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MODELLING AND CONTROL OF DIRECTLY COUPLED PV WATER PUMPING SYSTEM

by

Fernando Adelino

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Supervisor: Dr. Anges Akim Aminou Moussavou

Co-Supervisor: APRF KHALED MOHAMED ABOALEZ

Bellville Campus

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DECLARATION

I, Fernando Adelino, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Fernando Adelino 18.02.2025

Signed **Date**

Abstract

This paper consists of the modelling and control of a directly coupled PV water pumping system for rural areas in Angola. Water is a basic need for any human. No one on this earth can live without water. Every person needs water for different uses, such as drinking, cooking, agriculture, etc. There has been a rise in demand for water in Africa and around the world due to the exponential increase in the population. This increase in demand has forced the world to develop different alternative systems for water supply and transportation, such as the water pumping system, and one of these systems is the photovoltaic water pumping system. The population in rural areas of Angola has no access to water due to a lack of electricity to power the water pumping system.

This research aims to develop an efficient PV water-pumping system tailored to alleviate water scarcity in rural areas. This paper explores the concept and performance of solar PV water pumping systems, focusing on their potential for off-grid and remote applications. It looks into several control strategies and optimisation methodologies to increase system efficiency and dependability. Furthermore, the paper consists of modelling and controlling a directly coupled PV water pumping system using MATLAB/SIMULINK. The results of the simulations show that the directly coupled PV water pumping system developed in this research could operate efficiently at its maximum power point with good power and voltage stability. The results also demonstrated that the proposed directly coupled PV water pumping system can fill two tanks of 1000 litres while it is operating and as soon as the water pump is disconnected. The water stored in the tanks can be used for the household's basic needs. Furthermore, an economic analysis was conducted, and it was found that the installation cost of the directly coupled PV water pumping system was less than that of the diesel water pumping system. It is essential to identify a cost-effective system so that most of the population in rural areas can access water. The directly-coupled PV water pumping system has been considered the best option regarding efficiency and cost. Angola and the rest of Africa have a wide range of climates, including desert and semi-arid regions and tropical rainforests, despite having enormous water resources. Access to safe drinking water is a significant issue in many parts of Africa. Therefore, an efficient water pumping system can use water resources well.

Keywords

Water pumping system, Photovoltaic, remote rural areas, Modelling, Control, Soft computing.

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DEDICATION

This thesis is dedicated to my wife and my children. Moreover, this thesis is dedicated to my family and colleagues for their immense contribution and support.

GLOSSARY

PV:	Photovoltaic
TCSC:	Thyristor Controlled Series Capacitors
UPFC:	Unified power flow controller
SVC:	Static VAR compensator
DC:	Direct Current
AC:	Alternative Current
MPPT:	Maximum PowerPoint Tracking
FACTS:	Flexible alternative current for the transmission system
IPC:	Interphase Power Controller
AVIC:	Adaptive virtual impedance controller
RPM:	Revolutions per minute
VAWT:	Vertical Axis Wind Turbine
HAWT:	Horizontal Axis Wind Turbine
UIPC:	Unified Interphase Power Controller
FLC:	Fuzzy Logic Controllers
V:	Volts
NPC:	Net Present Cost
O&M:	Operating and Maintenance
OC:	Operation Cost
COE:	Cost of Energy

Table of Contents

List of Figures

List of Tables

CHAPTER 1. INTRODUCTION

1.1 Background and Context

Water is a fundamental resource for life, essential for drinking, sanitation, agriculture, and industrial activities. Its availability and quality directly influence the socio-economic development and quality of life in any region (Meunier et al., 2019). Despite the amount and quality of water resources that are accessible in a nation have a significant impact on its overall quality of life. It is estimated that each person needs five liters of fresh water on average every day to survive (Mnisi, Nhlanhla, 2021). Even while there is much clean water in the world, it is frequently not accessible in places where it is easily used. This makes it more essential to pump water from its source to the places where people need it the most. The population around the world has been increasing at an exponential rate, and the need for water has also been growing at the same rate. Due to the inability to connect the water pumping system to an electrical supply, the population in rural areas is severely impacted (Sinapis et al., 2021). This thesis addresses these challenges by proposing a cost-effective and sustainable water pumping solution powered by photovoltaic (PV) energy, leveraging advancements in renewable energy and pump technology.

A- Water Scarcity and Access Challenges

The world's population is growing daily, leading to an exponential rise in the need for electricity and water. More than 785 million people worldwide lack access to water, and over 759 million people lack access to electricity. Many people in remote areas are still facing challenges in getting access to water for agriculture, drinking, and cooking due to the lack of electricity to connect to the water pumping system (Iranzi et al., 2022). The population in the remote rural areas of many countries has to walk long distances to get water from wells and other sources for agriculture and other basic needs because they do not have an electrical water pumping system that can move the water from one area to the other. Some use diesel pumps, but it is challenging because they are noisy and harmful to the environment, the fuel supply is expensive, and the maintenance cost is high. Every individual need between 50 and 100 Liters of water daily to meet their physiological and hygienic demands, yet most people living in remote places only have access to 20 Liters. Therefore, it is essential to develop and design a water pumping system that will move the water from different sources to the population in remote rural areas at a lower cost but more efficiently. These challenges highlight the urgent need for sustainable and affordable water pumping solutions that operate independently of grid electricity.

B- Evolution of Water Pumping Technologies

Water pump technology originated in ancient societies that were the first to use water power for home and agricultural purposes. The first pumps, sometimes called "scoop wheels," were crude machinery that raised water out of wells or rivers using animal or human power (Massaq et al., 2021). Pump technology advanced significantly during the Middle Ages, especially in Europe. An important advancement was using water wheels and windmills as pump power sources. These mechanical tools made it possible to harvest water more effectively, increasing agricultural potential and promoting the expansion of urban areas. The Industrial Revolution, which occurred in the 18th and 19th centuries and saw tremendous technological improvement, included the adoption of electricity, which quickly rose to prominence in the pump sector. The electric motor transformed the pump design, which paved the way for creating centrifugal pumps. Recent advances in technology have greatly improved the capabilities of pumps. Furthermore, technologies like cutting-edge polymers and corrosion-resistant alloys have extended the lifespan and durability of modern water pumps in challenging conditions (Sinapis et al., 2021). These advancements have laid the groundwork for integrating renewable energy sources like solar power into water pumping systems.

C- The Role of Renewable Energy in Water Pumping

Diesel pumps are frequently used in isolated rural locations without practical access to electricity. Nevertheless, the system has some issues, including fuel supply. A photovoltaic (PV) energy-powered water pumping system offers an alternative. Globally, numerous systems have been created and tested. Their performance has been evaluated in a variety of isolated and climatic environments. These systems can be run on batteries, directly connected to AC or DC power, with a variety of pumps and in a range of climates (Nayak et al., 2020).

D- Agricultural and Socio-Economic Implications

The productivity of agriculture has not increased at the same rate as the population over the last ten years per capita. Since the dawn of human civilisation, irrigation has been a very old technique. It was one of the main forces behind the rise in household income, the reduction of rural poverty, and the growth in agricultural output, demonstrating the different ways that irrigation can affect poverty (Massaq et al., 2021). In most South African provinces, water used for irrigation schemes was not saved; however, in recent years, municipalities and local governments have begun to construct bulk water tanks, reservoirs, and dams. According to the Department of Agriculture, Forestry & Fisheries (DAFF), in 2015, South Africa could no longer afford water losses. As a result, efforts to reduce water consumption and conserve water resources need to be intensified. Water loss prevention and efficient water use provide excellent returns on investment. In order to assist municipalities in implementing water conservation and demand management, the department will also prioritise creating the water demand funding facilitation unit (Biswas and Iqbal, 2018). Due to the high expense of maintaining water supply and conservation, the majority of water infrastructure is neglected for extended periods of time (Nayak et al., 2020). According to (Heinz and Rieberer, 2021), cropland and pasture productivity may suffer from dwindling water availability or growing water scarcity.

E- Water Pricing and Accessibility

District-by-district variations in water costs were observed, contingent upon the nature of the supply and accessibility challenges. Due to the high demand and the distance between the city's surface sources and the rivers to the north and south, Luanda had expensive water prices (De Preneuf, 2023). Research indicates that the average household spends more than 4% of its budget on water, while many homes pay more than 5%. The poorest households were required to spend between 15% and 20% of their household income on water. In many homes, the high cost of water inevitably caused families to cut back on their use or reallocate money toward other necessities like food and medical bills. In peri-urban areas, many individuals are forced to purchase water from vendors, and the cost might reach ten times the official rate paid by those who have domestic connections to their homes. The closeness or availability of water from the piped system affects water pricing. Even inside the same bairro or street, the water level in a domestic tank supplied by a truck is always significantly more significant than that provided by a piped system. The distance from the primary water source, the Bengo River, and the piped supply generally corresponds to increased water pricing. The pricing is frequently impacted by difficult road conditions, particularly during the rainy season when access to water trucks is restricted. At the time of the study, the average daily water use in Luanda's musseques was just 22 liters per person. This is relatively low but also comparable to other African cities where water is expensive and scarce (Hadole et al., 2022).

This thesis focuses on developing a directly connected PV water pumping system to improve rural water access. By leveraging MATLAB for system modelling and optimisation, the research aims to enhance the efficiency and affordability of PV-powered pumps, making them a viable alternative to conventional systems. The study contributes to the growing knowledge on renewable energy applications in water management. It addresses a critical gap in providing sustainable water solutions for underserved populations. The findings have the potential to inform policy decisions, support agricultural development, and promote the adoption of renewable energy technologies in water-scarce regions.

1.2 Problem statement

The increasing demand for sustainable and efficient water supply systems, particularly in remote and rural areas, necessitates the development of renewable energy-based solutions. Directly coupled photovoltaic (PV) water pumping systems present a viable option for harnessing solar energy to meet water pumping requirements. The population in the rural areas has to walk long distances every day to get water. Addressing water inaccessibility through long-term solutions is critical for enhancing the quality of life and promoting socioeconomic growth in these rural communities (De Preneuf, 2023).

1.3 Research Aims and Objectives

This research aims to develop an efficient PV water-pumping system and its controller tailored for rural areas to alleviate water scarcity. Subsequently, to achieve this aim, the following objectives would be considered:

- To conduct comprehensive literature reviews on the PV water pumping systems and water accessibility in Africa;
- To assess the rural water supply in Angola, especially in the province of Huambo, focusing on identifying key challenges and opportunities.
- To design, model, and control a directly coupled PV water pumping system using MATLAB
- To determine the design gap and expected simulation results compared to the design gap
- To perform some MATLAB simulations and analyse the final results.
- To perform an economic analysis that clearly compares PV and diesel-powered systems, highlighting the cost-effectiveness and sustainability.

1.4 Scope and Limitations

This research focuses on the modeling and controlling a directly-coupled PV water pumping system for the population in remote rural areas in Angola, especially in the province of Huambo. The following points have been considered in the development of a suitable directly coupled PV water pumping system:

- Modelling of a directly-coupled PV water pumping system using MATLAB
- Testing of the design
- This involves simulations only.

- Conduct an economic analysis of the PV water pumping system

1.5 Significance of the study

The study conducted in this research provided many benefits in the remote rural areas of many countries by providing easy access to water at a lower cost and eliminating the need for long-distance walks to get water. The quality of life of many people can improve significantly when they have easy access to water, keeping in mind that water is a basic need for human beings. Houses, schools, churches, and companies cannot survive in this current world without water.

Every person has the fundamental human right to access water, and any society or nation's social, economic, and political growth is inextricably related to this right. Various accidents have been reported in Angola due to long walk distances to get water. Many girls in remote rural areas have been raped and wounded during the water transportation. Furthermore, the director of Lubango's Elementary School Number 98 in the rural area of Lubango reported that the school security officers have to get water and store it for the students to use. That reserve helps the school meet its basic needs, but if they go too many days without water, the toilets have to be closed, and the students cannot go to school. Agriculture highly contributes to the economy of many African countries. Agriculture accounts for 9.5% of Angola's US$121.4 billion GDP, but the country's economy has been affected due to water scarcity. Using an efficient PV water pumping system can significantly reduce the number of accidents caused to the population in rural areas during long walk distances to get water. It can allow the schools in rural areas to continue to educate the kids.

1.6 Organization of the Thesis

-Chapter One presents the research problem and statement. It also describes the research aims and objectives, the scope and limitations, and the significance of the research.

-Chapter Two sets out the literature review. It also presents the assessment of rural water supply in Africa of the proposed directly coupled PV water pumping system. Furthermore, the finding of the literature review is also presented.

-Chapter Three discusses the performance and operation of the proposed directly coupled PV water pumping system.

-Chapter Four presents the system design and modelling of the proposed directly coupled PV water pumping system.

-Chapter Five presents and discusses all the simulation results found using the MATLAB / SIMULINK software.

-Chapter SIX concludes the research. The research contributions are presented, a summary of the research is presented and recommendations for future work are suggested.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The global water problem poses a serious threat to socioeconomic development and human well-being, with rural Africa being especially vulnerable. The implications of unclean water scarcity on health, education, and employment opportunities are extensive. Unbelievably high percentages of Africans live without access to clean water sources, which fuels the spread of waterborne illnesses and obstructs the continent's efforts to meet sustainable development targets. This highlights the urgent need for long-term, creative ways to handle the water scarcity in these areas. One fundamental human right is having access to a sustainable water supply. However, several African countries have issues securing a sustainable water supply due to climate change, financial challenges, inadequate infrastructure, and population growth. Africa has the lowest service coverage rates of any continent and, despite having a significantly smaller population than Asia, contributes to over one-third of the world's population without access to improved water supplies. Water-associated diseases account for about 6% of the world's disease burden, and diarrheal and related illnesses kill two million people annually, most of whom are young children (Ashraf and Iqbal, 2020). Most people living in rural areas still face difficulties acquiring water for their basic requirements, and they must walk a considerable distance to do so. Most of these isolated residences are getting worse because they are not connected to the electrical grid. Moreover, it has been noted that agriculture is the main industry in many nations worldwide and that farmers have difficulty gathering enough water for irrigation during dry seasons. Renewable energy technologies, particularly photovoltaic (PV) systems, offer a promising avenue to address the challenges of water scarcity in rural Africa. The abundant solar resources in the region make PV systems an attractive option for powering water pumping systems, providing a reliable and cost-effective means of accessing clean water. However, efficient and effective PV water pumping systems implementation requires a comprehensive understanding of the technical, economic, and social factors involved. The sun is a free and limitless source of energy. so directly-coupled PV water pumping systems run on solar power without requiring payment to the utility company or relying on the power grid. Moreover, this system can run throughout the day without a battery or generator (Sontake et al., 2020).

The water pumping system is a device used to transport water from one area to another. These systems are used in many sectors such as the construction, industrial, and agriculture sectors.

The water pumping system can operate efficiently and supply water continuously to the population in urban and remote rural areas if it is connected to the power supply that operates continuously. PV water pumping systems can significantly reduce the costs compared to diesel and gasoline-based pumping systems. PV water pumping systems are reliable with minimum maintenance and environmentally friendly because they do not cause air and noise pollution (Hadole et al., 2022). Photovoltaic-based water pumping systems are viable for remote locations where grid power connections can be costly and complex. Because they require less maintenance, these systems are more reliable than those that rely on diesel pumps. However, irradiation, load type, and air temperature impact a photovoltaic system's performance. Maximum Power Point Tracking (MPPT) techniques maximise PV output power regardless of weather and operational conditions to overcome these shortcomings (Miqoi et al., 2019). The literature has reported several MPPT techniques, each with requirements, restrictions, and applications.

People daily require water for various uses, including household chores, agriculture, industrial processes, etc. For this reason, it's critical to guarantee that water is available to most people, especially those in rural areas. The water pumping system must function effectively to accomplish this goal and become independent of the power grid (Sabah et al., 2021). This research investigates the potential of PV systems to improve water access in rural African communities. Specifically, it will focus on developing and evaluating efficient, cost-effective water pumping systems powered by PV technology.

This chapter focuses on the literature review about water pumping systems in Africa to understand the current water situation in Africa and the functioning and limitations of the water pumping system to improve the performance of such systems. An efficient and effective water pumping system modelling can significantly improve water access for many households in Africa and around the world. Section 2.2 assesses the rural water supply in Africa. Section 2.3 elaborates on the findings based on previous literature reviews regarding water pumping systems; then finally, Section 2.4 provides the conclusion.

2.2 Assessment of Rural Water Supply in Africa

The state of rural water supply in Africa is a pressing humanitarian and developmental concern. 226 million people in Eastern and Southern Africa do not have access to essential water services, and 381 million do not have access to basic sanitary facilities. Compared to cities, rural communities have a worse situation. Eighty per cent of the region's underserved population resides in nine countries: Tanzania, Uganda, the Democratic Republic of the Congo, Ethiopia, Kenya, Madagascar, Mozambique, Sudan, and Tanzania. Enhancing the quality of life and encouraging economic expansion in these nine countries depends on addressing the lack of access to water and sanitation and further advances in other areas of the region (Chilundo et al., 2018).

Key challenges to improving rural water supply in Africa include:

- The infrastructure required for gathering, storing, and distributing water is lacking in many isolated communities. The present infrastructure may be antiquated, badly maintained, or unable to support the needs of a growing population (Hassan et al., 2022).
- Many rural areas lack consistent electricity, making running water pumps and treatment facilities challenging even in places with infrastructure. Communities are forced to rely on labour-intensive, time-consuming manual ways of gathering water, often resulting in contaminated water.
- Water infrastructure is exceedingly expensive to establish and maintain in rural areas. Furthermore, households, especially those in poverty, may find the cost of water alone to be a significant financial hardship (Singh et al., 2018).

Government policies, international aid, and community-based efforts all contribute to tackling these difficulties. However, the unequal and slow pace of progress highlights the need for creative and long-lasting solutions. With their capacity to offer stable and affordable water access in off-grid locations, photovoltaic (PV) water pumping systems offer a path toward enhancing rural water delivery in Africa.

2.2.1 Water Infrastructure and Management

The problems that African rural communities face are not limited to obtaining water resources; they are also rooted in the continent's current infrastructure, the practices used for management, and the requirement for innovative technical solutions.

There are several challenges with rural water infrastructure. The existing systems are usually old, poorly maintained, and incapable of meeting the rising population's demands. The predicament is aggravated by the fact that many rural areas lack consistent energy, making it impossible for water pumps and treatment facilities to operate.

In South Africa, providing inexpensive, safe water is still a top concern, but its implementation is still insecure. The nation is dedicated to providing free basic water, to provide every impoverished household with a daily supply of 25 liters of water per person at no cost to them (Mnisi, Nhlanhla, 2021). Even with these promises, many homes still can't seem to get their hands on water infrastructure. For example, according to the 2020 General Household Survey (GHS), thousands of South African families still rely on unsafe and unimproved drinking water sources in 2020. As seen in **Figure 2.1**, these include springs, rivers, streams, dams, and pools. When someone drinks contaminated water, they put themselves at risk of contracting diseases from bacteria, viruses, parasites, heavy metals, fertilisers, pesticides, and human and animal waste, among other toxins (Mnisi, Nhlanhla, 2021).

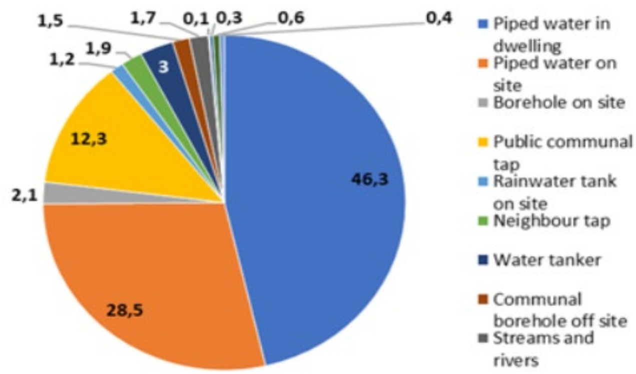

***Figure 2.1**: Distribution of households by source of drinking water (Mnisi, Nhlanhla, 2021)*

There are immediate health consequences when there is no water infrastructure. According to estimates from the World Health Organization, drinking tainted water causes 485,000 deaths from diarrhoea worldwide each year. Furthermore, about 20% of deaths among South African children under five are caused by diarrhoea (Mnisi, Nhlanhla, 2021). Furthermore, many households are forced to travel great distances to obtain drinking water due to inadequate water infrastructure. Their health is negatively impacted by this in numerous ways, including musculoskeletal problems and associated impairments. 200 million hours are spent a day gathering water by women worldwide. The amount of time that can be spent creating livelihoods or working for pay is decreased when bringing fuel and water is required (Mnisi, Nhlanhla, 2021).

Using the distribution of questionnaires, the study first identified some of the primary water sources for the study communities' inhabitants to assess the effects of climate change and governance on rural water security in the Eastern Cape, Province of the Republic of South Africa. Residents of the province's rural villages were discovered to obtain water from various sources, contingent upon their specific location and water availability at that particular time. The primary water sources for the populace are depicted in the diagram below, compiled from questionnaire responses and several interviews.

Prior research in South African rural communities has demonstrated that the absence of sanitary facilities and clean water in dwelling units encourages people to use outside dumping sites or collect drinking water (Bazaanah and Mothapo, 2023). The study's conclusions verified that practically every community member in South Africa's rural areas gets drinking water and uses restrooms outside of their homes. Getting access to clean water and proper sanitation is still a daily challenge. As seen in **Figure 2.2**, on average, 85% of the respondents walked more than 4 km, 11% walked 3 km, 3% walked 2 km, and 1% went 1 km or less to retrieve water or access a dumping site. Similarly, in revealing the burdens associated with water collection, a key informant stressed that "after the water has been collected from a remote water point, women then face a long walk home, sometimes in the dark, exposing themselves to snake bites, attacks, violence and even sometimes rape" (Bazaanah and Mothapo, 2023).

