side

Item	Parameters	Specifications
1	Total head	120 m
2	Flow rate	119 m³/h
3	sanction head	1.5 m

4	static head	23 m
5	Fuel consumption	20 L/ha
6	Operation Time	5 hrs.

4.3 Simulation results and discussion

Optimization of the irrigation system was done in consideration of the month of November (that requires more water per amount of radiation received) and the pipe size diameter of 110 mm with 2110-watt PV array which results in a lower unit cost of pumping amounting to 3.58 USD cents per m³ of water pumped. However, the initial step was to find the crop water requirement (load) for the growing cycle and irrigation schedule of beans, peas, and maize under different climate conditions using the CROPWAT 8.0 and CLIWAT 2.0 computer programs that use the Penman-Monteith equation to find the daily irrigation water requirement of 96 m³/ha.

An outlined result showed that a solar-PV system can operate for 6 hours per day to fulfill the water required by the plants with a power capacity of 24 kWh. The daily crop water requirements of the selected crops for different months are shown in Table 7. The radiation on the tilted surface of each month is also demonstrated. With an efficiency of 0.6, flood irrigation was chosen as the irrigation technology in this study [4]. The reason is that for cost-effective purposes, flood irrigation is considered economically viable as it does not require more components for installation.

The net irrigation water requirement (NWR) which is defined as the depth of water required to meet crop water requirements in excessive rainfall for crop growth was calculated using the irrigation technology proposed. As shown in Table 7, the designed month was chosen based on the month that requires the most water per amount of radiation received. As a result, the month of November, with 1.48 $mm/kWh/m^2$, is chosen as the designed month. The tilted surface irradiation of November in this regard is 6.47 kWh/m²/day, with a tilt factor of 0.9 calculated from the model.

Table 7: Crop water requirement (CWR) and the designed month

Crop water Requiment(CWR) and the designed month					Hectares	1
Month	CWR (mm/day)	Irr Eff	Net WR(mm)	Rad on tilted surface(Kh/m2/day)	NWR/GTI	(m3/day)
Jan	1.60	0.6	2.67	6.18	0.43	27
Feb	0.70	0.6	1.16	6.2	0.19	12
Mar	3.02	0.6	5.04	6.06	0.83	50
Apr	2.63	0.6	4.38	5.63	0.78	44
May	1.15	0.6	1.92	5.63	0.34	19
Jun	0.55	0.6	0.91	5.47	0.17	9
Jul	1.55	0.6	2.58	5.84	0.44	26
Aug	3.51	0.6	5.84	6.07	0.96	58
Sep	5.76	0.6	9.61	6.59	1.46	96
Oct	1.98	0.6	3.30	6.39	0.52	33
Nov	5.75	0.6	9.58	6.47	1.48	96
Dec	5.41	0.6	9.02	6.31	1.43	90

4.4 Flow Power Function

By way of definition in the methodology section, the flow power function expresses the flow output of the solar pumping system as a function of the time-step variation of the PV array power output for a specified pump and pipe size [17]. In Table 8, the coefficients of the flow-power function for the Lorentz PS2-4000-CS-F32-20-2 solar surface pump which is proposed by using a rough selection table in Figure 13 from a Lorentz partner with the designed flow rate of 16.5 m³/h and total dynamic head of 18.5 m plus flow velocity of 0.5 m/s are presented. T he calculated frictional loss per meter is found to be 0.003; this is very minor and it can be neglected based on the length of the pipe proposed.

Table 8: Lorentz PS2-4000-CS-F32-20-2 pump flow-power function coefficients.

Pipe diameter	63 mm	75 mm	90 mm	110 mm
q	14.2	17.6	20.4	22.3
qo	-7.8	-8.7	-9.2	-9.3

The designed flow rate was calculated by dividing the daily crop water requirement at the site by the month's peak sunshine hours. The carefully chosen pump is then coupled with a 143-meter PVC pipe of different diameters (63 mm, 75 mm, 90 mm, and, 110 mm, and a static head of 18 m). The specific manufacturers that measure the performance characteristics of a Lorentz PS2-4000-CS-F32-20-2 pump with a maximum flow rate of 42 m³/h and a maximum head of 30 m pump curves are shown in Figure 14. At this point, the pump curves represent the variation of the pump flow rate (Q) in response to the variation of power supplied by the PV array for a given constant total dynamic head (TDH) of an optimized system.
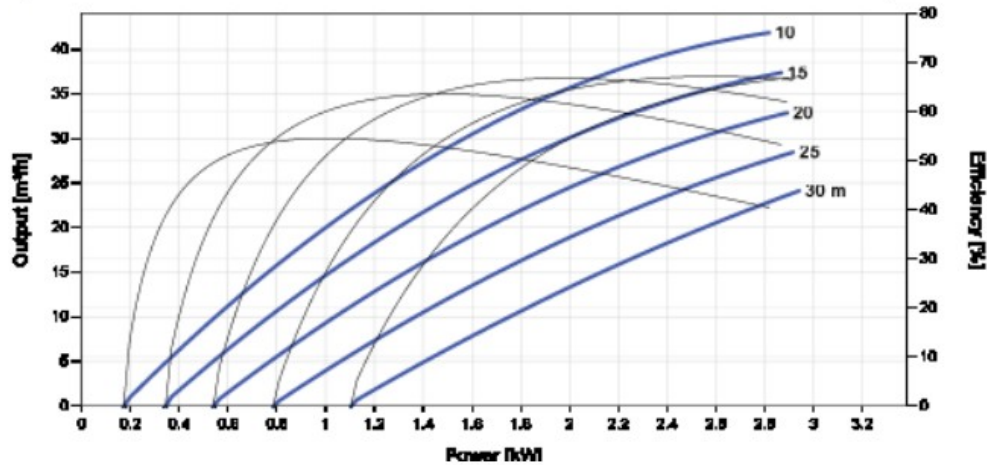
Figure 14: Pump chart for Lorentz PS2-4000-CS-F32-20-2 solar surface pump

Furthermore, as illustrated in Figure 15, pump characteristic curves were used to select the required head and capacity for a range of operating conditions at maximum system efficiency. The head and discharge as illustrated are developed by the pump under discussion. The point at which the Total Dynamic Head (TDH-Q) and the system head curves intersect is considered the actual operating point. Moreover, where the two curves meet, the head established by the pump is the same as the head required by the system at the flow rate.

In this regard, the operating point of the system should fall to the right side of the peak efficiency for competent performance even after the uninterrupted operation. In this pump simulation, the system head curves are time-dependent due to variations in the river drawdown, friction, operating conditions, the maximum source abstraction rate (static water level), and wear of pumping components.
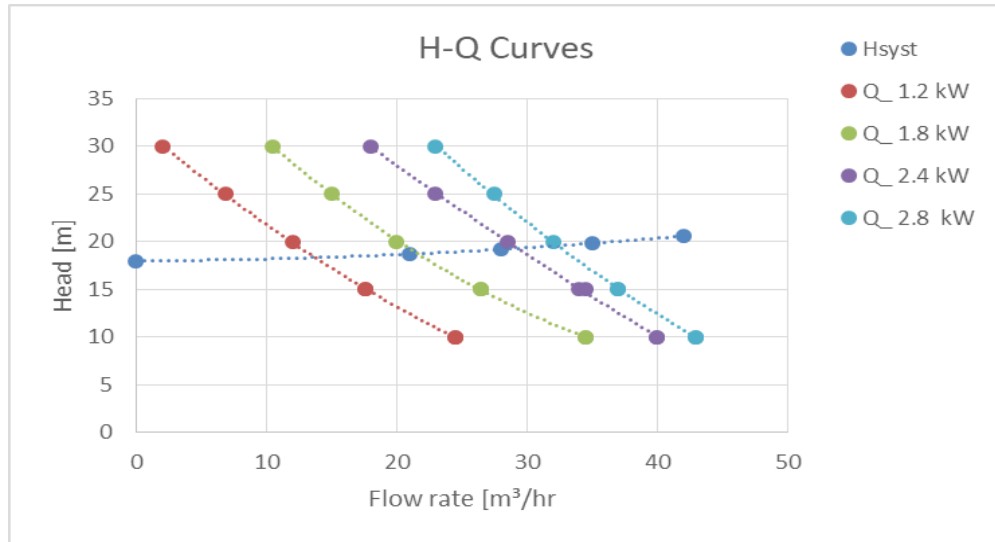
Figure 15: Operation point of the pump with different heads

4.5 The PV system

The schematic diagram depicted in Figure 16 (a) shows the connection between different pipe size diameters and the appropriate PV arrays for the solar pump pipe system. This merely shows that as the pipe diameter increases from 63 mm to 110 mm, the required PV array power decreases and is virtually curved up. In turn, the required PV array power is designed to transfer the daily average volume of water that is needed by the plants.

