ASSESSMENT OF TECHNICAL POTENTIAL OF FLOATING SOLAR PHOTOVOLTAIC SYSTEM FOR ELECTRICITY GENERATION IN ZAMBIA

By

Chrispin Lumpote

A dissertation submitted to the University of Zambia in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Electrical Power Engineering (EPE).

The University of Zambia

School of Engineering

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DECLARATION

I, Chrispin Lumpote, do declare that this work is my own and that the work of other persons utilized in this dissertation has been duly acknowledged. This work presented here has not been previously presented at this university or any other university for similar purposes.

Signature…….

Date ...…….

As a candidate's supervisor, I have read this dissertation and have approved it for examination;

Signature; ……

Date …….

CERTIFICATE OF APPROVAL

This dissertation by Chrispin Lumpote is in partial fulfillment of the requirements for the award of the Masters of Electrical Power Engineering by the University of Zambia (UNZA).

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Examiner 1	Signature	Date

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Examiner 2.	Signature	Date

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Examiner 3	Signature	Date

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Chairperson of the board	Signature	Date

ABSTRACT

Sustainable hydropower development provides a reliable and stable power source that is economical and environmentally friendly. However, its investment capital is huge and unbearable to third-world countries. Hence the requirement of an alternative power source that is manageable. Zambia's main electricity comes from hydropower whose hydrological pattern over the past decades has been facing serious threats from frequent droughts and severe weather conditions affecting the country's power generation systems. Zambia's hydropower is characterized by larger water Reservoirs (Mulungushi, Itezhi Tezhi, Kafue Gorge and Kariba North) which are also receiving high solar energy exceeding 2000 kWh/m^2 per year. Hence, integration of floating solar PV systems with hydropower could help boost hydropower production during dry periods and save loss of water through vapor. This study aimed at assessing the technical potential of floating solar Photovoltaic Systems for electricity generation in Zambia and integrating it with hydropower generated from the existing larger hydro Reservoir. The assessment was done using Simulation Software tools (PVGIS and PV system). The findings indicates that large hydropower Reservoirs have a total surface area of 11,146 km^2 and have got an equivalent annual solar energy theoretical potential of 25,610TWh. Furthermore, at 10% of total surface area coverage the geographical potential of the Monocrystalline, CIS and CdTe Solar technology were estimated at 172.76 GW_P, 141.44 GW_P and 116.10 GW_P equivalent to annual solar electricity generation technical potential of 304TWh, 244TWh, and 211TWh respectively and annual evaporation loss savings of 505.9million m^3. In short, Zambia has huge potential for integration of floating solar with hydropower using the existing power grid infrastructure and local conditions of the power stations to increase on the electricity generation for the nation. Additionally, solar energy profile fits well with electricity demand profile for Zambia which makes it a better alternative for energy mix for the country. These findings are vital to provide guidance to decision makers for inclusion of floating solar energy in the future national energy mix and conservation of land and reducing evaporation loss while optimizing utilization of existing grid infrastructures.

Keywords: Evaporation loss savings, Floating Solar Photovoltaic, Grid infrastructure, Hydropower substation, Substation reserve margins, technical potential

DEDICATION

This research work is dedicated to members of my family who continuously encouraged and supported me throughout my academic and professional life. Special dedication is extended to my wife Hildah Siamaimbo, my mother Eddesy Mungalu, my aunt Eledy (Lumpote) Simuyandi and my late father Donard Mudeene Lumpote who showed me the way to go in life. More importantly worth mentioning are my children Luyando Racheal Lumpote and Donard Mudeene Lumpote II for their understanding and moral support during the vigorous period of the study.

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ACRONYMS AND ABBREVIATIONS

EEE	Electrical and electronics engineering
EU	European Union
FSPV	Floating Solar Photovoltaics
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
REA	Rural Electrification Authority
IHA	International Hydropower Association
IRENA	International Renewable Energy Agency
CIS	Copper indium selenium
CdTe	Cadmium Telluride
I T	Itezhi-Tezhi
KGU	Kafue Gorge Upper
KNBS	Kariba North Bank Power Station
MU	Mulungushi
ERB	Energy Regulation Board
MoE	Ministry of Energy
CSP	Concentrate Solar Power Plant
LHCP	Lunsemfwa Hydro Power Company
WMO	World Meteorological Organization
ZESCO	Zambia Electricity Supply Corporation
GW	Giga watt
MW	Megawatt
NASA	National American Science Association
GWh	Gigawatt hour
MWh	Megawatt hour
TWh	Terawatt hour
VOA	Voice of America

CHAPTER ONE

1 INTRODUCTION

Renewable energy is one of the emerging energy technologies that has come on board and is a crucial component to sustainable development which is on top of the world's agenda to solve energy crisis affecting many countries in the world and the African continent inclusive (Kotaky *et al.,* 2015). Sustainable energy development gives a basis to have resources that are economically and environmentally friendly with acceptable social effects as a requirement by the United Nations sustainable Development Goals (UNDP, 2019).

Since the early century, human beings have been using fossil fuels as their primary energy source to power their activities. Today, fossil fuels (coal, oil and gas) represent 85% of the total global energy consumption (Spensor, 2019). The combustion of hydrocarbons releases CO_2 into the atmosphere which results in the green-house effect (Spensor, 2019). The continued accumulation of CO_2 (and other green-house gases) in the atmosphere as of 2019 was at approx. 410ppm (Spensor,2019) and is the main cause of the global temperature rise. Recently, the World Meteorological Organization (WMO) released its provisional 2019 global climate report where it concluded that temperatures have increased since the1980s and that the past decade, 2010-2019, has been the warmest on record (WMO, 2019).

1.1 Background

Electricity supply in Zambia started as early as the 21st century when a small thermal station was built in Livingstone to serve a section of the town for administration and domestic purposes. By then, the Victoria Falls had hydropower potential but it was not until 1938 that hydro-electric power was first generated at a small station in the third gorge at Section A below the falls with the capacity of 8MW (ZESCO Limited, 2023). Since then, the country has been using hydropower and the sector has relatively grown in capacity and there been also huge increases in power consumptions. There is enough demand that keeps on going up as energy is a key element required for sustainable development and prosperity of any society (Kotaky *et al.*, 2015).

Zambia has plenty of untapped technical potential of hydropower about 6000MW (Mwanza *et al*, 2017). However, in the past few decades, drought, has been affecting the country's hydrological

system. For instance, Southern Africa Development Coordination (SADC) region in 2016 saw the worst drought and prolonged poor climatical conditions (Guardian, 2016; VOA, 2017; IHA, 2021). Thus, climatically the availability of water resources have been altered due to droughts which have led to reduced hydropower generation (Figure 1.1) and increased energy deficit in the nation (Conway *et al*., 2017). This was caused by poor rainfall patterns as the results of raising temperatures experienced because of climate change (IHA,2020).

Higher temperatures are expected to increase evaporation affecting the average capacity factor of hydropower stations. This global rise in temperature has not spared Zambia whose main source of energy depends on hydropower which, accounts for 81% of the total country's energy needs (ERB, 2021). For the past decade hydropower has been facing challenges due to disturbances in the hydrological patten thereby plunging the country into erratic power supply (Guardian, 2017; VOA, 2019). This led to increased hours of load shedding among energy consumers for more than ten (10) hours per day with extreme cases reaching fifteen (15) hours (ZESCO, 2016). However, Zambia has larger hydro reservoirs receiving excellent solar radiation. These include the Kariba North, Kafue Gorge, Itezhi -Tezhi and Mulungushi reservoir (Imasiku, 2017; Mwanza et al 2017). Additionally, solar energy profile fits better with the Zambian daily energy consumption pattern which peaks between 06:00 and 18:00 hrs. Therefore, a combination of solar and hydropower provides one of the excellent solutions to mitigate energy needs of Zambia. Thus, the implementation of floating solar on existing large hydropower reservoirs will help combat current energy deficit and reducing evaporation therefore, increasing hydropower potential.

Considering the effects of climate change and its consequences on hydropower plants, other low carbon energy technologies such as Photovoltaic (PV) systems need to be prioritized and deployed at a large scale (IEA, 2020). African countries have an exceptional solar potential with a yearly average solar energy exceeding 2000 kWh/m^2 (Gonzalez *et al*., 2021). Currently, Africa accounts for a PV installed capacity of only 5 GW of which Zambia has 96 MW translating to less than 1% of the total installed capacity of Africa.

The International Energy Agency (2020) projected an estimated average future PV systems deployment of almost 15 GW per year, reaching 320 GW globally by 2040. This would make PV systems the largest electricity source to be installed globally exceeding natural gas and hydropower

(International Energy Agency, 2019). Considering the increasing energy needs in Zambia and its vast solar resources, this study presents the feasibility of an effective energy interdependence between solar PV and hydropower through the development of Floating PV systems (Sacramento, 2015). Furthermore, floating PV system could compensate greatly during reduction of hydropower output as a result of dry periods and also reduce water loss from evaporation (Glasnovic, 2009). floating solar photovoltaics (FSPV) Systems will offer reliable solutions to Zambia's hydropower shortages as they could rapidly cover up to the installed power capacities of the power station and use existing power system infrastructure including local expertise.

Additionally, FSPV have an additional advantage that is pertinent to Zambia's hydropower. Savings of surface land resources as the system will utilize much of the available water bodies, and act as a means of saving water from considerable evaporations, as the panel will cover wider top parts of some selected water bodies. The system will enhance solar efficiencies because of the cooling effects from water and improve water quality as the growth of algae will reduce. Many studies looking at generation of electricity using solar have been conducted using roof top mounted and land mounted. Mwanza and Ulgen (2020) carried out a study on Sustainable Electricity Generation Fuel Mix Analysis using an Integration of Multi-Criteria Decision Making and System Dynamics, but integration of floating solar PV system with hydropower considering the local power station conditions was not considered. Another study on complementary hybrid system which focused on optimizing the size of the PV plant, for the short and long terms was carried out with tests in Longyan Xia.

1.2 Problem Statement

Hydroelectric power generation has become a source of concern in Zambia. This has been a problem at domestic and industrial level. It has impacted families negatively at domestic level and slowed development at industrial level. To mitigate these problems, several interventions have been made by various stakeholders (industrial development corporation (IDC), African development bank (ADB) and world bank. Regarding hydropower generation in Zambia (MoE, 2021). Despite interventions by Government of the Republic of Zambia (GRZ) through the ministry of energy, PPP and ZESCO hydropower generation has continued to experience setbacks

thereby causing power deficit which has made it impossible to meet power demand of the end users in the recent past (ZESCO, 2021; ERB, 2021; MWED, 2016).

Power performance for the past decade and how generation has been affected is shown in the

Figure 1.1.

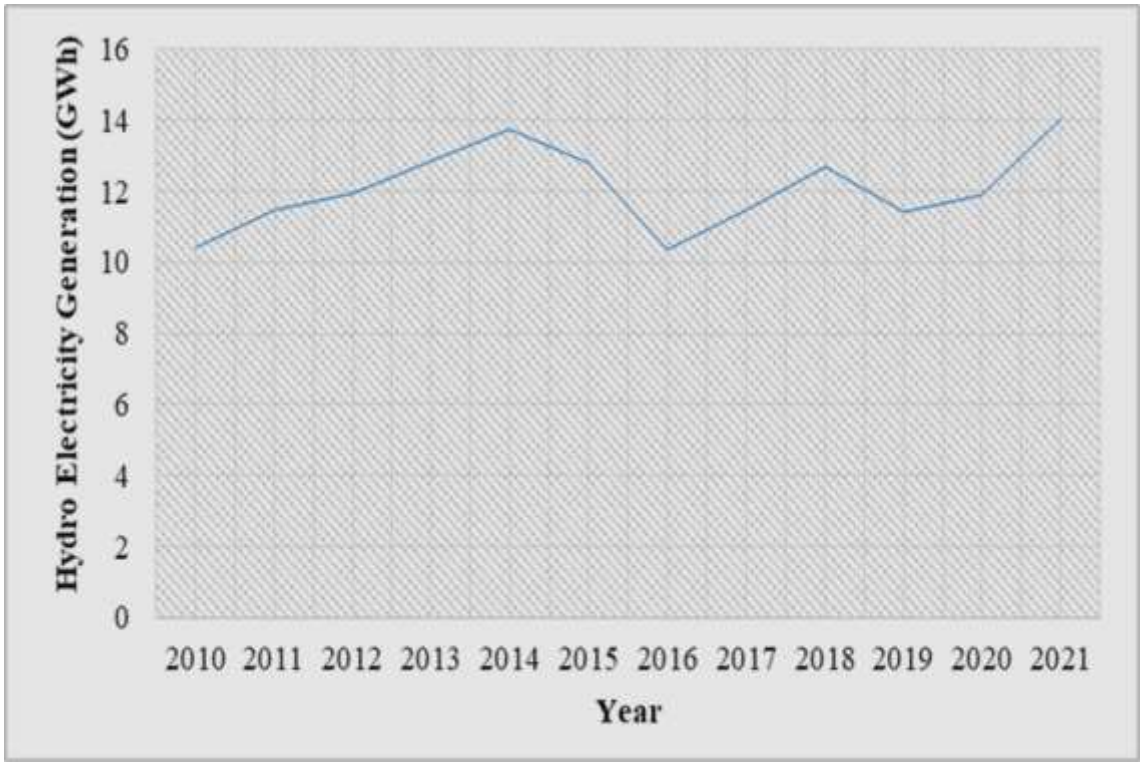


Figure 1.1 Hydropower Electricity Generation in Zambia (ERB, 2021; MoE, 2022)

Therefore, there is a need to know the installed power capacity of the four largest hydropower stations of Zambia, there is also need to know the theoretical and geographical potential of the largest hydro reservoirs. Furthermore, there is a need to know the technical potential of the four largest reservoirs considering the substation reserve margins, existing grid infrastructures and local conditions of each individual power station.

The aforementioned specific focus areas which are the reality, have been brought about because very little has been done regarding assessment of technical potential of floating solar photovoltaic systems for electricity generation in Zambia. This kind of assessment or study is needed because

it will contribute valuable information to the awakening debate on how to address the issue of low hydropower generation.

1.3 Research Objectives

The main aim of this research was to assess the technical potential for electricity generation of floating solar PV systems in Zambia on selected larger hydropower plant's water reservoirs.

1.3.1 Specific Objectives;

i. To quantify the theoretical and geographical solar potential on the useable surface areas of the reservoirs for implementation of floating solar PV system.
ii. To determine the substation reserve margins of the larger hydro power plants of Zambia.
iii. To determine the technical power and electricity generation potential of floating solar PV systems on the selected hydro reservoirs.

1.3.2 Research Questions

The questions that informed the research regarding the technical potential of floating solar PV systems on the existing four large hydro reservoirs of Zambia are:

i. How much is the substation reserve margins of the larger hydropower plants for floating solar PV integration?
ii. What are the reserve margins of the large hydropower stations in Zambia under different scenarios of water supply to the power stations from the reservoirs?
iii. What is the technical power and electricity generation potential of floating solar PV systems on the useable surface areas of the reservoir considering substation reserve margins during rain and dry periods?

1.4 Significance of the Study

The technological potential of floating solar PV systems in Zambia for the production of energy from the nation's four main hydropower reservoirs is thoroughly examined in this study and the following are the significance of the study;

i. The presence of enough solar radiation in Zambia makes solar PV system an alternative source of energy that can mitigate power shortages in the country during dry season or when there are machine failures at any selected power station.

ii. The study will give decision-makers vital information about possibilities and advantages of integrating floating solar PV systems with existing power systems grid and will encourage prospects for the future energy mix that can improve energy security in Zambia.

iii. Enough land could be saved for other economic activities as the implementation of floating photovoltaics will be done on water

iv. Solar PV systems are a superior option for Zambia's electricity to Combat power loss during climate variability caused by global warming

v. The use of solar energy will be vital for Zambia since Zambia's electricity requirements are high during the day, and solar PV systems generate energy mostly during the hours of 08:00 am to 16:00 pm when the sun is at its most effective.

vi. It is hoped that the research will act as a stepping stone for further research and contribute to the engineering body of knowledge.

1.5 Scope of the Research

This research covers only four (4) large existing hydropower plant reservoirs in Zambia. These are Kariba North, Kafue Gorge, Itezhi-Tezhi, and Mulungushi. The technical potential of floating solar PV systems for these large existing hydroelectric power plant reservoirs was assessed based on the available supporting infrastructure (substation reserve) and the available reservoir water surface areas. The research only quantified the theoretical and geographical solar energy potential including the technical potential, that is power and electricity generation potential of floating solar PV system based on existing hydropower plant Reservoirs, local weather condition, substation reserve margins, and characteristics of three solar PV technologies.

1.6 Ethical Consideration

This section indicates ethical issues that were considered during the study. According to Cohen *et al.* (2000), ethical issues are matters which are highly sensitive to the rights of others. In this regard, ethical clearance was obtained from the University of Zambia Natural and Applied Sciences Research Ethics Committee (NASREC) to conduct the research. Furthermore, consent was obtained from plant managers and safety officers before assessing the hydropower plants. Hence, they had the right to understand what the research involved and agreed to share the findings with them afterwards.