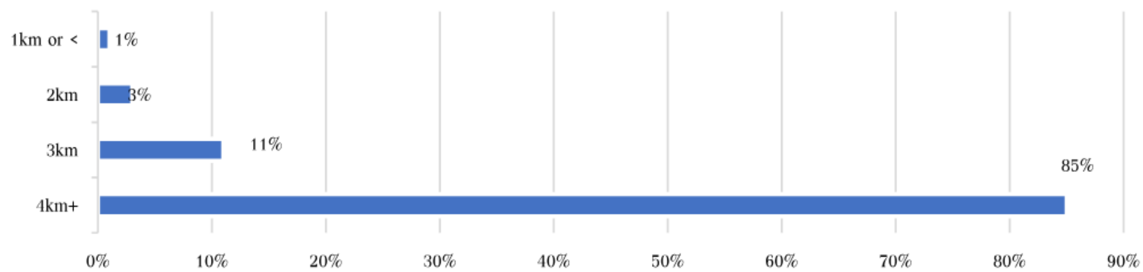

Figure 2.2: *Distance covered by households to access drinking water (Bazaanah and Mothapo, 2023)*

(Whaley and Cleaver, 2017) looked into community-level participatory water management techniques and offered insights into long-term rural water delivery initiatives in Mali. However, their investigation showed that facilities and programs related to water delivery are not sustainable. Furthermore, because climate change can potentially harm people and the economy, it presents a serious problem. To address the dangers facing water resources, adaptive management is necessary. Regrettably, the effects of climate change on water and sanitation systems have received little consideration. Actions to mitigate hazards include the integration of climate resilience into water safety strategies (Knuutinen et al., 2021). A recent study assessed the total cost of providing rural water services and the sustainable financing options. Nonetheless, the results indicate that finance options are insufficient, and cost estimation is still a significant obstacle (Okakwu et al., 2023).

Research has carried out an extensive examination of the difficulties related to water governance in rural water delivery. This was derived from in-depth fieldwork and Tanzanian action research case studies. According to (Muralidhar and Rajasekar, 2021) the results provide insightful information about the complex nature of water governance and its consequences for the sustainable management of rural water supplies. Furthermore, a study examined how Tanzania's Wami River Basin's seasonal and yearly rainfall fluctuation affects rural water supply services (Sinapis et al., 2021). Groundwater development has been considered the crucial and the most economical and sustainable option to secure rural water supplies in Sub-Saharan Africa; shortcuts in resource evaluation and community engagement, however, run the risk of creating unstable water supplies and raising the price of delivering water to more challenging locations (Sinapis et al., 2021).

(Vezin et al., 2020) have discussed sustainable water resource management in rural Nigeria in a thorough study. The emphasis has been placed on the legislative framework, community-based approaches to water management, and the opportunities and problems associated with ensuring sustainable access to water. Likewise, an evaluation of the rural water supply in a few Osun State towns was conducted. According to the assessment's findings, there are not many well-maintained water utilities generally (Khan et al., 2022). In a more recent assessment, the African Water Vision (AWV) 2025 progress has been examined by (Khan et al., 2022). The results demonstrate the impact of AWV 2025 on water governance and the growth of the water industry in Africa, with a focus on Kenyan rural areas in particular. However, it has been noted that there are obstacles to fulfilling international standards in the water sector and financial constraints related to infrastructure construction.

2.2.2 Access to Improved Water Sources

One key indicator of public health and wellness is the availability of "improved" water sources free of external contamination according to international standards. Piped water entering residences, standpipes or public taps, boreholes or tube wells, protected springs, protected dug wells, and rainfall collection are some examples of these sources. On the other hand, because of contamination, unimproved sources, including rivers, ponds, and unprotected wells, provide major health problems (Yaya et al., 2018). An assessment was conducted based on Improved and unimproved drinking water sources in some African countries, as shown in **Table 2.1**. Furthermore, the percentages of the population drinking unimproved water sources in rural areas of these countries are provided in **Figure 2.3**.

According to the latest data available from August 2023 of the Water Policy Group report, the percentage of people drinking unimproved water sources in rural areas of South Africa is around 25% (Knuutinen et al., 2021). These consist of springs, rivers, streams, dams, and pools. Drinking tainted water exposes the user to various pollutants, including heavy metals, pesticides, fertilisers, human and animal waste, and organisms that might cause diseases through the water, such as bacteria, viruses, and parasites. However, the South African government and international organisations have made significant efforts in recent years to improve access to clean water, especially in rural communities. However, there are still challenges in reaching remote areas and ensuring sustainable water infrastructure. The percentage of the population drinking unimproved water sources in rural areas of Nigeria accounts for 53% (Okakwu et al., 2022a). The percentage of people drinking unimproved water sources in rural areas of the Democratic Republic of the Congo (DRC) is around 71%. The DRC has faced significant challenges in providing access to clean water, especially in its vast rural regions. While progress has been made in recent years, most of the rural population still relies on unimproved water sources. The percentage of people drinking unimproved water sources in rural areas of Mali is around 52%. Mali has faced significant challenges in providing access to clean water, especially in its vast rural regions. While progress has been made in recent years, a large portion of the rural population still relies on unimproved water sources. The percentage of people drinking unimproved water sources in rural areas of Angola is around 63% (De Preneuf, 2023). Angola has made progress in improving access to clean water, but significant challenges remain, particularly in reaching remote rural communities (Bazaanah and Mothapo, 2023).

Table 2.1: *Improved and unimproved drinking water sources*

Status	Drinking Water Sources
Improved	• Piped water into dwelling, plot or • yard • Public tap / Standpipe Tube well / • borehole • Protected dug well • Protected spring • Rainwater collection
Unimproved	• Unprotected dug well • Unprotected spring • Cart with small tank/drum • Bottled water • Tanker truck • Surface water (river, dam, lake)

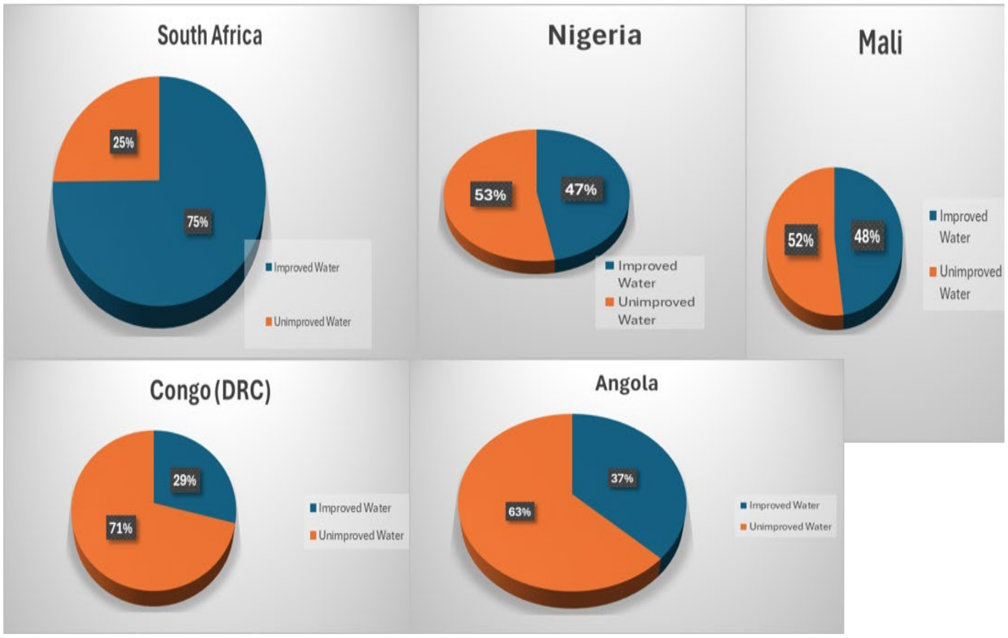

Figure 2.3: *The percentages of the population drinking unimproved water sources in rural areas*

(Knuutinen et al., 2021)

2.2.2.1 Case Studies from Angola: The Impact of Water Scarcity and the Potential of PV Systems

Some interviews were conducted by the World Bank in different places in Angola to have a deep understanding of the rural water challenge related to gender and equity, water infrastructure and management, and access to improved water sources.

1st Interview: The CEO of the Huila Provincial Water and Sanitation in The Highlands of Lubango

The third-largest city in Angola, Lubango, faces challenging trade-offs due to a decline in rainfall and high population growth. "Last year was the hardest in my 30-year career," said Domingas Tyikusse, CEO of the Huila Provincial Water and Sanitation Utility, which is in charge of managing Lubango's water supplies. Two years of extremely little rain reduced subsurface water resources, so institutions, businesses, and residents in Lubango have had to adjust to an intermittent water supply. To preserve its market dominance in 2022, the N'Gola facility was compelled to run at about 60% of its capacity and bring in extra water and beer (De Preneuf, 2023).

2nd Interview: The director of Lubango's Elementary School Number 98

When the water crisis was at its worst, Elementary School Number 98's water supply, which serves about 1,500 pupils in two shifts, was reduced to once a week. The school garden was destroyed. Water is reaching the pipe two or three days a week this year. When water is available, the school guard fills containers, and that reserve helps the school satisfy its basic demands. "Usually, we can hold onto enough water. However, we must close the restrooms if we do not have them for an extended period, said Filomena da Conceição de Freitas Barros, the school's director since 2012. "If there was enough water, the garden could grow back" (De Preneuf, 2023).

3rd Interview: The Vice Governor of Namibe province

The province of Namibe's coastal capital, Moçâmedes, enjoys Mediterranean weather and highly fertile soil. With irrigation, we can cultivate all year long," stated Emma Guimarães, the province's vice governor of Namibe, at her Moçâmedes office. The province has abundant mining, farming, and fishing resources and strong tourism potential. However, she worries about water: "There are a few rivers close by, but they are not always present." This leads to unstable access to water (De Preneuf, 2023).

These illustrations show how PV water pumping systems can enhance rural residents' access to water. These systems can enhance health outcomes, increase access to education, and promote economic growth by offering a reliable and sustainable source of clean water. Problems like high initial costs, maintenance requirements, and the requirement for technical skills must be addressed to preserve the long-term profitability of these systems. These challenges can be met with creative funding sources, community-based management strategies, and capacity-building initiatives to ensure PV systems realize their full potential in enhancing rural Africa's access to water.

2.3 Findings from the existing literature

In recent years, photovoltaic (PV) water pumping systems (PVWPS) have become a long-term solution for rural water supply, particularly in places with restricted access to the electrical grid. A wide range of subjects are covered in the literature that is currently available on PVWPS, such as technical performance and economic feasibility to environmental and social impacts.

Water cannot be moved from one location to another by humans or animals; this is the job of the water pumping system. A photovoltaic water pumping system (PVWPS) is a combination of a solar energy system and a water pumping system that maximises efficiency (Al-Badi et al., 2018). Photovoltaic (PV) water pumping systems have emerged as an effective solution for rural water supply, especially in areas with limited access to grid electricity. The findings from the literature review show that the integration of PV technology with water pumping applications can significantly improve the efficiency of the water pumping system and highly reduce the cost involved in the use of the water pumping systems (Bensaad et al., 2019). The literature review conducted in this project explored different areas of the PV water pumping system, such as the PV Water Pumping system costs, technical benefits of PV water pumping systems, Performance of the PV water pumping systems, and Modelling and design of the PV Water pumping systems.

A. PV Water Pumping systems Costs

The PV water pumping systems can minimise the operational costs of water pumping systems compared to diesel water pumping. The reduced operational costs of PV water pumping systems can have significant implications for rural and off-grid communities, where access to reliable and affordable water sources is crucial for domestic, agricultural, and livestock needs. By minimising the ongoing expenses, PV water pumping can enable more sustainable and equitable water access, especially in areas with limited financial resources. The lower operating expenses of PV water pumping systems can make them more financially viable and accessible for rural communities and small-scale farmers, who often have limited budgets and resources. This improved cost-effectiveness can lead to increased adoption, as the upfront investment in PV systems becomes more justifiable in the long run, compared to the ongoing fuel and maintenance costs of diesel-powered pumps. The cost savings generated by PV water pumping systems can be reinvested in other community development initiatives, such as improving irrigation systems, enhancing agricultural productivity, or investing in education and healthcare. Furthermore, the cost savings can also contribute to the overall affordability and scalability of PV water pumping solutions, making them more accessible to a wider range of communities and promoting the adoption of this sustainable technology for rural water supply applications (Manga et al., 2021). The PV system has improved the reliability and affordability of water access, allowing farmers to increase crop yields and diversify their agricultural activities. Maintenance costs have been significantly reduced, and the system has a lifespan of over 20 years. Another case study was done in Machakos County of Kenya, where several off-grid PV water pumping systems were installed to provide clean drinking water for rural communities. These systems draw water from boreholes and deliver it to centralised distribution points, benefiting over 10,000 people (Vezin, et al., 2020). For example, in Ethiopia's Afar region, a directly coupled PV water pumping system was installed to provide water for livestock in a remote, off-grid community. The system consisted of a 2.4 kW PV array directly connected to a submersible DC pump without needing batteries or inverters. The directly coupled PV system has significantly reduced the operational and maintenance costs while providing a reliable and continuous water supply for the livestock. The system's simplicity has also made it easier for the community to maintain and operate, reducing the need for external technical support (Singh et al., 2018).

B. Technical benefits of PV water pumping systems

Some case studies on PV water pumping systems have been conducted in different regions of Africa. These case studies demonstrated the technical benefits of PV water pumping systems in Africa, including increased reliability, affordability, and accessibility of water resources for various applications, such as irrigation, domestic use, and livestock watering. For instance, In the Matam region of Senegal, a PV water pumping system was installed to support small-scale irrigation for local farmers (Ibrahim et al., 2020). The system consisted of a 5.5 kW solar array, a submersible pump, and a water storage tank. Before the installation, farmers relied on diesel-powered pumps, which were costly and required regular maintenance. The PV systems have reduced the time and effort required for water collection, previously done manually or with diesel-powered pumps. The systems have also improved water quality and reduced the incidence of water-borne diseases in the communities (Ibrahim et al., 2020).

C. Performance of the PV water pumping systems

It was also found from previous literature reviews specified in **Table 2.2** PV water pumping systems are heavily dependent on the availability of solar irradiation, which can be variable and intermittent, depending on weather conditions. Areas with limited or inconsistent sunlight may not be able to fully leverage the benefits of PV systems, as the water pumping capacity may be reduced during periods of low solar radiation. The intermittence of the sun affects the performance of the PV water pumping system. The water demand in agricultural and rural communities often fluctuates seasonally, with peak demands during the dry or growing seasons. PV water pumping systems may not always be able to meet the increased water demands during periods of high usage, as the available solar energy constrains their performance (Okakwu et al., 2022a).It was also found that the PV water pumping system without a maximum power point tracking can seriously perform poorly. A PV water pumping system was installed in a rural community in the Afar region of Ethiopia. Still, it did not utilise a direct coupling between the PV array and the pump. Instead, it relied on a battery bank and an inverter to power the AC pump. Due to the energy losses in the battery bank and inverter, the system could only deliver an average of 15 cubic meters of water per day, significantly lower than the 25 cubic meters that the community required.

This shortfall in water delivery led to increased waiting times and conflicts within the community as they struggled to meet their daily water needs (Saidi et al., 2021).

Furthermore, It was also found that the directly coupled PV water pumping system is the best option for the population in rural areas because of its simplicity, higher efficiency, lower cost, improved durability, and reduced maintenance requirement which make it a particularly suitable and cost-effective solution for small-scale water pumping applications in rural or off-grid areas of Africa (Fakher et al., 2021). This simplicity of design makes the system more reliable, as fewer components can potentially fail, reducing maintenance requirements and improving overall system uptime.

Numerous reviews and research on PVWPS have been done, but they mainly concentrate on system performance, economic performance, environmental viability, water flow rate, and system sizing. Directly-coupled PV water pumping devices receive less attention. To enhance the performance of the PVWPS, (Gil-Antonio et al., 2019) built a converter controller that utilised the maximum power point technique (MPPT) and created modelling for a stand-alone photovoltaic water pumping system. During the modelling process, an efficiency test was carried out using the maximum fuzzy logic-based controller (MFLC). The findings indicate that the MFLC-based MPPT has the potential to enhance the motor's speed and boost the PV's efficiency to 6.85%. To forecast the PV water pumping system's hourly flow rate in Saudi Arabia, (Haddad, et al., 2020) created a model of the system using a numerical model. The polynomial regression method served as the foundation for the numerical model. (Yussif et al., 2020) used MATLAB/SIMULINK to model and simulate the PVWPS. The simulation results demonstrated that the most effective type of induction motor for agricultural irrigation in areas with unstable solar radiation is a photovoltaic array-fed induction motor with a single-stage MPPT Inverter and field-oriented control.

Researchers in Nigeria looked at the effects of solar radiation and total system head on farms (Okakwu et al., 2022a). According to the study, with a system head of 10 m and solar irradiation of 5.25 kWh/m^2 /day, the PV power ranges from 1.90 kW to 3.52 kW, and the pump power ranges from 0.158 kW to 0.293 kW. However, the life cycle cost of water varies from \$7004 to \$12331, while its unit cost falls between \$0.05 and \$0.054 per m^3. This shows what happens when the system head and solar radiation are changed.

A solar photovoltaic DC water pumping system was modelled and simulated by (Campana et al., 2017) using MPPT. Thus, an MPPT-equipped PV water pumping system was discovered to perform better than one without. To determine the optimal design, (Salman et al., 2021) conducted a study that considered variables that affect the system's performance, such as tank capacity, solar irradiance, and cell temperature. To minimise water and electricity consumption, the design combines sprinkler systems with economical, ecologically friendly photovoltaic technology. Variables, including tank capacity, solar irradiation, and cell temperature, were considered in the study. The design combines sprinklers with reasonably priced, ecologically friendly solar technology to save energy and water.

D. Modelling and design of the PV Water pumping systems

(Dujardin et al., 2022a) showed that the soft computing technique is the most effective modelling method for determining economic feasibility, controlling the water flow rate, and identifying defects. According to a study by (Sontake et al., 2020), the best array configurations for providing excellent energy at all pumping heads are the 4S×2P and 5S×2P configurations. Given that the population's daily water needs are reduced in the winter, the 13.34 m^3 pumped water supply may be sufficient to meet the populace's needs. (Saady et al., 2023) also discovered that the need for water rises in the summer. The study's findings indicate that the summer is when there is an increase in water pumping. During the summer, an estimated 25.41 m^3 of water was pumped daily. (Shepovalova et al., 2020) examined the layout of the PV array, the connections between the PV modules, and additional parts such as the pumps and inverters. Additionally, the efficiency of the PV system needed to be evaluated after the water is consumed rather than at the pump output or the point of end-user consumption. The fuzzy logic controller was designed and modelled by (Bhowon et al., 2022) to track a 65-watt photovoltaic system's highest power point. The findings show that, when it comes to managing power loss and oscillations in photovoltaic systems at the operational point, fuzzy logic controllers are a solid choice. The modelling and design were done with MATLAB/Simulink. An overview of the studies on the modelling and control of PV water pumping systems is shown in **Table 2.2.**

The family of PV array current-voltage curves, ranging from 200 W/m2 to 1000 W/m2, is depicted in **Figure 2.4.** The maximum power points Parray = Pmax array are dotted and two load characteristics I = ϕ 1(V) and I = ϕ 2(V) are shown concerning different electric motors and pumps. An increase of current in the PV array will increase the voltage. This is an important detail to consider during the design phase.

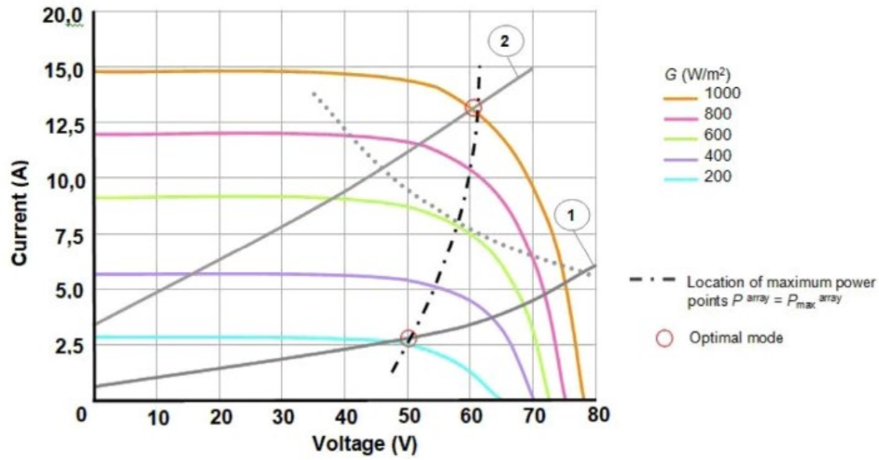

Figure 2.4: *The family of PV array current-voltage from 0 to 80 V*

(Verma et al., 2021)

Table 2.2: **Review overview of the modelling and control of the PV water pumping systems**

Paper author and year	The aim of the paper/chapter	Method /Strategy/Technique	Used hardware/Software	Achievements
(Saidi et al., 2021)	Use a converter-controller and simulate a standalone photovoltaic water pumping system to improve the PVWPS's performance.	Maximum power point technique (MPPT)	MATLAB/SIMULINK	PV efficiency is increased by 6.85%, and the motor's speed is increased.
(Ibrahim et al., 2020)	The design methodology and modelling of a photovoltaic pumping system with enhanced performance.	Maximum power point technique (MPPT)	PowerWord Simulator	The flow rate of a PVWPS can be increased by a ferrite magnet synchronous reluctance motor by 15% at a high irradiation level.
(Miqoi et al., 2019)	Water pumping systems with photovoltaic power are designed to maximize efficiency.	None	PVCAD	When assessing the financial viability of solar-powered water pumping systems, tilt angle fluctuations don't significantly impact system performance until the tilt angle reaches approximately 20 degrees latitude.
(Fara et al., 2021)	Using a numerical model, the PV water pumping system in Saudi Arabia is modelled in order to determine its hourly flow rate.	Polynomial regression technique	MATLAB/SIMULINK	Less computation was required to determine the water flow rate.