Conversely, the costs of each system differ based on the different PV arrays and pipe sizes even though they all supply the same volume of water per day. Furthermore, due to different pipe diameters, a marginally different annual amount of water is delivered as illustrated in Figure 16 (b). Nevertheless, during the forecast month of November which needs more water per unit of radiation, all pipes distribute the same amount of water.

(a)	(b)
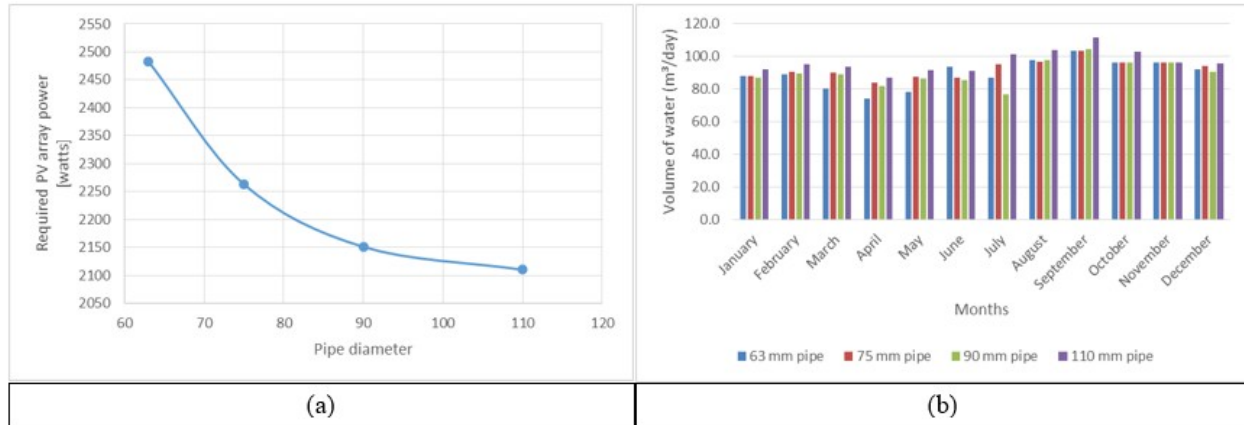
Figure 16: The required PV array variation with pipe diameter (a); Annual volume of water delivered by different pipes (b)

Based on the nominal operating power and voltage of the pump and the chosen module (NES72-6340P polycrystalline silicon) [92], the PV power configuration for the designed system was selected. As a result, the optimization was performed by matching the maximum pump-rated voltage for the chosen pump. The rated voltage of the selected module as denoted in Table 9 is 36.6 V at 340 W.

To set the 238-volt rating to match the pump-rated voltage, seven modules that will yield 2380 watts are needed. Therefore, the size and scope of the deviation from the designed value are 2380 watts divided by 2110 watts, resulting in a 1.1% discrepancy from the design point. Then, as an outcome, oversizing has managed to be avoided in this revision.

Table 9: Solar pump and Panel Manufacturers' specifications

Item	Max Voltage [V]	Max Power [Watts]	Efficiency [%]
Lorentz PS-4000-CS-F32-20-2	238	4000	92
NES72-6340P polycrystalline silicon	36.6	340	17.5

4.6 The system efficiencies

The diagram in Figure 17 (a) indicates the Lorentz PS2-4000-CS-F32-20-2 solar surface pump system efficiencies which are connected to a 110 mm diameter pipe and 2110 Watts PV array power. The modeled hourly variation of the pump system efficiencies is determined on the

average day of the designed month which is a recommended monthly average isolation on the tilted surface as shown in Table 10 [93].
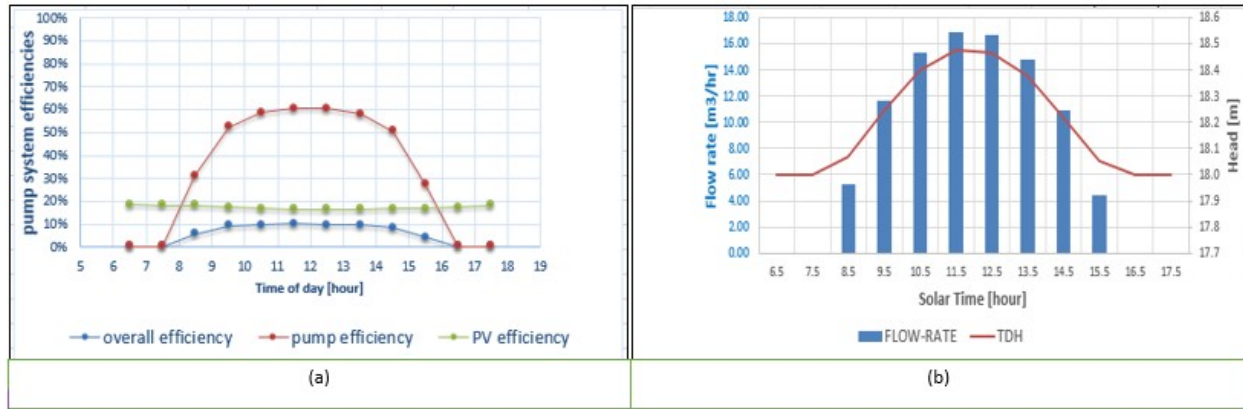
Figure 17: The hourly variation of System efficiencies (a) and hourly flow rate-related fluctuation for the intended month.

As it can be observed from the graph (Figure 17 (a)), the PV efficiency is greater between 6:30 a.m. and 17:30, and around that time the ambient and cell temperatures are normally lower as compared to mid-day hours when they are higher. Throughout the midday hours, the pump productivity is greater, and it then drops gradually late in the afternoon.

This demonstrates that more water is pumped during the day based on solar time as shown in Figure 17 (b) where the hourly variation of the flow-head relation for the designed month is validated. Likewise, the overall system efficiency escalates from zero around 7:30 a.m. and peaks in the mid-morning hours. From 14:30, the overall solar pumping system efficiency dropped progressively over the day, and then dropped to zero later in the afternoon.

Table 10: Recommended Average Days for Months

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average day	17	16	16	15	15	11	17	16	15	15	14	10

4.7 The diesel Generator

One of the components used as a backup source is a diesel generator, and the fuel consumption at any given time defines its performance. An optimized architecture of the diesel generator required to meet a demand of a 4 kW Lorentz PS2-4000-CS-F32-20-2 pump with an efficiency

of 0.92 is found to be a 4.5 kW diesel generator (BPD5000S) with a power factor of one [94]. The required rating power $P_{gen,rated}$ of the diesel generator that will be suitable to drive the pump was determined by dividing the pump power by its efficiency as described by   (10.