1.7 Dissertation Outline

The dissertation is arranged in five chapters:

Chapter1: provides the introduction to the assessment of technical potential of FSPV system for electricity generation in Zambia, the objective of the research, the research questions that needed to be answered to meet the specific objectives demands.

Chapter 2: provides the literature review of solar radiation distribution in Africa and Zambia, useful water bodies, their locations and their surface areas. The chapter also reviewed literature on how to come up with correct power scenarios needed to find solution of how substations and power plant reserve margins can be supplemented in order to stabilise power profiles of the power stations.

Chapter 3: provides the methodology used in the study. Detailed research design, tools and materials used and also assumptions used in the study are discussed in this chapter.

Chapter 4: gives the results and discussion of these results in line with the set objectives. While Chapter 5: gives the conclusions and recommendations.

1.8 Summary of the Chapter

An introduction and background to the assessment of technical potential of FSPV system for electricity generation in Zambia has been given. The problem statement of the research and its justification, the main objectives and research question have been outlined.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Electricity Industry Players in Zambia

Electricity supply industry in Zambia mainly comprises of a vertically integrated state utility ZESCO and the Copperbelt Energy Corporation (CEC), that purchases power from ZESCO and supplies it to the mines (Mahere, 2010). In addition, there are other Independent Power Producers like; Lunsemfwa Hydropower Company (LHCP), Maamba Collieries Ltd, Itezhi-Tezhi Power Corporation, Dangote Industries Zambia Ltd, Ndola Energy Company Ltd, Bangweulu Power Company Ltd, Ngonye PV Power Company Ltd, and Zengamina Power Company (ZPC), as well as some small-scale solar based energy service companies supplying power to some rural areas which also participate in the industry (Mwanza, *et al*. 2017). Other players include, North-Western Energy Corporation Ltd and Rural Electrification Authority (REA). According to the Ministry of Mines, Energy and Water Development of Zambia (MEWD, 2008), ZESCO currently dominates electricity generation, transmission, distribution and supply in Zambia.

2.2 Existing Generation and Deficit

2.2.1 Zambia's Installed Generation Capacity

Hydropower accounts for the biggest portion of Zambia's 3318 MW installed generation capacity, followed by fossil fuels (coal, heavy fuel, and diesel), while solar energy accounts for the smallest portion of all (ZESCO, 2021; MoE, 2021). Despite the industry having a sufficient amount of potential for solar energy generation, solar usage is still low. In terms of electrifying rural areas, solar energy represents the highest proportion with 7.2%, followed by grid extension with 4.4% (ERB, 2020). Zambia's energy-generating mix in 2021 is depicted in Figure 2.1. It is clear that hydropower makes the largest contribution, at 81%, followed by coal at 10% and all other sources combined, at 3%. Not only does Zambia have enough hydro-potential but also has its highest energy generation as it can be seen from Figure 2.1.

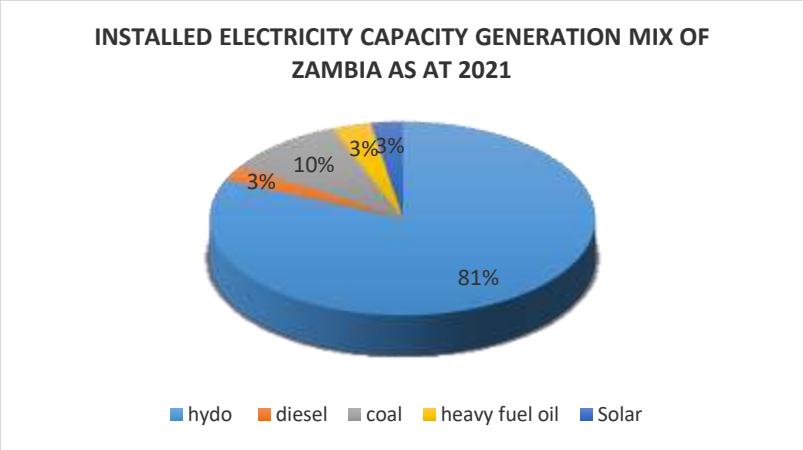


Figure 2.1 Electricity generation mix of Zambia as at 2021(Source ERB 2021)

2.2.2 Generation Deficit and Energy Demand in Zambia

Zambia had nearly 3,000 MW of installed capacity in 2018, most of which was generated from hydro. Peak electricity demand was higher than the actual electricity generation resulting to a deficit of about 650 MW in the same year. However, the generation capacity in 2019 reduced as a result of drought leading to a supply deficit of more than 810 MW (ZESCO, 2021). Nevertheless, with the commissioning of 4 x 150MW units at Kafue Gorge Lower power station which brought on board 600 MW, the current deficit is 210 MW (ZESCO, 2021). The national electrification target is 66% of the population by 2030 while installed capacity is expected to double from its 2018 figures to around 6,000 MW (ERB, 2020).

2.2.3 Energy Demand in Zambia

Electricity consumption in Zambia has been rising steadily estimated at approximately 6% per year (Mwanza *et al.*, 2017). For the past decades the country has been experiencing energy deficit due to lower generation from hydropower plants due to droughts and climate change effects (IHA, 2020). The energy peak demand varies depending on the season. For instance, in 2009, the winter peak demand was about 1450 MW while the summer peak demand was about 1400 MW. However, in 2014 the peak demand was forecasted to be between 2,612 MW and 2,260 MW in winter and summer respectively (Mwanza *et al*. 2012). Energy demand is expected to reach 21600000MW in the fiscal year 2030 respectively (Walimwipi, 2012; Mwanza & Ulgen, 2020).

In Zambia, traditional wood fuels like charcoal and firewood have continued to be the main source of energy accounting for roughly 70% of the country's total energy demand, just like in many other Sub-Saharan African nations (Likonge et al, 2013). While being the second most popular source of power, hydropower makes around 14 % of all energy used. Around 12 % of the country's energy needs are met by petroleum products. Although, coal has great potential in the southern province, it only makes up around 2 % of the entire energy supply. According to (MWED, 2008) only 2% of Zambia's entire energy balance comes from alternative energy sources like renewable energy.

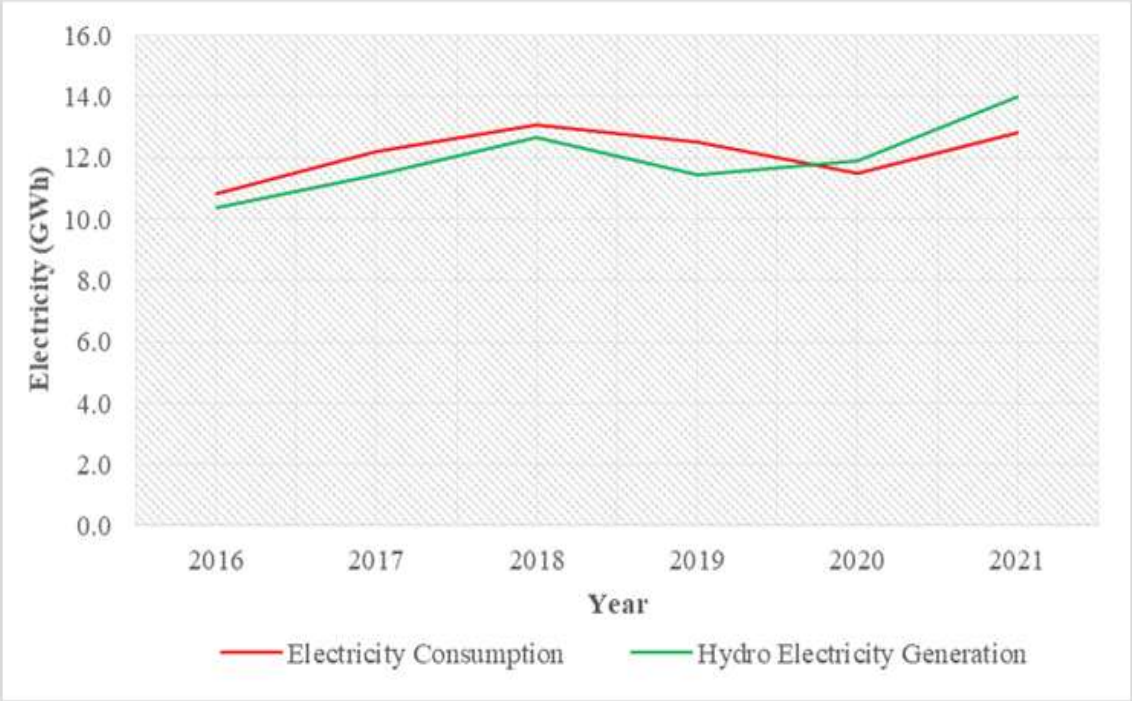


Figure 2.2 Electricity Generation vs Consumption in Zambia (ERB, 202; MoE, 2022)

2.2.4 Availability of Water Bodies in Zambia for PV installations

Zambia has adequate water bodies and reservoirs as compared to other countries in Southern Africa with the water surface area of about 9,22 km^2 (Mwanza *et al.*,2017). The country shares vital water bodies with the neighbouring countries as the main river basins are transboundary. For instance, the Zambezi River is shared by many neighboring countries and drains about three quarters of the country's water into the neighboring countries as it goes to the Indian ocean (Imasiku *et al.*, 2017).

Additionally, the nation is also rich in rivers and lakes. The main rivers are the Zambezi, Kafue, Luapula, Chambishi, and Luangwa. And the main lakes are Mweru, Bangweulu, and Tanganyika plus man-made lakes such as Kariba and Itezhi-Tezhi (Imasiku *et al.*, 2017). Several current water bodies, especially lakes, have the capacity to accommodate floating PV solar systems except a few of them. This coincides with the fact that, Zambia's electricity is characterized by large reservoirs such as Kafue Gorge Upper, Kariba, Mulungushi and Itezhi-Tezhi with the total surface area of 11,146 km^2 receiving excellent solar radiation as shown in Table2.2. This solar radiation can be integrated into the national energy mix after being converted to electricity using floating solar PV system. This integration would make use of the existing hydropower plants infrastructure (Imasiku 2017; Mwanza *et al.,* 2017).

Table 2.1 Larger Hydropower stations surface areas and solar radiation parameters (ZESCO, 2021)

Hydro Reservoir	Province	Installed Capacity (MW)	Solar Radiation kWh/m^2	Reservoir Surface Area (km^2)
Kariba North	Southern	1080	5.86	5580
Mulungushi	Central	31.3	5.90	4963
Kafue Gorge	Lusaka	990	5.93	805
Itezhi-Tezhi	Southern	120	5.93	392
Zambia		**2221.3**	**5.91**	**11,146**

The main focus of sustainable water development is the hydropower reservoirs, but these facilities are susceptible to evaporation losses because of Zambia's rising air temperature, predicted to be increasing by 0.0360 C per year (Bathsheba & Lina, 2013). If this is the case, annual reservoir evaporation losses which are currently estimated at1.68 m^3/m^2/year for Itezhi-Tezhi, 1.86 m^3/m^2/year for Kafue Gorge, and 1.59 m^3/m^2/year for Kariba North are expected to keep rising (Pedro et al., 2021). Therefore, to reduce power shortage and increased water evaporation, it would be wise to incorporate floating solar on the surface areas of the hydropower reservoir. It is possible to anticipate reduced reservoir evaporation, which will improve hydropower potential.

Table 2.2 Annual reservoir evaporation rates and losses (DM,1993)

Hydropower Reservoir	Annual Evaporation Rate (mm)	Average Annual Rainfall(mm)	Annual Evaporation Losses (km^3)
Kafue Gorge	1840	850	1.5
Kariba North	2000	700	8.9
Mulungushi	2051	1200	15.4
Itezh Tezh	1784	700	0.66

2.3 Solar Energy in Zambia

Solar energy is the radiant heat and light that the sun emits, and it is captured using a variety of constantly developing technologies, including solar heating, PVs, solar thermal energy, solar architecture, molten salt power plants, thermal plants made of solar concentrates, and synthetic photosynthesis (Takouleu, 2020). According to Mwanza *et al.* (2017), Zambia has a good solar environment with an average of six to eight hours of sunshine per day throughout the nation and 5.5 kWh/m^2/day of solar radiation on a monthly average. In order to generate electricity using solar technology, this energy is sufficient. In a few chosen larger hydro-reservoirs, floating systems can be installed to increase electricity production and decrease evaporation, thereby decreasing load shading and national power shortages (Gonzalez *et al.*, 2021).

The nation has a sizable capacity for solar energy generation for both power production and thermal from solar energy technologies according to Mwanza et al. (2016a) and NASA (2021). Table 2.3 displays the daily solar radiation and total annual evaporation for each province in Zambia.

Table 2.3 Annual Average pan –Evaporation & Daily Solar Radiation for Provinces in Zambia (Mwanza et al., 2017; DM, 1993)

Provinces	Annual Average Solar Radiation (kWh/m^2-Day)	Annual Average Pan-Evaporation (mm)
Lusaka	5,70	2,218
Luapula	5,78	1,983
Central	5,76	2,105
Copperbelt	5,75	1,865
Northern	5,83	1,907
N-Western	5,74	1,932
Western	5,89	2,300
Southern	5,80	2,015
Eastern	5,68	2,211
Zambia	5,77	2,061

Note: Pan Evaporation shows average annual evaporation rate or reduction in water levels of the reservoirs.

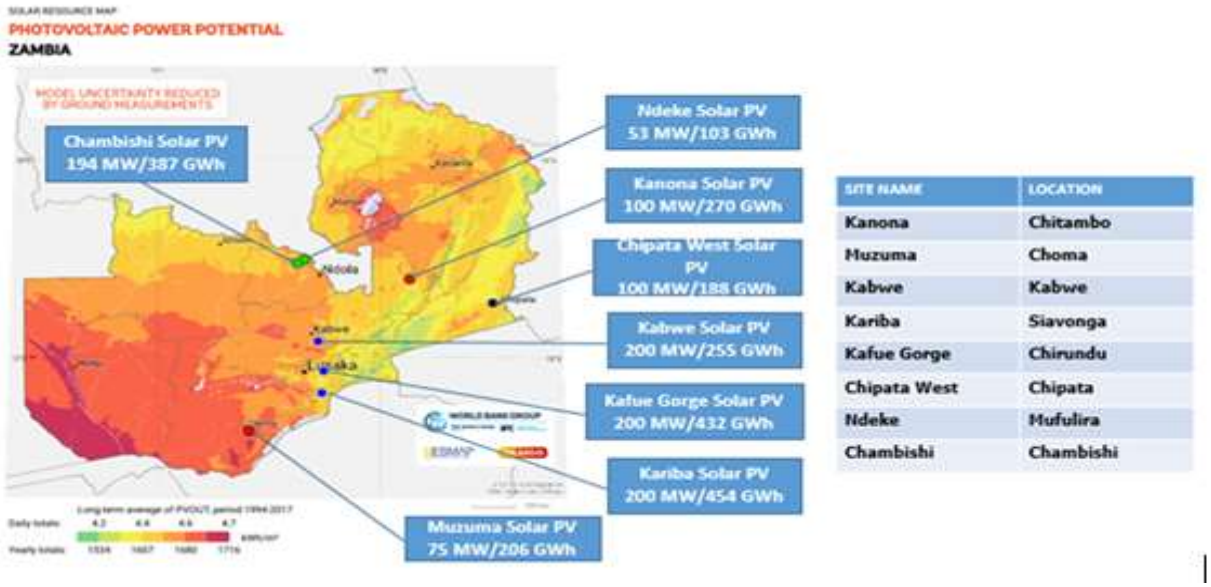
2.4 Solar Projects in Zambia

As part of its commitment to vision 2030, the Zambian government, through the REA project, embarked on solar PV projects that involve the installation of 200MW combined solar off-mini and micro grid in various villages throughout the country. This includes the 60 MW in Samfya district of Luapula province which has been decommissioned and the construction of solar PV farms like the 55MW and 35MW solar PV farms in Multi-Facility Zone (MFZ) Lusaka District of Lusaka Province under IDC (World Bank, 2019).

Similarly, Zambia has more than eight (8) planned solar PV farm projects (1122MW) underway as shown in Figure 2.3 including plans to construct 200MW concentrated solar power plant (CSP) in Kalulushi to provide power to the Copperbelt Province and nearby regions (Takouleu, 2020). There are also plans to develop wind power farms in Katete District, Eastern Province.

The implementation of the 1122MW ground solar PV projects will require approximately 2244 hectares ($22.44km^2$) of land representing about 0.003% of Zambia's surface area which can be

used for other economic activities. If these projects are integrated on hydropower plant reservoirs only 0.20% of largest hydro reservoir surface area is required saving the (22.44 km^2) of land.