(Meunier et al., 2019)	A verified model of an off-grid rural community's solar water pumping system.	Normalized Root Mean Square Error (NRMSE)	Arena	When employing climatic data, the modelling accuracy using the NRMSE technique exceeds 95%.
(Tiwari and Kalamkar, 2016)	The effectiveness of solar water pumping systems with direct coupling at various pumping heads and PV configurations.	None	MATLAB/SIMULINK	The optimal array designs for optimal energy provision at all pumping heads are 4SH2P and 5S×2P.
(Naval and Yusta, 2022a)	Evaluation of various solar tracking methods for water pumping stations powered by photovoltaic cells.	Mixed-integer nonlinear Technique	MATLAB/SIMULINK	Compared to a two-axis tracker, a single-axis tracker can save operating costs and boost solar efficiency.
(Okakwu et al., 2023)	Investigation into the impact of the PV pumping system's techno-economic design for ground water irrigation.	None	MATLAB/SIMULINK	At greater system heads, the PV-pumping system operates poorly; but, at higher solar radiation, it performs well.
(Saady et al., 2023)	Optimizing and managing a solar water pumping system using a multilayer inverter fed DTC-IM and a kalman filter based MPPT.	Maximum power point technique (MPPT)	MATLAB/SIMULINK	The Kalman Filter outperforms VSS-P&O and VSS-INC in terms of power oscillation and time responsiveness under sudden irradiance.
(Miqoi et al., 2019)	Adaptive sliding mode controller design to increase MPPT efficiency for PV water pumping.	Maximum power point technique (MPPT)	PowerWord Simulator	Better outcomes are obtained with the adaptive sliding mode controller for the PVWPS armature voltage, DC motor speed, and output PV power.

(Jain et al., 2016a)	PVWPS modelling and simulation with MATLAB/SIMULINK	None	MATLAB/SIMULINK	Field-oriented control is used to feed an induction motor from a solar array.
(Biswas and Iqbal, 2018)	Libyan direct-coupled solar water pumping system modelling, control, and analysis.	None	MATLAB/SIMULINK	Performance of PVWPS.
(Bright Samson and University of Ibadan., 2019)	The management of a pumping system under fluctuating solar radiation over the sun.	None	MATLAB/SIMULINK	When the radiation increases, the PMDC supply voltage rises as well.
(Syahputra and Soesanti, 2021)	Solar photovoltaic dc water pumping system modelling and simulation.	Maximum power point technique (MPPT)	MATLAB/SIMULINK	An MPPT-equipped PV water pumping system performs better than one without one.
(Shepovalova et al., 2020)	Examining studies on solar-powered water pumping systems	None	None	PV To have improved performance, the system efficiency needs to be evaluated after the water usage.

While the existing literature provides valuable insights into PVWPS, it also reveals some limitations. Many studies focus on technical aspects and performance optimization, often overlooking the social and cultural contexts in which these systems are implemented. Moreover, comprehensive research evaluating PVWPS's long-term feasibility and scalability across a range of geographic and socioeconomic conditions is scarce.

2.4 Conclusion

Water supply in Africa remains a significant concern, especially in rural and isolated locations. PVWPS offers a promising solution to water scarcity by utilising solar energy resources; Water may be transported between locations at a reasonable cost and without interruption using PVWPS. Rural communities find that photovoltaic water pumping systems are a promising solution for meeting their water needs, particularly in areas with limited access to grid electricity. By harnessing abundant and renewable solar energy, these systems offer a sustainable and reliable solution for water supply, with the potential to significantly improve the quality of life and support the socioeconomic development of rural populations.

The literature review conducted in this chapter focused on PV water pumping systems. An assessment of rural water supply was conducted, demonstrating that many African countries still face water challenges, and most of the population in rural areas has access to unimproved water sources. The cost of maintaining a sustainable water program was high and significant. It was also observed that Nigeria has been trying to overcome the water challenge due to a lack of good management and enough finance to support water management programs. Furthermore, it was also found that most of the population in rural areas in South Africa, Angola, and many other African countries have been walking long distances to get water for their basic needs. Therefore, the performance of the PVWPS was analysed through a study of different literature reviews. The best solution for supplying water to isolated rural areas has been determined to be the Direct-Coupled Photovoltaic Water Pumping solution. Thanks to this technology, water may be transported between locations at a reasonable cost and without interruption.

The Direct-Coupled Photovoltaic Water Pumping system for the residents of rural locations can be significantly enhanced by ideal modelling. while indirectly improving the economy of any nation, as most agricultural fields are situated in remote rural areas. In addition, it will lower carbon dioxide emissions in Sub-Saharan Africa. More research and investment are required to overcome technical and economic (equipment) constraints and promote the broad deployment of PVWPS throughout Africa. Furthermore, future research must also be done to allow the water pumping system to operate at its peak efficiency. Innovations such as using advanced PV materials, efficient pumps, and integrated control systems are expected to drive further improvements in the performance and accessibility of these systems, making them increasingly viable and attractive for rural water supply applications. The next chapter will discuss in detail the performance of the Direct-Coupled Photovoltaic Water Pumping system as well as all the components of this system.

CHAPTER THREE

THE PERFORMANCE AND OPERATION OF DIRECTLY- COUPLED PHOTOVOLTAIC WATER PUMPING SYSTEMS

3.1 Introduction

Finding a viable substitute for diesel is necessary to power a pumping system, as diesel costs and electricity consumption are rising. Directly coupled Photovoltaic water pumping systems are feasible for remote locations where grid power connections can be costly and complex. Because they require less maintenance, these systems are more dependable than those that rely on diesel pumps. However, three factors, irradiation, load type, and air temperature, have an impact on a photovoltaic system's performance. Maximum Power Point Tracking (MPPT) techniques maximise the PV output power regardless of the weather and operational conditions to overcome these disadvantages. Numerous MPPT methods have been documented in the literature; each has its own set of specifications, restrictions, and uses.

Some data collected highlight the superior performance characteristics of the directly coupled PV water pumping system, including its water delivery efficiency, adaptability to changing conditions, environmental resilience, scalability, and operational simplicity – all of which contribute to its suitability and effectiveness in meeting the water access needs of rural communities in Africa. For instance, In a field study conducted in Malawi, researchers observed that a directly coupled PV water pumping system was able to deliver an average of 40 cubic meters of water per day, which was a significant improvement over the previous diesel-powered pump that could only deliver 25 cubic meters per day. The system's ability to directly convert solar energy into water-pumping power without intermediary conversion steps resulted in a higher overall efficiency, leading to more water delivered per unit of input energy. The other case was in Namibia, where the directly coupled PV water pumping system was observed to maintain consistent performance even under varying solar irradiance conditions and fluctuations in water demand from the community. The system's inherent responsiveness to changes in available PV power allowed it to automatically adjust its operation, ensuring a reliable and continuous water supply without the need for complex control systems or energy storage. A case study from Tanzania evaluated the directly coupled PV water pumping system after several years of operation in a harsh, dusty environment. The system was found to have minimal degradation in performance, with the PV array and pump maintaining their efficiency levels. The simplicity of the system design, with fewer moving parts and electronics, contributed to its resilience and long-term durability, reducing the need for frequent maintenance or replacements. The simplicity of the directly coupled PV water pumping system has also contributed to its performance. In a series of community workshops conducted in Kenya, the end-users of the directly coupled PV water pumping system expressed their appreciation for its straightforward operation, allowing them to quickly understand and maintain the system without the need for extensive technical knowledge or external support. The simplicity of the system design was a key factor in empowering the community to take ownership of the water pumping infrastructure and ensure its long-term sustainability.

The directly coupled PV water pumping system can perform poorly if there is no maximum point tracking included. In a remote community in Namibia, a PV water pumping system was installed without direct coupling and MPPT, relying on batteries and an inverter. The system's dependency on the battery bank and the need for regular replacements due to the high cycling wear reduced the overall sustainability of the water supply infrastructure. The community faced challenges in securing the necessary financial resources and technical expertise to maintain the system, leading to periods of water scarcity and a decline in the community's trust in the technology. It is also essential to understand each component of the PV water pumping system to get a full understanding of the impact of each on the performance of the system

This chapter has many sections, each providing specific information needed to develop an efficient, Directly coupled PV water pumping system. Section 3.2 discusses the benefits and drawbacks of the directly coupled PV water pumping system. Section 3.3 explains in detail the role of each component of the directly coupled PV water pumping system. Section 3.4 discusses the sizing of PV solar water pumping systems. Section 3.5 discusses the processes and operations involved in this system. Section 3.6 discusses different configurations of this pumping system. Section 3.7 details the performance of the Directly-Coupled PV water pumping system. Section 3.8 consists of a general discussion regarding the directly coupled PV water pumping system-based maximum power point technique. Section 3.9 concludes the proposed fuzzy logic controller for PV and Wind Energy Systems.

3.2 Water Pumping Systems

Water pumping systems are systems for moving water from one place to another. Most water pumping systems are utilised to supply water to homes, businesses, and enterprises in agriculture. Some of these systems run on gasoline and diesel engines, but most require electricity. However, gasoline and diesel fuel are costly, releasing carbon dioxide (CO2) into the atmosphere and harming the ecosystem. It is also crucial to remember that many people live in rural areas without access to the electrical grid and that extending power lines is typically very costly. Thus, the solution to a problem that many rural communities problem is using renewable energy for water pumping equipment. The main distinctions between a diesel or gas-powered system and a PV-powered system are listed in **Table 3.1.**

Table 3.1: PV-powered vs Diesel-powered system (Saady et al., 2023)

System Type	Advantages	Disadvantages
PV Powered System	• Low Maintenance • Long Life • No fuel • No fumes • Easy to install • Low maintenance cost	• High initial cost • Low output in cloudy weather
Diesel (or Gas) Powered System	• Moderate capital costs • Easy to install • Can be portable	• Needs constant maintenance and placement • Noisy • Emit fume • Emit Carbon dioxide • Fuel is expensive

3.2.1 Types of water pumps

The primary purpose of a water pump is to increase liquid or water pressure so that it can be moved from one location to another by converting kinetic energy into hydrodynamic energy. As **Table 3.2** illustrates, there are many types of water pumps, each functioning differently. These include centrifugal pumps, submersible pumps, gear pumps, rotary vane pumps, and many more (Verma et al., 2021).

Table 3.2: **Different types of water pumps, Operating principles, and Applications** (Verma et al., 2021)

Type of Water Pumps	Operating Principles	Applications
Centrifugal Pump	• Work to produce flow or raise a fluid from a lower level to a higher level. • Turns rotational energy coming from a motor into energy in a moving fluid.	• Cosmetic, agriculture, wine-making, dairy, mining, petroleum, and food processing.
Submersible Pump	• Pushes water to the surface by converting rotary energy into kinetic energy into pressure energy.	• Pumping sewage, wastewater, irrigation, sludge, and slurry from mines, quarries, and construction.
Piston Pump	• Work with the help of the pumping mechanism force to increase the volume of the liquid. •	• Medical, Industrial, Dispensing Systems, and Spraying Systems.
Gear Pump	• It uses the gear's actions to move liquids. • The rotating part extends the seal of liquid by the pump case to create suction at the inlet of the pump.	• Automotive fuels and oils, Hydraulic oils, Solvents, and alcohol.
Rotary Vane Pump	• Work using a positive-displacement principle. Rotary vane vacuum pumps consist of a rotor mounted inside a stator or housing.	• Power steering, air conditioning, and automatic transmissions.

3.2.1.1 Centrifugal Pump

The centrifugal pump is made up of an impeller via which fluid enters by the suction or inlet and exits through the outlet or discharge. Kinetic energy is transformed into hydrodynamic energy throughout this process. The majority of the time, centrifugal pumps are utilized in agriculture, however, they are always preferable when the liquid's viscosity is low (Verma et al., 2021).

Below are the key mathematical equations for centrifugal pumps:

Head (H):

$$\mathrm{H} = \frac{V_2^2}{2g} - \frac{V_1^2}{2g} + \frac{\mathrm{p}_2}{\mathrm{pg}} - \frac{\mathrm{p}_1}{\mathrm{pg}} \tag{3.1}$$

Where:

H = Head (in meters)

v_1 = Velocity at pump inlet (m/s)

v_2 = Velocity at pump outlet (m/s)

g = Acceleration due to gravity (m/s^2)

p_1 = Pressure at pump inlet (Pa)

p_2 = Pressure at pump outlet (Pa)

ρ = Fluid density (kg/m^3)

Power (P):

$$P = \rho \times \mathrm{Q} \times \mathrm{H} \times \frac{g}{\eta} \tag{3.2}$$

Where:

P = Power (in watts)

Q = Volumetric flow rate (m^3/s)

H = Head (in meters)

g = Acceleration due to gravity (m/s^2)

η = Pump efficiency (dimensionless)

Impeller Diameter (D_2):

$$D_2 = (60 \times \frac{Q}{\pi \times V_2})^{\frac{1}{2}} \tag{3.3}$$

Where:

D_2 = Impeller diameter (m)

Q = Volumetric flow rate (m^3/s)

v_2 = Velocity at pump outlet (m/s)

Centrifugal pumps have an efficiency of roughly 94%, although most of the time, small centrifugal pumps have an efficiency of 55%, and large centrifugal pumps have an efficiency of 70%. Centrifugal pumps come in sizes ranging from 40 to 760 mm (Zhou et al., 2020).

Centrifugal pumps have several benefits that should be considered, including:

- They can be used to pump hazardous substances without the pump deteriorating.
- They do not have any leaks because they do not have a drive seal
- They are less noisy when operating
- Their structural arrangement prevents heat transmission between the motor and the chamber
- Their design makes them energy-efficient (Naval and Yusta, 2022b)

The loss of energy resulting from the magnetic resistance of centrifugal pumps is another major drawback of these devices. It is also essential to understand that the centrifugal pump can perform differently depending on the blade and vane configurations.

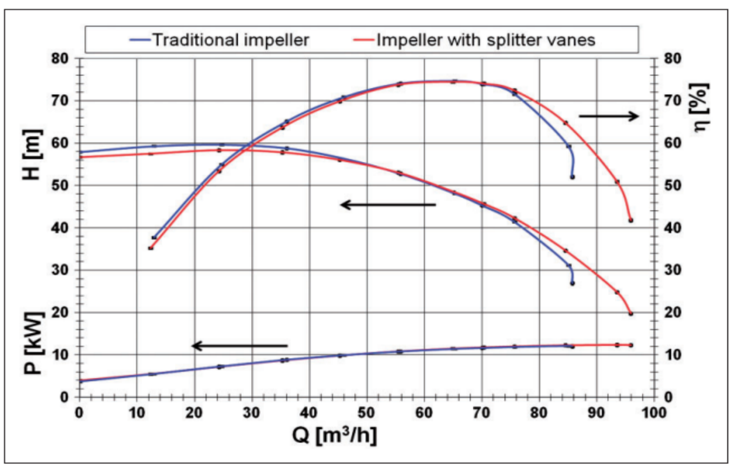

Figure 3.1: **Performance curves of the centrifugal pumps with and without splitter vanes (Schmitter et al., 2018)**

Figure 3.1 shows the performance curves of the centrifugal pumps with and without splitter vanes. The x-axis represents the water flow rate, the y-axis on the right side represents the efficiency of the centrifugal pump, and the y-axis on the left side represents the pump's head. The centrifugal pump with splitter vanes performs better than the one without.

3.2.1.2 Submersible pump

The submersible pump is composed of a motor that is hermetically sealed to allow the pump to submerge in a liquid by lowering the flowing pressure. Deep wells and wastewater are pumped using submersible pumps (Verma et al., 2021).

Below are the key mathematical equations for the submersible pump:

Head (H):

$$\mathrm{H} = \frac{V_2^2}{2g} - \frac{V_1^2}{2g} + \frac{\mathrm{p}_2}{\mathrm{pg}} - hf \tag{3.4}$$

Where:

H = Total dynamic head (in meters)

v_1 = Velocity at pump inlet (m/s)

v_2 = Velocity at pump outlet (m/s)

g = Acceleration due to gravity (m/s^2)

p_1 = Pressure at pump inlet (Pa)

p_2 = Pressure at pump outlet (Pa)

ρ = Fluid density (kg/m^3)

hf = Frictional head loss (in meters)

Power (P):

$$P = \rho \times \mathrm{Q} \times \mathrm{H} \times \frac{g}{\eta} \tag{3.5}$$

Where:

P = Power (in watts)

Q = Volumetric flow rate (m^3/s)

H = Total dynamic head (in meters)

g = Acceleration due to gravity (m/s²)

η = Pump efficiency (dimensionless)

Net Positive Suction Head (NPSH):

$$NPSH = \mathrm{p}_1 + \frac{\rho g h_1}{\rho g} - \frac{\text{Vapor Pressure}}{\rho g} \tag{3.6}$$

Where:

NPSH = Net Positive Suction Head (in meters)

p_1 = Pressure at pump inlet (Pa)

h_1 = Elevation of pump inlet (m)

ρ = Fluid density (kg/m³)

g = Acceleration due to gravity (m/s²)

Vapor pressure = Pressure at which the fluid starts to vaporise (Pa)

Because groundwater levels are erratic, submersible pumps cannot be operated at the intended head and discharge. Consequently, these pumps are operating at a reduced efficiency of between 18% to 35% year-round, as opposed to the typical laboratory efficiency of 64% (Fakher et al., 2021). The submersible pumps do not need much energy to pump water into them, and they are also incredibly efficient. However, there is a single issue with the submersible pump. The corrosion of the seal developed with time, and as a result, water began to enter the motor. Repairing the corrosion on the submersible pumps seal is a very challenging task (Fakher et al., 2021).

(Fakher et al., 2021) conducted a study of the performance of the submersible pump during operation, as shown in **Figure 3.2**. It was observed that there is an important relationship among the pump discharge (Q), total dynamic head (H), and hydraulic power (Ph). As the total dynamic head increased, the pump discharge decreased. Hydraulic power fluctuated between increasing and decreasing. Every point was appropriate for the demands of the operational field. The ideal values for the total dynamic head, hydraulic power, and discharge were 2.22 meters, 18.35 watts, and 51 °C/min, respectively.

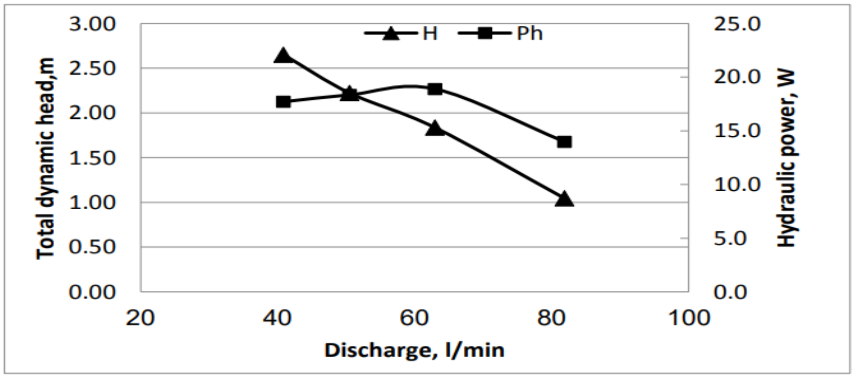

Figure 3.2: **Performance characteristics curve of Submersible Pump (Fara et al., 2021)**

3.2.1.3 Piston pump

The piston pump is used mainly for water irrigation and other high-pressure applications. It operates by responding through the piston to a high-force seal. Their sizes range from 1.6 to 20 cm^3 and can operate at up to 700 bar.

Below are the key mathematical equations for the piston pump:

Volumetric Flow Rate (Q):

$$Q = A \times v \tag{3.7}$$

Where:

Q = Volumetric flow rate (m^3/s)

A = Cross-sectional area of the piston (m^2)

v = Piston velocity (m/s)

Discharge Pressure (P):

$$P = \frac{F}{A} \tag{3.8}$$

Where:

P = Discharge pressure (Pa)

F = Force applied to the piston (N)

A = Area of the piston (m²)

Every hydraulic system has a minimum of one pump. One of the system's main components is the pump, which converts mechanical energy into hydraulic energy. As a result, the pump efficiency dramatically influences the whole system's efficiency. The two main types of losses that affect piston pump efficiency are mechanical (friction) and volumetric (leakage). **Figure 3.3** illustrates how the fluid viscosity mainly influences these losses. It can be observed that at the speed of 3000 rpm, the pump efficiency increases when the fluid viscosity decreases. Therefore, It is essential to identify the impact of the fluid viscosity before deciding to use the piston pump for a specific application.

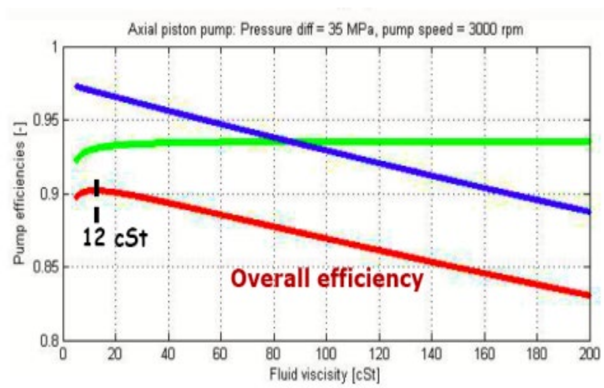

Figure 3.3: **Efficiencies versus fluid viscosity for Piston Pump at a speed of 3000 rpm(Fara et al., 2021)**

A piston pump's benefits mostly consist of the following:

- There is a large pressure range;
- Force can be controlled without changing the flow rate.
- Changes in pressure and flow rate somewhat impact the act.

Piston pump drawbacks primarily consist of the following:

- They can only manage lower flow rates;
- They are often big and bulky;
- They have substantial maintenance and running costs.
- Pulsating flow (Fara et al., 2021)

3.2.1.4 Gear Pump

The gear pump uses the repeating motion created by the gears' revolution to move a liquid. Pumping oils and other viscous liquids is a better application for the gear pump (Verma et al., 2021).

Below are the key mathematical equations for the gear pump:

Volumetric Flow Rate (Q):

$$Q = V \times N \tag{3.9}$$

Where:

Q = Volumetric flow rate (m^3/s)

V = Displacement volume per revolution (m^3/rev)

N = Shaft speed (rev/s)

Pressure Difference (ΔP):

$$\Delta P = \frac{F \times N}{V \times n\_v} \tag{3.10}$$

Where:

ΔP = Pressure difference between inlet and outlet (Pa)

F = Force required to drive the gears (N)

N = Shaft speed (rev/s)

V = Displacement volume per revolution (m^3/rev)

η_v = Volumetric efficiency (dimensionless)

An important consideration when buying a pump is the pump performance curve. Based on manufacturer-conducted testing, the performance is represented by the performance curve. The performance of the gear pump is shown in **Figure 3.4**. The gear pump's pressure is represented by the x-axis in Kpa, the y-axis in KW represents power, and the y-axis on the left shows the flow rate. The pressure and flow performance of a pump is indicated by the pump performance curve.