As a result, the size and scope of deviation from the designed value is 4.5 kW divided by 4 kW which also yields 1.1%. In that manner, oversizing the generator is also avoided. Based on the manufacturer's measured characteristics performance, an enhanced diesel generator can operate for 8 hours per day connected to a 110 mm pipe, with a discharge rate of 12 m³/hr. to meet the daily water requirements. For fuel consumption, the generator consumes 1.8 L/hr. at 75% load, and at 100% load, it consumes 2.3 L/hr. which is approximated to 2880 L/year at 200 days of operation at the growing cycle of 3 crops.

4.8 Storage Prediction

Prediction of the storage size for water that will be used in days of autonomy is very fundamental. In that instance, poor sizing of the storage configuration is very sensitive as it can distress the system reliability and further develop a shortage in the daily water demand. Likewise, as much as a battery storage system is versatile in electrical transformation; it is not achievable due to its high costs and sustainability. Hence, the alternative decision adopted in this study for storing water is a storage tank.

So, for the variable PV output, the simple traditional method of sizing the storage is employed. The reason is that it is quite clear based on the meteorological data collected that Lesotho has abundant solar radiation for electricity production and the days of autonomy are habitually between 2 and 5 days [17]. This ordinary method of calculating water storage was also used by Miran et al [29]. It shows that if the daily water requirement is **X** Litres, the storage capacity should be at least **3X** Litres**.**

So, for this study, the storage capacity required to maintain and balance the supply of water for a maximum of 3 days when there is no sunshine is a 288 m³ storage tank, at the pump flow rate of 16.5 m³/h. Hence, to achieve this, a pump type Lorentz PS2-4000-CS-F32-20-2 of 4 kW will take 17.5 hours at full power to fill the tank and in that way; the storage capacity is 70 kWh. The energy required to pump the necessary amount of water to fill the storage is represented by the electric power load demand.

4.9 Economic Analysis

Economic considerations play a major role in solar PV and diesel pump irrigation system expansion. It is also considered the primary indicator that worries stakeholders. Hence, the goal of these irrigation powered systems is to obtain a system with a low cost per cubic meter of water pumped. The economic analysis in this study also takes into consideration the investment cost of the PV array, the individual components that make up the system such as the DC pump, PVC pipes, the diesel generator, the operation and maintenance costs, and the replacement cost of the pump as well.

As a result, the life cycle cost analysis (LCC) is employed for economic appraisal and comparison, where all future costs are discounted to their present value by a 10% discount rate. Similarly, the life-cycle cost analysis assists in estimating the overall costs of a project and its alternatives to select the design that ensures the facility has the lowest overall cost of ownership. Hence, the matric technique of the unit cost of pumping approach is used to compare the life cycle cost of a solar PV pumping system for a life of 25 years, and a diesel-operated pump for a life of 10 years. The command area of both systems is one hectare and irrigation is applied in three crops per growing cycle per year.

4.9.1 Comparison of the Life cycle cost of the solar PV and diesel Generator pumping systems.

The costs and the total life-cycle cost (LCC) for the solar PV and diesel pumping systems are shown in . The prices of some individual components were derived from the manufacturers' websites. The costs of the pump and the generator were recovered from www.BunduPower.co.za whereas the pipe cost and the PV panel cost per watt were retrieved from https://www.alibaba.com. The metric system of the unit cost of pumping was then completed based on different pipe diameters to calculate the pipe size that has the lowest unit cost of pumping.

The unit cost of pumping was therefore determined as the annualized cost of the sum of the capital costs of the pipeline, PV array and pump, plus the annual operation and maintenance costs, divided by the volume of water pumped per annum. As depicted in , the annualized cost of solar PV at a 10% discount rate is $1263.00, and for diesel generators, it is $5517.00, with 35314

m³ of water pumped per annum. The cost of the solar PV per watt including installation at the initial stage is 0.42 $/watt while the diesel generator is 0.41 $/watt.

Pumping costs per unit were calculated to be 3.58 USD cents per cubic meter for solar PV and 16.1 USD cents per cubic meter for diesel generators. This implies that even though the initial cost of solar PV per watt including installation is slightly higher than that of a diesel generator system, pumping with solar PV is much less expensive over the long term compared to pumping with a diesel generator system. It shows that the diesel generator will continue to cost more based on the daily increase in fuel prices.

Table 11: Summary of LCC analysis for solar PV and diesel-operated system

Parameter	Solar-PV	Diesel generator
Pump cost [$]	5,358	5,358
Cost/watt [$/w]	0.42	0.41
Lifespan (years)	25	10
Fuel consumption cost [$]/annum	0	4051.6
Annualized cost at 10% discount rate [$]	1263	5517
Annual water pumped [m³]	35314	35314
Cost of pumping [cents/ m³]	3.58	16.1

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

The issue of energy for irrigation has been complicated by subsidized power. In an effort to get around some of the problems, numerous, new solar photovoltaic models and interventions have been considered. Thereafter, a recent intervention which exemplifies the new study methodology is described, of which this study adopted. Hove and Mungofa computer Excel Model for sizing and simulating the performance of solar pumping system at the reference study site was studied. The economic comparison of solar and diesel generators for irrigation applications was also described.

In addition to the empirical data on the performance of the solar pump, the prescribed model of sizing and performance extrapolation approach also made use of data on the solar radiation and ambient temperature of the location. The empirical functions of the flow rate as opposed to solar power were similarly derived for different pipe size diameters. The best solar pumping system was then chosen based on the pump, pipe diameter, and the PV-array size that produced the lowest pumping cost per unit of energy.

The simulation results outlined here indicate that the best system configuration which results in the least unit cost of pumping is comprised of a 4 kW Lorentz PS2-4000-CS-F32-20-2 centrifugal solar surface pump, 110 mm pipe size, and 2110-watt PV array. As a caveat, it is important to point out that solar photovoltaic (PV) seems to be a promising energy alternative to support irrigation development in Lesotho because solar pumping systems have low operating costs. They do not require fuel and they have minimal maintenance requirements which make them a cost-effective and sustainable option in the long run.

The unit cost of pumping for a solar PV-operated pump for irrigation application is 3.58 USD cents/ m³ while it is 16.1 USD cents/ m³ for a diesel generator. The annualized cost of solar PV at the 10% discount rate is found to be $1263.00, and that of a diesel generator is $5517.00, with 35314 m³ of water pumped per annum. The cost of solar PV per watt including installation at the initial stage is 0.42 $/watt while it is 0.41 $/watt for the diesel generator.

The proposed system was also found not only cost-effective but also environmentally friendly as it emits zero amount of greenhouse gases. The amount of greenhouse gases saved as per

simulation when using a diesel generator for irrigation purposes is 32.3 tons of carbon dioxide (CO_2) per year. Fuel consumption determined by the study ($ 4051.6/ha//year) was compared with the fuel consumption of the study site which is $5660.87/ha/year. The unit cost of pumping for the study site using a diesel generator is 22.74 cents/ m³ whereas for the study it is 16.1 US cents/ m³. This concludes that the diesel generator at the study site is over utilized and it leads to needless expenditures.

5.2 Recommendations

For the discussed study, there are some boundaries that need to be improved for further research which involves the source of meteorological data. Due to the shortage of data and the absence of a meteorological station which is close to the study site, and the possibility that the applied data would not have fully matched the real site data, the study retrieved meteorological data from PVGIS. Another boundary observed in this study is the applied model since it does not cater for the diesel generator optimization and emitted greenhouse gas calculations. Hence, for further research, a comparative evaluation of various energy sources is required.