SITE NAME	LOCATION
Kanona	Chitambo
Muzuma	Choma
Kabwe	Kabwe
Kariba	Siavonga
Kafue Gorge	Chirundu
Chipata West	Chipata
Ndeke	Mufulira
Chambishi	Chambishi

Figure 2.3 Solar Radiation and on -Grid planned Solar PV projects in Zambia

Therefore, compared to solar PV farms on land, floating solar farms provide a better option. It is crucial to carefully assess the technological potential of a floating solar system for energy generation and integration with the existing hydro system in order to make informed choices.

2.5 PV Systems configuration

There are many other kinds of solar installations, but the rooftop, ground mount, and parking canopy sites are the three most common choices for commercial solar arrays. The following provides a visual representation of several solar mountings.

i. Roof Top Solar PV: Large commercial structures and distribution facilities frequently have an abundance of empty rooftop space, which is a fantastic site to install solar panels. It's crucial to take into account the age of the current roof, geographic latitude, weather patterns, roof slope, and shadowing from nearby structures or plants when analyzing rooftop solar. Figure 2.4 shows an example of a roof top solar PV array.

Figure 2.4 Roof top solar PV (Source: Melink Solar, 2023)

ii Ground mounted solar: Solar panels that are mounted on the ground can be found in open spaces. Because they may be installed with a greater optical tilt angle, they often produce more energy to absorb the most sunlight possible. The panels of a ground-mounted solar system are held at a set angle by a metal frame that is anchored to the earth. Other ground-based systems might make use of pole mounts that can adjust the solar panel at the perfect angle both daily and seasonally. An image of a ground-mounted solar panel is shown in Figure 2.5.

Figure 2.5 Ground mounted solar (source: Melink solar, 2023)

iii Solar Canopy mounted: A solar PV canopy is an elevated building that lifts solar panels placed above paved areas like parking lots. Vehicles can park there and benefit from the shaded area.

Several solar canopies have built-in charging ports so that electric car owners can recharge their batteries while their cars are parked (Melink solar,2023). Solar canopies frequently educate and raise public awareness of solar energy due to their visibility and convenient parking options. In actuality, solar canopies are comparable to ground-mounted solar panels in that both offer an alternative to rooftop solar, whether a roof is unable to support solar panels or a property's electrical requirements are too great for a rooftop solar system. An example of a canopy mounted solar PV system is shown in Figure 2.6.

Figure 2.6 Solar Canopy mounted PV (Source: Melink solar, 2023)

In a number of different countries, land resources are limited for large-scale ground-mounted solar PV systems. In addition, rooftop areas in housing, commercial and industrial buildings may not be essential for rooftop solar solution. Therefore, floating solar PV systems are the acceptable ecological alternative solutions in the case of Zambia. Floating solar PVs also known as “photovoltaics” cover a reasonable surface area on a water body and may have no significant negative effects on aquatic life. Figures 2.7 and 2.8 show the layout of floating solar PV system.

Figure 2.7 lay out of floating solar system on water Reservoir in California

Figure 2.8 Floating solar photovoltaic system

2.6 Benefit of Solar PV systems

As opposed to land-mounted solar, floating solar has various benefits, including improved PV panel performance, reduced water evaporation and photosynthesis, and improved water quality, these are shown in Table 2.4.

Table 2.4 Advantages and disadvantages of floating solar PV system (Sudhakar et al.,2016)

Floating Solar PV System	
Advantages	Disadvantages
Land conservation	Potential erosion of PV components.
Reduction of water evaporation	Obstruction to fishing and transportation.
The natural cooling effect provided by water improves solar PV efficiency than ground-mounted PV systems (Choi et al, 2019	Water pollution
Improve water quality by reducing photosynthesis and algae growth (Bontempo et al, 2020).	Aquatic habitat loss

2.7 Related Works

This section presents reviewed related literature to the current study on the assessment of floating solar PV system for electricity generation in Zambia.

The closest study to the current study on the African continent was conducted by Gonzalez *et al.* (2020) on the assessment of floating solar PVs potential in existing hydropower reservoirs in Africa. The study showed that Africa is characterized by a very high solar potential, with a yearly sum of solar irradiation exceeding 2000 kWh/m^2 (Gonzalez *et al.,* 2020). Many African countries are heavily dependent on hydropower; however, increasingly frequent droughts have been severely affecting hydropower generation in the last few decades. Thus, the installation of FSPV in existing hydropower reservoirs, would provide solar electricity to help compensate hydropower production during dry periods and reduce evaporation losses while helping to sustainably satisfy the current and future energy needs of the fast-growing African population (Gonzalez *et al.*, 2020).

Gonzalez *et al.* (2020) study provides a comprehensive analysis of the potential of FSPV installation in Africa, by using highly accurate water surface data of the largest 146 hydropower reservoirs in the continent. In addition, to electricity production, evaporation savings and the potential extra hydroelectricity generated by these water savings are also estimated at reservoir

level for four different cases and two types of floating structures. The results of this previous study indicates that with a total coverage of less than 1%, the installed power capacity of existing hydropower plants can double and electricity output can grow by 58%, producing an additional 46.04 TWh annually. In this case, the water savings could reach 743 million m^3/year, increasing the annual hydroelectricity generation by 170.64 GWh.

Besides that, the study conducted in Pakistan by Huzaifa *et al.* (2018) on the integration of floating solar PV with hydroelectricity power plants in large water reservoirs revealed various advantages for hydropower generation from PV system. In addition to being economically feasible, floating solar power plants also conserve water below by minimizing water evaporation (Hartzell, 2016). Many significant water reservoirs in Pakistan were highlighted in this study (Ahmad *et al*, 2001). The installation of a Floating Solar Photovoltaics (FSPV) system on these bodies of water can generate a significant amount of electrical energy. Benefits of installing FSPV plants on reservoirs include the utilization of existing infrastructure.

Sahu, *et al* (2015) carried out a study on floating solar in developing countries. This study showed the economic advantage of PV solar system. As the cost of water surface is much lower than the cost of land the demand for Floating PV is expected to increase and will spread all over the world. In addition, the availability of the water resources, demand and supply gap of electricity in India and China are also high in comparison to the developed countries which in turn expected to boost the market of floating solar technology. India took a challenge of installing 100GW capacities of solar power plants by the year 2022. Such technology can contribute to the share of the generation targets and save the limited water sources availability.

Yan-Wei *et al*. (2013) studied the potential of solar PV power at the regional scale in China's Fujian Province using a GIS-based technique. They demonstrated the spatial variance of solar energy in their analysis, which is important for determining where to build in Fujin and for estimating the potential of the region. In order to assess the entire potential of solar PV generation at the regional scale, the study presented a high-resolution grid map of solar radiation mixed with the other limiting variables.

Solar energy is the process of turning sunlight directly into electricity using PVs or indirectly using concentrated solar power (CSP) (CSP). One of the finest solutions for the world's future sustainable energy needs is PV electricity. The PV market has been expanding at a global pace of 35 to 40 percent per year, with PV production totaling about 10.66 GW in 2009 (Razykov *et al*, 2011). China's newly installed PV capacity in the same year is 160 MW, with a 300 MW installed capacity overall. According, to the recently released "Development Plan for Renewable Energy during the 12th Five-Year Term," China targeted to increase solar PV electricity to 10 GW by 2015 (Xu,2011). If successful, the Chinese PV market would represent the beginning of a period of rapid development.

A study on the technical potentials of renewable energy was conducted in the United States of America by (Lopez et al.2012). The Idaho National Laboratory provided the source point locations of the hydropower estimations, which were acquired from Hall *et al*, (2004). and analyzed using a GIS-based survey (2006). Based on a prior study (Hall *et al*. 2004), which evaluated the gross power potential of every stream in the United States), these point locations were chosen. Hall *et al*. (2004) created and applied a feasibility study and development model to produce their own estimates.

Other economic potential criteria, such as site accessibility, load closeness, or transmission proximity, as well as technical possible exclusions of land use or environmental sensitivity, were incorporated in the feasibility study. A development model that didn't call for the construction of a reservoir was used to process sites that met the Hall et al. (2006) feasibility criteria to create electricity potential. The development model predicted that only a modest hydroelectric plant between 1 MW and 30 MW in size would be constructed. They aggregated the aforementioned source point locations to the state level to produce state technological potentials.

Another study on the effectiveness of power generation and future prospects of floating solar systems was conducted in China by Liu *et al*, (2017). The total number of natural lakes in China with a surface area of 1 km^2 or more is 2,865, and their combined surface area is around 78,000 km^2, according to the country's first national water census bulletin of 2013 (Ministry of Water Resources, 2013). Water resources, however, are not evenly distributed throughout the nation, and the amount available is quite small. China has built 46,758 hydroelectric facilities. Unfortunately, due to inadequate water storage, several hydroelectric plants in recent years were unable to operate

at their full potential. In many parts of China, the battle for water resources between electrical production and agricultural output has intensified. As a result, China has found it extremely important and urgent to promote the sustainable development of renewable energy sources while also conserving its water resources. China intends to raise its use of non-fossil fuels to 20% of its total primary energy consumption by 2030, as stated in its Intended Nationally Determined Contribution (INDC) (Yuan, 2017).

The total installed PV plant capacity had increased to 43.18 GW by 2015. The development of PV in China is experiencing huge obstacles with land resource due to the fact that typical terrestrial PV systems require a big area of land surface (approximately $8m^2$ for 1 kW), especially in Southeast China. Installing, PV cells on a floating device on the surface of the water is a new technology of solar electricity generating. In order to evaluate the performance of floating PV cells with conventional terrestrial PV systems, the first study on floating PV cells was carried out by (Zahedi, (2006).

Another study was conducted by (Ayompe and Duffy, 2013) in Cameroon. The researchers concentrated on using datasets of solar radiation acquired from satellites to evaluate the potential energy production of PV systems in Cameroon. In study, the monthly average daily global horizontal solar irradiation from long-term satellite derived data available in solar GIS software was used to evaluate the energy output, capacity factor, and performance ratio of photovoltaic systems in 33 locations spread across ten regions

Another study conducted by Wei *et al.* (2022) in China looked at the estimation of global reservoir evaporation losses using the two new datasets, the Global Reservoir Surface Area Dataset and the Global Reservoir and Dam Database. In trying to address inaccessibility and provide an opportunity to bridge the gap, they used the two datasets to estimate the monthly reservoir evaporation volume of the global 7242 large reservoirs from 1985 to 2016. Around 339.8 km^3 of water is estimated to evaporate from these large reservoirs annually during 1985–2016. The results can benefit the regulation and operation of reservoirs and realize their role in global water conservation and management.

Rural Electrification Authority (REA) program embanked on PV projects of installing solar off-min grid in Mpanta, Samfya District of Luapula Province, Kafue lower hydropower project in

Kafue District of Lusaka Province and Kalulushi solar concentrated power plant (SCP). This is a complex system being made up of mirrors that will concentrate the sun's rays to heat a thermal fluid and turn turbines to produce 200 MW of electricity to provide power to the Copperbelt Province and nearby regions (Takouleu, 2020).

International Energy Agency (2020 looked at how African hydro power plants are more likely to be affected due to global warming effects. Nevertheless, a thorough assessment of technical potential of floating solar system for electricity generation to integrate with the existing hydro system has not been done. Consequently, it is imperative to assess the theoretical, geographical and technical potential of mounting floating solar system on waters among the largest hydro reservoirs in countries like Zambia taking advantages of the existing power infrastructure and local condition of the selected power stations. Much of the shown literature review are similar to the study except that none of them looked at combining solar energy and hydropower considering the substation reserve margins and local condition of the power stations under review.

2.8 Chapter Summary

This chapter presented the literature that highlighted the role the installation of FSPV would play in the energy supply situations of different regions and countries in the World. Various studies done in some countries such as China were reviewed. The literature showed that out of all renewable resources, solar power generation is one of the most rapidly growing sources and should be embraced. It also reviewed works based on previous research conducted on renewable energy and floating solar systems. However, of the few studies done on solar systems in Zambia none of them has ever been conducted on integrating floating solar photovoltaic systems with the existing power system infrastructure of the main energy utility company ZESCO.

CHAPTER THREE

3 RESEARCH METHODOLOGY

3.1 Chapter Introduction

This chapter gives a general summary of the materials, techniques, and methodologies that were employed and had an effect on the study's outcomes.

3.2 Study Areas

For the purpose of evaluating floating solar photovoltaic systems for energy generation in Zambia, the following largest water reservoirs (Kariba North, Kafue Upper Gorge, Mulungushi, and Itezhi-Tezhi) were taken into considerations. Figure 3.1 shows the biggest hydroelectric power plants of Zambia.

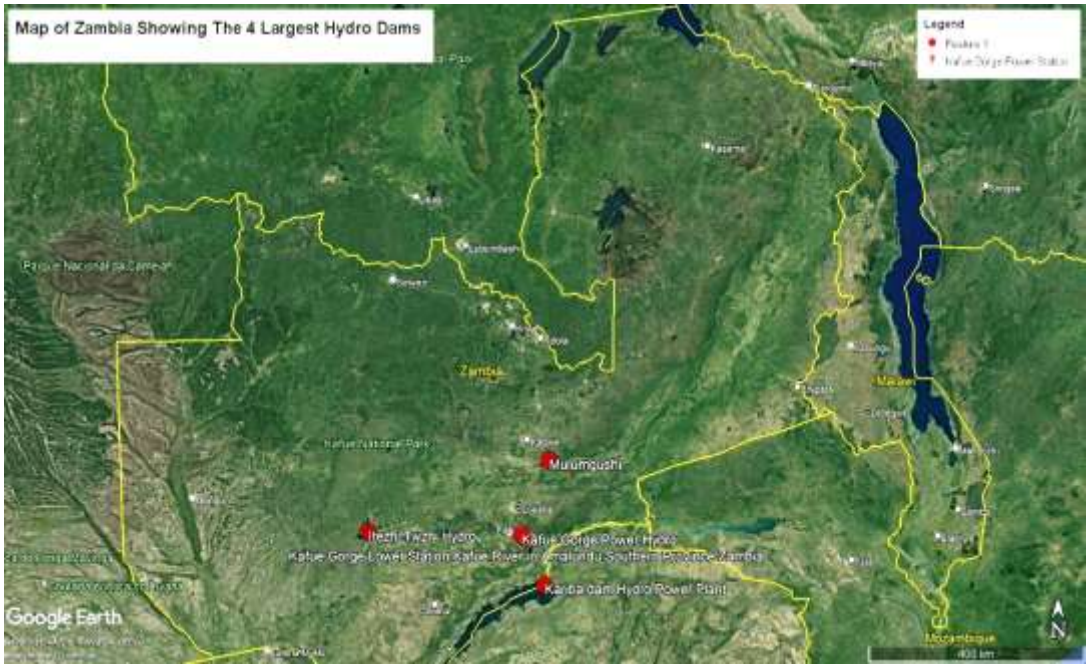


Figure 3.1Map of Zambia showing the 4 largest Hydropower stations

3.2.1 Description and Geographical locations of the study areas

Kariba hydropower plant Kariba hydropower station is located on a man-made lake Kariba in Siavonga district of Southern Province. Its installed power capacity is 1080 MW, and its coordinates are -16.522º latitude and 28.762º longitude east of the Prime Meridian. It is

connected to a water reservoir which has a total surface area of 5580 km^2 and is equally shared by Zambia and Zimbabwe (ZESCO, 2021; ZRA, 2021).

i. Mulungushi Hydropower plant

Mulungushi hydropower station is located at latitude of -14.700 and Longitude of 28.821 in Kabwe city, Central Province of Zambia and has a total surface area of 4963 km^2. Its installed power capacity is 31.3 MW.

ii. Kafue Upper Gorger Hydropower plant

Kafue hydropower station is located at latitude of -15.807 and longitude of 28.421 in Kafue district, Lusaka Province of Zambia and has a total surface area of 805 km^2. Its installed power capacity is 990 MW.

iii. Itezhi-Tezhi Hydropower plant

Itezhi-Tezhi hydropower station is located at latitude of -15.760 and longitude of 26.021 in Itezhi -Tezhi district, Southern Province of Zambia and has the total surface area of 392km^2. Its installed power capacity is 120 MW.

3.3 Study design

The study theoretically assessed the technical potential of combining Hydropower and floating solar photovoltaic system from the four largest hydropower station considering the substation reserve margins for possible solar energy injection into the system during water level variations of any power plants. Furthermore, employed were applied techniques for building power and energy scenarios models based on the power capacity of each power plant (discussed in detail in section 3.8). During the simulation process, Theoretical, Geographic, and technical power and energy models were simulated.