According to an experiment by (Wei and Sun, 2017), a more prominent tooth notch impacts the operating gear pump pressure, and the operating pressure drops as the tooth notch widens.

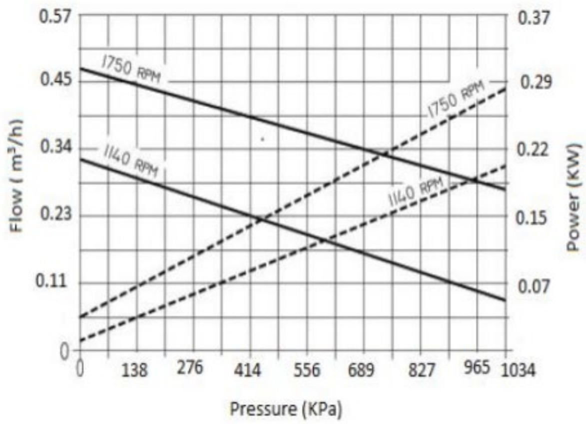

Figure 3.4: **Gear Pump performance curve** (Wei and Sun, 2017)

The efficiency of the gear pumps is approximately 85%. They have fewer parts, which makes them less expensive. These pumps are employed when low to medium pressure, roughly 2500–4000 psi is required.

The following are some of the benefits of gear pumps:

- The product requires minimal maintenance and can handle various viscosities.
- Controllable output that is simple to reconstruct

The two primary drawbacks of gear pumps are as follows:

- The liquid must be clear of abrasives before operation.
- During operation, interlocking gears can also be loud (Wei and Sun, 2017)

3.2.1.5 Rotary Vane Pump

A vane mounted on a rotor is used by the rotary vane pump to transfer liquids and gases. The liquid and gases are then compressed and transported to the pump outlet. In comparison to other pumps, the rotary vane pump produces less noise. It is mainly employed in the water treatment and food and beverage sectors (Zhou et al., 2020).

Below are the key mathematical equations for the rotary vane pump:

Volumetric Flow Rate (Q):

$$Q = V \times N \tag{3.11}$$

Where:

Q = Volumetric flow rate (m^3/s)

V = Displacement volume per revolution (m^3/rev)

N = Shaft speed (rev/s)

Pressure Difference (ΔP):

$$\Delta P = \frac{F \times N}{V \times n\_v} \tag{3.12}$$

Where:

ΔP = Pressure difference between inlet and outlet (Pa)

F = Force required to drive the vanes (N)

N = Shaft speed (rev/s)

V = Displacement volume per revolution (m^3/rev)

η_v = Volumetric efficiency (dimensionless)

Figure 3.5 presents the simulated operating points and the tendency lines at constant revolution speed. The x-axis represents the water flow rate, and the y-axis represents the pump's pressure. The operating curves follow a parabolic trend for very low-pressure rises (0–5 bar); after that, the fit becomes linear, consistent with the sliding vane pump's volumetric nature. This characteristic is consistent with experimental findings on a water sliding vane pump, which also demonstrated that operating curves at high revolution speeds tend to be vertical lines due to increased volumetric efficiency. The higher centrifugal force at high revolution speeds reduces fluid leaks between successive vanes by lowering the tip clearance gap (Zhou et al., 2020).

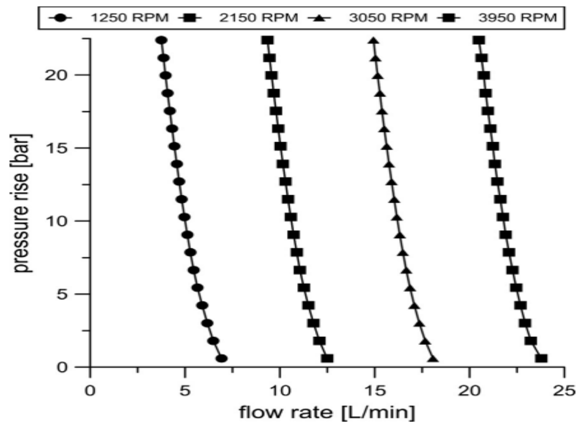

Figure 3.5: **Operating Curves of the Rotary Vane Pump (Zhou et al., 2020)**

Although rotary pumps can work at discharge pressures of up to 1,000 psi, their typical designs have pressure ranges of 25 to 500 psi with mechanical efficiencies of 80% to 85%.

There are several benefits to rotary vane pumps that should be considered.

- Longer longevity because of strong veins
- Silent functioning
- It can operate entirely dry
- It has low maintenance requirements.
- It is lightweight and small.
- It has a stable flow rate with no pulsation.
- It discharges liquid that is not sensitive to changes in viscosity
- It has slight vibration.

Although rotary vane pumps work wonders for moving liquids, there are certain hazards and drawbacks to consider, including:

- More prone to harm when using thicker liquids
- Less durable when in touch with abrasive materials
- Not appropriate for extremely high pressures

3.3 Photovoltaic System

This system consists of one or more solar panels with inverters and other electrical components that use the sun as a source of energy to generate electricity. The sun is a free and inexhaustible source of energy. About 1.018 Kilo joules of solar energy reach Earth annually as shown in **Figure 3.6** but many countries still neglect the use of such a potential source of energy. PV systems can significantly decrease global carbon dioxide emissions, which have been negatively affecting the environment, society, and economy of various countries around the world (Hassan et al., 2022).

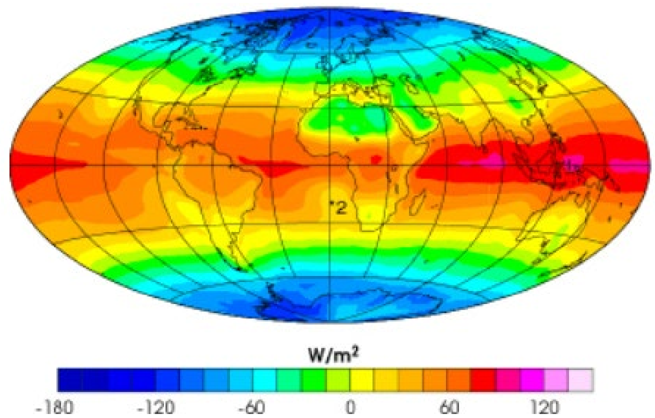

Figure 3.6: **Annual average solar irradiance distribution over the surface of the Earth (Hassan et al., 2022)**

3.3.1 Elements of PV system

The PV system is composed of four main elements namely; panel, inverter, racking, and solar battery storage as shown in **Figure 3.7** (Hassan et al., 2022).

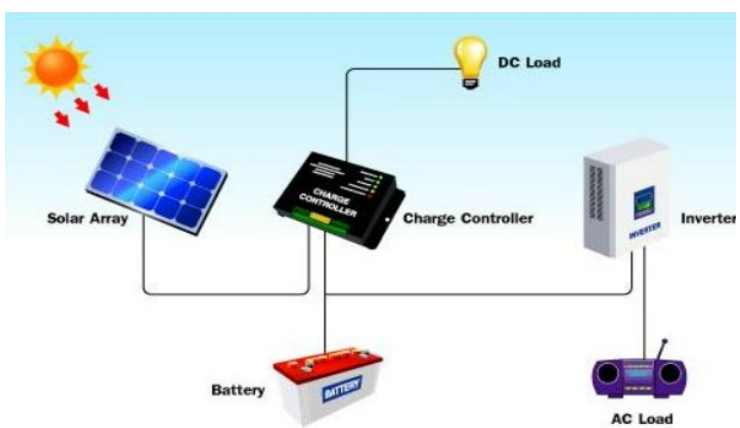

Figure 3.7: **Elements of the solar energy system (Hassan et al., 2022).**

3.3.1.1 Panels

Solar panels are also called photovoltaic modules. These devices generate DC electricity from the sun and are composed of seven components as shown in **Figure 3.8**. Solar panels also consist of many wiring that are responsible for the flow of the current through the silicon cells. As far as the current is flowing through the silicon cells the panel can generate energy (Yussif et al., 2020).

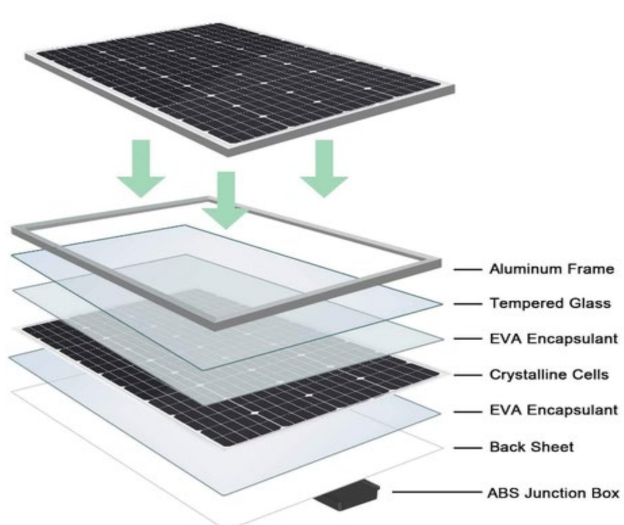

Figure 3.8: **Main Components of the Solar Panel(Yussif et al., 2020).**

3.3.1.2 Inverters

One component of the solar system that changes the direct current the solar panel produces into an alternating current is the inverter. A solar system's inverter is an essential part, and selecting the right one can greatly enhance the PV system's performance (Mitali et al., 2022).

An inverter's efficiency tells you how much DC power it can convert to AC power. In addition to standby power used to maintain the inverter in powered mode, some power may be lost as heat. **Figure 3.9** shows the inverter efficiency curve. In power output below 10-15%, efficiency is quite low. The efficiency is steadily high with some small variations at high output power.

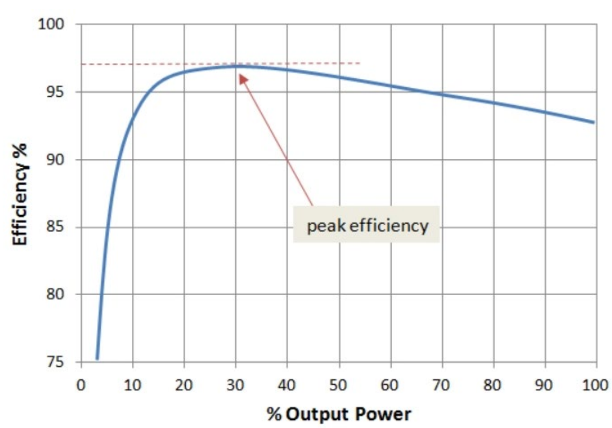

Figure 3.9: **Inverter’s Efficiency Curve (Mitali et al., 2022)**

A.Types of Inverters

Three types of inverters are available for solar energy systems: string inverters, microinverters, and power optimisers. Inverters are essential components of the system. These three inverters can perform differently in a non-shaded and shaded area. Therefore, it is important to understand each inverter's behaviour and performance during different seasons of the year and different environments. According to a study conducted by (Mitali et al., 2022), the string inverter is the most efficient in a non-shaded area because it produces more energy in a non-shaded area, and the microinverter is more efficient in a shaded area because it produces more energy in a shaded area, as shown in the tables and figures below.

A.1 String Inverters

One central currency exchange station or centralised inverter is in string inverters. According to (Iranzi et al., 2022)- These inverters are ideal for solar panels facing the same direction. The benefits and disadvantages of these inverters have been described in **Table 3.3**.

Table 3.3: The benefits and disadvantages of the String inverters (Iranzi et al., 2022)

Benefits of the String Inverter	Disadvantages of the String Inverter
• Lowest price	• Production drops if one panel is damaged or shadowed
• Standard inverter	• The panel cannot be checked separately
• Excellent performance in areas without shade	• Growing power requirements are more challenging and can necessitate installing a second central inverter

A.2 Microinverters

Microinverters are tiny power conversion devices that are integrated into each solar panel. Because of this configuration, the panels may work at maximum efficiency even in partially shaded areas, and if efficiency drops, only one panel will be impacted. By focusing on fixing the damaged panel only rather than the complete set of panels, this streamlines the repair procedure (Schmitter et al., 2018). The benefits and disadvantages of these inverters have been described in **Table 3.4**.

Table 3.4: **The benefits and disadvantages of the Microinverters** (Schmitter et al., 2018)

Benefits of the Microinverter	Disadvantages of the Microinverter
• The shadow provided by a nearby tree will not lower the total solar panel system's power output	• Expensive upfront
• Installing a second central inverter is easier and less expensive when power requirements increase	• Not required if every panel is facing the same direction and is not shaded

A.3 Power Optimizers

Regarding functionality and cost, power optimisers fall between string inverters and micro-inverters. They do an excellent job of maximising power before transferring it to the central inverter (Sinapis et al., 2021). The benefits and disadvantages of these inverters have been described in **Table 3.5.**

Table 3.5: **The benefits and disadvantages of the Power Optimizers** (Sinapis et al., 2021)

Benefits of the Power Optimizer	Disadvantages of the Power Optimizer
• More cost-effective than micro-inverters	• Expensive
• More efficient than string inverters	• Unnecessary if every panel faces the same direction
• Offers individual panel monitoring	

3.4 PV water pumping systems (PVWPS)

Solar energy is converted into electrical energy and used to power the water pump in photovoltaic water pumping systems. Because solar water pumping technology is economical and environmentally beneficial, so it has been viewed as a viable substitute for pumping systems that rely on electricity, fuel, or gasoline. Even without an energy source, water can be gathered from various sources, including wells, rivers, and basins, using solar pumping devices. These systems make water available in even the most remote locations. They are frequently used for agriculture, drinking water, and filling reservoirs. PV systems can be utilised for desalination, drinking water delivery, and water purification in addition to irrigation (Sinapis et al., 2021)

As seen in **Figure 3.10**, the photovoltaic water pumping system comprises numerous parts, including water pumps, PV arrays, solar batteries, pump controllers, solar inverters, and a water storage tank. Numerous factors, including the high initial implementation costs, low efficiency, the performance of PV arrays, the choice of an appropriate motor pumping system, the weather, the availability of water resources, and the water demand, influence the acceptance and application of PVWPS in many countries. Therefore, it is essential to develop a PVWPS that is trustworthy and reasonably priced so that a large number of people may start utilising it for agriculture, irrigation, and other daily needs (Chilundo et al., 2018).

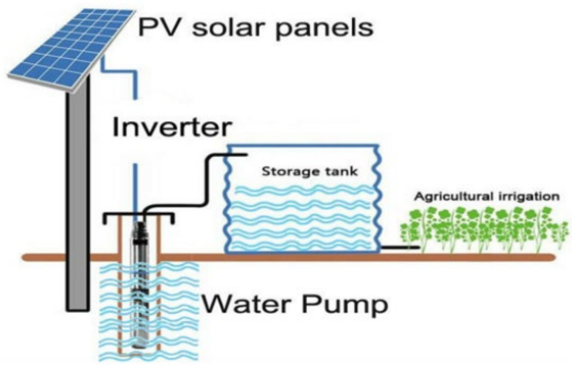

Figure 3.10: **Photovoltaic water pumping system** *(Sinapis et al., 2021)*

Thanks to increasingly affordable PV modules, PVWP systems are now significantly more affordable and dependable. Costs of PVWP systems have decreased by two-thirds since 2000, despite a >250% increase in fuel prices. Numerous systems, like the one in Estacion Torres in Sonora, Mexico, that were installed 20 years or more ago, are still in use. The off-the-shelf capabilities of PVWP have increased to 25 kW and will shortly surpass 100 kW. Global sales of PVWP systems are rising rapidly and are getting close to 100,000 units annually. Millions of small farmers and ranchers will eventually choose PVWP as their pumping technology as funding becomes more readily available. Having dependable and reasonably priced water pumping is essential for raising global agricultural productivity. Rain-fed land yields less than three times as much productivity as irrigated land. Large-scale commercial sales of PVWP can revolutionise agriculture in underdeveloped areas. Due to its excellent reliability and falling costs, PVWP is expected to increase significantly over the next ten years, enabling more farmers and ranchers to benefit from this affordable technology.

3.4.1 PV system hardware configurations

Solar PV systems come in two primary hardware configurations: Off-grid, or standalone, and grid-tied or grid-connected solar PV systems (Simpson et al., 2021).

3.4.1.1 Grid Connected PV Systems

As seen in **Figure 3.11**, a grid-connected photovoltaic system connects the PV array directly to the grid-connected inverter, doing away with the need for a storage battery. Should the photovoltaic system generate sufficient energy, the utility provider will not supply electricity. The meter will reverse if the system produces more energy than is required since the extra energy will be exported into the energy utility grid. All of the energy needed by the building will come from the power grid at night when the PV system is not producing any electricity. The energy utility provider will then have to give energy credits to suppliers in accordance with the quantity of solar energy produced (Simpson et al., 2021). The benefits and disadvantages of the grid-connected PV systems have been described in **Table 3.6**.

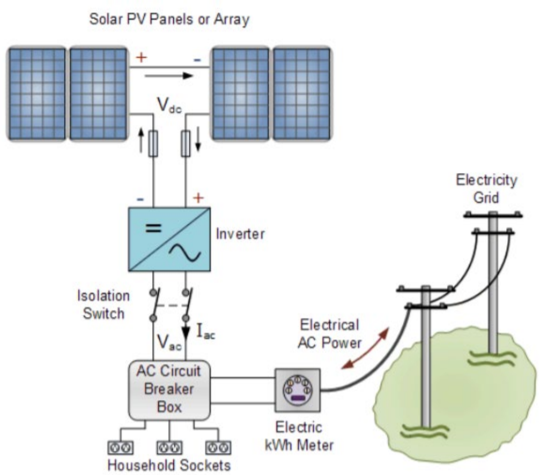

Figure 3.11: **Grid Connected PV System** *(Simpson et al., 2021)*

Table 3.6: The benefits and disadvantages of the Grid-Connected System (Simpson et al., 2021)

Benefits of the Grid-Connected System	Disadvantages of the Grid-Connected System
• Increasing the output of renewable energy, lowering reliance on utility power, and improving the environment can all be accomplished with a grid-connected system.	• Is unable to stop grid power outages
• It does not require batteries and requires less surface space for panels	• It can be powered by a small battery bank
• It Is less expensive	

3.4.1.2 Standalone PV Systems

Photovoltaic off-grid installations are disconnected from the electrical grid. An automated solar system that produces electricity during the day to charge battery banks for use at night when solar energy is not available is a simple freestanding photovoltaic system as shown in ***Figure 3.12***. The batteries and solar panels are connected to a charge controller (Simpson et al., 2021). The benefits and disadvantages of the Off-Grid system have been described in **Table 3.7.**

Table 3.7: The benefits and disadvantages of the Off-Grid System (Eteiba, et al., 2018)

Benefits of the Off-Grid System	Disadvantages of the Off-Grid System
• The system provides all of the building's electrical needs. • Functions in distant areas • Protects against power outages • It has no link to the traditional power system.	• Needs a system that is far more powerful. It needs to generate more energy than is often used. • Considerably more costly • May run out of electricity

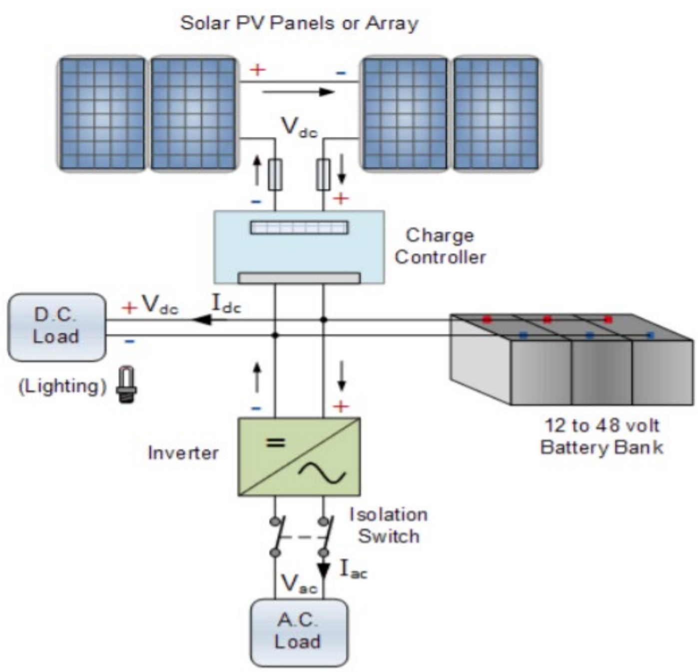

Figure 3.12: Off-Grid PV System

(Huang et al., 2020)

To electrify remote locations or offshore locations without access to the utility grid or in situations where running power lines to these isolated buildings would be extremely expensive, standalone photovoltaic systems are perfect. Installing a standalone photovoltaic system can sometimes be more cost-effective than hiring a local utility company to run cables and electricity lines inside the home (Huang et al., 2020).

3.4.1.3 Grid Tied with Battery Backup System

By adding a battery bank to the system, the energy produced by the PV system and kept in the batteries can be used during a power outage, as shown in **Figure 3.13**. When natural disasters or irregular grid power frequently cause power outages, a grid-tied PV system with battery backup is ideal (Huang et al., 2020).

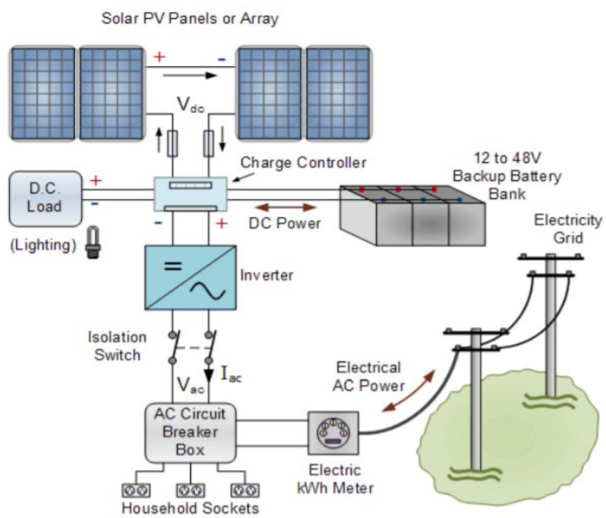

Figure 3.13: **Grid Tied with Battery Backup** ***(Huang et al., 2020)***

3.4.2 Performance of the PV water pumping system in different fields and applications

The PVWPS has been applied in many fields and for many applications. (Chilundo et al., 2018) implemented the PV Water Pumping Systems with a PV capacity of 2400 W for agricultural purposes in some rural areas. The results showed that applying the PV water pumping systems enhances the performance and the power quality at 3-Phase AC mains. (Shepovalova et al., 2020) experimented on the PV water pumping system using the Boost converter. The authors discovered that by efficiently transferring power between the PV Water Pumping Systems and the single-phase grid, a Permanent Magnet Brushless motor based on PV Water Pumping can be used to achieve continuous operation of the system. Grid-interfaced unidirectional PV water pumping systems for home and agricultural use were modelled by (Verma et al., 2021). The outcomes demonstrated that it can function well in both dynamic and steady-state scenarios.