In a nutshell, to create future inclusive renewable energy integrated systems, further research is recommended in the following areas;

- Creating the best possible control approach to manage the community's energy consumption and irrigation system effectiveness.
- Examining the potential outcome of intermittent generation owing to unreliable solar photovoltaics.
- For accurate results comparisons, the use of solar radiation measured from the ground is also advised.
- Creating a professional case model that includes stakeholders and decision-makers.

References

[1]   P. E. Campana, H. Li, J. Zhang, J. Liu, and J. Yan, 'Economic optimization of photovoltaic water pumping systems for irrigation', *Energy Convers. Manag*, vol. 95, pp. 32–41, 2015.

[2]   G. Falchetta *et al.*, 'A renewable energy-centred research agenda for planning and financing Nexus development objectives in rural sub-Saharan Africa', *Energy Strategy Rev.*, vol. 43, p. 100922, Sep. 2022, doi: 10.1016/j.esr.2022.100922.

[3]   G. Falchetta *et al.*, 'A renewable energy-centred research agenda for planning and financing Nexus development objectives in rural sub-Saharan Africa', *Energy Strategy Rev.*, vol. 43, p. 100922, Sep. 2022, doi: 10.1016/j.esr.2022.100922.

[4]   S. Hilarydoss, 'Suitability, sizing, economics, environmental impacts and limitations of solar photovoltaic water pumping system for groundwater irrigation—a brief review', *Environ. Sci. Pollut. Res.*, Feb. 2021, doi: 10.1007/s11356-021-12402-1.

[5]   M. Z. Abid, M. Yousif, S. Ullah, and M. Hassan, 'Design, sizing and economic feasibility of a hybrid PV/diesel/battery based water pumping system for farmland', *Int. J. Green Energy*, vol. 19, no. 6, pp. 614–637, May 2022, doi: 10.1080/15435075.2021.1954007.

[6]   A. Parvaresh Rizi, A. Ashrafzadeh, and A. Ramezani, 'A financial comparative study of solar and regular irrigation pumps: Case studies in eastern and southern Iran', *Renew. Energy*, vol. 138, pp. 1096–1103, Aug. 2019, doi: 10.1016/j.renene.2019.02.026.

[7]   E. Mulenga, A. Kabanshi, H. Mupeta, M. Ndiaye, E. Nyirenda, and K. Mulenga, 'Techno-economic analysis of off-grid PV-Diesel power generation system for rural electrification: A case study of Chilubi district in Zambia', *Renew. Energy*, vol. 203, pp. 601–611, Feb. 2023, doi: 10.1016/j.renene.2022.12.112.

[8]   C. S. Guno and C. B. Agaton, 'Socio-Economic and Environmental Analyses of Solar Irrigation Systems for Sustainable Agricultural Production', *Sustainability*, vol. 14, no. 11, Art. no. 11, Jan. 2022, doi: 10.3390/su14116834.

[9]   H. Xie, C. Ringler, and Md. A. H. Mondal, 'Solar or Diesel: A Comparison of Costs for Groundwater-Fed Irrigation in Sub-Saharan Africa Under Two Energy Solutions', *Earths Future*, vol. 9, no. 4, p. e2020EF001611, 2021, doi: 10.1029/2020EF001611.

[10] 'World-Bank-Rev.pdf'. Accessed: Mar. 05, 2023. [Online]. Available: https://unstats.un.org/unsd/accsub-public/docs/World-Bank-Rev.pdf

[11] C. Dick-Sagoe, K. N. Hope, and P. Asare-Nuamah, 'Perceived impact of climate variability and change on livelihoods of smallholder farmers in Lesotho', *Afr. J. Sci. Technol. Innov. Dev.*, vol. 0, no. 0, pp. 1–10, May 2022, doi: 10.1080/20421338.2022.2058339.

[12] M. M. M., 'The Analysis of Threats and Opportunities in Sustainable Irrigation Development in Lesotho', *Inf. Manag. Bus. Rev.*, vol. 6, no. 5, pp. 220–225, Oct. 2014, doi: 10.22610/imbr.v6i5.1118.

[13] Noliwe Velaphe, 'Poverty reduction, economic growth-mcc', *Government of Lesotho*, Apr. 19, 2022. https://www.gov.ls/poverty-reduction-economic-growth-mcc/ (accessed Apr. 21, 2022).

[14] Ministry of Energy and Meteorology, 'Lesotho First National Determined Contribution', Dec. 2017. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Lesotho%20First/Lesotho%20First %20NDC.pdf (accessed Mar. 28, 2022).

[15] M. Abu-Aligah, 'Design of Photovoltaic Water Pumping System and Compare it with Diesel Powered Pump', vol. 5, no. 3, p. 8, 2011.

[16] M. Abu-Aligah, 'Design of Photovoltaic Water Pumping System and Compare it with Diesel Powered Pump', vol. 5, no. 3, p. 8, 2011.

[17] T. Hove and E. Mungofa, 'Sizing and performance prediction of solar-powered pump-pipe systems using empirical solar radiation and pump characteristic data as applied in Zimbabwe', p. 1.

[18] N. I. Sarkar, A. I. Sifat, N. Rahim, and S. M. S. Reza, 'Replacing diesel irrigation pumps with solar photovoltaic pumps for sustainable irrigation in Bangladesh: A feasibility study with HOMER', in *2015 2nd International Conference on Electrical Information and Communication Technologies (EICT)*, Khulna, Bangladesh: IEEE, Dec. 2015, pp. 498–503. doi: 10.1109/EICT.2015.7392004.

[19] P. C. Pande, A. K. Singh, and P. Kumar, 'Solar PV pumping system for irrigation purpose and its economic comparison with grid- connected electricity and diesel operated pumps', *Indian J. Econ. Dev.*, vol. 4, p. 7, 2016.

[20] International Water Management Institute (IWMI), 'International Water Management Institute (IWMI)', International Water Management Institute (IWMI), 2021. doi: 10.5337/2021.204.

[21] Derek Clarke, Martin Smith, and Khaled El-Askari, '(PDF) CropWat for Windows : User guide', Oct.1998.https://www.researchgate.net/publication/312903822_CropWat_for_Windows_User_gu ide (accessed Aug. 15, 2022).

[22] 'PVGIS Photovoltaic Geographical Information System'. https://joint-research-centre.ec.europa.eu/pvgis-photovoltaic-geographical-information-system_en (accessed Aug. 15, 2022).

[23] T. Hove and E. Mungofa, 'Towards the Optimal Sizing of Solar-Powered Pump-Pipe-Storage Systems', in *Proceedings of the ISES Solar World Congress 2019*, Santiago, Chile: International Solar Energy Society, 2019, pp. 1–12. doi: 10.18086/swc.2019.34.02.

[24] K. K. Gopinathan, 'The distribution of global and sky radiation throughout Lesotho', *Sol. Wind Technol.*, vol. 5, no. 1, pp. 103–106, Jan. 1988, doi: 10.1016/0741-983X(88)90095-1.

[25] M. Iqbal, 'Prediction of hourly diffuse solar radiation from measured hourly global radiation on a horizontal surface', *Sol. Energy*, vol. 24, no. 5, pp. 491–503, Jan. 1980, doi: 10.1016/0038-092X(80)90317-5.

[26] T. Hove and J. Göttsche, 'Mapping global, diffuse and beam solar radiation over Zimbabwe', *Renew. Energy*, vol. 18, no. 4, pp. 535–556, Dec. 1999, doi: 10.1016/S0960-1481(98)00782-4.

[27] I. Kecili, R. Nebbali, and S. Ait Saada, 'Optimal tilt angle of a solar panel for a wide range of latitudes. Comparison between tilted and horizontal configurations', *Int. J. Ambient Energy*, vol. 43, no. 1, pp. 8697–8709, Dec. 2022, doi: 10.1080/01430750.2022.2101522.