3.4 Simulation flow process

Reservoir data, Power plant, technical data, Meteorological data, and Solar technological data were all part of the data that was gathered for this study. In order to achieve the desired results, the majority of the data was simulated using PVGIS, and reservoir data was used to determine the size of the research sites. Coordinates were used as input parameters for the simulation of all power potentials in order to help ensure that the results were accurate for each study location. geographic, theoretical, and technical. Using coordinates, areas were located using Google Earth. And the surface areas of the four huge (water reservoir) were determined by the

PVGIS software. To create the charts and bar graphs, Excel was utilized. The findings were confirmed in light of what the literature review indicates. The process of data collection and analysis is summarised in the flow chart displayed in Figure 3.1

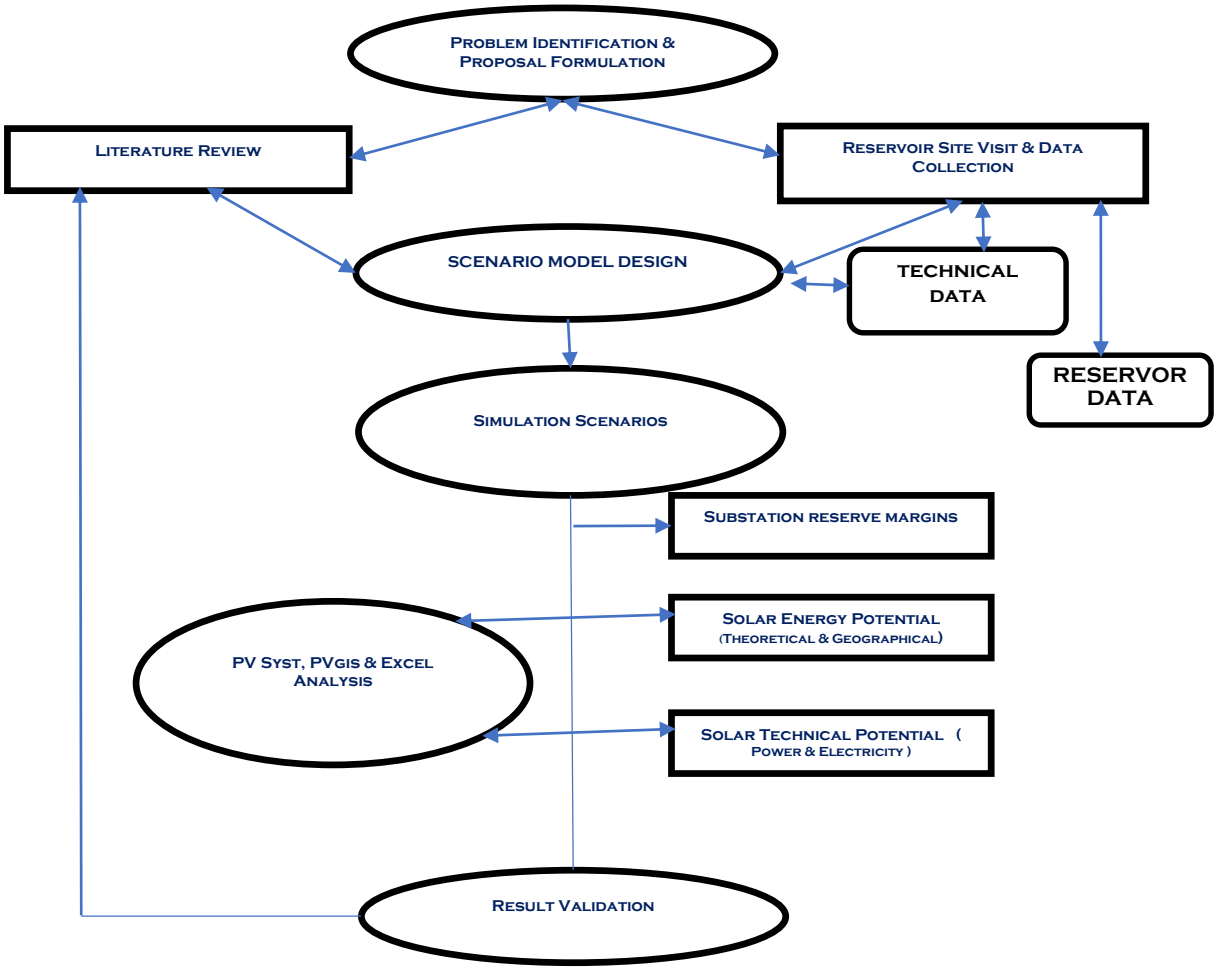


Figure 3.2The research approach adopted for this study

3.5 Data collection

Data collection was essential to the meeting of the study's objectives. It involves both secondary and primary data collection.

3.6 Types of Data Collected

Table 3.1 shows the type of data collected, its description in terms of constituents and its source or sources. As the table shows, the sources of data included the Ministry of Energy in which the Department of Energy and Hydrological Department, where involved, reports and other stakeholders such as the power utility companies.

Table 3.1 Types of data collected from the study sites through interviews

DATA TYPE	DATA DESCRIPTION	SOURCES
Meteorological Data:	Solar Radiation, Ambient Temperature.	NASA data set, PVGIS Meteorological Department of Zambia
Technological Data:	Solar Modules: Types Characteristics (power, area, Efficiency), etc	From ZESCO owned hydro power stations, Itezhi - Tezhi independent power company and Mulungushi Hydro Power station
Hydrological Data:	Reservoirs Surface Areas	Itezhi-Tezhi independent power company, Zambia electricity supply cooperation and Mulungushi power company
	Evaporation levels, etc	Meteorological Department of Zambia ZESCO hydrological department and, Mulungushi Lunsemfwa hydro company
Power Plant Data:	Installed Capacity, Energy Generation Data, Generation Deficit both Power and Energy, Transformer Substation Capacity etc.	From ZESCO owned power stations, Itezhi Tezhi independent power company and Mulungushi Lunsemfwa hydro company

3.7 Generation Resources

The following Hydropower plants and their water reservoirs were considered for implementation of floating solar system for electricity generation. Their total installed generation capacity is 2221.3 MW which is dominated by high inertia hydroelectric power plants.

Table 3.2 shows larger Hydropower plants (Source: ZESCO, ITTPC & MULUNGUSHI ,2021.)

Hydropower Station	Coordinates	type	Units / (MW)	Installed capacity (MW)
Kariba North	-16.522 /28.762	Hydro	6 X 180	1080
Kafue Gorge	-14.700/28.821	Hydro	6 X 165	990
Itezhi-Tezhi	-15.807 /28.421	Hydro	2 X 60	120
Mulungushi	-15.760 /26.021	Hydro	2 X 6.1 1 X 11.5 1 X 7.6	31.3
Total				2221.3

Note: The installed power capacity was used to make sure that the energy contribution wouldn't be more than the power plant could handle. While the essential coordinates were used to collect

the specific reservoir, areas required for the study, the transformer units were used to model the power scenarios and capture the best approach to address the power shortages faced at all times during seasonal variations.

3.8 Data Analysis

This section highlight how data was analyzed in order to achieve the objectives of the study.

3.8.1 Flow of data analyzed

The sub section shows all the steps that were taken to analyze data, the tools used, scenarios developed and all the assumptions made to ensure the effective and logical implementation of the study.

3.8.2 Modeling of Substation's Scenarios

To determine the power deficit the power station experiences whenever there are low water levels, the performance of the power plants during the dry and rainy seasons was evaluated. Three plausible generation situations (scenarios) were identified. The adopted substation scenarios also sought to ascertain the extent to which hydropower stations' ability to produce energy is impaired by the rainy and dry seasons, when water levels rise and fall. This was accomplished in addition to determining how much space is available for solar energy injection into the grid in order to maintain the substation's stability (Substation reserve margins).

3.8.3 Scenario under consideration:

1. Best case scenario
2. Optimal scenario
3. The worst-case scenarios

i. Considerations under Best Case scenario

The best-case scenario represents the hydroelectric plant under consideration in an ideal environment. In this case, it was quite helpful to take into account the power plant's installed power capacity as well as the generators' ratings and efficiency. A significant factor was the quantity of operating generators and their output in terms of electricity generation. Based on

the information from the discussions with the informants from the concerned utilities, some of the variables that were utilized to determine the scenarios are listed in Table 3.3

Table 3.3 Types of data collected from the study sites using interviews

Sn	Parameters	Kafue Gorge Hydro	Kariba Hydro	Mulungushi Hydro	Itezhi-Tezhi Hydro
1	Generator Capacity (MW)	165	180	31.3	60
2	Number of Generators	6	6	1	2
3	Plant Capacity (MW)	990	1080	31.3	120
4	Transformer Capacity (MVA)	135	200	41.9	71
5	Number of Transformers	10	6	1	2
6	Power factor	0.9	0.9	0.9	0.9
7	Substation Capacity (MVA)	1350	1200	41.9	142
8	Substation Capacity (MW)	1215	1080	37.71	127.8

With the given technical data, substation reserve margins were calculated using Equations 3.1, 3.2 and 3.3 as:

$$SS_c = T_c * nT \tag{3.1}$$

Where SS_c is the substation capacity, T_c is the transformer capacity (MVA), nT is the number of transformers in substation?

$$SS_r = ss_{co} - np_n \tag{3.2}$$

Where SS_r is substation reserve margins, ss_{co} is the original substation capacity (MW), np_n is new power plant capacity (MW).

$$SS_C = ss_C * P^f \tag{3.3}$$

Where SS_C is the substation capacity (MW), SS_C is the substation capacity (MVA), P^f is the power factor

Table 3.4 Power generation capacities for the best-case scenario of the four power stations

Hydropower station	Installed plant capacity	Original generator capacity (MW)	Number of generators	Generator capacity (MW) at (B/S)	Number of generators (New)	Substation Reserve margins
KNBS	1080	180	6	150	6	180
KGU	990	165	6	165	6	360
MU	31.3	31.3	1	31.3	1	6.41
IT	120	7.8	2	60	2	7.8
Total reserve						554.21

Note: S/S Substation and MW is megawatt an electrical unit.

TX is Transformer

B/S is best case scenario

Power factor = 0.9

MU = Mulungushi

KNBS = Kariba north bank power station

KGU = Kafue gorge upper

IT = Itezhi - Tezhi

Number of generator (new) show the number of generators working at a particular scenario.

ii. Considerations under optimal case scenario

Table 3.5 show the best-case scenario of the four power stations

Hydropower station	Installed plant capacity	Original generator capacity (MW)	Number of generators	Generator capacity (MW) at (O/S)	Number of generators (New)	Substation Reserve margins
KNBS	1080	180	6	150	5	330
KGU	990	165	6	155	6	420
MU	31.3	31.3	1	N/A	N/A	N/A
IT	120	60	2	55	2	17.8
Total reserve						767.8

Since the power company only functions at full capacity when there is enough water available for power generation and shuts down when there is not enough water, Mulungushi power station was not taken into consideration for the optimal scenario.

iii. Considerations under worst case scenario

Table 3.6 The best-case scenario of the four power stations

Hydropower station	Installed plant capacity	Original generator capacity (MW)	Number of generators	Generator capacity (MW) at (W/S)	Number of generators (New)	Substation Reserve margins (MW)
KNBS	1080	180	6	150	2	780
KGU	990	165	6	147	3	909
MU	31.3	31.3	1	31.3	0	31.3
IT	120	120	2	55	1	72.8
Total reserve						2,074.8

In this scenario, power plants are working at their poorest capacities because of low water levels or more generators are out of use because of faults or maintenance, which results in power outages. Due to large reserve margins that are currently present, it is determined that this is the ideal moment when sufficient solar energy can be injected into the system.

3.8.4 Simulations Tools

i. The PVGIS

PVGIS is a public domain software that is used both by commercial utilities and consultants for simulating the performance of electricity generation plants (off grid and on grid). The software is an online simulation program. The software was employed in this work as a simulation tool because of it is widely used and it does not require one to get a license. Figure 2.3 shows the PVGIS simulation tool opening window.

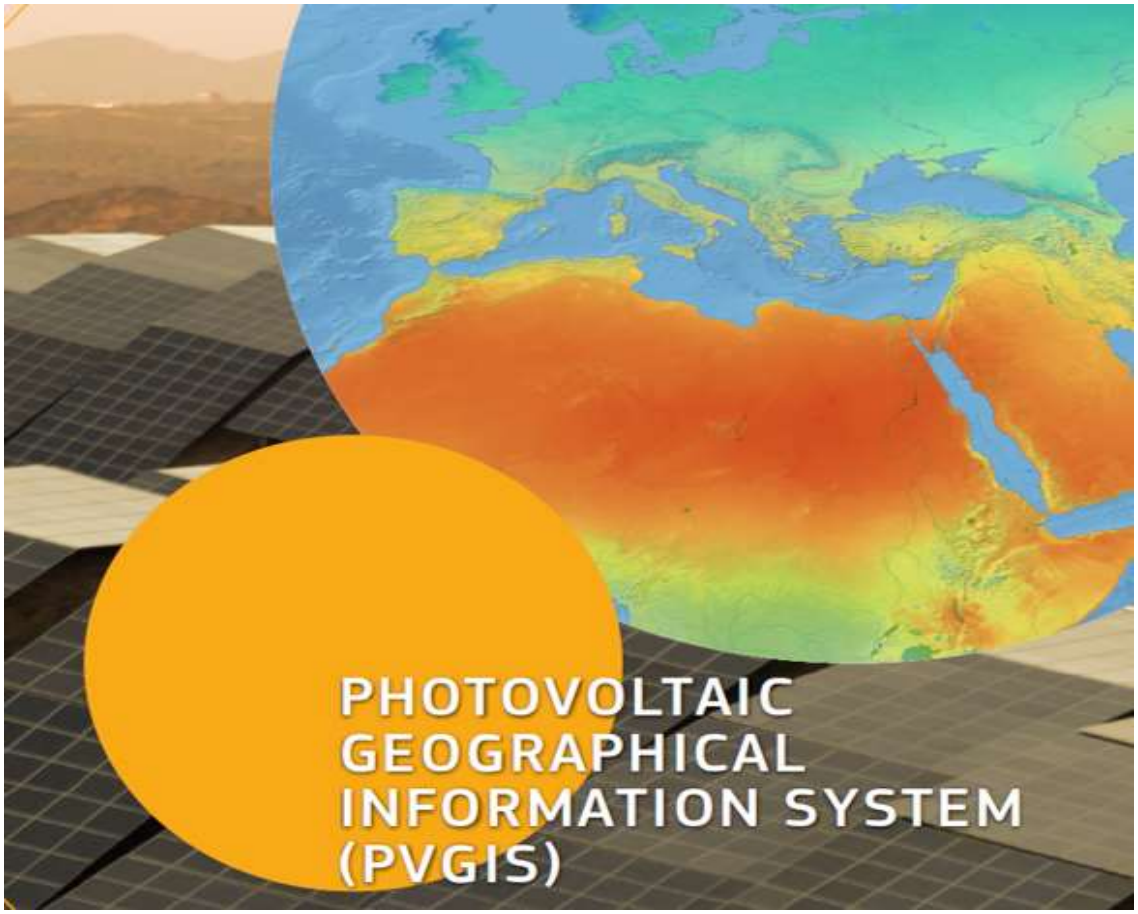


Figure 3.3 PVGIS Online Tool opening window (Joint Research Centre,2022)

PVGIS provides information about solar radiation and photovoltaic (PV) system performance for any location in Europe and Africa, as well as a large part of Asia and America. The default language is English, but French, Italian, Spanish and German are also available.

i. Features of PVGIS

It is a free and open access software used for:

- PV electricity generation potential for different technologies and configurations
- Solar radiation and temperature, as monthly averages or daily profiles
- Full time series of hourly values of both solar radiation and PV performance
- TMY data for nine climatic variables, formatted for building energy calculation tools
- APIs for fast, automated access needs
- Maps of solar resource and PV potential, by country or region, in ready to print files

- PVMAPS, a software suite for users to make customized maps

PVGIS uses high-quality solar radiation data obtained from satellite images, as well as ambient temperature and wind speed from climate reanalysis models. The energy yield model is validated from measurements performed on commercial modules at the JRC's European Solar Test Installation (ESTI). ESTI is an ISO 17025 accredited photovoltaic calibration laboratory for all photovoltaic materials (JRC, 2021).

The PVGIS satellites from which data was downloaded were SARAH and SARAH-2, and the software used was PVGIS 5.1. The tool was used for a variety of purposes, including: Daily solar exposure, grid-connected PV, horizontal profile, monthly solar radiation, daily solar radiation is grid less PV systems, climate-typical year generator and PV tracker system in PVGIS. With these capabilities, the software calculates the effective sunshine hours from the location of the site based on the provided coordinates.

3.8.5 Operational principles of PVGIS Software

PVGIS is a computer aided online engineering tool for the analysis of solar radiation and photovoltaic (PV) system performance. This program can generate the following data: average daily, monthly, and annual values of solar irradiation measured on square meters of horizontal surface or surface tilted under a certain angle in relation to the horizontal surface, change in the optimal tilting angle of the solar modules throughout the year, relationship between global and diffused sun radiation, average daily temperature, and daily, monthly, and annual electricity generated by fixed PV solar plants.