3.5 Directly-Coupled PV Water Pumping System Performance

Water is intended to be pumped during the day using a directly coupled PV water pumping system. The type of pump used to gather water and the amount of sunshine that reaches the PV panels determine how much water is pumped. The amount of water collected changes during the day because the pump operates during the full duration of daylight. When the sun is at its greatest point, the pump operates at maximum efficiency or the largest volume of water that can be gathered. The pump's efficiency would also decline on overcast days (Mokeddem et al., 2011).

Below are the key mathematical equations for the directly coupled PV water pumping system:

Pressure Head (H):

$$Q = \frac{P\_out - P\_in}{\rho \times g} \tag{3.13}$$

Where:

H = Pressure head (m)

P_out = Outlet pressure (Pa)

P_in = Inlet pressure (Pa)

ρ = Density of the fluid (kg/m^3)

g = Acceleration due to gravity (m/s^2)

Power (P):

$$P = \frac{Q \times \rho \times g \times H}{\eta\_p} \tag{3.14}$$

Where:

P = Power (W)

Q = Flow rate (m^3/s)

ρ = Density of the fluid (kg/m^3)

g = Acceleration due to gravity (m/s^2)

H = Pressure head (m)

η_p = Pump efficiency (dimensionless)

In this project, a case study in Huambo in Angola will be conducted to analyse the performance of the Directly-Coupled Water Pumping System in the Province of Huambo. This is done to account for differences in the amount of sunshine available. Next, each case's optimised values have been considered. There is no need for a battery with a direct-coupled pumping mechanism. Because the batteries, not the PV panels, regulate the operating voltage, using batteries lowers the system's total performance. When there is the most sunlight, the solar panels' voltage is one to four times higher than the voltage provided by the batteries. The suggested system's block diagram is displayed in ***Figure 3.14***.

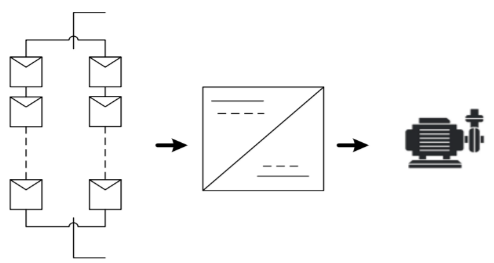

Figure 3.14: **Block Diagram of the Proposed System *(Bai et al., 2019a)***

The performance of these systems depends on many factors, but the main factors are:

- PV array configurations
- Pumping heads
- Variation of solar radiation level

3.5.1 PV array configurations

The Partial shading conditions (PSCs) affect the performance of PV water pumping systems. It is crucial to analyse and discuss the different PV array configurations in detail to reduce the shading conditions' negative effect (Pachauri et al., 2020). Below are the key mathematical equations for the PV array configurations:

Power Output (P):

$$P = V \times I \times FF \times \eta\_pv \times A\_pv \times G \tag{3.15}$$

Where:

P = Power output (W)

V = Voltage (V)

I = Current (A)

3.5.2 Pumping Heads

Its head and flow rate determine a water pump's performance; this is graphically represented as the pump characteristic curve, also known as the performance curve, in ***Figure 3.15***. The primary justification for using head instead of pressure to evaluate a pump's performance is that the liquid's specific gravity has no bearing on the height of the fluid column. A pump's head and flow rate define its performance; this is represented graphically in the image as the performance curve or pump characteristic. The main variables influencing a centrifugal pump's maximum pump head are the impeller's outer diameter, the shaft's rotating speed, and its angular velocity. As the volumetric flow rate through the pump is raised, the head will likewise alter as ***Figure 3.15*** illustrates.

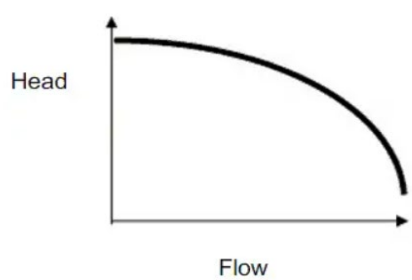

Figure 3.15: **Head and Flow rate Curve *(Jalil et al., 2022)***

Various studies regarding the water pumping heads have been conducted, and the optimal configuration was identified. An ideal photovoltaic (PV) array arrangement that can sufficiently supply a PV pumping system with an optimal amount of energy was experimentally explored by (Naval and Yusta, 2022a). ***Figure 3.16*** depicts a single-stage pump performance curve at 50 Hz speed and 20°C working fluid. Typical pump performance curves indicate operation under specific pressure head and flow rate. Some curves also display the Best Efficiency Point (BEP) that is proportionate to the maximum efficiency range. The pump's impeller experiences the least amount of radial force at the BEP, allowing for quiet, vibration-free operation (Naval and Yusta, 2022a).

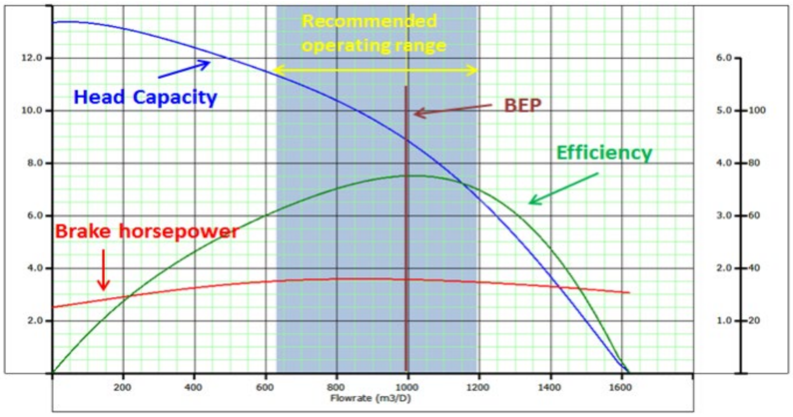

Figure 3.16: **Typical Pump Performance Curve** ***(Naval and Yusta, 2022a)***

Below are the key mathematical equations for the pumping heads:

Total Dynamic Head (H_T):

$$H\_T = H\_s + H\_f + H\_v + H\_z \tag{3.16}$$

Where:

H_T = Total dynamic head (m)

H_s = Static head (m)

H_f = Friction head loss (m)

H_v = Velocity head (m)

H_z = Elevation head (m)

3.5.3 Variation of Solar Radiation

The variation of solar radiation can significantly affect the performance of PV water pumping systems. it is crucial to understand the full concept of solar radiation and the effects of the Solar insolation for a specific location where the Water Pumping system will be installed. Direct normal irradiance and horizontal diffuse irradiance make up this composition. A pyranometer typically monitors solar radiation globally, while a pyrheliometer can measure direct radiation. The amount of solar radiation varies based on location, season, latitude, and longitude. Solar irradiation data can be used to compute solar insolation. The solar insolation value can then calculate the lowest and maximum flow rate values.

Below are the key mathematical equations for the variation of solar radiation:

The solar constant represents the amount of solar radiation received outside the Earth's atmosphere on a surface perpendicular to the sun's rays.

Solar Irradiance (G):

$$G = S\_c \times \cos(\theta\_z) \tag{3.17}$$

Where:

G = Solar irradiance (W/m²)

Solar Constant (S_c) = 1.367 kW/m²

θ_z = Zenith angle (angle between the sun's rays and the normal to the surface) (rad).

3.5.4 Techniques and Methods to Improve the efficiency of the Directly-coupled PV water pumping system

The approach and technology employed in the system determine how well the system performs. To guarantee the systems' excellent performance and efficiency in pumping water, the Maximum Power-Point Technique (MPPT) will be used to develop this project's Directly-coupled PV water pumping system.

3.5.4.1 Maximum Power-Point Technique (MPPT)

The power, voltage, and current this renewable energy source produces are unstable because of the sun's irregularity, affecting PV systems' efficiency and performance. Maximum power point tracking is one of the primary methods for overcoming the PV system's instability and inefficiency.

PV panel voltage and current are nonlinear. Various environmental variables, including temperature and sun irradiation, influence them. These external sources cause variations in power, voltage, and current. Consequently, it is critical to ensure that wind turbines and PV panels are running at their maximum power point to maximise the efficiency of PV panels. When there are erratic conditions, MPPT maximises the power that may be extracted from solar panels or wind turbines. The maximum power often varies with solar temperature and irradiance (Guntupalli et al., 2022). After carefully examining every MPPT technique. The project will employ the maximum power point technique based on a directly coupled PV water pumping system. Due to their irregularity, PV systems cannot be modelled as a continuous DC source because their output power fluctuates with temperature and solar irradiation. PV system control with MPPT.

3.4.5. Types of Maximum Power-Point Technique

A system may employ a variety of MPPT algorithms, including the extreme seeking control (ESC), incremental conductance, open circuit voltage (OCV), short circuit current (SCC), fuzzy logic control, hybrid methods, and the Perturb and Observation (P&O) technique. Below is a discussion of the Technique's specifics. Since each method has a variety of applications, some are used for complicated systems, while others are used for simpler systems, it is crucial to comprehend each one to determine which one will work best for the system under study. Having a solid grasp of these methods will be essential for making decisions (Guntupalli et al., 2022).

3.5.5.1 Perturb and Observation (P&O) Technique

The most widely used MPPT technique is this one. With this method, the system is forced to operate in the direction that the PV systems' output power increases. The P&O technique's power shift is depicted in the equation below (Guntupalli et al., 2022).

$$P = P_K - P_{k-1} \tag{3.18}$$

If the change in power in the preceding equation is positive, the system will maintain the current's direction; if it is negative, the system will automatically reverse the current's direction. Excellent performance of this approach has been shown in steady-state conditions where the wind speed and sun irradiation change slowly.

Each parameter stated in the flow chart has been described in **Table 3.8**.

Table 3.8: **Parameters of the Perturb and Observation Controller** (Guntupalli et al., 2022)

Parameters	Meaning
V(k)	The current value of the PV output voltage
V(k) − 1	The previous value of the PV output voltage
I(k)	The current value of the PV current
P(k)	The current value of the PV output power
P(k) − 1	The previous value of the PV output power
Vref	The reference output voltage of the P&O controller.

3.5.5.2 Fuzzy Logic Control (FLC) Technique

Its straightforward design and excellent performance have made this technique widely recommended. A particular model is not necessary for the FLC approach to work. Three stages comprise FLC:

- **Fuzzification:** The variables are transformed into linguistic variables at this point.
- **Decision making:** In this step, the controller's behaviour is defined by defining the rules using IF-THEN statements.
- **Defuzzification:** In this phase, a signal is sent to regulate power and raise the operating point to its maximum power (Tchoketch Kebir et al., 2018).

The fuzzy logic controller receives two inputs: a change in error and an error (E). The inaccuracy can be caused by temperature and solar irradiance for PV systems and wind speed and solar irradiance for wind systems (Tchoketch Kebir et al., 2018).

Below is the key mathematical equation for the fuzzy logic controller:

Membership function:

$$\mu\_A(x) = f(x) \quad (3.19)$$

Where:

μ_A(x) = Membership function of fuzzy set A

x = Input variable

f(x) = Membership function (usually a triangular or trapezoidal function)

3.5.2.3 Open circuit voltage (OCV) method

This method results in power losses in the system since it cannot precisely follow the maximum power point and requires frequent load shedding to measure the VOC. Pilot cells must be used to determine VOC to prevent these power outages (Saidi et al., 2021).

Below is the critical mathematical equation for the Open circuit voltage (OCV):

$$OCV = E_0 + \frac{RT}{nF} \times ln(Q) \quad (3.20)$$

3.5.2.4 Short circuit current method (I_{SCC})

The short circuit current approach is one way to determine how much current the system can give and compare the current with other protective devices. The short circuit current measurement is interrupted by a load, so I_{SCC} is unable to supply the load with the output power (Saidi et al., 2021). Below is the key mathematical equation for the short circuit current method (I_{SCC}):

$$\mathrm{I\_scc} = \frac{\mathrm{V\_oc}}{\mathrm{R\_int}} \tag{3.21}$$

Where:

I_sc = Short circuit current (A)

V_oc = Open circuit voltage (V)

R_int = Internal resistance of the battery (Ω)

3.5.2.5 Extremum seeking control method (ESC)

This approach, which uses real-time optimisation, is more suited for tracking vehicle targets, maximising vehicle traction, and reducing aircraft power (Saidi et al., 2021).

Below is the key mathematical equation for the extremum-seeking control method (ESC):

$$\dot{x} = -k_1 \times \sin(\omega_1 t) \times \frac{\partial J}{\partial x} \tag{3.22}$$

Where:

x = Controlled variable

k_1 = Adaptation gain

ω_1 = Perturbation frequency

J = Objective function or cost function

$\partial J/\partial x$ = Gradient of the objective function with respect to the controlled variable x

3.6 Conclusion

This chapter discusses in detail different PV array configurations, effects of variation of solar radiation in the PV water pumping system, as well as different techniques and methods to improve the performance of the PV water pumping system, such as the Maximum Power Point

Techniques. It was found that even in a variety of climatic circumstances, the Directly Coupled PV water pumping system may be significantly enhanced by the Maximum Power Point Technique. Additionally, it was shown that selecting the ideal PV array layout is essential for a PV water pumping system. An extensive literature review was conducted on previous papers covered by different researchers, and the impact of different PV array configurations on PV water pumping systems was remarkable. Chapter four discusses the system development and modelling of the Directly coupled PV water system.

CHAPTER FOUR

SYSTEM DESIGN AND MODELLING OF DIRECTLY COUPLED PHOTOVOLTAIC WATER PUMPING SYSTEMS

4.1 Introduction

Diesel pumps are frequently used in isolated rural locations without practical access to electricity. Nevertheless, the system faces several issues, including fuel availability, technological expertise, and running expenses. An option for these issues is a water pumping system directly integrated with photovoltaic (PV) technology. This system needs the sun to operate, and renewable energy sources such as solar energy produce unstable power due to the inconsistency of sunlight. This inconsistency stops the system from operating at the maximum power point. It is crucial to develop a PV water pumping system that can operate at maximum power points to ensure a continuous flow of water.

When solar energy is scarce or inaccessible in sufficient amounts to power the system, solar water pumping systems typically need a storage system to help them function. Water tank storage was one of the storage methods that this thesis covered. Water tanks, which are widely used as storage systems worldwide, are typical features in rural Angolan areas where agriculture is practised, as shown in **Figure 4.1**.

In this Chapter, the design and modelling of the PV water pumping systems will be performed, then the boost converter will be introduced to achieve the maximum point technique. All the simulations will be performed using MATLAB software to observe and discuss the results.

The purposes of the simulation activities discussed in this chapter are based on developing an efficient Directly-coupled PV water pumping system that can perform efficiently so that the population in rural areas can easily have access to water for their basic needs. Section 4.2 states the methodology used to achieve this project. Section 4.3 consists of the design and the modelling of the Directly-Coupled PV water pumping system. Section 4.4 analyses and presents the simulation results of the performance of the system. Then Section 4.5 presents the conclusion on the development of a Directly-coupled water pumping system and provides some recommendations.

Figure 4.1: **Solar water pumping system with water tank in Angola (Constantino et al., 2022)**

4.2 Methodology

Four activities were conducted to develop and evaluate the performance of the proposed directly coupled PV water pumping system, and they are as follows:

Activity One

The first activity was to perform the design calculation to determine the crucial elements such as the quantity of water needed, the storage size, the total pump head size, the water pump size, and much more.

.

Activity Two

The second activity was determining the parameters of the PV systems and developing the converter that will be integrated into the PV system. To achieve all the requirements, the following steps will be followed:

1st Step) Calculate and determine the parameters of the PV system: The parameters, such as the inductor, capacitor, switching frequency, and converter variables, were determined.

2nd Step) Modelling of DC-DC Boost Converter: The DC-DC boost converter was developed through MATLAB software for the PV system to prevent the current in the inductor from reaching zero during the time interval and to achieve the maximum point technique. This converter was composed of inductance, capacitance, and resistors.

Activity Three,

The third activity was modelling the PV system with the boost converter on the maximum power point technique controller.

Activity Four

The fourth activity was modelling and testing the directly coupled PV water pumping system. Some essential considerations need to be taken during each of these activities. The number of consumers and the quantity of water demand need to be considered during the design calculations. Because the sun is inconsistent, temperature fluctuations and solar irradiation must be considered when modelling the Directly-coupled PV water pumping system.

4.3 Design of a Directly Coupled PV Water Pumping System

In Angola, 49.3% of the population cannot access safe drinking water. More than half (54.7%) of schools do not have adequate sanitary facilities, and the majority (68.6%) do not have on-site hand washing stations. Because just 28% of schools provide suitable menstruation facilities for females, the issue becomes even more challenging for girls as they approach puberty (De Preneuf, 2023).

The third-largest city in Angola, Lubango, is forced to make severe trade-offs due to rapid population expansion and decreased rainfall. According to Domingas Tyikusse, CEO of the Huila Provincial Water and Sanitation Utility, which is in charge of Lubango's water supply, subsurface water reserves were depleted after two years of extremely low rain. Institutions, companies, and citizens in Lubango are forced to adjust to the intermittent water supply. Nowadays, a few natural springs, like the Tundavala Spring, and a series of vertical boreholes supply Lubango's water. The natural reserve where the boreholes are situated is large and well-guarded, with vegetation encouraging water infiltration. However, because insufficient rainfall impacts aquifer recharge, boreholes, like natural springs, are susceptible to fluctuations in the weather. As a result, during droughts, water levels have steadily decreased in these locations (De Preneuf, 2023).

Furthermore, it can be noticed that the provinces of Huambo and Namibe have abundant resources for mining, farming, and fishing, and they have strong tourism potential. A few rivers are nearby, but they are seasonal and intermittent rivers. This leads to unstable access to water. Numerous boreholes supply water to commercial crops that are pretty productive. Water trucks, equipped with devices dubbed "giraffes," zigzag over the region to supply communities living off the grid. Residents fill up containers for use between days when they can access water. In addition, women still need to bring bulky jerry cans of drinking water to supplement fewer drinkable supplies. One of the most prominent hotels in Namibe, called “Hotel Chik Chik”, has been facing enormous challenges due to non-continuous access to water. However, the hotel pays monthly water utility rates of around 180,000 kwanzas, or roughly $170 (De Preneuf, 2023).

4.3.1 Water Parameters

People generally use 189 to 378 Liters per person per day in their homes (757 to 1514 Liters per day for a family of four). The household water use estimates in the province of Huambo in Angola are given in **Table 4.1.**

Table 4.1: **Water Consumption of a household of 4 people**

(Ramos-Paja et al., 2022)

Appliance	Water Use
Clothes washer (top-loading)	143 Liters
Dishwasher (standard)	26 Liters
Kitchen sink	11 Liters
Bathroom sink	2 Liters
Toilet	6 Liters
Drinking and cooking Water	95.75 Liters
TOTAL PER PERSON	283.75 Liters/person
TOTAL PER HOUSEHOLD OF 4 PEOPLE	1135 Liters/Household

Solar water pumps continue to grow in popularity, and for a good reason: they can handle any water supply project, from domestic supply to large-scale irrigation. That said, the wrong-size solar water pump can turn a wise investment into a big headache.

Table 4.2 Highlights the water demands and corresponding solar water pumps for different-sized households.

Table 4.2: **Solar water pump size** (Ramos-Paja et al., 2022)

Water needs	Quantity of water per day	Type of water pump	Pump power (DC)	Pump voltage (DC)
Small domestic (2 people)	454 Liters	Submersible	50W-150W	12V- 30V
Domestic (family of 4)	1,135 Liters	Submersible	50W-250W	12V- 30V

Water needs	Quantity of water per day	Type of water pump	Pump power (DC)	Pump voltage (DC)
Domestic+ (family of 5 + swimming pool)	1,703 Liters	Submersible	150W-270W	12V- 30V
Circulation pump for swimming pool	17,034 Liters	Above ground	500W	48V
Agricultural irrigation	18,927 Liters	Submersible	1500W	110V

Solar water pump size

To determine the size of the solar water pump required, the following steps need to be conducted:

- **Minimum pumping flow**: Calculate the minimum flow from the daily water needs.
- **Total dynamic head**: Calculate the total dynamic head from the depth of the well and the distance from the water source to the storage cistern or house in **Figure 4.2.**
- **Correct solar water pump**: Source the correct pump with matching specifications.

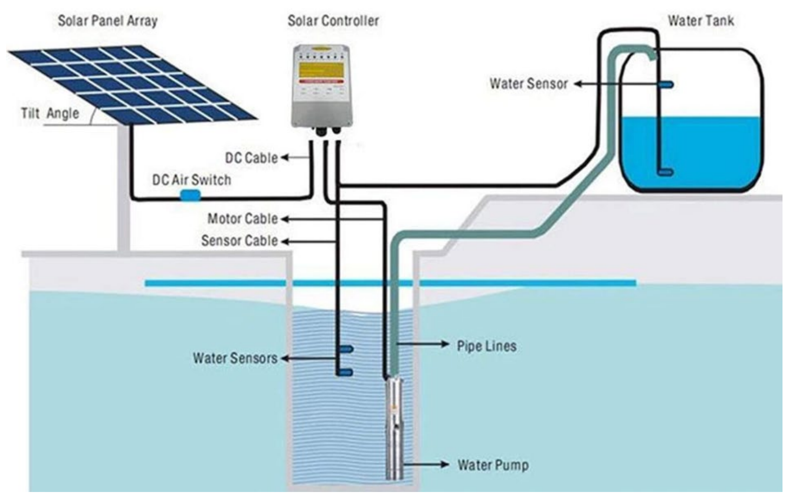

Figure 4.2: Configuration of PV Water Pumping System (Jalil et al., 2022)

a) The minimum pumping flow

To calculate the minimum pumping flow, the water needs must be estimated.