[28] K. K. Gopinathan, 'Solar radiation on variously oriented sloping surfaces', *Sol. Energy*, vol. 47, no. 3, pp. 173–179, Jan. 1991, doi: 10.1016/0038-092X(91)90076-9.

[29] S. Miran, M. Tamoor, T. Kiren, F. Raza, M. I. Hussain, and J.-T. Kim, 'Optimization of Standalone Photovoltaic Drip Irrigation System: A Simulation Study', *Sustainability*, vol. 14, no. 14, p. 8515, Jul. 2022, doi: 10.3390/su14148515.

[30] A. Asif, N. R. Naomi, and A. F. M. Saleh, 'A multicriteria analysis on solar and traditional technologies in irrigation development', p. 11, 2022.

[31] U. G. Onu, G. S. Silva, A. C. Zambroni de Souza, B. D. Bonatto, and V. B. Ferreira da Costa, 'Integrated design of photovoltaic power generation plant with pumped hydro storage system and irrigation facility at the Uhuelem-Amoncha African community', *Renew. Energy*, vol. 198, pp. 1021–1031, Oct. 2022, doi: 10.1016/j.renene.2022.08.059.

[32] M. Aliyu, G. Hassan, S. A. Said, M. U. Siddiqui, A. T. Alawami, and I. M. Elamin, 'A review of solar-powered water pumping systems', *Renew. Sustain. Energy Rev.*, vol. 87, no. C, pp. 61–76, 2018.

[33] M. M. Abo-Habaga, E. B. El-Banna, and A. H. Silim, 'Diesel and Solar Energies Costs Assessment under Drip Irrigation System', *J. Soil Sci. Agric. Eng.*, vol. 12, no. 11, pp. 819–822, Nov. 2021, doi: 10.21608/jssae.2021.212202.

[34] C. S. Guno and C. B. Agaton, 'Socio-Economic and Environmental Analyses of Solar Irrigation Systems for Sustainable Agricultural Production', *Sustainability*, vol. 14, no. 11, Art. no. 11, Jan. 2022, doi: 10.3390/su14116834.

[35] J. W. Powell, J. M. Welsh, and R. Farquharson, 'Investment analysis of solar energy in a hybrid diesel irrigation pumping system in New South Wales, Australia', *J. Clean. Prod.*, vol. 224, pp. 444–454, Jul. 2019, doi: 10.1016/j.jclepro.2019.03.071.

[36] S. M. Wazed, B. R. Hughes, D. O'Connor, and J. K. Calautit, 'A review of sustainable solar irrigation systems for Sub-Saharan Africa', Accessed: Apr. 05, 2023. [Online]. Available: https://core.ac.uk/display/162666412?source=2

[37] F. Grant *et al.*, 'Creating a Solar-Powered Drip Irrigation Optimal Performance model (SDrOP) to lower the cost of drip irrigation systems for smallholder farmers', *Appl. Energy*, vol. 323, p. 119563, Oct. 2022, doi: 10.1016/j.apenergy.2022.119563.

[38] C. Gopal, M. Mohanraj, P. Chandramohan, and P. Chandrasekar, 'Renewable energy source water pumping systems—A literature review', *Renew. Sustain. Energy Rev.*, vol. 25, pp. 351–370, Sep. 2013, doi: 10.1016/j.rser.2013.04.012.

[39] P. E. Campana, H. Li, J. Zhang, R. Zhang, J. Liu, and J. Yan, 'Economic optimization of photovoltaic water pumping systems for irrigation', *Energy Convers. Manag.*, vol. 95, pp. 32–41, May 2015, doi: 10.1016/j.enconman.2015.01.066.

[40] L. Diop, 'Technical and economic feasibility of solar irrigation pumping system: a review', *Knowl.-Based Eng. Sci.*, vol. 1, no. 01, pp. 1–22, Dec. 2020, doi: 10.51526/kbes.2020.1.01.1-22.

[41] M. Relebohile and K. J. B. Keregero, 'Turning chall enges into opportunity: Potential for adoption of e-extension in Lesotho', *J. Agric. Ext. Rural Dev.*, vol. 11, no. 11, pp. 184–191, Nov. 2019, doi: 10.5897/JAERD2019.1040.

[42] I. M. Moholo, 'Evaluation-and-optimisation-of-solar-water pumping-systems-for-lesotho', May 2020. http://nul-erc.s3.amazonaws.com (accessed Jul. 05, 2023).

[43] 'A mini review on solar energy based pumping system for irrigation', *Mater. Today Proc.*, vol. 43, pp. 417–425, Jan. 2021, doi: 10.1016/j.matpr.2020.11.716.

[44] K.K Gopinathan, 'Solar Energy Utilization in Lesotho | Gopinathan | International Energy Journal', vol. 11, pp. 61–68, 1989.

[45] B. M. Taele, K. K. Gopinathan, and L. Mokhuts'oane, 'The potential of renewable energy technologies for rural development in Lesotho', *Renew. Energy*, vol. 32, no. 4, pp. 609–622, Apr. 2007, doi: 10.1016/j.renene.2006.02.014.

[46] M. Mpholo *et al.*, 'Lesotho electricity demand profile from 2010 to 2030', *J. Energy South. Afr.*, vol. 32, no. 1, pp. 41–57, Feb. 2021, doi: 10.17159/2413-3051/2021/v32i1a7792.

[47] M. Salman, A. Abdelfattah, W. Ahmad, and C. Simongini, *The use of solar energy in irrigated agriculture*-. 2022.

[48] M. Kumar, R. V. Adake, K. S. Reddy, and K. S. Reddy, 'Development of green energy based micro-sprinkler irrigation system for small holdings of SAT region', *Clean. Eng. Technol.*, vol. 7, p. 100433, Apr. 2022, doi: 10.1016/j.clet.2022.100433.

[49] M. T. Islam and M. E. Hossain, 'Economic Feasibility of Solar Irrigation Pumps: A Study of Northern Bangladesh', *Int. J. Renew. Energy Dev.*, vol. 11, no. 1, pp. 1–13, Feb. 2022, doi: 10.14710/ijred.2022.38469.

[50] S. S. Chandel, M. Nagaraju Naik, and R. Chandel, 'Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies', *Renew. Sustain. Energy Rev.*, vol. 49, pp. 1084–1099, Sep. 2015, doi: 10.1016/j.rser.2015.04.083.

[51] B. S. V and S. W. S, 'Solar photovoltaic water pumping system for irrigation: A review', *Afr. J. Agric. Res.*, vol. 10, no. 22, pp. 2267–2273, May 2015, doi: 10.5897/AJAR2015.9879.

[52] A. Waleed *et al.*, 'Solar (PV) Water Irrigation System with Wireless Control', in *2019 International Symposium on Recent Advances in Electrical Engineering (RAEE)*, Aug. 2019, pp. 1–4. doi: 10.1109/RAEE.2019.8886970.

[53] A. Bhattacharjee, D. K. Mandal, and H. Saha, 'Design of an optimized battery energy storage enabled Solar PV Pump for rural irrigation', in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India: IEEE, Jul. 2016, pp. 1–6. doi: 10.1109/ICPEICES.2016.7853237.

[54] Salman Maher, Abedelfattah Ahmed, Waqas Ahmad, and Simongini Camilla, *The use of solar energy in irrigated agriculture*. FAO, 2022. doi: 10.4060/cb8459en.

[55] P. Jadhav and D. Doifode, 'Energy for Irrigation – Solution Development in Context'.

[56] S. Verma *et al.*, 'Solar PV powered water pumping system – A review', *Mater. Today Proc.*, vol. 46, pp. 5601–5606, Jan. 2021, doi: 10.1016/j.matpr.2020.09.434.