3.8.6 Input and embedded parameters of PVGIS

i. The input parameters of photovoltaic geo information system online tool are;
ii. Geographical coordinate of a location (longitude and latitude)
iii. Assumed solar input power from the scenarios
iv. Solar technology
v. Capacity factor (embedded)
vi. Efficiency of the system and the optimum angle (embedded)

3.8.7 Output of the PVGIS

This engineering program generates a report that includes the average solar energy produced for the specified time period after taking into account the anticipated periods of no sunlight

after acquiring the provided settings. The simulation examines the ideal solar technology's efficiency, system losses, and ideal angle.

3.8.8 Power potentials simulated by PVGIS

The power potentials that were considered for simulation by PVGIS are:

i. Theoretical power potential

ii. Geographical power potential

iii. Technical power potential

The key coordinates of the study locations and the substation reserve margins of each individual power plant were the sole determinants for all power potential simulations.

3.9 Technical characteristics of solar photovoltaic technologies

In order to determine the optimal power generated under various power scenario conditions, the simulation software considered the efficiency of the solar technology in addition to its output. To confirm the solar efficient, the efficiency of the solar technologies (Table 3.7) under consideration was examined.

Table 3.7 PV solar radiation coverage (m^2 /kW) and efficiency

Materials	Area Coverage (m^2/Kw)	Thickness	Efficiency
Monocrystalline silicon solar cells	6.51	0.3mm	15-18%
Cadmium telluride (CdTe) solar cell	7.88	0.008mm+3mm Glass substrate	6-9% (module)
Copper-Indium Di selenide (CIS) solar cell	9.6	0.003mm+3mm glass substrate	7.5- 9.5% (module)

3.10 Total surface areas of the study

The regions designated for the construction of floating solar photovoltaic systems for the generation of power are included in the study's total surface area. Its dimensions are given in millimetres, square meters, or kilometres. The four largest reservoirs' combined surface area is 11146 km^2. The surface areas of the research sites were calculated using secondary sources and Google Maps. The biggest solar panel type, in terms of size, covers a larger surface area on water hence becomes the best solar panel to be installed for water conservation.

3.11 Power potentials considered

Power potentials of the research areas were simulated using PVGIS in order to achieve the required results. The geographic locations of each study site, the type of solar technology employed, and the installed solar power in KW or MW were crucial to the software's input data.

3.11.1 Theoretical Potential

Theoretical solar energy potential involved the assessment of the solar energy that is received on the surface of each of the four (4) large hydropower reservoirs in Zambia. This potential involved identifying the four (4) hydropower reservoirs' boundary and the size of the reservoirs' surface area, including the magnitude of the annual average daily solar radiation received on the site.

$$E_{TH} = A_{ADS} \times H_R \times T_{TSH} \quad (3.1)$$

3.11.2 Geographical Potential

Assessing the solar energy collected on the available and acceptable land area entailed determining the geographic solar energy potential. So, according to literature, the first step in evaluating this potential involves omitting the restricted water intake areas of the power plant, fishing sites, boat cruise locations, surface water body areas, and protected national parks water front. As a result, the remaining water surface area was chosen as the best land for the deployment of floating solar energy technologies (Gomez and Hoogwijk, 2004). Ggeographical solar energy potential was calculated using Equation 3.2 (Mwanza et al. 2017; Choi et al. 2019).

$$E_{G= A_{ADS}\times H_R} \quad (3.2)$$

Where E_G is geographical solar energy potential (TWh/year), A_{ADS} is available suitable area (m^2), and H_R is Total average yearly solar radiation (kWh/m^2-year)

3.11.3 Technical Potential

The process of determining the extractable energy potential from the sun for any surface involves firstly excluding areas not suitable for this technology within the defined hydropower rreservoir boundaries. Then, consideration is given to the estimated geographical potential and technical characteristics of PV generation systems to convert the solar energy to electrical

energy taking into account local conditions. The technical potential was evaluated considering reservoir surface area coverage which was varied between 0.01% and 10% considering three (3) solar PV technologies; Monocrystalline, CIS, and CdTe. Thus, the technical solar energy potential for the existing available suitable rreservoir surface area was estimated using Eequation 3.3 (Mwanza et al., 2017).

$$E_{T\ =P_{PD}} \times CF \times T_{tsh} \times A_{ADS} \quad (3.3)$$

Where E_T is solar electricity generation potential (TWh/year), P_{PD} is reservoir site power density (TW/km^2), CF is site solar PV capacity factor (%) considering the local condition (local air temperature, wind speed, cloud cover, etc), and T_{tsh} is total effective sunshine hours in a year A_{ADS} is hydropower reservoir's available suitable area (km^2) considering reservoir coverage percentage (between 10%, 7.5%. 5% 1%, 0.5% 0.05%, 0.025%, 0.0125% and 0.01%).

Note: The percentage coverages in the case of Kariba were meant to cover the whole reservoir water surface as the idea was to know the power potential that can be generated at that study site if such percentage ranges were to be implemented. How ever on the reservoir surface area for the Zambian side, to get the same energy that can be generated using the earlier percentages, the percentage coverage needs to be doubled in the range of 20%, 15%, 10%, 2%, 1%, 0.1%, 0.05%, 0.025%, and 0.02%.

The technical potential was evaluated considering hhydropower plant power installed and available capacity including generation deficit and the substation installed capacity including substation reserve margin while taking into account the installed and available power plant capacity. According to data collected from the power plants, the substation reserve margin were found to be 360 MW for Kafue Gorge upper, 180 MW for Kariba North bank, 6.67 MW for Mulungushi, and 8 MW for Itezhi-Tezhi at best power plant operation period. However, it was noted that during the dry seasons, several of the generators at the power plants are typically turned off or run at reduced capacity, reducing the amount of available power plant capacity and raising substation reserve margins. Therefore, for optimal case and worst case the substation reserve margin were found to be; Optimal Case (420 MW for Kafue Gorge upper, 331MW for Kariba North bank, and 17.3MW for Itezhi Tezhi) and Worst Case (909 MW for Kafue Gorge upper, 780MW for Kariba North bank, 37.3MW for Mulungushi, and 73.3MW

for Itezhi Tezhi). Thus, for each of the scenarios (best, optimal and Worst cases), the substation reserve margin utilization was varied between 10% and 75% considering three (3) solar PV technologies; Monocrystalline, CIS, and CdTe. Hence, 3 scenarios [best, optimal and worst] were conducted as shown in Table 3.1 with 44 cases in total and 12 per scenario per hydropower plant in three power station and 8 scenario in the other station

Table 3.8 Scenarios the Technical potential

Scenario	Substation Reserve Utilization (%)	KG	KN	MU	IT	Total Capacity (MW)
		(MW)				
Best	10	36	18	1	1	56
	25	90	45	2	2	139
	50	180	90	3	4	277
	75	270	135	5	6	416
Optimal	10	42	33	-	2	77
	25	105	83	-	4	192
	50	210	165	-	9	384
	75	315	248	-	13	576
Worst	10	91	78	4	7	180
	25	227	195	9	18	449
	50	455	390	19	36	900
	75	682	585	28	55	1350

Thus, the technical energy potential for the available rreservoirs surface areas was estimated considering the substation reserve margins during dry and rain season.

3.12 Evaporation Loss Savings

Evaporation from hydropower rreservoir water surface is sensitive to air temperature and can lead to significant amount of water loss. The amount of water lost from the reservoir due to evaporation are influenced mainly by the reservoir water surface area, shape, depth, air temperature, sunshine hours, wind speed, humidity, surrounding topography, vegetation, and its location. The estimation of reservoir water evaporation loss saving is often a critical issue as the hydropower generation demand increases. The estimation of evaporation water loss saving for the four selected largest hydropower reservoirs in Zambia has been estimated

considering the net evaporation loss and the surface area of reservoir to be covered by floating solar PV system.

The evaporation gross loss from a reservoir water surface area due to evaporation was estimated using equation 3.4 (DM, 1993; Tanny et al., 2008)

$$E_{GROSS} = 0.67 * E_{PAN} \quad (3.4)$$

Where E_{GROSS} (mm) is loss from a rreservoir surface area due evaporation, E_{PAN} (mm) is evaporation from a Class A Open pan for the period of interest, and 0.67 is a conversion factor. The net evaporation loss from surface of hydropower reservoir evaluation takes into consideration the amount of water gained from annual rainfall direct onto the rreservoir surface and gross evaporation loss due to evaporation. Thus, the net evaporation loss was estimated using equation 3.5 (DM,1993; Tanny et al., 2008).

$$E_{NET} = E_{GROSS} * R_{RAINFALL} \quad (3.5)$$

Where E_{net} (mm) is the net losses from the surface of hydropower reservoir and R(mm) is annual rainfall over the period of interest.

The total evaporation saving from the reservoir was calculated by multiplying the surface area covered by floating solar PV system in kilometer square and the net evaporation loss. Equation (3.6) (DM, 1993; Tanny et al., 2008).

$$E_{Reservoir\ (km^3)} = \left(\frac{E_{Net} \times A_{Top}}{1000000}\right) \quad (3.6)$$

Where $E_{Reservoir}$ (km^3) is the total evaporation saving from the reservoir due to evaporation and A_{Top} (km^2) is the total surface of the reservoir covered by floating solar PV system

3.13 Assumptions and data considered during data analysis

a) Selection of the four large hydropower reservoirs was aimed at getting study site that have got big power station and would give enough substation reserve margins to allow huge power to be injected into the system in order to solve energy problems faced by the country whenever water levels go down

b) While analyzing the theoretical power potentials of the four study areas, theoretical power was defined as the actual energy received at a particular place. The computation took into account the reservoirs' total surface areas as well as the locations' solar radiation. During this process of calculating theoretical power potentials. It was taken into account that lake Kariba is a shared lake between two countries Zambia and Zimbabwe (ZRA,2021). The results of this area represent the total theoretical potential of the two countries which is supposed to be divided by two. The rest of the results remain the same as the study areas are not shared with any country.

c) Analysis of Geographical potential involved generational of power according to water reservoir utilization in terms of percentage coverage and the input to PVGIS software were: critical coordinates values of the study sites, substation reserve margins in MW. In the case of Kariba reservoir, substation reserve margins used were for the Zambian hydropower station (KNB power station) excluding the Zimbabwean part of the reservoir. The use of substation reserve margin of the Zambian power station automatically shows that the results for geographical potential are of the Zambian water reservoir as can be seen from the aerial map (Figure 3.4).

Figure 3.4 Map of Kariba power station

Total surface area of lake Kariba is 5580 km^2 and its half is 2790 km^2 which is for the Zambia side. The reservoirs utilisation is ranging from (0.01%, 0.0125%, 0.025%, 0.05%, 0.500%,

1.0%, 2.5%, 5.0%, 7.5% and 10%) and was selected according to what literature guides. (Clifton and Boruff,2010). Though 10% of Kariba water is 558 km^2 it was not used in the calculations as according to literature (Hoogwijk, 2004; Gómez et al., 2010; Yan et al., 2013; MWANZA et al., 2017) unsuitable areas for geographical power are removed automatically by the PVGIS. This means that generating at that percentage is still within the shared surface areas of Zambia. Simulation was done by PVGIS where there is only solar power input, critical coordinates, the type of solar technology used. With that in mind the software took account of social activities like, environmental aspects and economical usage. The water resort areas, boat cruising, fishing, accesses to national parks, water frontage for domestic use, highly restricted areas including hydropower plant water intake areas were also not disturbed (Clifton and Boruff, 2010).

When calculating power potentials of Mulungushi hydropower station, consideration was taken into account that small generating units were summed to make one transformer. Technical potential of this area was calculated using this assumption but the results were not affected to alter the intended purpose. Similarly, the total surface area of the study site covered the entire water reservoir from its beginning through up to the reservoir wall of Mulungushi hydropower station. Covering the entire reservoir was necessitated by the fact that along this water reservoir, there are some small doted power companies that generate electricity and these are the ones that have been summed to come up with one transformer size of 31.3 MW (Mulungushi-Lunsemfwa hydropower company, 2021). With this in mind, all calculations that required transformer capacity and reserve margins used this value as its input data. The Google Map aerial view of the Mulungushi water reservoir is shown in Figure 3.5.

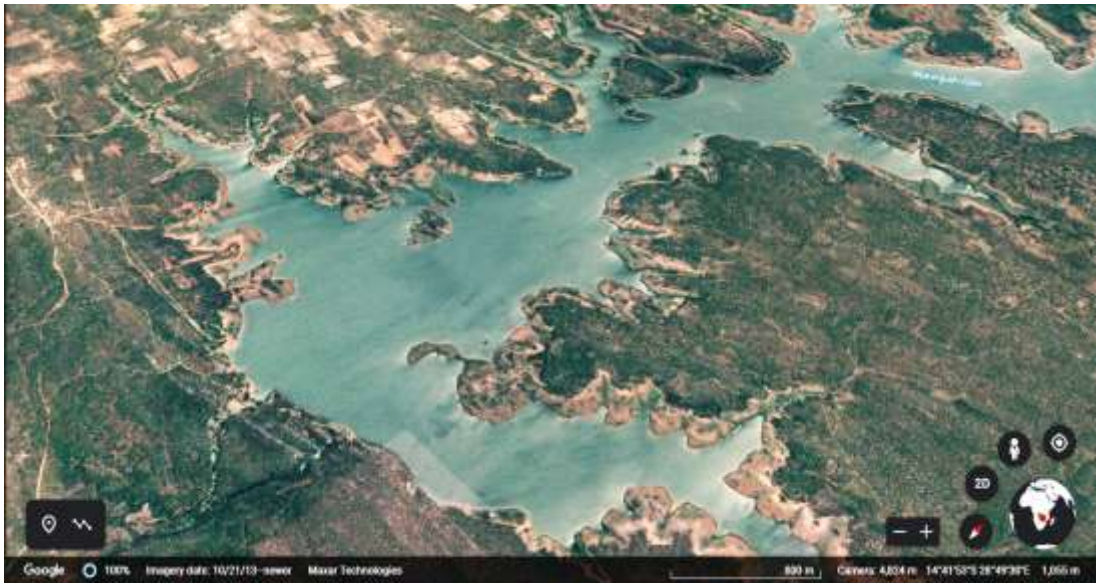


Figure 3.5 Map of Mulungushi power station

i) PVGIS was used to simulate energy generation in power stations, and power generated was determined by solar technology performance because the software takes care of solar technology efficiency and capacity factor. Although PVGIS only provides extracted electricity for the area under consideration, none-sun hours are also taken into account.

ii) Under geographical potential calculation, all panels were assumed to be 310W each with a total surface area of $2m^2$. The power capacities for the three types of solar panels used in the study are shown in Table 3.8.

Table 3.8 Three solar technological power capacity

Solar panels types	Power capacity (m^2/kW)
Crystalline Panel	6.51
CIS Panel	7.88
CdTe Panel	9.6

3.14 Description of terms used

Power deficit - it is the gap between electricity required and supplied.

Dry season - This is a period between June and November before the onset of serious rains.

Power scenario installation - This means the installed solar power during all the three developed scenarios. Best case, optimal case and worst case.

Energy scenario – This means the energy generation situation during the three scenarios.

Utilization -This refers to the area that has been covered by solar panels on water surfaces where they have been installed.

Utilization factor - This refers to the coverage of water by different technology in relation to the total surface area of each study site.

Substation – This is the area of the power infrastructure where high voltage switches from the generator power house are made. The typical view of a substation is shown in Figure 3.6. Its main parts are transformers, which are devices used to change power into high or low voltages. The power capacity is mostly determined by the generator section's size. It is safe to load it up to 75% and yet leave room for it to function regularly because it charges continuously. In order to prevent voltage increases while it is in use, it has maximum limitations (Wang et al., 2013). In light of this, the scenarios show that the amounts of solar energy fed into the system will range between 10%, 25%, 50%, and 75%.

Figure 3.6 The typical set up of a substation (ShuterStock,2022)

3.15 Chapter Summary

The chapter presented major aspects of the research execution. These are approaches to the collection of both secondary and primary data. Secondary data was collected from the reports

published by the Meteorological department and the depart of Energy in the Ministry of Energy. The data was also collected from the utility companies' publications. Primary data was gathered through interviews with the utility companies, Google Earth and through the PVGIS software. PVGIS was also the major data analysis software. Its major features are that it only requires the location of the power station (using coordinates) and solar panel type. From the location information, the software determines the total effective sunshine hours, the area that is available for PV installation and the geographical and technical generation potential. The chapter also highlighted the assumptions that were made for the logical implementation of data analysis. The study's findings will be presented and discussed in the next chapter. Also, it will describe how the findings were reached after drawing inferences and making suggestions in light of the findings

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter provides an overview of the results and findings of the study categorised as follows: sites and areas, substation reserve margins, reservoir data, technical information of the hydropower stations, (Theoretical, Geographical and Technical power/ energy) potentials of the four largest water reservoirs using the three solar technologies Crystalline, CIS and CdTe).