Let's assume the solar pump will operate during peak sunshine hours in Angola, which is 6.24 hours (374.4min). If the household consumes 1135 Liters daily, that's 3.03 Liters per minute (1135 Liters /374.4 minutes)

b) Variable power

As it is named, a solar water pump needs solar panels. Solar panels are variable power generators. Their power output varies throughout the day and year. Consequently, a solar water pump's water production also varies. This can become problematic as the water needs are relatively stable, though there is often an increase during summer. The most common solution to a variable water supply is to store water in a cistern or tank. As a rule of thumb, a 7-day water storage capacity is recommended. In our case, a family of 4 using 1135 Liters daily would need a cistern of 7945 Liters (Okakwu et al., 2023).

c) The total dynamic head

To correctly size the solar water pump, it is essential to consider the depth of the well and the friction from the pipes that slows the water flow. In other words, the more profound the well and the longer the pipes, the bigger the water pump must be (Okakwu et al., 2023).

Pump manufacturers commonly use the total dynamic head (TDH) to calculate the impact of friction loss on the water flow.

TDH = Static Water Depth + Friction loss

To calculate the total dynamic head, the following steps need to be followed:

- Static head: This is the distance between the well's water level and the top of the water tank.
- Friction loss relates to your pipe's type, length, and diameter.

Let's assume the well in Angola is at a depth of 40m. The tank is at the same level, located 60m from your solar pump. Therefore, the TDH is:

$$40 + 0.04 = 40.04 \text{ m}$$

This configuration will use a solar pump with a minimum flow rate of 3.03 Liters/min and a dynamic head of 40.04m.

4.3.2 PV System

To develop and design an efficient controller, the PV system must first be modelled to understand the system better. In **Figure 4.3,** the PV system's block diagram developed in this project consists of the PV module, the DC-DC converter, and the Maximum Power Point Technique (MPPT) algorithm. Therefore, the modelling of each component needs to be done (Guntupalli et al., 2022).

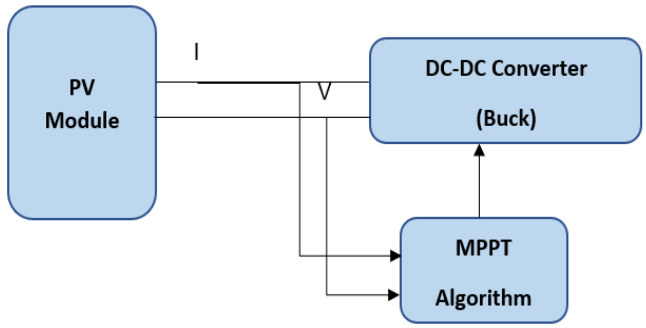

Figure 4.3: **Block Diagram of the photovoltaic (PV) system**

The curve fitting parameter of the PV system can be calculated using the mathematical model in **Equation 4.1.**

$$oneI\ (V) = \frac{I_X}{1 - e^{\left(\frac{-1}{b}\right)}} \left[1 - e^{\left(\frac{V}{bV_X} - \frac{1}{b}\right)}\right] \tag{4.1}$$

Vx= Represents the open circuit voltage

Ix= Represents the short circuit current

Equations 4.2 and 4.3 below show the mathematical model of the open circuit voltage including the parameters of solar irradiance and the temperature.

$$V_X = s\frac{E_i}{E_{iN}}\ TC_V\ (T - T_N) + sV_{max} - s(V_{max} - V_{\min})e^{\left(\frac{E_i}{E_{iN}}\ln\left(\frac{V_{max} - V_{OC}}{V_{max} - V_{mIN}}\right)\right)} \tag{4.2}$$

$$I_X = p\frac{E_i}{E_{iN}}\ [I_{sc} +\ TC_i\ (T - T_N)] \tag{4.3}$$

Table 4.3: **Parameters of PV Module**

Parameters	Description
S	The number of PV modules connected in series
p	The number of PV modules connected in parallel
Ei	The effective irradiation of the PV modules
EiN	The irradiation constant of 1000W/m^2
T	The temperature of the PV modules
TC_V	The temperature coefficient of the voltage
TC_i	The temperature coefficient of the current
T_N	The temperature constant
Vmax	The maximum voltage
Vmin	The minimum voltage
I_{sc}	The short circuit current
V_{OC}	The pen circuit voltage 3

For this project, the PV module type is Canadian Solar CS6K-280P and all the specifications of the PV system are shown in **Table 4.4*.***

Table 4.4: **Specification of a PV system**

CS6K	265P	270P	275P	280P
Nominal Max. Power (Pmax)	265 W	270 W	275 W	280 W
Opt. Operating Voltage (Vmp)	30.6 V	30.8 V	31.0 V	31.3 V
Opt. Operating Current (Imp)	8.66 A	8.75 A	8.88 A	8.95 A
Open Circuit Voltage (Voc)	37.7 V	37.9 V	38.0 V	38.2 V
Short Circuit Current (Isc)	9.23 A	9.32 A	9.45 A	9.52 A
Module Efficiency	16.19%	16.50%	16.80%	17.11%
Operating Temperature	-40°C ~ +85°C			
Max. System Voltage	1000 V (IEC) or 1000 V (UL)			
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)			
Max. Series Fuse Rating	15 A			
Application Classification	Class A			

Table 4.5 shows the PV Cell Parameters

Table 4.5: **PV Cell Parameters**

Module type	CS6K-280P
Number of cells per module	60
Number of series connected module per string	60
Number of parallel strings	1

4.3.3 Inductor

Equation (3) can be used to determine the boost converter inductor value needed to run the converter in continuous conduction mode. The maximum voltage ripple of 2% (Saidi et al., 2021).

$$\mathrm{L} = \frac{V_{om}(1 - D_{mP})}{2\Delta I_{om} f_s}$$

$$\mathrm{L} = \frac{12(1-0.5106)}{2\mathrm{x}0.02\mathrm{x}8.47\mathrm{x}20X10^3} = 0.000866H\ or\ 866.7\ \mu H$$

$$\mathrm{R} = \frac{2\mathrm{L}f_s}{(1 - D_{mP})^2} = \frac{2x866.7x10^{-6}x20x10^3}{(1 - 0.5106)^2} = 144.74\ \Omega$$

4.3.4 Capacitor

Equation (4) is used to get the output capacitor value, assuming a voltage ripple of 2% to produce the necessary peak-to-peak output voltage ripple.

$$C_{out} = \frac{(D_{mP}\ I_{om})}{\Delta V_{om} f_s}$$

$$C_{out} = \frac{I_{Om} D_{mP}}{\Delta V_{Om} f_s} = \frac{8.47\ x\ 0.5106}{0.02x12x20x10^3} = 0.0009F$$

$$\mathrm{R} = \frac{D_{mP}}{C f_s\ (\frac{\Delta V_{Om}}{V_{Om}})} = \frac{0.5106}{0.0009x\ 20x10^3\left(\frac{0.02x12}{12}\right)} = \frac{0.5106}{0.36} = 1.418\ \Omega$$

4.3.5 DC-DC Boost Converter

The DC-DC Boost converter was used in the designing process as a control device to stop the current in the inductor from reaching zero during the time interval, the DC-DC converter will be designed as shown in **Figure 4.4** so that it operates in a continuous conduction mode (Sontake et al., 2020). Improving the Angolan power transmission network is our primary objective for this project research, and the conversion process of direct current from one voltage level to another in a PV system involves some variations that can negatively impact the power transmission network. Therefore, the DC-DC converter is needed to ensure that the conversion process remains efficient with minimum variations and to regulate the constant output under various operating conditions of photovoltaic cells. Furthermore, The DC-DC converter in the project research also helped to maximise the solar energy generated from the PV system. This is done by performing Maximum Power Point Tracking.

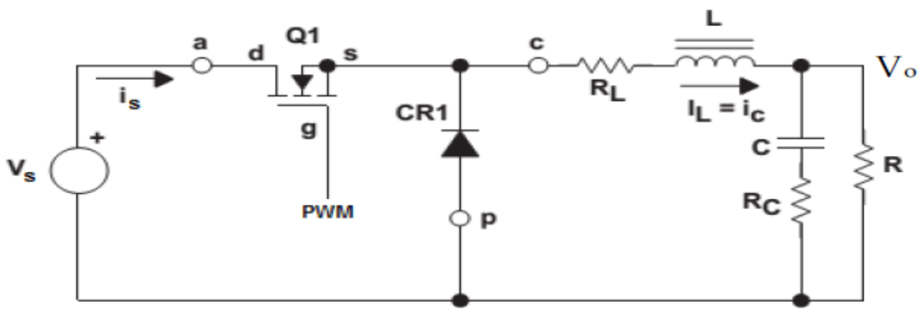

Figure 4.4: **Boost Converter Circuit**

The ripple of the inductor can be calculated using **Equation 4.4.**

$$V_L = \frac{L\Delta I_L}{\Delta t} \tag{4.4}$$

Equations 4.22 and 4.23 below show the positive and negative changes during off-state.

$$\Delta I_L(+) = \frac{(V_o - V_{DS} - I_L R_L) - V_o}{L} T_{on} \tag{4.5}$$

$$\Delta I_L(-) = \frac{(V_o + (V_d + I_L R_L)}{L} T_{off} \tag{4.6}$$

The following equations will be calculated to find the other elements of the circuit.

$$\Delta I_L(+) = \frac{(V_s - V_o)}{L} T_{on} \tag{4.7}$$

$$I_L(-) = \frac{V_o}{L} T_{off} \tag{4.8}$$

The duty cycle can be calculated as shown in **Equation 4.9**

$$D = \frac{T_{on}}{T_s} = \frac{V_o}{V_s}$$

$$(4.9)$$

4.3.5.1 Inductor Design of the DC to DC Boost converter

It is important to ensure an efficient design of the inductor to keep the balance of the power system and minimize its disturbance. The selection of the inappropriate inductor can cause the production of unstable DC output and stop the system from operating in continuous conduction mode (CCM) as shown in **Equation 4.10** (Wongsathan, 2020).

$$i_o(crit) = \frac{\Delta I_L}{2} \tag{4.10}$$

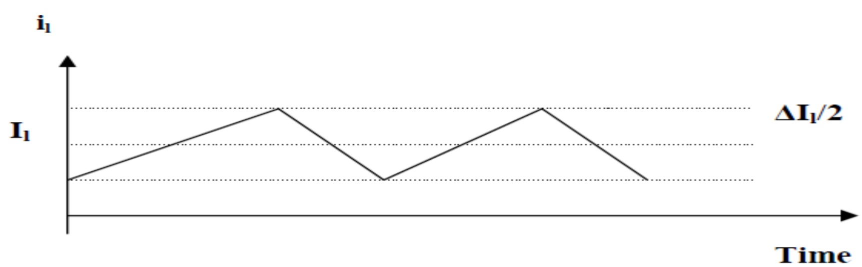

Figure 4.5: **Inductor Currents for Continuous Conduction Mode**

The method for obtaining the maximum and minimum inductor current is depicted in **Figure 4.5** above. Additionally, it is demonstrated that while the peak-to-peak ripple in the inductor current remains constant, the average inductor current decreases as the load resistance increases.

The inductor can be obtained using **Equation 4.11**

$$L_{min} \geq \frac{V_o\left(1 - \frac{V_o}{V_s}\right)T_s}{2i_o(crit)} \tag{4.11}$$

The maximum power and voltage can be calculated using the ripple value of 10% and the PV module parametersError! Reference source not found.. The maximum output power is calculated in **Equation 4.12.**

$$\Delta I_L = 0.1 \times \ i_o(max) = 0.541 \ A \tag{4.12}$$

The minimum value of the inductor is calculated in **Equation 4.13**

$$L_{min} \geq \frac{12 \ \times \left(1 - \frac{17}{17.71}\right) \times 50}{2 \times 0.2705} \geq 357.57 \ \mu H \tag{4.13}$$

4.3.5.2 Capacitor Design of the DC to DC Boost converter

The current in the capacitor can be found using **Equation 4.14**.

$$i = \frac{\Delta Q}{\Delta t} = C \frac{\Delta V_c}{\Delta t} \tag{4.14}$$

The variation of the load can be found using **Equation 4.15.**

$$\Delta Q = \frac{\Delta I_L T_s}{8} \tag{4.15}$$

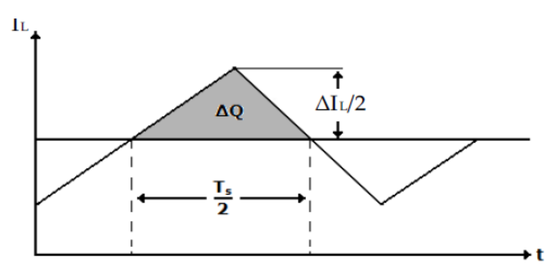

Figure 4.6: **Variation of time the current**

The design of the capacitor is obtained using **Equation 4.16.**

$$C \geq \frac{\Delta I_L T_s}{8 \ \Delta V_c} \tag{4.16}$$

Equation 4.17 can be found by using a ripple value of 0.1%

(4.17)

$$\Delta V = (0.001) \times V_o = 0.012\ V$$

The minimum value of the capacitor can be found using **Equation 4.18**

$$C \geq \frac{\Delta I_L T_s}{8\ \Delta V_c} \geq 279.63\ \mu F \tag{4.18}$$

4.3.5.3 Modelling of Boost Converter

The boost converter that is used in this project was modelled using MATLAB/Simulink as shown in **Figure 4.7.**

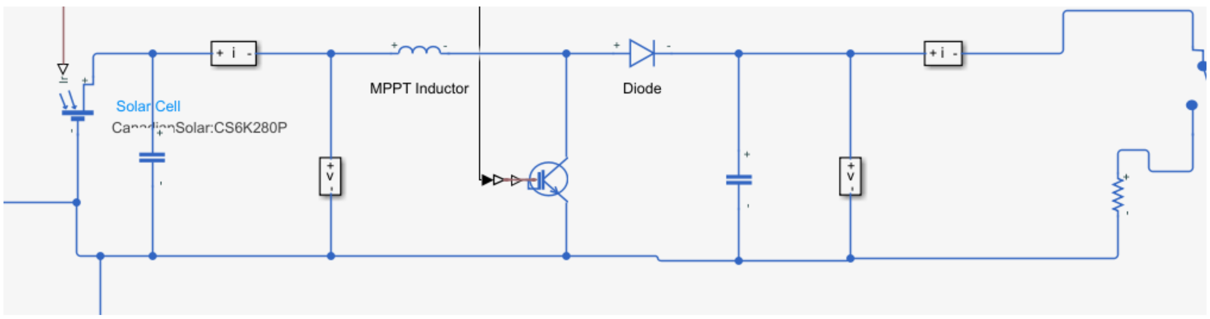

Figure 4.7: **Boost Converter**

Figure 4.7 above shows the boost converter modelled using the fundamental blocks of MATLAB/Simulink. The physical modelling connector ports V+ and V- represent the voltages in each branch of the Boost Converter. The Series RLC Branch represents the boost Converter's single resistor, inductor, and capacitor. It also describes the boost converter's impedance, frequency, and parasitic behaviours. Furthermore, a Switch is responsible for turning on the Boost converter when a positive signal is at the gate and turning off the buck converter when the signal is equal to zero at the gate.

The voltage measurement is responsible for supplying the voltage between two electric nodes. The diode allows the current in the Boost converter to flow in one direction and prevents the current from flowing in the opposite direction. In turn, the inductor stores the energy in a magnetic field when the electric current flows in the Buck converter. The current measurement measures the current flowing through the Boost converter.

4.3.6. Testing of the design

A comprehensive testing methodology was developed to evaluate the effectiveness of the designed directly coupled PV water pumping system. This approach combines theoretical modelling, simulation, and practical experiments to validate the system's performance.

Methodology

1. **Experimental Setup**

Components: The system comprises a PV array, a DC water pump, a flow meter, and necessary piping.

2. **Testing Procedure**

Baseline Testing: The initial test was conducted at peak solar conditions to establish a baseline performance metric.

Variable Conditions: A Subsequent test was performed under varying weather conditions to evaluate the system's responsiveness to changes in solar input.

3. **Data Collection**

Duration: Each test was conducted for a duration of 5.8 seconds.

Parameters Recorded: Key parameters included:

- Water output flow rate (litres per minute)
- Solar irradiance (W/m²)
- Pump voltage and current (V and A)

Results

1. **Baseline Performance**

Under optimal conditions (solar irradiance of 1000 W/m²), the system achieved a maximum water output flow rate of 1,005 litres per day, consistent with the expected performance outlined in the design specifications.

2. **Impact of Variable Conditions**

During reduced solar irradiance of 800 W/m², as shown in **Figure 4.8**, the flow rate decreased to approximately 15 litres per minute. This demonstrates the system's sensitivity to changes in solar input.

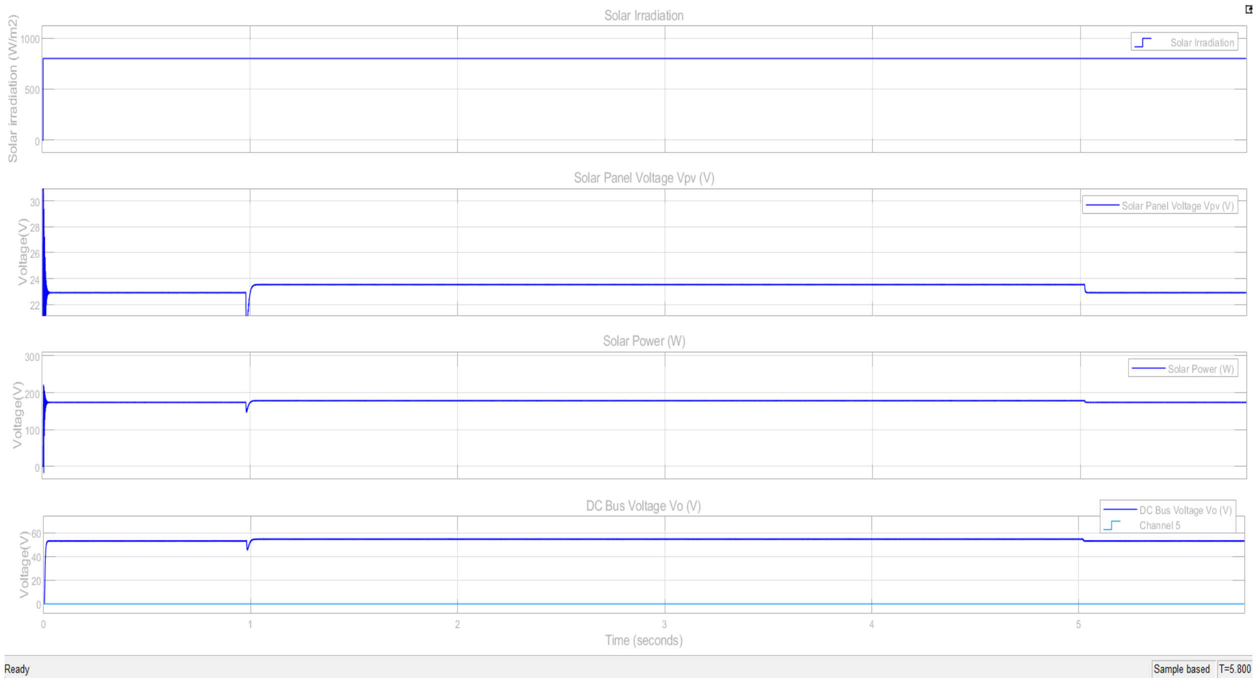

Figure 4.8: **Testing Simulation Output Results of Solar Irradiation, PV Voltage, PV Power, DC Bus Voltage**

Discussion

The testing results indicate that the directly coupled PV water pumping system performs effectively under optimal conditions, achieving flow rates that meet design expectations. However, the noticeable decline in output during periods of low solar irradiance indicates a design gap that could be addressed through improved control strategies or energy storage solutions.

Conclusion

This testing phase has successfully evaluated the performance of the directly coupled PV water pumping system based on the water output flow rate. The results reveal both strengths and weaknesses in the design, providing a valuable foundation for further optimisation and research. Future work will focus on enhancing control mechanisms to improve performance during variable solar conditions and exploring additional strategies to maximise efficiency.

CHAPTER FIVE

SIMULATION RESULTS AND DISCUSSION

5.1 Simulation Results

A comprehensive simulation study was conducted following Chapter Four's design calculation and parameters to understand better the performance characteristics and potential benefits of a directly coupled PV water pumping system. This study aimed to assess the system's behaviour and output under various operating conditions, including changes in solar irradiance, water demand, and other influential factors.

The simulation results and discussion of the directly coupled PV water pumping system are presented in this chapter. Each element of the system shown in ***Figure 5.1*** will be described, and the results will be analysed in three sequences to fully understand the system's behaviour. The results of Solar Irradiation, PV Voltage, PV Power, and DC Bus Voltage will be discussed in detail, as well as the impact of river, reservoir, and pump enabling. Motor RPM will be analysed to understand the system's efficiency. Due to limited resources, the simulation is reduced to 5.5 seconds.

5.1.1 Simulation Setup

The simulation model consisted of the following key components:

- Solar Cell: Represents a solar cell current source, which includes solar panels and associated electronics for converting sunlight into electricity. It is directly connected to a boost converter. The solar cells were selected based on the solar radiation of the province of Huambo in Angola. The average solar radiation in Huambo is between 896 to 975 W/m^2 (De Preneuf, 2023).
- Boost Converter: Responsible for increasing the input voltage from the solar cell and controlling power output to ensure correct voltage and current levels for the pump's motor, using MPPT. Both voltage control and MPPT modes were simulated.

- Water Supply System: This system comprises two tanks representing a river and reservoir, connected through a network of pipes (1.5 km), valves, and fittings that direct water from the source to the destination. It includes a DC motor and centrifugal pump. The

DC motor converts electrical energy into mechanical energy to drive the centrifugal pump's impeller. The impeller creates a low-pressure zone, drawing water in and then expelling it with increased velocity and pressure through the piping system. Additionally, the system includes two water tanks and a water sensor. The pump, powered by a DC motor connected to the boost converter, transfers water from the river to the tanks.