[57] A. Haffaf, F. Lakdja, R. Meziane, and D. O. Abdeslam, 'Study of economic and sustainable energy supply for water irrigation system (WIS)', *Sustain. Energy Grids Netw.*, vol. 25, p. 100412, Mar. 2021, doi: 10.1016/j.segan.2020.100412.

[58] H. El Ghetany, A. AbedElhakaim, A. Elsayed, and I. Zedan, 'Theoretical analysis of different solar water pumping irrigation systems for seasonal crops in three geographical locations in Egypt', *Egypt. J. Chem.*, vol. 0, no. 0, pp. 0–0, Sep. 2021, doi: 10.21608/ejchem.2021.78302.3834.

[59] I. Citaristi, 'International Energy Agency—IEA', in *The Europa Directory of International Organizations 2022*, 24th ed.Routledge, 2022.

[60] D. Feldman, K. Dummit, J. Zuboy, J. Heeter, K. Xu, and R. Margolis, 'Winter 2021/2022 Solar Industry Update', National Renewable Energy Lab. (NREL), Golden, CO (United States), NREL/PR-7A4081900,Jan.2022.Accessed:Mar.05,2023.[Online].Available:https://www.osti.gov/biblio/1843833

[61] Mohamad Waleed AlShaar, Zakaria Al-Omari, W. Emar, M. Alnsour, and G. Abu-Rumman, 'Application of PV-Thermal Array for Pumping Irrigation Water as an Alternative to PV in Ghor Al-Safi, Jordan: A case study', *Evergreen*, vol. 9, no. 4, pp. 1140–1150, Dec. 2022, doi: 10.5109/6625725.

[62] I. Saady *et al.*, 'Study of a Photovoltaic Pumping System Application for Irrigation the Palm in Beni Mellal City', in *Digital Technologies and Applications*, S. Motahhir and B. Bossoufi, Eds., in Lecture Notes in Networks and Systems, vol. 454. Cham: Springer International Publishing, 2022, pp. 661–671. doi: 10.1007/978-3-031-01942-5_66.

[63] P. C. Pande, A. K. Singh, and P. Kumar, 'Solar PV pumping system for irrigation purpose and its economic comparison with grid- connected electricity and diesel operated pumps', *Indian J. Econ. Dev.*, vol. 4, 2016.

[64] M. Mobarra, M. Rezkallah, and A. Ilinca, 'Variable Speed Diesel Generators: Performance and Characteristic Comparison', *Energies*, vol. 15, no. 2, Art. no. 2, Jan. 2022, doi: 10.3390/en15020592.

[65] S. Adhikari, P. Mahapatra, V. Sapkota, and S. Puppala, 'Characterizing Emissions from Agricultural Diesel Pumps in the Terai Region of Nepal', *Atmosphere*, vol. 10, no. 2, p. 56, Feb. 2019, doi: 10.3390/atmos10020056.

[66] J. Lukuyu, G. Bensch, T. Conlon, A. Patel, V. Modi, and J. Taneja, 'Diesel GenSat: using satellite data to detect diesel-powered irrigation for guiding electrification in Ethiopia', in *Proceedings of the Thirteenth ACM International Conference on Future Energy Systems*, Virtual Event: ACM, Jun. 2022, pp. 325–337. doi: 10.1145/3538637.3538862.

[67] L. C. Kelley, E. Gilbertson, A. Sheikh, S. D. Eppinger, and S. Dubowsky, 'On the feasibility of solar-powered irrigation', *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 2669–2682, Dec. 2010, doi: 10.1016/j.rser.2010.07.061.

[68] M. Benghanem, K. O. Daffallah, S. N. Alamri, and A. A. Joraid, 'Effect of pumping head on solar water pumping system', *Energy Convers. Manag.*, vol. 77, pp. 334–339, Jan. 2014, doi: 10.1016/j.enconman.2013.09.043.

[69] M. Aliyu, G. Hassan, S. A. Said, M. U. Siddiqui, A. T. Alawami, and I. M. Elamin, 'A review of solar-powered water pumping systems', *Renew. Sustain. Energy Rev.*, vol. 87, pp. 61–76, May 2018, doi: 10.1016/j.rser.2018.02.010.

[70] A. K. Tiwari, V. R. Kalamkar, R. R. Pande, S. K. Sharma, V. C. Sontake, and A. Jha, 'Effect of head and PV array configurations on solar water pumping system', *Mater. Today Proc.*, vol. 46, pp. 5475–5481, Jan. 2021, doi: 10.1016/j.matpr.2020.09.200.

[71] A. Tiwari, I. ARIF, and V. Kalamkar, *Effect of pumping head on solar water pumping system*. 2015.

[72] I. Odeh, Y. G. Yohanis, and B. Norton, 'Influence of pumping head, insolation and PV array size on PV water pumping system performance', *Sol. Energy*, vol. 80, no. 1, pp. 51–64, Jan. 2006, doi: 10.1016/j.solener.2005.07.009.

[73] E. M. Salilih, Y. T. Birhane, and S. H. Arshi, 'Performance analysis of DC type variable speed solar pumping system under various pumping heads', *Sol. Energy*, vol. 208, pp. 1039–1047, Sep. 2020, doi: 10.1016/j.solener.2020.08.071.

[74] I. K. Okakwu, A. S. Alayande, D. O. Akinyele, O. E. Olabode, and J. O. Akinyemi, 'Effects of total system head and solar radiation on the techno-economics of PV groundwater pumping irrigation system for sustainable agricultural production', *Sci. Afr.*, vol. 16, p. e01118, Jul. 2022, doi: 10.1016/j.sciaf.2022.e01118.

[75] EEE Department ,ManavRachna International , Institute of Research & Studies. and R. Khera, 'A study of solar powered water pumping system using pvsyst.', *Int. J. Adv. Res.*, vol. 7, no. 5, pp. 1114–1119, May 2019, doi: 10.21474/IJAR01/9140.

[76] 'Optimum Design and Evaluation of Solar Water Pumping System for Rural Areas', *Int. J. Renew. Energy Res.*, no. v7i1, 2017, doi: 10.20508/ijrer.v7i1.4838.g6960.

[77] P. K. Kundu *et al.*, 'Low-Cost Solar Pump Irrigation System for Irrigated Rice Production', *Bangladesh Rice J.*, vol. 25, no. 2, pp. 1–10, Jan. 2023, doi: 10.3329/brj.v25i2.62702.

[78] C. S. Guno and C. B. Agaton, 'Socio-Economic and Environmental Analyses of Solar Irrigation Systems for Sustainable Agricultural Production', *Sustainability*, vol. 14, no. 11, p. 6834, Jun. 2022, doi: 10.3390/su14116834.

[79] O. US EPA, 'Inventory of U.S. Greenhouse Gas Emissions and Sinks', Feb. 08, 2017. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (accessed Mar. 31, 2023).

[80] A. A. Setiawan, S. A. Ramadhan, N. S. Wahyuni, A. N. Hidayah, M. L. N. R. Arifin, and H. Suyatna, 'Economic Analysis Comparison between Solar Photovoltaic and Diesel Generator for Water Pumping System in an Indonesia Rural Karsts Area', *KnE Energy*, pp. 8–15, Dec. 2015, doi: 10.18502/ken.v2i2.351.

[81] Chourasia Kumar Sooraj and Dr. Shailendra Singh Pawar, 'A smart solar power irrigation system (SSPIS): simulation and analysis using MATLAB/SIMULINK model', *Int. Res. J. Mod. Eng. Technol. Sci.*.