The chapter shows how the total installed power capacity, energy production capacity, and energy generation deficit during the dry seasons were investigated from (Kariba North, Kafue Gorge, Itezhi-Tezhi, and Mulungushi Power Plants). The chapter also shows how the three power potentials were calculated and simulated in order to get the required results (Theoretical, Geographical and Technical power potentials). In order to assess properly, reservoir data, surface areas of the reservoirs, average solar radiation around the study site and operational power scenarios were of great importance. Besides area and site, reservoirs data and hydropower technical information, all power potentials were simulated in order to get the installed solar power (MW) and generated solar energy both in (GWh and TWh). The findings from the assessment of technical potential of floating solar photovoltaic systems for electricity generation in Zambia are outlined as follows:

4.2 Existing largest reservoirs, locations and their surface areas

This study covered four major hydro reservoir of Zambia which includes; lake Kariba, Kafue upper gorge, Mulungushi and Itezhi-Tezhi hydro water reservoirs with a total surface area of 11146 km^2. Critical coordinates of the reservoirs were used to locate the areas once entered in PVGIS. The software then, brought out local weather conditions, PV characteristics, energy generation and system losses of the solar plant. Figure 4.1 shows the main locations of the largest hydropower plants of Zambia.

Figure 4.1 The Locations of study areas in Zambia

4.3 Solar PV pattern of the four study areas of Zambia

Figure 4.2 shows different solar radiations of the four study areas. As can been from the figure, there are different solar radiations that are seen though almost in the same range. Latitudinal locations have an influence on these different patterns of annual solar radiation because of differences in exposure to the sun rays. According to the figure, all the selected sites have their highest solar radiation in October the dry period as expected but mainly because of the geographical locations of the country that gives it enough access to direct sun rays of the tropics.

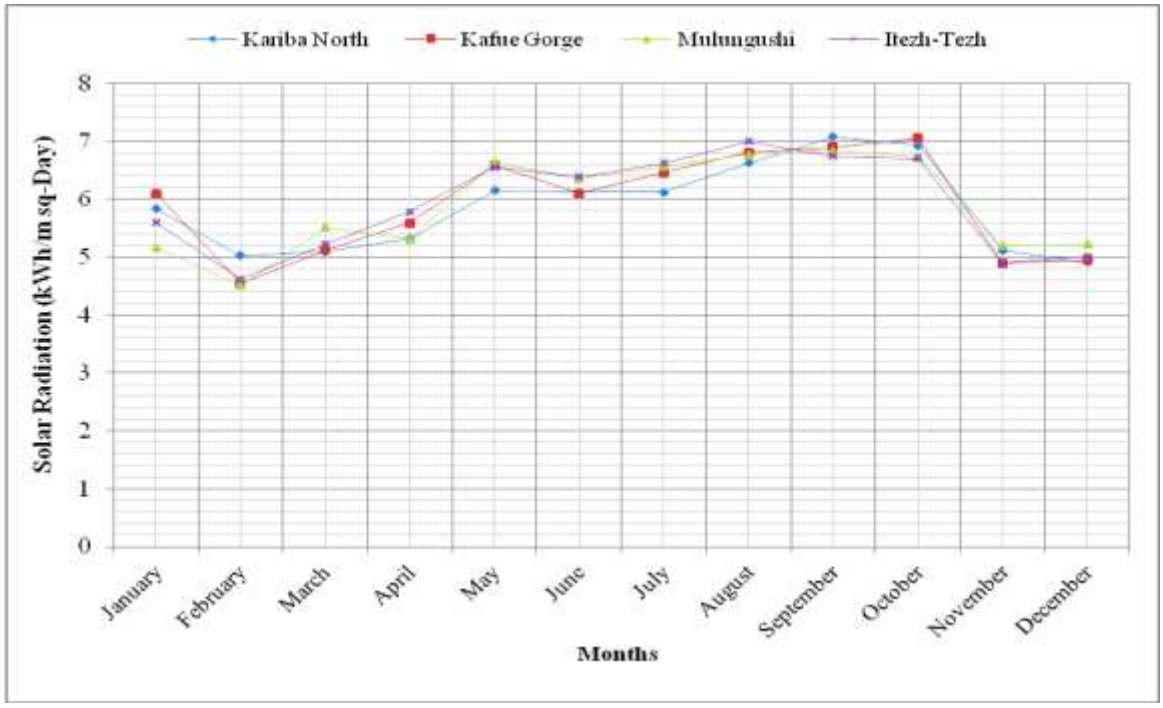


Figure 4.2 Monthly Average Solar Radiation Variation for the Hydropower Reservoirs Sites

Figure 4.2 gave rise to the assessment of theoretical, geographical and technical potential of floating solar PV system for electricity generation.

4.4 Theoretical potential of the four study areas

The actual solar energy received at a particular area from the four selected study areas was calculated using the PVGIS with an embedded formular (3.1). The software was used to calculate theoretical energy, and the capacity factor took care of the number of productive sunshine hours in a year.

4.4.1 Kariba reservoir's theoretical potential

Following the simulations of theoretical potential of lake Kariba, it is seen that generation of power in the months of November and December went down due poor solar radiation. Figures 4.3, shows annual solar radiation of the lake where in November and December solar energy installation was low. This is also reflected in Table 7.1 of Appendix 2. Figure 4.4 shows solar energy generation. The figure shows that September and October recorded the highest theoretical potential which is in line with (Rothhardt *et al.*, 2014) where the correct periods are stated when you get good solar radiation enough to generate electricity. Moreover, the figure

shows that in January there was a record of good energy generation contrary to normal trends as it is a month in Zambia where there is a lot of rain an obstacle to good solar radiation. From the figures given, it is also seen that the further you drift away from the equator going southwards, the less solar intensity you get hence affecting solar energy generation. Failure to get consistence in solar radiation is as a result of latitudinal extent and global warming where solar intensity varies seasonally (Château *et al.*, 2019).

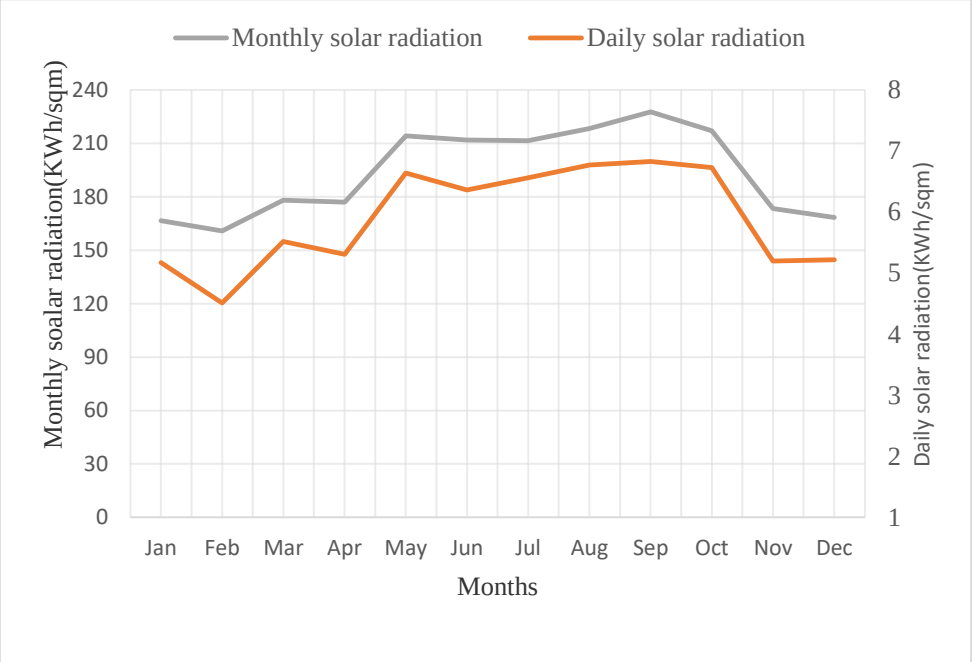


Figure 4.3 Solar energy kWh/m^2 at optimum angle 22^0 of Kariba Reservoir

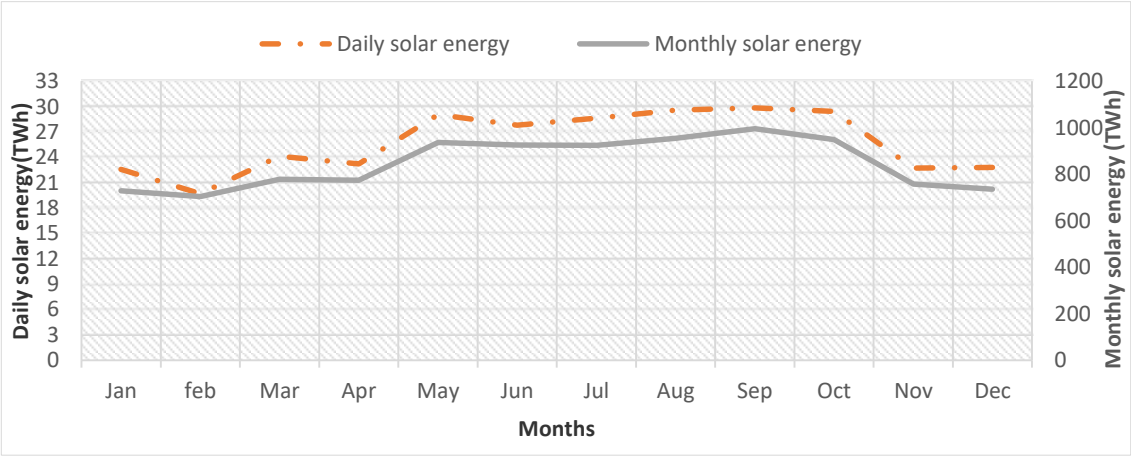


Figure 4.4 Solar energy in (TWh) at optimum angle 22^0 of Kariba Reservoir

4.4.2 Mulungushi Hydro reservoir's theoretical potential

Results of this study area are presented in Figures 4.5 and 4.6 where average daily solar energy installation and generation were in the range of 25.78 GWh and 10159.62 (TWh). Findings of this study show that the bigger the surface area of the water reservoir, the more solar energy can be generated. It has also been observed that solar energy that can be generated is much bigger than the capacity of the hydro power station which is 31.3 MW. This is also seen from Table 7.2 of Appendix 2 where the solar radiation and electricity generation are being shown on daily and monthly basis. The results also show that the month of February has the lowest solar radiation and electricity generation while October has the highest generation as can be seen from Figure 4.5

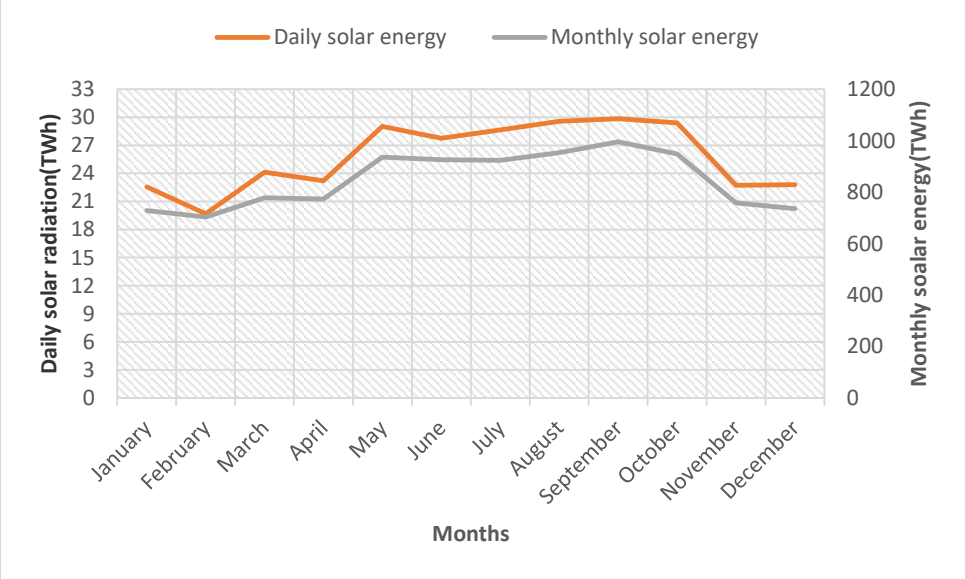


Figure 4.5 Solar energy at optimum angle 15^0 of Mulungushi Reservoir

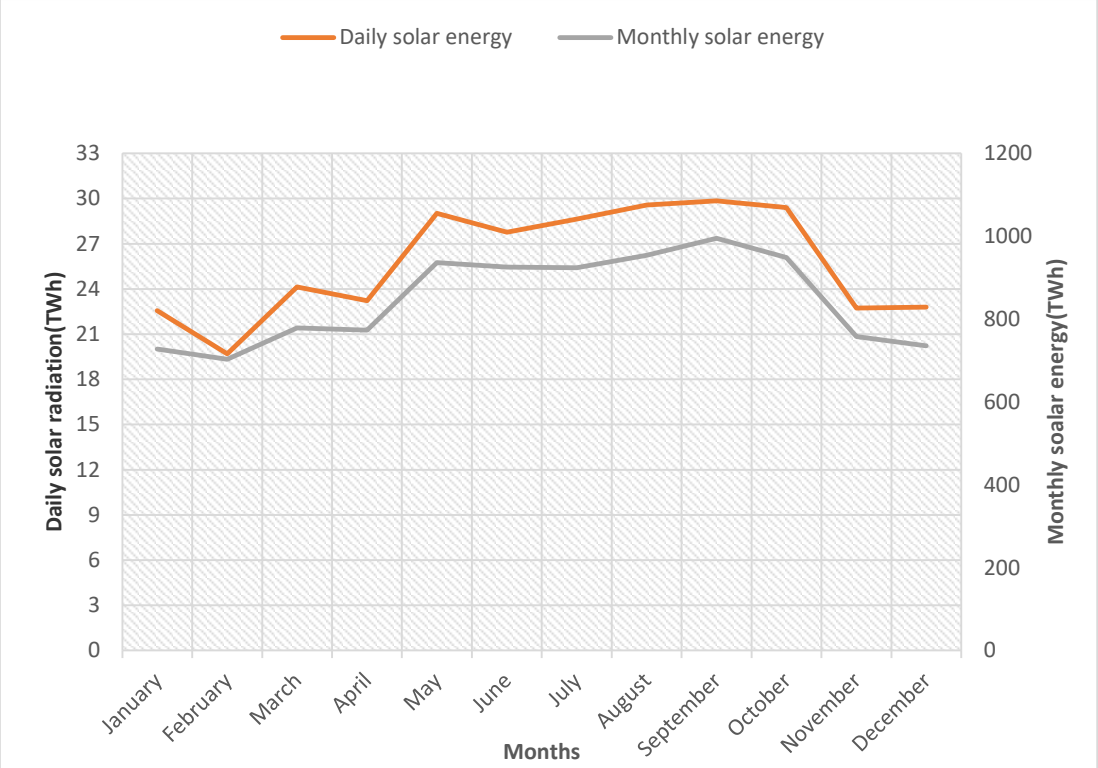


Figure 4.6 Solar energy at optimum angle 15º of Mulungushi

4.4.3 Kafue upper gorge Hydro reservoir's theoretical Potential

Analyzed and simulated results of this study site showed that the month of February recorded very low solar radiation as compared to the month of October which recorded the highest. The general results remain enough for electricity generation. These results are influenced by the reginal climate of having rainfall in the first quarter of the year and enough sun light during the dry season. Climatically, the month of October has good sun light that is good for electricity generation through solar. From the results of the study, electricity can be generated from this area following results shown in Figures 4.7 and 4.8 and Table 7.3 in Appendix 2.