The first element of the Directly coupled PV water pumping system developed in this project is the Solver Configuration block, which specifies the simulation options for the physical system of the Directly coupled PV water pumping system. Then, there is a Solar Cell block representing a solar cell current source in the system that is directly connected to a boost converter that efficiently increases the input voltage to a higher output voltage and is also responsible for controlling the power output of a solar PV system. Both voltage control and MPPT modes are available with this boost converter. The voltage control mode is used only in situations where the load power, given the incident irradiance and panel temperature, is less than the maximum power generated by the solar PV plant. Above the boost converter, the simulation output in MPPT mode is displayed in scope. The solar panel voltage (Vpv), solar power (P), solar PV current, and DC voltage bus (V) make up the simulation's output.

The system's right side shows a water supply system consisting of one centrifugal pump and two tanks located at 60m concerning the reference plane, respectively. The centrifugal pump is responsible for pumping the two tanks, and it is powered by a DC motor, which is directly connected to the boost converter. Since each tank is big enough to presume that the fluid level stays relatively constant, the Constant Head Tank block can be used to simulate it. One tank in the system is used to supply any water shortage to the consumer during operation, and the tank is a secondary resource in case of emergency or in case of interruption of water that may occur due to some technical issues in the PV panel. The initial volume of water in each tank is set to 0.1 m^3. Furthermore, the water sensor is located 40 m from the water source. The results of the river, reservoir, and motor have been illustrated in the scope block at the top right side of the system, as shown in ***Figure 5.1***.

5.1.2 Simulation parameters and scenarios:

The simulation parameters were based on real-world data, including:

Solar *cell*: *An average of* 1000 W/m² (representing peak sunlight*)* is used in the study. The cell characteristics are shown in **Table 5.1**.

Table 5.1: The solar cell characteristics

Settings | Description

NAME	VALUE	
Modeling option	No thermal port	
Selected part	CanadianSolar:CS6K280P	
Cell Characteristics		
Parameterize by	By equivalent circuit parameters, 8 parameter	
Diode saturation current, Is	2.45628376944746e-07	A
Diode saturation current, Is2	5.22730283983957e-09	A
Solar-generated current for measurement...	9.53013488383241	A
Irradiance used for measurements, Ir0	1000	W/m^2
Quality factor, N	1.42401479139318	
Quality factor, N2	2.22894701389056	
Series resistance, Rs	0.00321550421021659	Ohm
Parallel resistance, Rp	24.2803144896678	Ohm
Panel Configuration		
Number of series-connected cells per stri...	60	
Number of parallel-connected strings	1	

Load Conditions: Switched between a Television (representing household TV) and a pump load (representing water demand) to simulate typical daily usage patterns.

Tank: The tank capacity is 1 m^3 or 1000 Liters. The other parameters of the tank have been described in **Table 5.3**.

Pump Specifications: shown in **Table 5.2**.

Table 5.2: The parameters of the centrifugal pump

Centrifugal Pump (TL) — Auto Apply

Settings | Description

NAME	VALUE	
Parameters		
Pump parameterization	Capacity, head, and brake power at reference shaft speed	
Nominal capacity	45	lpm
Nominal head	40	m
Nominal brake power	0.85	kW
Maximum head at zero capacity	60	m
Maximum capacity at zero head	80	lpm
Reference shaft speed	1770	rpm
Minimum shaft speed threshold as fractio...	1e-2	
Impeller diameter scale factor	1	
Mechanical orientation	Positive angular velocity of port R relative to port C correspo	
Cross-sectional area at ports A and B	0.01	m^2
Check if operating beyond normal pump ...	None	

Table 5.3: The parameters of the Tank

Tank (TL) — Auto Apply

Settings | Description

NAME	VALUE	
Parameters		
Number of inlets	1	
Pressurization specification	Atmospheric pressure	
Tank volume parameterization	Constant cross-section area	
Tank cross-sectional area	1	m^2
Configurability	Compile-time	
Inlet height	0.1	m
Inlet cross-sectional area	0.01	m^2
Liquid level below inlet height	Error	
Liquid volume above max capacity	None	
Gravitational acceleration	9.81	m/s^2
Initial Targets		
Nominal Values		

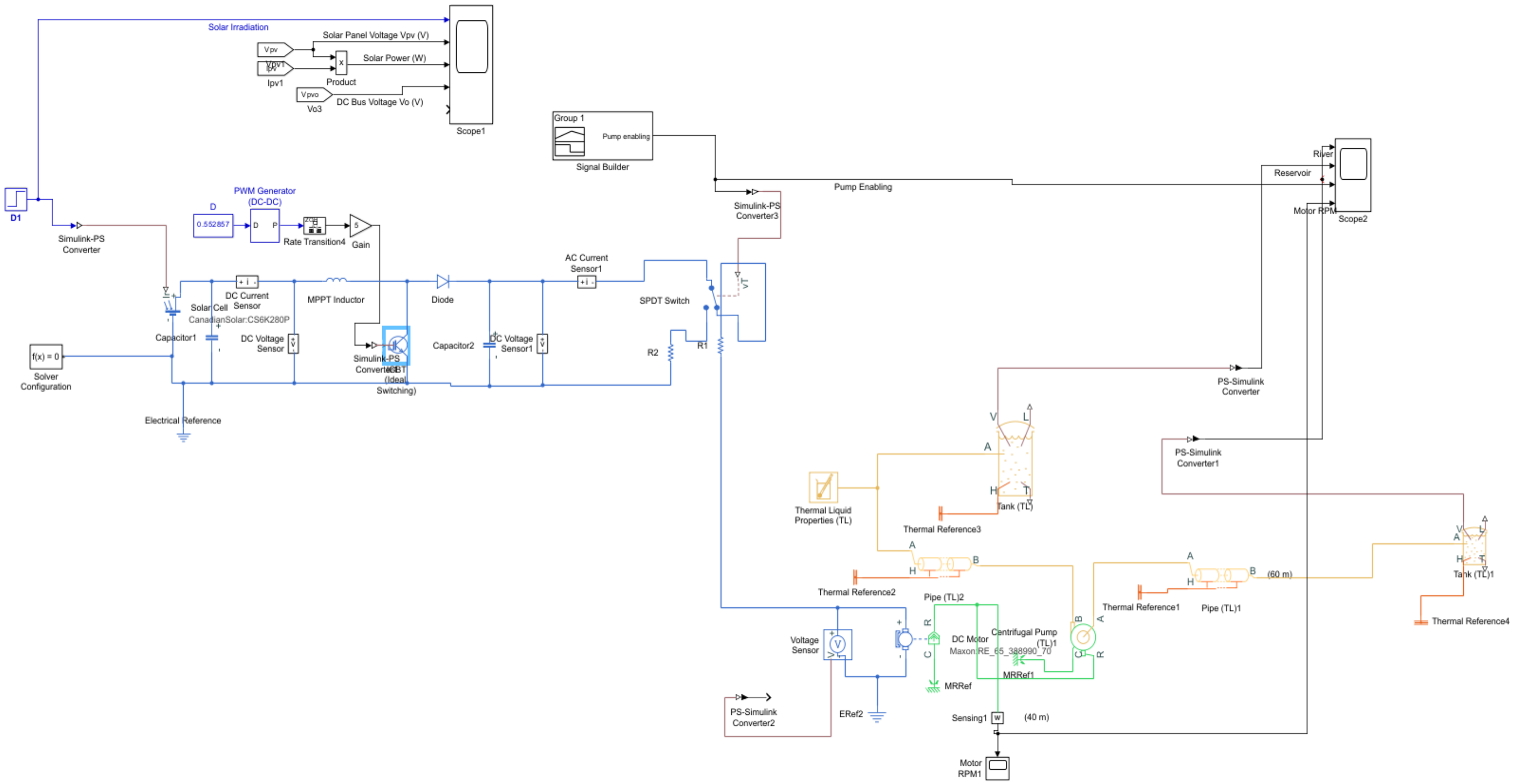

Figure 5.1: Directly Coupled PV Water Pumping System

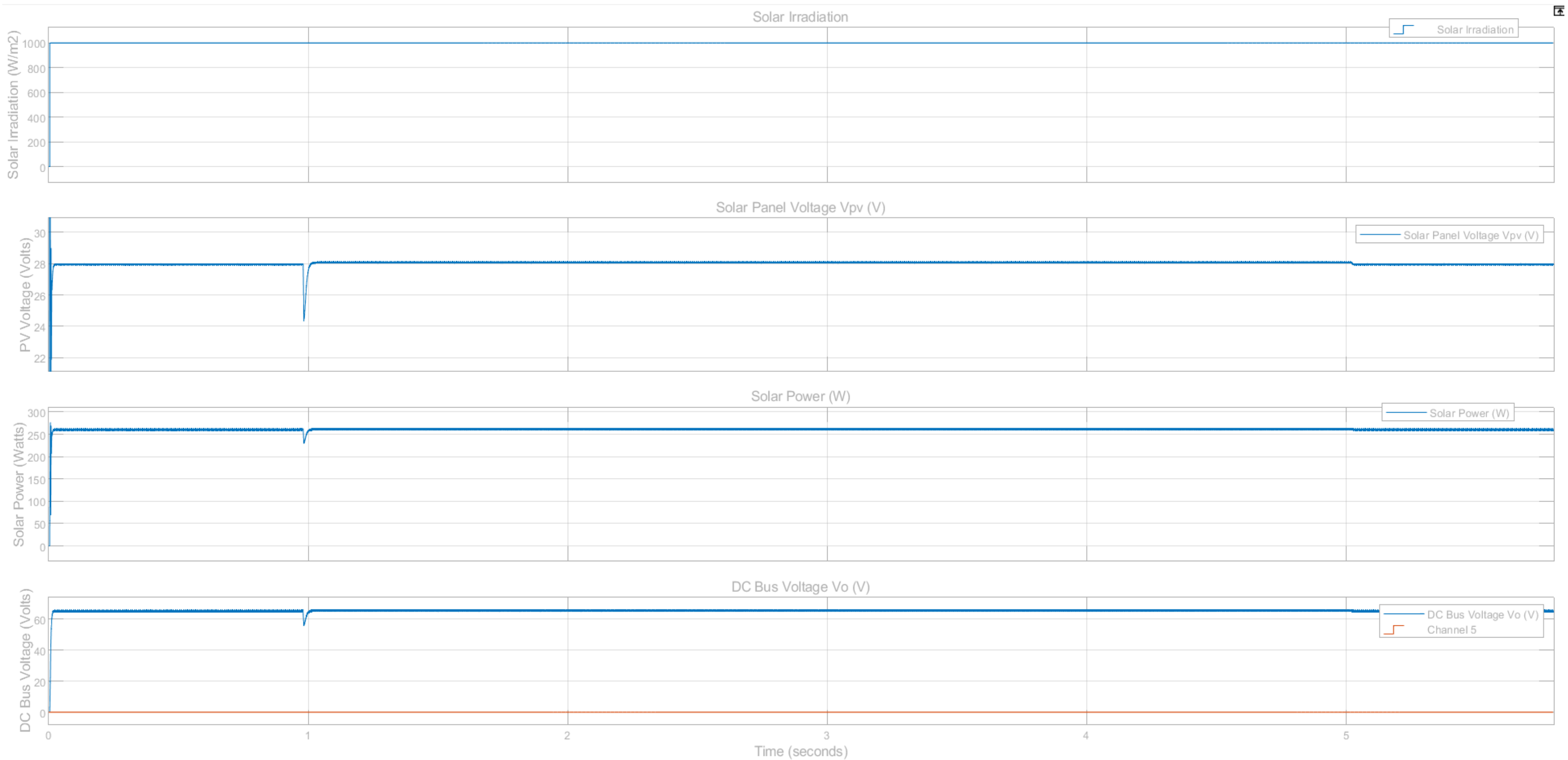

Figure 5.2: Simulation Output Results of Solar Irradiation, PV Voltage, PV Power, DC Bus Voltage

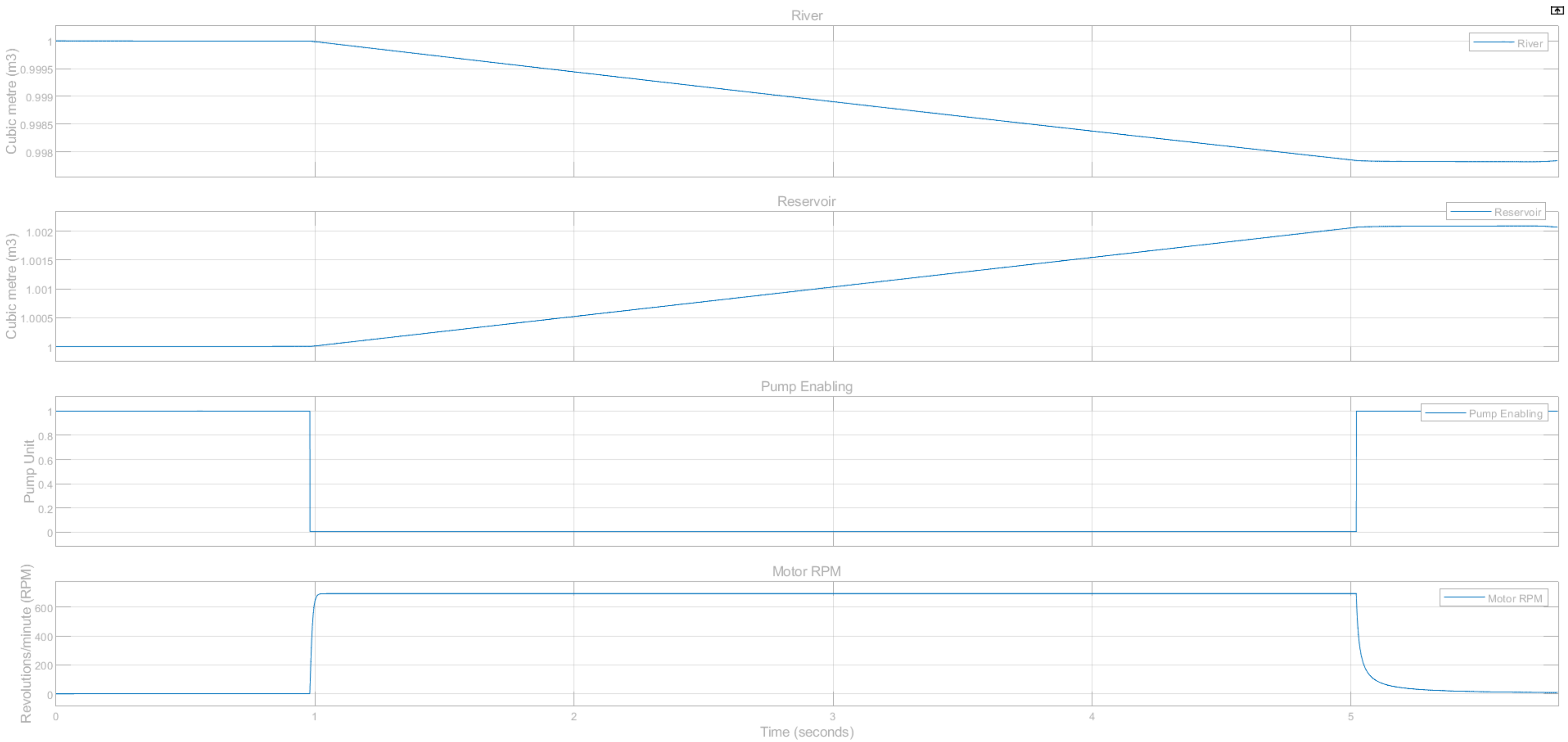

Figure 5.3: Simulation Output Results of River, Reservoir, Pump Enabling, Motor RPM

5.1.3 Simulation Results and Analysis

A low-cost Directly Coupled PV Water Pumping System is designed and simulated to cover the long distance of water transport to villages and rural areas. The PV system developed in this research project has two loads: the television (TV) and the water pump. The system was analysed during a total simulation time of 5.8 seconds. It is essential to break down the total simulation process into three different scenarios to analyse the simulation results in detail. The solar irradiance remains constant throughout the simulation; for each scenario, the PV voltage, the PV power, the DC bus voltage, the state of the river and reservoir, and the behaviour of the pump unit and motor, have been discussed in detail. The simulation results were analysed in three distinct scenarios, each representing a different phase of system operation:

- The first scenario occurs from 0 to 1 second,
- The second scenario occurs from 1 to 5 seconds,
- The third scenario occurs from 5 seconds to 5.8 seconds.

1st scenario: For the first part of the simulation, between 0 and 1 second, solar irradiation is at a constant value of 1000 W/m2. From 0 to 1 second, only the television (TV) is connected to the PV system, and the water pump is not yet activated during this period. The pump is activated and operational from 1 second to 5 seconds. The power supply in the PV system during this period was used for television only.

From 0 to 1 second, the solar PV produces a constant voltage and power of 28 V and 261 Watts, respectively. While the water in the river and reservoir remains at the same level of $1m^3$ when the pump enabling graph initially shows that the pump is off, the water pump is not yet activated during this period.

From 0 to 1 second, the voltage of the solar panels increased rapidly from 0 V to approximately 28 V within the first 0.005 seconds and remained constant for the rest of the period. Following a similar pattern, the solar output rose sharply from 0 W to around 621 W within the initial 0.005 seconds and then stabilised. This demonstrated that the solar panels generated electrical power when exposed to solar radiation. The DC-DC boost converter quickly increased from 0 V to about 66 V within the initial 0.005 seconds and remained constant, as seen in **Figure 5.2**. This period showcased how the solar panels quickly generated power under constant solar irradiation of 1000 W/m^2. From the initial transient to the rapid rise and stabilisation of the solar panel voltage, power, and DC bus voltage, the system effectively regulated the output voltage to meet the desired load demand. During the same period (0 to 1 second) shown in **Figure 5.3**, the river and reservoir water remained at a constant level of 1 m^3 when the Pump Enabling graph initially indicated that the pump was off; during this period, the water pump was not yet activated, and the initial RPM of the motor started at 0 RPM.

From 1 second onward, there was a slight drop in voltage and power due to switching loads from the television to the pump. However, the system quickly recovered and stabilised, returning to its initial operating conditions just after 1 second. The designed MPPT and current control restored the output voltage to 66 V. Similarly; there was a brief drop from 261 W to 230 W around 1 second, then recovered to 261 W. The system demonstrated resilience by quickly stabilising and returning to normal operating conditions.

In the 2nd scenario, the change in priority occurred when the village needed to pump water from the river to the reservoir tank. This part depicted the transition from switching off the TV to enabling the DC pump and initiating the water transfer.

From 1 second, there was a slight drop in voltage and power due to switching loads from the television to the pump. The system returned to normal between 1 second and 5 seconds. The MPPT (Perturb and Observation (P&O) technique) and current control restored the output voltage to 66 V and power to 266 W, as shown in **Figure 5.2**.

The water pump was activated and operational from 1 to 5 seconds in Figure 5.3. It quickly ramped up to around 700 RPM at about 0.5 seconds and maintained this speed until approximately 5 seconds. The pump’s activation caused water to be transferred from the river to the reservoir. The volume of river water gradually decreased from 1 to about 0.9995 m^3, indicating continuous water withdrawal from the river, while the reservoir's water level started low and gradually increased in volume from 1 to about 1.0005 m^3. There was a small but noticeable change in the water volumes of both the river and the reservoir, reflecting the operation of the pumping system, with the reservoir potentially supplying water to meet demand elsewhere.

The 3rd scenario represents the change in priority when the village needs more than water from the reviver to the reservoir tank. This part shows the transition between the switching on the TV and the DC pump.

From 5 to 5.3 seconds, the following changes occur in the system simulation: The solar irradiation Remained constant and stable at around 1000 W/m^2, ensuring a steady input of solar energy. The solar panel voltage, solar power output, and DC bus voltage all remain stable at 28 V, 261, and 66 V, respectively, except for a slight drop in these values during a transition time of 5 seconds. The system operates smoothly and without any disturbances or fluctuations. The analysis of this scenario underlines the importance of continuous solar irradiation for maintaining stable power output in a solar power system. It also reveals the system's capability to manage and regulate voltage amid energy generation and demand fluctuations.

The pump is disabled at 5 seconds and remained disabled at 0 units throughout this period. The pump's continuous off state should correspond with stabilising the water volumes in the river and reservoir. It should confirm that the water transfer operation has ceased. Simultaneously, the motor RPM remained at 0 RPM throughout this period. The motor being off indicates that there is no mechanical action driving the pump and reinforces the observation that the pumping process has stopped. The river's volume remained stable at approximately 0.9995 m^3; this indicated that there was no further withdrawal of water. This also shows that the pump is off, and no more water is being pumped from the river. The reservoir's volume remained stable at approximately 1.005 m^3. The stabilisation of the reservoir volume implies no further addition of water.

In the 3rd scenario, a change occurred when the TV is back on. This part depicts the transition from switching on the TV to disabling the DC motor, as shown in Figure 5.2. When the pump was deactivated, and the TV was activated, the quantity of water in the river and the reservoir stabilised. From 5 to 5.3 seconds, the following changes occurred in the system simulation:

In **Figure 5.3**, the solar irradiation remained constant and stable at around 1000 W/m^2, ensuring a steady solar energy input. The solar panel voltage, solar power output, and DC bus voltage all remained stable at 28 V, 261 W, and 66 V, respectively, except for a slight drop in these values during a transition at 5 seconds. The directly coupled PV water pumping system developed in this research project also included a few other elements that contributed to the system's performance and enabled operation at the maximum power point. Elements such as the boost converter raised the bus voltage from 28 V to 66 V to meet the load requirements. The system operated smoothly without disturbances or fluctuations. The analysis of this scenario underscored the importance of continuous solar irradiation for maintaining stable power output in a solar power system. It also highlighted the system's capability to manage and regulate voltage despite energy generation and demand fluctuations.

In **Figure 5.3**, the pump was disabled at 5 seconds and remained inactive throughout this period. The continuous off state of the pump corresponded with the stabilisation of water volumes in both the river and reservoir, confirming that the water transfer operation had ceased. Additionally, the motor RPM remained at 0 throughout this period, indicating no mechanical action driving the pump and reinforcing that the pumping process had stopped. The river's volume remained stable at approximately 0.9995 m^3, indicating no further water withdrawal, thus confirming that the pump was indeed off and no more water was being extracted. The reservoir's volume also remained stable at approximately 1.005 m^3, implying that no additional water was being added to the reservoir. This low-cost system is designed to cover the long distance of water transport to villages and rural areas.