[82] A. R. Al-Ali, A. Al Nabulsi, S. Mukhopadhyay, M. S. Awal, S. Fernandes, and K. Ailabouni, 'IoT-solar energy powered smart farm irrigation system', *J. Electron. Sci. Technol.*, vol. 17, no. 4, p. 100017, Dec. 2019, doi: 10.1016/j.jnlest.2020.100017.

[83] C. Brandoni and B. Bošnjaković, 'HOMER analysis of the water and renewable energy nexus for water-stressed urban areas in Sub-Saharan Africa', *J. Clean. Prod.*, vol. 155, pp. 105–118, Jul. 2017, doi: 10.1016/j.jclepro.2016.07.114.

[84] S. J. Al-Swaiedi, A. I. Altmimi, and A. A. Al-khalidi, 'Design of a Sustainable City in Iraq Using SAM Program to Calculate Renewable Energy', *Iraqi J. Sci.*, pp. 4475–4488, Dec. 2021, doi: 10.24996/ijs.2021.62.11(SI).28.

[85] I. H. Ibrik, 'Techno-economic assessment of on-grid solar PV system in Palestine', *Cogent Eng.*, vol. 7, no. 1, p. 1727131, Jan. 2020, doi: 10.1080/23311916.2020.1727131.

[86] M. Zamanlou and M. T. Iqbal, 'Design and Analysis of Solar Water Pumping with Storage for Irrigation in Iran', in *2020 IEEE 17th International Conference on Smart Communities: Improving Quality of Life Using ICT, IoT and AI (HONET)*, Dec. 2020, pp. 118–124. doi: 10.1109/HONET50430.2020.9322660.

[87] R. J. Chilundo, G. A. Maúre, and U. S. Mahanjane, 'Dynamic mathematical model design of photovoltaic water pumping systems for horticultural crops irrigation: A guide to electrical energy potential assessment for increase access to electrical energy', *J. Clean. Prod.*, vol. 238, p. 117878, Nov. 2019, doi: 10.1016/j.jclepro.2019.117878.

[88] 'Lorentz PS2-4000 HR-14HL Helical Rotor Submersible Solar Pump - Motor - Pump Unit - Controller', *Pumps and Pipes*. https://pumpsandpipes.net.au/shop/lorentz-helical-rotor-ps2-4000-hr-14hl-submersible-solar-pump-system/ (accessed Mar. 31, 2023).

[89] C. Oertel, J. Matschullat, K. Zurba, F. Zimmermann, and S. Erasmi, 'Greenhouse gas emissions from soils—A review', *Geochemistry*, vol. 76, no. 3, pp. 327–352, Oct. 2016, doi: 10.1016/j.chemer.2016.04.002.

[90] 'Maseru, Lesotho - Climate & Monthly weather forecast'. https://www.weather-atlas.com/en/lesotho/maseru-climate (accessed Dec. 06, 2022).

[91] M. E. Kiger and L. Varpio, 'Thematic analysis of qualitative data: AMEE Guide No. 131', *Med. Teach.*, vol. 42, no. 8, pp. 846–854, Aug. 2020, doi: 10.1080/0142159X.2020.1755030.

[92] 'CNBM Solar South Africa | CNBM Cape Town | SP-Energy'. https://sp-energy.co.za/product-category/solar-panels/solar-brands/cnbm-solar/ (accessed Jan. 27, 2023).

[93] 'Calculation of monthly average insolation on tilted surfaces', *Sol. Energy*, vol. 19, no. 4, pp. 325–329, Jan. 1977, doi: 10.1016/0038-092X(77)90001-9.

[94] 'Bundu Power Generators | Diesel Generators | Gas Generators | Solar Power'. https://www.bundupower.co.za/ (accessed Mar. 31, 2023).

Annexes

Annex 1: Excel Model Interface

COMPUTER PROGRAM INPUTS				
INPUT	VALUE	UNIT		
MONTH	Nov-00			
Average date	14-Nov			
LONGITUDE	27.55	DEGREES		
LATITUDE	-29.399266	DEGREES		
AZIMUTH	180	DEGREES		
TILT	34	DEGREES		
Ta max	24.2	oC		
Ta min	11.9	oC		
GHI	25.95	MJ/m2	7.21	KWh/m2
DHI	2.40	MJ/m2	0.67	KWh/m2
Tilt Factor			0.90	
Tilted plane radiation			6.47	KWh/m2
PV module parameters				
ηSTC	20.1%			
β	0.004	/oC		
fm	0.9			
NOCT	47	oC		
PV POWER	2113	Watts		

Annex 2: Simulation results tables of November for different pipes

63 mm pipe

Hour	G	Ta	Tc	ηPV/ηREF	Ppv	η$_{system}$	Pmotor	Qop [m3/hr]	THD	ρgQopTDHop	npv	CUF	ηop	etaover
6.5	112	12.1	15.1	0.94	263	0.92	242	0.00	18.0	0	18.8%	100.0%	0.0%	0.0%
7.5	291	13.1	20.9	0.91	665	0.92	611	0.79	18.1	39	18.4%	100.0%	6.3%	1.2%
8.5	481	14.7	27.6	0.89	1071	0.92	985	7.58	19.8	409	17.9%	100.0%	41.5%	7.4%
9.5	658	16.7	34.4	0.87	1425	0.92	1311	11.64	21.7	689	17.4%	100.0%	52.6%	9.1%
10.5	795	18.9	40.3	0.84	1679	0.92	1544	13.97	23.1	881	17.0%	100.0%	57.0%	9.7%
11.5	870	21.0	44.4	0.83	1804	0.92	1660	15.00	23.8	973	16.7%	100.0%	58.6%	9.8%
12.5	870	22.7	46.1	0.82	1791	0.92	1648	14.89	23.7	964	16.6%	100.0%	58.5%	9.7%
13.5	795	23.8	45.2	0.83	1643	0.92	1512	13.67	22.9	854	16.6%	100.0%	56.5%	9.4%
14.5	658	24.2	41.9	0.84	1380	0.92	1270	11.19	21.5	655	16.9%	100.0%	51.6%	8.7%
15.5	481	23.8	36.8	0.86	1031	0.92	949	7.04	19.6	376	17.2%	100.0%	39.6%	6.8%
16.5	291	22.7	30.5	0.88	639	0.92	588	0.24	18.0	12	17.7%	100.0%	2.0%	0.4%
17.5	112	21.0	24.0	0.90	254	0.92	234	0.00	18.0	0	18.2%	100.0%	0.0%	0.0%
average/sum	6413	19.5	34.0	0.87	13645	0.92	12554	96.00	20.69	5850	17.1%	100.0%	46.6%	8.0%

75 mm pipe

Hour	G	Ta	Tc	ηPV/ηREF	Ppv	η$_{system}$	Pmotor	Qop [m3/hr]	THD	ρgQopTDHop	npv	CUF	ηop	etaover
6.5	112	12.1	15.1	0.94	238	0.92	219	0.00	18.0	0	18.8%	100.0%	0.0%	0.0%
7.5	291	13.1	20.9	0.91	602	0.92	553	0.00	18.0	0	18.4%	100.0%	0.0%	0.0%
8.5	481	14.7	27.6	0.89	969	0.92	892	6.68	18.6	339	17.9%	100.0%	38.0%	6.8%
9.5	658	16.7	34.4	0.87	1290	0.92	1186	11.71	19.6	626	17.4%	100.0%	52.7%	9.2%
10.5	795	18.9	40.3	0.84	1520	0.92	1398	14.60	20.4	811	17.0%	100.0%	58.0%	9.8%
11.5	870	21.0	44.4	0.83	1633	0.92	1502	15.88	20.8	898	16.7%	100.0%	59.8%	10.0%
12.5	870	22.7	46.1	0.82	1621	0.92	1491	15.74	20.7	889	16.6%	100.0%	59.6%	9.9%
13.5	795	23.8	45.2	0.83	1488	0.92	1369	14.23	20.3	786	16.6%	100.0%	57.4%	9.5%
14.5	658	24.2	41.9	0.84	1249	0.92	1149	11.15	19.5	592	16.9%	100.0%	51.5%	8.7%
15.5	481	23.8	36.8	0.86	934	0.92	859	6.01	18.5	303	17.2%	100.0%	35.3%	6.1%
16.5	291	22.7	30.5	0.88	579	0.92	532	0.00	18.0	0	17.7%	100.0%	0.0%	0.0%
17.5	112	21.0	24.0	0.90	230	0.92	211	0.00	18.0	0	18.2%	100.0%	0.0%	0.0%
average/sum	6413	19.5	34.0	0.87	12351	0.92	11363	96.00	19.19	5243	17.1%	100.0%	46.1%	7.9%