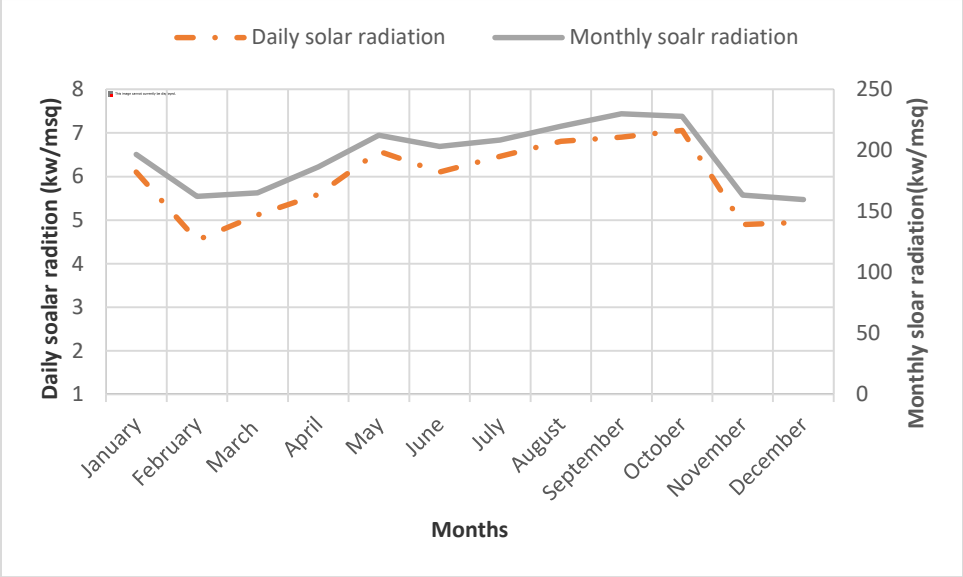


Figure 4.7 Solar radiation kWh/m^2 at optimum angle 22º of Kafue Upper Reservoir

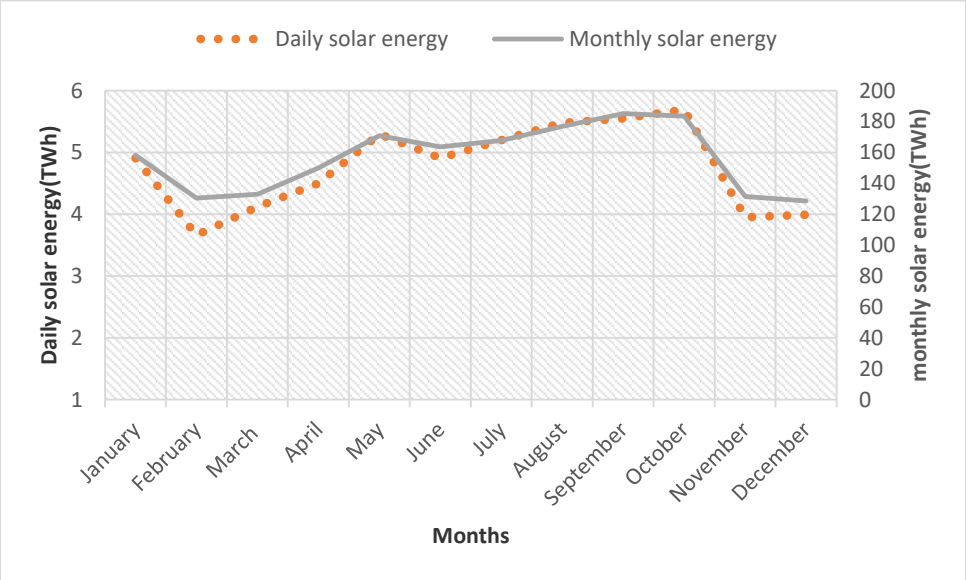


Figure 4.8 Solar energy at optimum angle 22º of Kafue Reservoir

4.4.4 Itezhi-Tezhi hydro reservoir's theoretical Solar potential

Theoretical potential of this study area shows that electricity can be generated as can be seen from Figures 4.9 and 4.10 and Table 7.4 in Appendix 2. The patten of monthly and annual solar radiation per meter squared is the same as that of the Kafue study area. The solar distribution is similar in these two areas and both have the same climatic patten; rain, winter and dry season with same characteristics as shown from Figures 4.9 and Figure 4.10. Equally, February

recorded the lowest solar energy generation potential while October recorded the highest. The results of this area reasons reflect its being closer to the equator thereby having good access to enough sunshine of the tropics. This theoretical energy potential information is tabulated in Table 7.4 in Appendix 2.

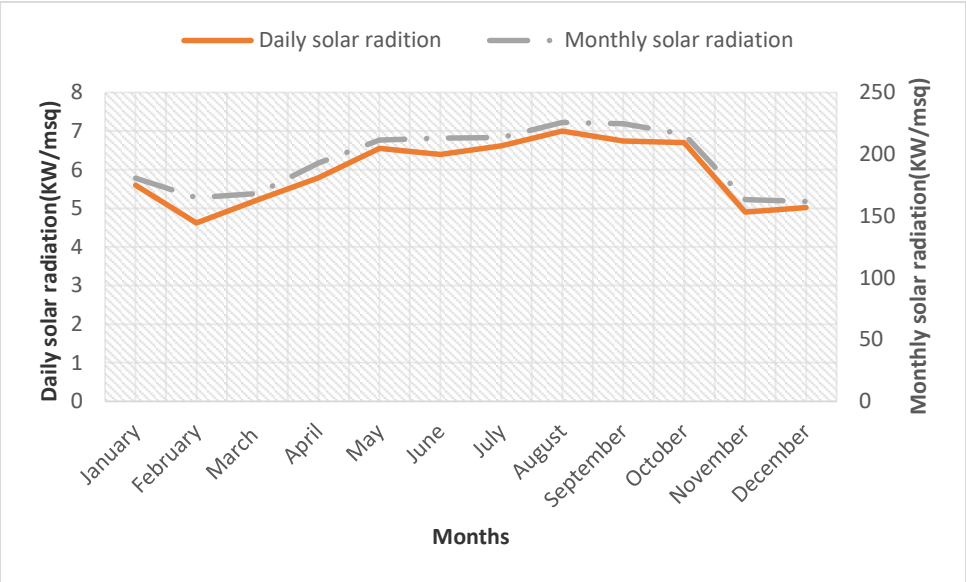


Figure 4.9 Solar energy kWh/m^2 at optimum angle 15º of Itezhi-Tezhi reservoir

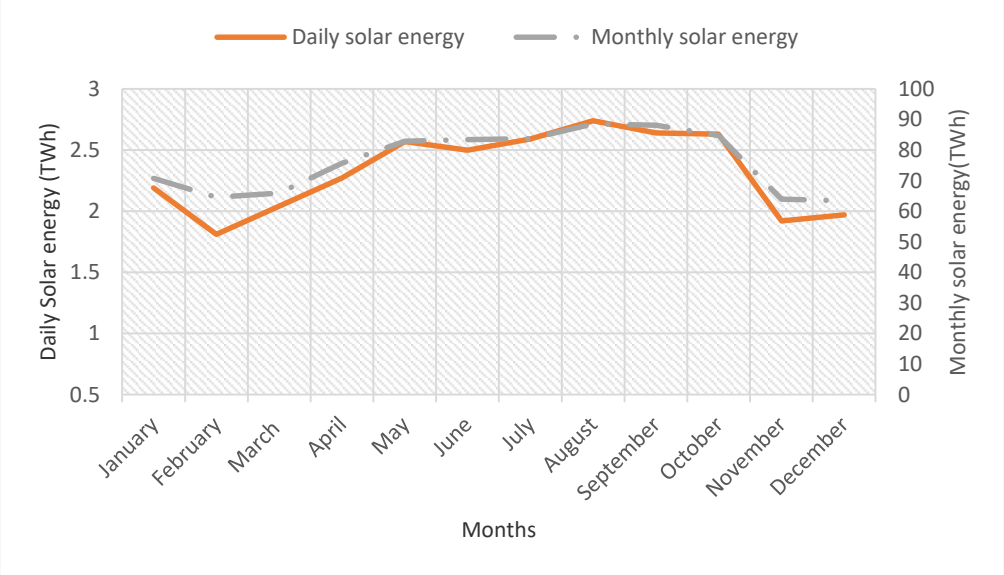


Figure 4.10 Solar energy at optimum angle 15º of Itezhi- Tezhi reservoir

4.4.5 Summary of all the theoretical potential results of the study areas

In Zambia, particularly in the rural areas where large and suitable land areas for solar PV farms implementation are available, it is difficult and costly to implement on-grid solar due to distances to grid. If the grid exists, the capacity is usually not permissible to take huge solar farms due to stability issues. However, on-grid FSPV systems more ideal due to availability of larger hydropower rreservoir's (11,146 km^2) with existing grid infrastructures capable of integrating larger solar PV farms. The results of the study show that annual theoretical potential of all the study areas is 25,611TWh as shown in Table 4.1 . Kariba reservoir receives 12,655TWh annually with a total surface area of (5580 km^2), followed by Mulungushi with 10,160TWh with a total surface area of (4963 km^2). these results also show that Mulungushi reservoir has got a big theoretical potential despite it having the smallest installed hydropower station with only 31.3MW. Kafue Gorge and Itezhi Tezhi have an annual theoretical potential of 1,880TWh and 916TWh with 805 km^2 and 392 km^2 surface areas respectively. Due to available larger rreservoir's surface areas, Kariba North and Mulungushi reservoir have a high theoretical potential as highlighted in Table 4.1.

Table 4.1 Theoretical Potential for four (4) Larger Hydropower Reservoirs in Zambia

Month	*Theoretical Solar Energy Potential (TWh/Year)*				*Total Solar Energy (TWh)*
	Kariba North	Kafue Gorge	Mulungushi	Itezhi-Tezhi	
January	1049	158	728	71	2006
February	905	131	703	65	1804
March	916	133	778	66	1893
April	958	150	774	76	1958
May	1106	171	936	83	2296
June	1102	164	926	83	2275
July	1102	168	924	84	2278
August	1190	177	954	89	2410
September	1274	185	995	88	2542
October	1247	183	949	85	2464
November	920	132	758	64	1874
December	884	129	736	63	1812
Total	12,655	1,880	10,160	916	25,611

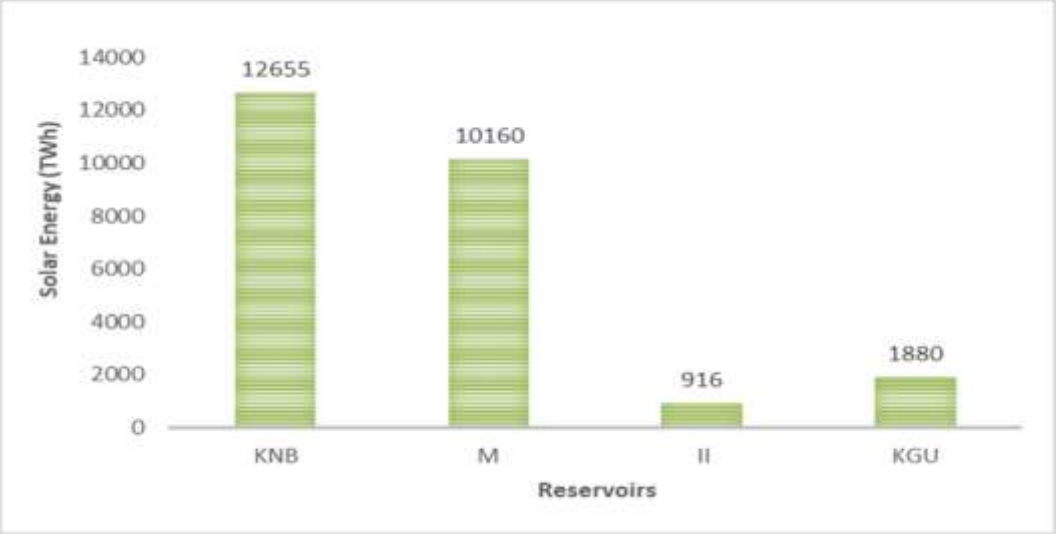


Figure 4.11 Summarized theoretical potential of the four large hydro reservoirs in Zambia.

4.5 Geographical Potential of the four study areas

Geographical solar energy potential involved assessing the solar energy that is received on the available and suitable area. Thus, the process of assessing this potential involved firstly excluding the restricted water intake areas of the power station, fishing areas, boat cruise areas and protected national parks water front according to the literatures. Therefore, the remaining water surface area was taken as the most suitable land area for floating solar energy technologies deployment according to Hoogwijk (2004) and Gómez *et al.(2010).* The geographical solar energy potential can be estimated using equation (3.2)

The geographical solar energy potential was evaluated considering percentage of the reservoirs surface area coverage which was varied as 0.01%, 0.0125%, 0.025%, 0.05% ,0.5%, 1.0%, 2.55, 5.0%, 7.5%, 10%. These values were adopted from a study that looked at the simulation of geographical potential using coverage percentages to know how much can be obtained if the surface areas were covered to the extent of any of these percentages (Clifton and Boruff, 2010). As these percentages are implemented, sensitive and economical areas are excluded by the PVGIS software while capacity factor takes into account of none sunshine hours.

4.6 Geographical Potential of Kariba Reservoir

Geographical potential of the Kariba reservoir was simulated and analyzed and the results are as shown in Table 4.2. From the table, it can be seen that the energy generation increased as reservoir utilization increased whereby at 0.01 % of the reservoir utilization, the total surface area covered was 0.56 km^2 with a total energy generation of 1.19TWh. At 1% of the reservoir utilization, the total surface area covered was 56 km^2 with a total energy generation of

119.35TWh. At 10% of reservoir utilization, the total surface area coverage of the reservoir was 558 km^2 with a total energy generation of 1193.51TWh. The findings of this study shows that the more you cover the reservoir the more you generate energy.

Table 4.2 Geographical Energy Potential of Kariba Hydro Reservoir

Scenario	Reservoir Surface Area (Km2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar Energy Generation (TWh)
1	5580	0.010	0.56	1.19
2	5580	0.0125	0.70	1.49
3	5580	0.025	1.40	2.98
4	5580	0.050	3	5.97
5	5580	0.500	28	59.68
6	5580	1.0	56	119.35
7	5580	2.5	140	298.38
8	5580	5.0	279	596.75
9	5580	7.5	419	895.13
10	5580	10	558	1193.51

4.6.1 Geographical potential of Mulungushi Hydro Reservoir

Geographical potential of the Mulungushi Reservoir was simulated and analyzed and the results are as shown in Table 4.3. According to the results in the table, energy generation increased as the reservoir utilization increased. At 0.01 % of the reservoir utilization, the total surface area covered was 0.44 km^2 while energy generation was 0.94TWh. At 1% of the reservoir utilization, the total surface area covered was 43.69 km^2 and energy generation 94.09TWh. At 10% of total surface area coverage, the surface area of the reservoir covered was 436.68km^2 and energy generation 940.86TWh. Findings of this study show that any increase to the coverage area of the reservoir, increases energy generation.

Table 4.3 Geographical Energy Potential of Mulungushi Hydro Reservoir

Scenario	Reservoir Surface Area (Km^2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar Energy Generation (TWh)
1	4369	0.010	0.44	0.94
2	4369	0.0125	0.55	1.18
3	4369	0.025	1.09	2.35
4	4369	0.050	2.18	4.70
5	4369	0.500	21.85	47.04
6	4369	1.0	43.69	94.09
7	4369	2.5	109.23	235.22
8	4369	5.0	218.45	470.43
9	4369	7.5	327.68	705.65
10	4369	10	436.90	940.86

4.6.2 Geographical potential of Kafue Upper Gorge Hydro Reservoir

Geographical potential of the Kafue Upper Gorge reservoir was simulated and analyzed and the results are as shown in Table 4.4. According to the results, energy generation increased as the reservoir utilization increased. At 0.01% of the reservoir utilization, the total surface area covered was 0.08 km^2 and energy generation was 0.17T Wh. At 1%, total surface covered was 805 km^2 while energy generation was 17.42TWh. At 10% of reservoir utilization, total surface area covered was 80.50 km^2 while total energy generation was 174.24TWh. The findings for this study area show that the increase in surface area coverage increases energy generation.

Table 4.4 Geographical Energy Ppotential of Kafue Upper Gorge Hydro Reservoir

Scenario	Reservoir Surface Area (Km^2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar Energy Generation (TWh)
1	805	0.010	0.08	0.17
2	805	0.0125	0.10	0.22
3	805	0.025	0.20	0.44
4	805	0.05	0.40	0.87
5	805	0.50	4.02	8.71
6	805	1.0	8.05	17.42
7	805	2.5	20.13	43.56
8	805	5.0	40.25	87.12
9	805	7.5	60.38	130.68
10	805	10	80.50	174.24

4.6.3 Geographical potential of Itezhi –Tezhi's Reservoir

Geographical potential of Itezhi–Tezhi reservoir was simulated and analyzed and the results are as shown in Table 4.5. According to the results, energy generation increased as the reservoir utilization increased. At 0.01 %, the total surface area covered was 0.04 km^2 and the energy generated was 0.1TWh. At 1% of the reservoir utilization, the total surface area covered was 4km^2 and the energy generation was 8.5TWh. At 10% of the reservoir utilization, the total surface area covered was 39 km^2 with a total energy generation of 84.8TWh. The findings of this study area were that any increase to area of the reservoir, increases energy generation.

Table 4.5 Geographical Energy Potential of Itezhi-Tezhi Hydro Reservoir

Scenario	Reservoir Surface Area (Km^2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar Energy Generation (TWh)
1	392	0.010	0.04	0.1
2	392	0.0125	0.05	0.1
3	392	0.025	0.10	0.2
4	392	0.050	0.20	0.4
5	392	0.500	2	4.2
6	392	1.0	4	8.5
7	392	2.5	10	21.2
8	392	5.0	20	42.4
9	392	7.5	29	63.6
10	392	10	39	84.8

Table 4.6 shows total geographical solar power potential considering the total rreservoir surface area coverage between 0.01% and 10%. It can be seen that Zambia has annual solar energy geographical potential between 2.4TWh and 2393.5TWh based on the selected reservoirs. This available solar energy is enough for conversion to electricity using FSPV systems. Furthermore, it should be noted that only 0.20% of the largest hydro rreservoir surface area is required to implement all the eight (8) solar PV projects current underway (1122MW). It is worth noting that the implementation of the FSPV will result in annual evaporation water loss saving amounting to $0.0101km^3$ (10.1million m^3) representing 3.74% of the total water supply consumption and 4.8% of total water used for irrigation for 2010 of Zambia (UN-Water,2012). Additionally, utilization of 0.5% of the total rreservoir's surface areas would result in 119.7TWh of annual solar energy geographical potential. This potential translates to annual water saving from evaporation loss of approximately 0.0253 km^3 (25.3 million m^3) (Table 4.6).