5.1.4. Design gap and expected simulation results

Based on the boost converter calculation, it can be noticed that the boost converter maximises solar power during peak sunlight. After the control, there is a slight increase in PV voltage and solar power. The control takes some time before it goes back to normal, and the difference is minimal. This performance gap necessitates further optimisation of the converter design to enhance efficiency across a broader range of operating conditions.

5.2 Economic Analysis

This section presents an economic analysis and comparison of between the Directly coupled PV water pumping system developed in this project and the diesel system for well water pumping for irrigation in Huambo, Angola. Every factor that affects these systems is considered in the analysis, including the capital cost of the parts, installation, construction, fuels, and operating and maintenance (O&M) expenses. The following characteristics led to the conclusion of the economic study and comparison:

- Net present cost (NPC)
- Operating and maintenance cost (O&M)
- Operation cost (OC)
- Cost of energy (COE)

In this project, the type of solar cell used is the Canadian Solar CS6K280P as shown in **Table 5.1**. The rated capacity of the Canadian Solar CS6K280P photovoltaic (PV) module is 280 watts (W). The number of modules per string of the PV system developed in this project is 60, so the total PV array capacity is 60 modules × 280W per module = 16,800W or 16.8kW.

Now, let's determine the total PV module cost using the formula in **Equation 5.1** and **Equation 5.2,** keeping in mind that a PV module unit costs $0.70 per watt ($/W).

Total PV module cost = Total PV array capacity × PV module unit cost 5.1

Total Photovoltaic (PV) module cost = 16,800W × \$0.70/W = \$11,760 5.2

The type of DC pump used in this project is the Centrifugal pump with a nominal head is 40m and a nominal capacity of 45 liters per minute (LPM), as shown in **Table 5.2**. according to the market, this type of pump costs 5000 \$. Based on the cost of the components of the directly coupled PV water pumping system developed in this project. An economic analysis was conducted.

The initial capital cost of a directly coupled PV water pumping system typically includes the following components and can be calculated using **Equation 5.3**.

- **Photovoltaic (PV) Modules:** 11,760 \$
- **DC Pump (Centrifugal Pump):** 5,000 \$
- **Mounting Structure:** 1,000 \$
- **Electrical Components (Wiring, Cables, junction boxes, disconnects, and other electrical accessories):** 750 \$
- **Installation and Labor:** 4,581 \$
- **Other Costs:** 750 \$

The Total Initial Cost is 15,341 \$+ 5,000 \$+ 1,000 \$ + 750 \$+ 1,000 \$ + 750 \$ = **23,841** \$ 5.3

NPC (Net Present Cost):

The cost of the components used in directly-coupled PV water pumping system developed in this project has been used to determine the Net Present Cost. For a PV water pumping system, the NPC would include the upfront capital cost of the PV panels, inverters, pumps, and other equipment and the discounted present value of all future operating and maintenance costs over the system's lifetime. The formula would be as shown in **Equation 5.4.**

NPC = Initial Capital Cost + Σ (Annual Operating & Maintenance Costs / (1 + Discount Rate)^n) 5.4

Where n represents the year of the cash flow over the system's lifetime, the discount rate has been considered 5%.

The net present cost (NPC) will be calculated for the PV system developed in this project as shown in **Equation 5.5.**

$$\mathbf{NPC} = \frac{23841}{(1+0.05)^{20}} = \mathbf{24743}\$ \quad 5.5$$

The formula for the NPC of a diesel system is presented in **Equation 5.6**

$$\mathbf{NPC} = \frac{Ct}{(1+r)^n} \quad 5.6$$

Ct = Total costs in year t, including:

The initial capital cost of the diesel generator and installation

- Annual fuel costs
- Annual operating and maintenance (O&M) costs
- Any replacement or overhaul costs over the lifetime

r = Discount rate (or cost of capital)

where n is the lifetime of the diesel system

For the Diesel system developed in this project, the net present cost (NPC) will be calculated as shown in **Equation 5.7 and Equation 5.8**

Total costs= system cost + replacements + fuel cost = 33715 + 28459 + 98605= 160779 5.7

$$\mathbf{NPC} = \frac{160779}{(1+0.05)^{20}} = \mathbf{60596}\$ \quad 5.8$$

O&M (Operations & Maintenance cost):

The O&M costs for a PV water pumping system would include things like:

- Regular maintenance and cleaning of the PV panels
- Replacement of inverters, pumps, or other components over time
- Labor costs for technicians to perform inspections and repairs

There is no single formula, as the O&M costs can vary greatly depending on the system size, operating conditions, and maintenance requirements.

For the PV system developed in this project, the operation and maintenance cost is the sum of the cleaning of the PV panel Cost, the replacement cost of PV components over time, and the Labor costs for technicians to perform inspections and repairs, as shown in **Equation 5.9**.

$$O\&M = 460\$ + 1301\$ + 633\$ = 2394\ \$ \quad (5.9)$$

For the Diesel system developed in this project, the operation and maintenance cost is the sum of fuel cost, routine maintenance, and spare parts and repairs as shown in **Equation 5.10**.

Total Annual O&M Cost = Fuel Cost + Routine Maintenance + Spare Parts and Repairs 5.10

$$O\&M = 460\$ + 1301\$ + 633\$ = 2394\ \$ \quad (5.11)$$

OC (Operating Costs):

Operating Costs include all the expenses required to run a business or project, beyond just the maintenance and operations. This includes labour, materials, utilities, rent, insurance, and other overhead. The formula for OC is presented in **Equation 5.12.**

Operating Costs (TOC) = ∑(FOC + VOC) over the system's lifetime 5.12

The operating cost for the PV system developed in this project will be calculated as shown in **Equation 5.13** and **Equation 5.14.**

System lifetime: 20 years

Annual Fixed Operating Costs (FOC):

FOC = 35 $ per year

Annual Variable Operating Costs (VOC):

VOC = 26.85 $ per year

Operating Costs (OC) over 20 years:

$$OC = \sum(FOC + VOC) \text{ over 20 years} \quad (5.13)$$

$$OC = (20 \times 35\$) + (20 \times 26.85\$) = \mathbf{1237\ \$/Year} \quad (5.14)$$

For the Diesel system developed in this project, the operating cost will be calculated as shown in **Equation 5.15; Equation 5.16; and Equation 5.17.**

$$\textbf{Operating Costs (TOC)} = \sum(\textbf{FOC} + \textbf{VOC}) \textbf{ over the system's lifetime} \quad (5.15)$$

System lifetime: 20 years

Annual Fixed Operating Costs (FOC):

FOC = 155 $ per year

Annual Variable Operating Costs (VOC):

VOC = 73.15 $ per year

Operating Costs (OC) over 20 years:

$$OC = \sum(FOC + VOC) \text{ over 20 years} \quad (5.16)$$

$$OC = (20 \times 155\$) + (20 \times 73.15\$) = \mathbf{4563\ \$/year} \quad (5.17)$$

COE (Cost of Energy):

The cost of energy (COE) of a photovoltaic (PV) system is a metric that represents the total lifetime cost of producing electricity from the PV system, expressed in dollars per kilowatt hour ($/kWh).

For the PV system developed in this project, the cost of energy (COE) will be calculated based on the developed PV array capacity which is 16800 Watts or 16.8 Kw based on the type of solar cell used which is the Canadian Solar CS6K280P as shown in **Table 5.1**.

Total PV system cost: 23841$

PV solar power Capacity (kW)= 16800 Watts or 16.8 Kw

Lifetime of the PV system: 20 years

Weighted Average Cost of Capital (WACC): 6%

O&M costs: 1237 $ per year

Capacity Factor= 15% or 0.15

Annual Electricity Generation= PV array capacity (kW) x Capacity Factor x Hours **per Year** = 16.8 x 0.15 x 8,760 hours = 22075.2 kWh 5.18

COE = (Total system cost × WACC) + Annual O&M costs / Annual electricity generation 5.19

COE = ($23841 × 0.06) + $1237 / 22075.2 kWh=0.12 $/kWh or 0.12 $ per kilowatt-hour (kWh) 5.20

For the Diesel system developed in this project, the cost of energy (COE) will be calculated based on a diesel system capacity of 112kW as shown in **Equation 5.21; Equation 5.22;** and **Equation 5.23**

Annual Operation Costs= 4563 $/year

Diesel system Capacity (kW)= 112 kW

Annualized Capital Cost= 60191 $

Capacity Factor= 15% or 0.15

Annual Electricity Generation= Diesel system Capacity (kW) x Capacity Factor x Hours per Year = kWh=112 kW x 0.15 x 8,760 hours =147168 kWh 5.21

COE = (Annual Operation Costs + Annualized Capital Cost) / Annual Electricity Generation 5.22

COE = (4563 $ +60191 $) / 147168 kWh= $0.44 per kWh 5.23

The simulation results show that the proposed directly coupled PV water pumping system operates at a motor speed of 700rpm at its maximum power. This speed is connected to the Operating and maintenance cost (O&M) and the Net Present Cost (NPC). Higher RPM and water delivery may lead to more frequent maintenance, such as pump and motor overhauls, component replacements, and repairs. The maintenance cost of the proposed directly coupled PV water pump is very low compared to the diesel pump because the motor speed per revolution is at its average. The simulation analysis estimates a 75% reduction in annual Operating and maintenance cost (O&M), amounting to $2,394 per year for the directly coupled PV water pumping system, compared to $9,359 for the diesel-powered solution as shown in ***Table 5.7***. The simulation-derived water delivery capacity and energy efficiency parameters have been used to determine the appropriate scale of the PV array and pump, leading to a total Net Present Cost (NPC) of $24,743 for the directly coupled PV water pumping system and $60,596 for the diesel system as shown in ***Table 5.7***. The results of the NPC analysis demonstrate the clear economic advantage of the directly coupled PV water pumping system. With a discounted NPC, the PV system exhibits a significantly lower life-cycle cost than the diesel-powered alternative. The simulation results have also shown the directly coupled PV water pumping system to be highly responsive and reliable, with reduced maintenance requirements compared to the diesel-powered.

Numerous variables may affect the analysis of the water pumping system using various technologies, such as diesel or photovoltaic (PV), including location, weather, water levels, water demand, components, running maintenance, and operation expenses. This research project examines how the water pumping system operates economically with two distinct technologies: diesel and photovoltaic. The electrical energy source powering each of the two suggested systems varies. These configurations are;

- Directly coupled PV water pumping system: the pump is driven by a pump controller, and PV panels only produce the necessary electrical energy during the day.
- A diesel unit, where the diesel merely provides the energy needed to pump water.

The study examines the functioning of the suggested systems from an economic perspective, taking into account all costs and the components of each system (NPC, O&M, OC, and COE). For a predetermined amount of time, as indicated in ***Table 5.3***.

Table 5.4: Time Frame Parameters of Directly Coupled PV Water Pumping System

Parameters	Value
Hours of operation	10 hours
Period of operation	30 weeks
System Lifetime	20 years

Assuming that the controller has a 0.29 utilisation factor and that the PV power needed to run the system for 10 hours a day, 30 weeks a year, is 11.94 kW. ***Table 5.4*** displays the characteristics of the PV system cost analysis.

Table 5.5: Economic Analysis of Directly Coupled PV Water pumping system

Items	Cost
PV Unit	0.75 $/PV Watt
Controller	1.3 $/kW
PV Structure	0.27 $/PV Watt
Cabinet & Cables	0.1 $/PV Watt
Installation	5% of the capital cost

Table 5.5 below shows the results of the economic analysis of the PV system.

Table 5.6: Cost Analysis of the Directly Coupled PV Water Pumping System

Parameters	Value
PV Cost	8958.3 $
Controller Cost	7800 $
PV Structure Cost	3225 $
Cabinet & Cables Cost	1301 $
Installation Cost	1064 $
NPC	24743 $
O&M	2394 $
OC	1237 $/year
COE	0.12 $/kWh

5.2.1 Diesel Systems

The diesel unit utilised fuel to power the water pump. Thus, the diesel unit, fuel, replacements, and maintenance and operations are all included in the system's overall cost. The diesel power in the diesel unit system is 8 kW. The cost analysis of this system is displayed in ***Table 5.6***.

Table 5.7: **Cost Analysis of the Diesel Systems**

Parameters	Diesel
System	15300 $
Replacements	13198 $
Fuels	22240 $
NPC	60596 $
O&M	9359 $
OC	4563 $/year
COE	0.321 $/kWh

Table 5.5 and ***Table 5.6*** make it evident that using a directly coupled PV water pumping system results in significantly higher capital costs than conventional systems due to the higher capital costs of renewable energy sources. However, the system's operating costs are significantly lower than those of a diesel system, which produces optimal COE rates for PV. One might think about the many benefits of utilizing photovoltaic energy in the future because its costs reduce as its efficiency rises. The NPC, M&O, OC, and COE for the three systems in use are compiled in ***Table 5.7***.

Table 5.8: **NPC, M&O, OC, and COE for the two used systems**

Parameters	Directly coupled PV System	Diesel unit
NPC	24743 $	60596 $
M&O	2394 $	9359 $
OC	1237 $/year	4563 $/year
COE	0.12 $/kWh	0.321 $/kWh

The PV system has the lowest NPC cost compared to the diesel unit because of its extremely low running expenses and long PV panel life (more than 20 years) Additionally, the system NPC is impacted by the cost of diesel fuel.

5.3 Discussion

The simulation results indicate that the directly coupled PV water system can reliably deliver enough water per day, meeting the community's daily water demand. This water delivery capacity is 20% higher than the alternative diesel-powered pumping system currently in use. By reducing the reliance on costly and environmentally harmful diesel fuel, the directly coupled PV system can generate significant cost savings for the community. The PV system designed for the directly coupled PV water pumping system developed in this project could operate efficiently with two loads, the television and the water pump. The PV system supplied power for the Television when the water pump was disconnected. As soon as the water pump was connected, the PV system could switch efficiently from one load to another, allowing the water pump to get enough water from the river and fill the two tanks, as shown in **Figure 5.3** so that when the water pump is disconnected, there is still enough water to be used for daily use of a household.

Based on the cost of the components of the directly coupled PV water pumping system developed in this project, such as the photovoltaic (PV) module (Type CS6K280P), The centrifugal pump, and other electronic components, it was found that the proposed directly coupled PV water pumping system has higher upfront capital costs but significantly lower operating costs over 20 years. Conversely, the diesel system has lower initial capital costs but much higher fuel and maintenance expenses. The Diesel system considered in this study has high fuel costs that can add up significantly over the system's lifetime. The NPC calculated for both systems shows how these differing operating costs impact the overall lifecycle costs. The directly coupled PV water pumping systems generally have longer lifetimes and more gradual performance degradation than diesel generators. By analysing the results of the NPC, it becomes clear whether the higher upfront cost of the directly coupled PV water pumping system is offset by the lower long-term operating costs and other benefits, making it the more cost-effective option over the system's lifetime compared to the diesel alternative.

Diesel generators produce greenhouse gas emissions and air pollutants that may require the payment of carbon taxes or other environmental compliance costs. PV systems have zero direct emissions during operation, avoiding these regulatory expenses. The economic analysis strongly favours the directly coupled PV water pumping system. From the description above, we can see that the Directly coupled PV water pumping system has the lowest selling price of $12.5/L. Meanwhile, the diesel pump is the most expensive system, with a water selling price of $37.5/L.

5.4 Conclusion

The directly-coupled PV water pumping system developed in this study has a low design cost, less complicated electronic control and auxiliary systems, and local components that are not necessarily meant for photovoltaic pumping. The system is appropriate for applications with low delivery flow rates. As long as the sun shines on the panels and pumped water is kept in the two tanks, it can operate without outside assistance. It is abundantly evident that such a system is straightforward, simple to construct, and would require little upkeep. It was found that the proposed directly-coupled PV water pumping system could fill two tanks of 1000 litres while operating so that when the water pump is off, the water stored in the reservoir can be used by the household for daily basic needs. It was also found that the proposed directly coupled PV water pumping system could keep the PV voltage and current stable during the water pump operation, and the system could operate at a stable condition with minimum variations. This system's photovoltaic (PV) module is CS6K280P, which is less expensive than other PV modules. Due to the affordable price of PV modules and other components, the proposed directly coupled PV water pumping system's total cost is less than the diesel water system's cost. Furthermore, it can be observed that the system was operating at the maximum power point technique (MPPT) because the PV voltage and power were able to increase quickly to its maximum after a drop.

More research needs to be conducted on the maintenance system cost of the directly coupled PV water pumping systems because they require frequent maintenance due to the direct connection between the PV array and the water pump, which can increase the overall cost of ownership. The economic aspect of the directly-coupled PV water pumping systems needs to be deeply analysed to promote the broad deployment of this system throughout Africa and allow most of the population in rural areas to install the system and easily maintain the system at an affordable cost. The inconsistency of the sun in nature will always impact the directly coupled PV water pumping systems. Therefore, a cost-effective storage system should be discussed and considered to increase the performance of these systems.

Water supply in Africa remains a major concern, especially in rural and isolated locations. The directly-coupled PV water pumping systems offer a promising solution to water scarcity by utilising solar energy resources. The directly coupled PV water pumping system can provide a reliable and sustainable water supply for various applications through efficient system design, control strategies, and optimisation techniques. It is essential to carefully size the PV array to match the pump's power requirements, considering the maximum water demand and the available solar irradiation to experience better system performance.

CHAPTER SIX

CONCLUSION, FINDINGS, AND RESEARCH CONTRIBUTION

6.1 Finding of the Study

This study created and recommended a directly connected photovoltaic water pumping system for rural populations. The existing PV water pumping system was thoroughly reviewed in the literature, and it was discovered that the maximum point technique may greatly enhance the system's performance. It was found that the proposed Directly coupled water pumping system could perform under sudden changes in solar irradiance. Furthermore, it was also found that the system was stable during operation and was able to keep operating at its maximum power. This confirms that the proposed directly coupled PV water pumping system can supply water continuously.

6.2 Achievement of the objectives of the study

This research's main objective was to improve the PV water pumping system so that many people can easily access water. The other objectives of this research project were to minimise the physical efforts done daily by the population in remote areas to get water and to improve the efficiency of the photovoltaic water pumping system. These objectives were achieved because it was found that the Directly coupled water pumping system was stable and operating efficiently at the maximum point.

6.3 Research Contributions

The directly coupled water pumping system developed in this research project can significantly improve the rural water supply in Angola and many other African countries. This research can contribute in many aspects such as the population in rural areas will have more access to water at a lower cost, the reservoir or tanks will always be able to supply water to the population in remote rural areas during cold seasons when there is less solar irradiation, the cost of supplying water to rural areas will decrease because the directly coupled PV water pumping system will be operating with the sun which is available in the nature, the Dependence on the diesel and electrical power from the national grid in Angola is reduced.

6.4 Discussion on the reviews

The primary aim of this research project is to establish optimal modelling and control of directly coupled PV water pumping systems to improve water access in rural areas in Africa; the literature review technique helps to achieve this goal. Upon conducting an extensive review of numerous articles and experiments concerning the diverse types of PV water pumping systems, it was discovered that while these systems had been employed in the past for a variety of purposes such as including drinking, cooking, and irrigation, specific issues had emerged in each case.

Depending on the solar tracking configurations, the operational expenses of the PV water pumping systems were examined in three separate case situations to determine the best design. The water pumping system is more efficient in the first situation where a fixed-axis pump arrangement is used. Still, this arrangement has the disadvantage of using a lot of electricity and reducing the equipment's lifespan. In the second and third scenarios, photovoltaic production increases with single-axis and two-axis pumping designs; however, the issue is that the storage pond quickly fills up to capacity and cannot continue to deliver water to the PV facility (Naval and Yusta, 2022a)

The Direct-Coupled Photovoltaic Water Pumping System is powered by the sun, and different water storage tanks may be used anytime there is a noticeable decrease in solar irradiation. For most rural homes to have simple access to water, it is crucial to upgrade the water pumping equipment to minimise initial and ongoing expenditures. Because the Direct-Coupled Photovoltaic Water Pumping System does not require complicated electrical control devices or a battery, it offers extremely cheap startup and ongoing costs. Due to the sun's irregularity in nature, its structure is straightforward and quickly returns to a steady state following abrupt adjustments (Shepovalova et al., 2020). Based on the gaps in the previous and current investigations as well as the literature evaluations, the gaps found in previous studies performed are:

- No research has been done on how to make directly-coupled solar water pumping systems operate better in isolated rural locations. A few earlier studies verified, following certain simulations, that the motor pumping system efficiency performance of the directly-coupled photovoltaic water pumping systems does not surpass 30%. However, no additional research was conducted to determine how this efficiency might be increased from 30% to perhaps 45% or 50%.
- Research has not been done on enhancing the directly-coupled photovoltaic water pumping systems' performance under varying solar irradiation conditions. Most prior and current research focuses on the behavior of PV water pumping systems under different solar irradiances. Studying these characteristics alone, however, is insufficient; it is also critical to examine strategies for enhancing the performance of different kinds of water pumping systems.

The following is a collection of responses to the research questions that were created:

- What can be done to improve the rural water supply in Africa?

The rural water supply can be improved by creating a water pumping system that is affordable for anyone and easily accessible even when there is no electricity from the grid.

- What can be done to improve the water pumping system?

The water pumping system can be improved by introducing a sustainable power supply such as renewable energy to enable it to operate continuously and efficiently.

- What is a unique benefit that the proposed system can provide?

The unique benefit of the proposed system is that it offers an affordable water pumping system that runs off-grid electricity, making water easily accessible to most people living in rural areas.

- Why is that so important to improve the water pumping systems?

It is important to improve the water pumping systems so that the population in rural areas can easily get water for basic needs such as drinking and cooking.

It is evident from the gaps and difficulties listed above that there is a great need for PV water pumping systems that are economical and effective in terms of setup and functionality. The research project's review indicates that the directly-coupled photovoltaic pumping system is the best choice for achieving both inexpensive and efficient performance. Through a few simulations using MATLAB/SIMULINK, this research project seeks to address the issue of directly-coupled photovoltaic pumping systems' efficiency and performance in several ways. The goal is to ensure that the modelling and control of these systems can achieve high efficiency and performance while maintaining cost-effectiveness.

6.5 Further Research

This research discussed the Directly coupled PV water pumping system but In the future, The cost and benefits analysis should be also conducted to understand in detail the cost involved in fully installing a solar energy system. This will clarify how to extend the implementation of this renewable energy system in Angola. Further studies should be also conducted on the storage of renewable energy at an affordable cost.

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