90 mm pipe

Hour	G	Ta	Tc	ηPV/ηREF	Ppv	η$_{system}$	Pmotor	Qop [m3/hr]	THD	ρgQopTDHop	npv	CUF	ηop	etaover
6.5	112	12.1	15.1	0.94	227	0.92	209	0.00	18.0	0	18.8%	100.0%	0.0%	0.0%
7.5	291	13.1	20.9	0.91	573	0.92	527	0.00	18.0	0	18.4%	100.0%	0.0%	0.0%
8.5	481	14.7	27.6	0.89	923	0.92	850	5.83	18.2	289	17.9%	100.0%	34.0%	6.1%
9.5	658	16.7	34.4	0.87	1229	0.92	1130	11.66	18.7	593	17.4%	100.0%	52.5%	9.1%
10.5	795	18.9	40.3	0.84	1448	0.92	1332	15.02	19.0	779	17.0%	100.0%	58.5%	9.9%
11.5	870	21.0	44.4	0.83	1556	0.92	1431	16.49	19.2	864	16.7%	100.0%	60.3%	10.1%
12.5	870	22.7	46.1	0.82	1544	0.92	1421	16.34	19.2	855	16.6%	100.0%	60.2%	10.0%
13.5	795	23.8	45.2	0.83	1417	0.92	1304	14.58	19.0	754	16.6%	100.0%	57.8%	9.6%
14.5	658	24.2	41.9	0.84	1190	0.92	1095	11.01	18.6	558	16.9%	100.0%	51.0%	8.6%
15.5	481	23.8	36.8	0.86	889	0.92	818	5.06	18.2	250	17.2%	100.0%	30.6%	5.3%
16.5	291	22.7	30.5	0.88	551	0.92	507	0.00	18.0	0	17.7%	100.0%	0.0%	0.0%
17.5	112	21.0	24.0	0.90	219	0.92	201	0.00	18.0	0	18.2%	100.0%	0.0%	0.0%
average/sum	6413	19.5	34.0	0.87	11766	0.92	10825	96.00	18.50	4942	17.1%	100.0%	45.7%	7.8%

110 mm pipe

Hour	G	Ta	Tc	ηPV/ηREF	Ppv	η$_{system}$	Pmotor	Qop [m3/hr]	THD	ρgQopTDHop	npv	CUF	ηop	etaover
6.5	112	12.1	15.1	0.94	222	0.92	204	0.00	18.0	0	18.8%	100.0%	0.0%	0.0%
7.5	291	13.1	20.9	0.91	562	0.92	517	0.00	18.0	0	18.4%	100.0%	0.0%	0.0%
8.5	481	14.7	27.6	0.89	905	0.92	833	5.27	18.1	259	17.9%	100.0%	31.1%	5.6%
9.5	658	16.7	34.4	0.87	1204	0.92	1108	11.63	18.2	578	17.4%	100.0%	52.2%	9.1%
10.5	795	18.9	40.3	0.84	1419	0.92	1305	15.29	18.4	767	17.0%	100.0%	58.7%	10.0%
11.5	870	21.0	44.4	0.83	1525	0.92	1403	16.90	18.5	851	16.7%	100.0%	60.7%	10.1%
12.5	870	22.7	46.1	0.82	1514	0.92	1393	16.74	18.5	842	16.6%	100.0%	60.5%	10.0%
13.5	795	23.8	45.2	0.83	1389	0.92	1278	14.82	18.4	742	16.6%	100.0%	58.1%	9.7%
14.5	658	24.2	41.9	0.84	1167	0.92	1073	10.92	18.2	542	16.9%	100.0%	50.5%	8.5%
15.5	481	23.8	36.8	0.86	872	0.92	802	4.43	18.1	218	17.2%	100.0%	27.1%	4.7%
16.5	291	22.7	30.5	0.88	540	0.92	497	0.00	18.0	0	17.7%	100.0%	0.0%	0.0%
17.5	112	21.0	24.0	0.90	215	0.92	197	0.00	18.0	0	18.2%	100.0%	0.0%	0.0%
average/sum	6413	19.5	34.0	0.87	11534	0.92	10611	96.00	18.19	4800	17.1%	100.0%	45.2%	7.7%

Annex 3: 2022 Emission Factors for Greenhouse Gas Inventories

Fuel Type	kg CO_2 per unit	Unit
Aviation Gasoline	8.31	gallon
Biodiesel (100%)	9.45	gallon
Compressed Natural Gas (CNG)	0.05444	scf
Diesel Fuel	10.21	gallon
Ethanol (100%)	5.75	gallon
Kerosene-Type Jet Fuel	9.75	gallon
Liquefied Natural Gas (LNG)	4.50	gallon
Liquefied Petroleum Gases (LPG)	5.68	gallon
Motor Gasoline	8.78	gallon
Residual Fuel Oil	11.27	gallon

Source: Environmental Protection Agency (EPA)

Annex 4: Pump technical sheet

Solar Surface Pump System

System Overview

Head	max. 30 m
Flow rate	max. 42 m³/h

Technical Data

Controller PS2-4000

- Controlling and monitoring
- Control inputs for dry running protection, remote control etc.
- Protected against reverse polarity, overload and overtemperature
- Integrated MPPT (Maximum Power Point Tracking)
- Integrated Sun Sensor

Power	max. 4,0 kW
Input voltage	max. 375 V
Optimum Vmp**	> 238 V
Motor current	max. 14 A
Efficiency	max. 98 %
Ambient temp.	-40...50 °C
Enclosure class	IP68

Motor ECDRIVE 4000 CS-F

- Maintenance-free brushless DC motor
- Premium materials, stainless steel: AL/AISI 304

Rated power	4,0 kW
Efficiency	max. 92 %
Motor speed	900...3.300 rpm
Insulation class	F
Enclosure class	IPX4

Pump End PE CS-F32-20-2

- Premium materials
- Centrifugal pump

Efficiency	max. 74 %

Annex 5: Diesel generator technical sheet

GENERAL DATA	
Model:	BPD5000S
Prime Power (P.R.P):	4.5 kVA
Stand-by Power (L.T.P):	5.0 kVA
Amps:	21.7 A
Power Factor / COS:	1
Frequency:	50 Hz
Voltage:	230 V
Phases:	Single Phase
Engine Speed:	3000 RPM
Length:	915 mm
Width:	530 mm
Height:	680 mm
Weight:	155 kg's
Tank Capacity:	15 l

ADDITIONAL	
Running Time:	8 Hours @ 75% load
Structure Type:	Silent
Noise Level (7m):	76 dBA
Auto Voltage Regulator:	Constant voltage AVR
ISO9001 Certified:	Yes
CE Certified:	Yes
Fuel Cons. @ 100% Load:	2.3
Fuel Cons. @ 75% Load:	1.8
Fuel Cons. @ 50% Load:	1.2