Table 4.6 The Geographical Potential of the four water reservoirs

Reservoir Coverage (%)	*Annual Solar Energy Geographical Potential (TWh)*				*Total Solar Energy (TWh)*	*Reservoirs Area Covered (km^2)*
	KNBS	MU	KG	IT		
0.01	1.19	0.94	0.17	0.1	2.4	1.1
0.0125	1.49	1.18	0.22	0.1	3.0	1.4
0.025	2.98	2.35	0.44	0.2	6.0	2.8
0.05	5.97	4.70	0.87	0.4	12.0	5.6
0.5	59.68	47.04	8.71	4.2	119.7	55.7
1.0	119.35	94.09	17.42	8.5	239.3	111.5
2.5	298.38	235.22	43.56	21.2	598.4	278.7
5.0	596.75	470.43	87.12	42.4	1196.7	557.3
7.5	895.13	705.65	130.68	63.6	1795.1	836.0
10	1193.51	940.86	174.24	84.8	2393.5	1114.6

Table 4.7 illustrates the reservoir surface area coverage and evaporation loss saving for the selected hydropower reservoirs. From the table it can be observed that the annual evaporation saving and therefore water savings increases with increase in reservoir coverage. The amount of water loss from the hydropower reservoirs can be significant. It is proportional to the total amount of water stored in the reservoirs and the reservoir's' surface areas. Thus, reducing the total reservoir water surface area exposure to daily air temperature through integration of FSPV system on the surface of these reservoirs can significantly reduce the evaporation losses and help increase hydropower generation potential. As seen from the findings, if 10% of the total surface area of the reservoir's is covered by FSPV systems not only can enough solar energy (2393.5TWh/year) be captured for conversion into electricity but a total of 505.9 million m^3 per year of water can be saved too. This is 1.04 times more than the 2010 water used for both irrigation and water supply for consumption in Zambia. (UN water, 2010).

Table 4.7 Hydropower Reservoirs Annual Water Loss Saving

Reservoir Coverage (%)	Annual Evaporation Loss Saving (km^3)				Total Water Saving (km^3)	Reservoirs Area Covered (km^2)
	KNBS	MU	KG	IT		
0.01	0.0004	0.0001	0.00004	1.94E-5	0.0005	1.1
0.0125	0.0004	0.0001	0.00005	2.43E-5	0.0006	1.4
0.025	0.0009	0.0002	0.00011	4.85E-5	0.0013	2.8
0.05	0.0018	0.0004	0.00021	9.71E-5	0.0025	5.6
0.5	0.0179	0.0043	0.00214	0.0010	0.0253	55.7
1.0	0.0357	0.0086	0.00429	0.0019	0.0506	111.5
2.5	0.0893	0.0216	0.01072	0.0049	0.1265	278.7
5.0	0.1786	0.0432	0.02145	0.0097	0.2529	557.3
7.5	0.2678	0.0648	0.03217	0.0146	0.3794	836.0
10	0.3571	0.0864	0.04289	0.0194	0.5059	1114.6

Figure 4.7 shows that KNB had the highest annual evaporation loss savings compared to the other three major reservoirs at 10% reservoir coverage. This was followed by MU reservoir. The individual reservoir energy geographical potentials are given in Appendix 3.

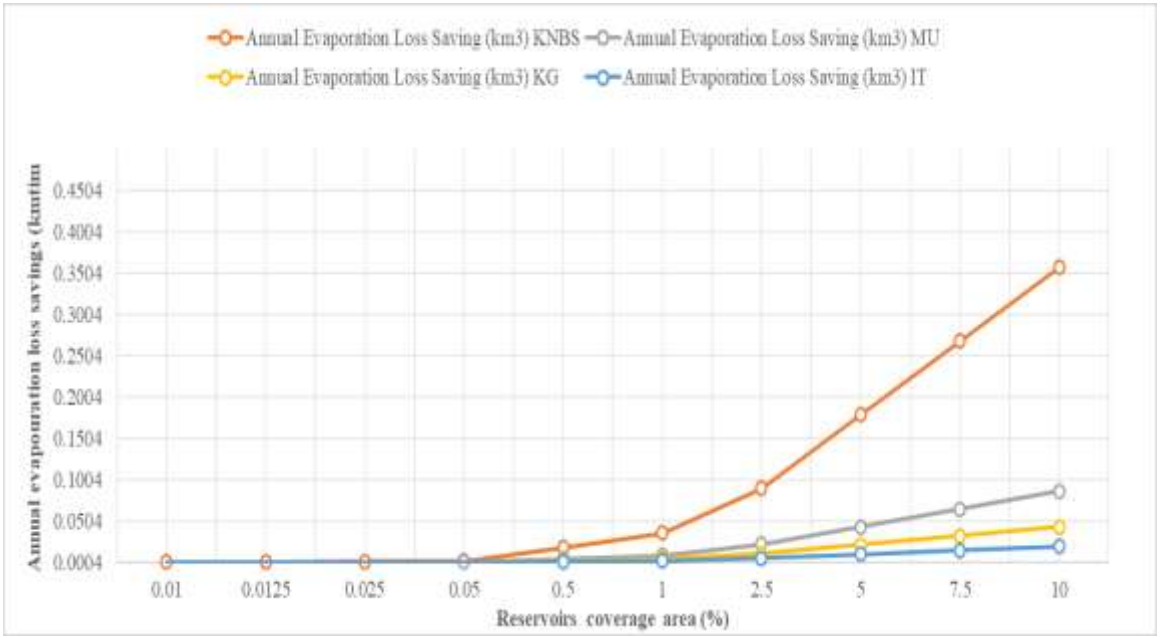


Figure 4.12 The four reservoirs annual evaporation loss savings (km^3)

4.7 Technical Solar Potential

Technical potential involved the installed solar power and energy generated from three different solar technologies monocrystalline, CIS and CdTe in accordance with reservoirs surface area utilizations. The following are the three categories in which technical potential was calculated:

i. Installed solar power in MW or GW
ii. Generated solar energy in GWh or TWh
iii. Generated solar energy in GWh or TWh with surface area coverage

The results of installed power capacity and generated energy obtained from individual study areas is presented as outlined.

4.7.1 Kariba North Bank Hydropower Reservoir

The technical assessment of this site involved two scenarios and these are:

i. Injectable energy into the grid through the substation reserve margins at four different percentage levels (75%, 50%, 25% and 10%) and
ii. Water reservoirs utilization at ten different percentage levels as is seen in Table 4.8.

At 0.01% solar power installation of 86 MW, 71 MW and 58 MW using Crystalline, CIS and CdTe generated 0.15TWh, 0.13TWh and 0.10TWh respectively. At 1% installation of 8649MW, 7081MW and 5813MW generated 14TWh, 12TWh and 11TWh respectively according to crystalline, CIS and CdTe. At 10%, the highest of water reservoirs coverage, the installation of 86490 MW, 70812 MW and 58125 MW generated 152TWh, 150TWh and 151TWh respectively according to crystalline, CIS and CdTe solar technologies. Table 4.5 shows that at all the three percentage levels, crystalline solar technology was the best performing technology of all. Table 4.8 shows the breakdown of different solar technologies and their performance.

Table 4.8 Technical Potential of Kariba Hydro reservoir

Scenario	Reservoir Surface Area (Km^2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar PV Power (MW)			Solar Energy Generation (TWh)		
				Crystalline	CIS	CdTe	Crystalline	CIS	CdTe
1	5580	0.010	0.56	86	71	58	0.15	0.13	0.10
2	5580	0.0125	0.70	108	89	73	0.19	0.16	0.13
3	5580	0.025	1.40	216	177	145	0.38	0.31	0.26
4	5580	0.050	3	432	354	291	0.74	0.60	0.53
5	5580	0.500	28	4325	3541	2906	7	6	5
6	5580	1.0	56	8649	7081	5813	14	12	11
7	5580	2.5	140	21623	17703	14531	37	30	26
8	5580	5.0	279	43245	35406	29063	77	62	53
9	5580	7.5	419	64868	53109	43594	111	90	79
10	5580	10	558	86490	70812	58125	152	150	151

4.7.2 Technical potential of Mulungushi Hydro reservoir

Mulungushi's technical potential was calculated using solar radiation and reservoirs utilization percentage. The amount of solar generated was dependent on the usable surface area covered and the reservoir's geographical location. The reservoir's technical potential was calculated at ten different percentage coverages and at the 0.01% coverage installed solar capacity of crystalline 68 MW, CIS 55MW and CdTe 46MW, the generation was 0.12TWh, 0.10TWh and 0.09TWh respectively. At 1% coverage, the installed capacity of 6,772 MW, 5544MW and 4,551.MW (crystalline, CIS and CdTe) generated 12TWh, 10TWh and 8TWh respectively. At 10%, the highest percentage, installed capacity of 67720 MW, 55,444 MW and 45,510MW respectively (crystalline, CIS and CdTe) generated 119TWh, 97TWh and 84TWh which is way much bigger than what is currently being generated 31.2 MW. The findings of the study show that 119TWh can be generated by crystalline solar technology making it the best performing technology of the three solar technologies used in this study as it can be seen from Table 4.9.

Table 4.9 Technological solar energy potential of Mulungushi hydropower

Scenario	Reservoir Surface Area (Km^2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar PV Power (MW)			Solar Energy Generation (TWh)		
				Crystalline	CIS	CdTe	Crystalline	CIS	CdTe
1	4369	0.010	0.44	68	55	46	0.12	0.10	0.09
2	4369	0.0125	0.55	85	69	57	0.15	0.12	0.11
3	4369	0.025	1.09	169	139	114	0.31	0.24	0.21
4	4369	0.050	2.18	339	277	228	0.60	0.48	0.42
5	4369	0.500	21.85	3,386	2,772	2,279	6	5	4
6	4369	1.0	43.69	6,772	5,544	4,551	12	10	8
7	4369	2.5	109.23	16,930	13,861	11,378	30	24	21
8	4369	5.0	218.45	33,860	27,722	22,755	59	48	42
9	4369	7.5	327.68	50,790	41,583	34,133	89	73	63
10	4369	10	436.90	67,720	55,444	45,510	119	97	84

4.7.3 Technical potential of Kafue Upper Gorge Hydro Reservoir

Kafue's technical potential was calculated using solar radiation and usable surface area of the water reservoir. The amount of solar generated depended upon the usable surface area coverage and the reservoir's geographical location. The performance of the three solar technologies was assessed at ten different percentage levels of the whole reservoir. At 0.01% surface area coverage, the installed solar capacity of crystalline 12 MW, CIS 10MW and CdTe 8MW generated 0.02TWh, 0.02TWh and 0.01TWh of energy respectively. At 1% surface area coverage, the installed capacity of crystalline 1248 MW, CIS 1022 MW and CdTe 839.MW generated 2TWh, 2TWh and 2TWh respectively. At 10%, installed capacity of crystalline 12478MW, CIS 10216MW and CdTe 8385 MW generated 22TWh, 22TWh and 23TWh respectively. The results of the study shows that there is high technical energy potential more than the energy being generated by the current power station. These results also showed that the best solar technology is the crystalline which gave 22TWh. The study area recorded good solar energy the major reason being its longitudinal proximity to the equator where there is direct sunlight enough for energy generation. Table 4.10 shows how the three solar technologies performed with crystalline generating 22 000000MW which is more than what is being generated (990 MW)

Table 4.10 Technical potential of Kafue Upper Gorge Hydro Reservoir

Scenario	Reservoir Surface Area (Km^2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar PV Power (MW)			Solar Energy Generation (TWh)		
				Crystalline	CIS	CdTe	Crystalline	CIS	CdTe
1	805	0.010	0.08	12	10	8	0.02	0.02	0.01
2	805	0.0125	0.10	16	13	10	0.03	0.03	0.02
3	805	0.025	0.20	31	26	21	0.05	0.04	0.04
4	805	0.05	0.40	62	51	42	0.11	0.09	0.08
5	805	0.50	4.02	624	511	419	1	1	1
6	805	1.0	8.05	1248	1022	839	2	2	2
7	805	2.5	20.13	3119	2554	2096	5	4	4
8	805	5.0	40.25	6239	5108	4193	11	9	8
9	805	7.5	60.38	9358	7662	6289	16	13	12
10	805	10	80.50	12478	10216	8385	22	22	21

4.7.4 Technical potential of Itezhi –Tezhi's Reservoir

The technical potential of Itezhi Tezhi was calculated using solar radiation and the reservoir utilization percentage. The amount of solar generated depended on the usable surface area covered and the reservoir's geographical location. At 0.01% surface area coverage, the installed capacity of crystalline of 6 MW, CIS 5 MW and CdTe 4 MW generated 0.01TWh, 0.01TWh and 0.01TWh of energy respectively. At 1%, the installed capacity of crystalline 608 MW, CIS 497 MW and CdTe 408.MW respectively generated 1TWh, 1TWh and 1TWh respectively. At 10%, the installed capacity of crystalline 6076MW, CIS 4975MW and CdTe 4083 MW generated 11TWh, 9TWh and 7TWh which are more than what is being generated 120 MW or 0.00012TWh. The key findings of the study show that using crystalline technology would generate 11TWh which is far more that what is being generated. The detailed performance of all the solar technologies is in Table 4.11 which also shows that the Crystalline technology generated more than the other two technology (CIS and CdTe)

Table 4.11 Technical Potential of Itezhi-Tezhi Hydro Reservoir

Scenario	Reservoir Surface Area (Km^2)	Reservoir Surface Coverage (%)	Reservoir Surface Area Covered (Km^2)	Solar PV Power (MW)			Solar Energy Generation (TWh)		
				Crystalline	CIS	CdTe	Crystalline	CIS	CdTe
1	392	0.010	0.04	6	5	4	0.01	0.01	0.007
2	392	0.0125	0.05	8	6	5	0.01	0.01	0.009
3	392	0.025	0.10	15	12	10	0.03	0.02	0.018
4	392	0.050	0.20	30	25	20	0.05	0.04	0.036
5	392	0.500	2	304	249	204	1	0.43	0.369
6	392	1.0	4	608	497	408	1	1	1
7	392	2.5	10	1519	1244	1021	3	2	2
8	392	5.0	20	3038	2487	2042	5	4	4
9	392	7.5	29	4557	3731	3063	8	6	6
10	392	10	39	6076	4975	4083	11	9	7

Summary of results of all the three solar technologies per study area with respect to their installed capacities and energy generation are outlined in Appendix 2 Tables 7.7 to 7.12. Table 7.13 shows the summarized installed power for all the three solar technologies and Table 7.14 shows the generated energy of all the three solar technologies in all the four large water reservoirs of Zambia. The findings of the study in all cases show that, crystalline solar technology was the best for both power installation and energy generation.

4.8 Summary of technical potential of all the four-study area

Table 4.12, Figure 4.13 and Figure 4.14 show the solar energy technical potential. Three (3) solar PV technologies were used and the reservoir surface area coverage varied between 0.01% and 10%. Mmonocrystalline PV technology generated more than the other two technologies. This is shown in Table 4.13 of which at 0.01% surface area coverage, monocrystalline generate 0.30TWh of electricity as compared to 0.26TWh by CIS and 0.12TWh for CdTe. Furthermore, with monocrystalline PV technology, 172.764MW can be generated from a reservoir surface area coverage of 10% as compared to 141.447MW for CIS and 116.103MW for CdTe. It should also be noted that at 1% of total hydropower reservoir's surface area for implementation of FSPV systems, the country would be able to generate 1.34, 1.15, and 1.02 times more electricity using monocrystalline, CIS and CdTe solar PV technology respectively. This is 1% of the total reservoir surface area coverage translate to annual evaporation loss water saving equivalent to 50.5 million cubic meters.

Table 4.12 Solar Energy Technical Potential

Reservoir Coverage (%)	Solar Power Technical Potential (MW)			Annual Solar Electricity Generation Potential (TWh)		
	Mono	CIS	CdTe	Mono	CIS	CdTe
0.01	172	141	116	0.30	0.26	0.12
0.0125	217	177	145	0.38	0.32	0.27
0.025	431	354	290	0.77	0.61	0.53
0.05	863	707	581	1.50	1.21	1.07
0.5	8639	7073	5808	15	12.43	10.4
1.0	17277	14144	11611	29	25	22
2.5	43191	35362	29026	75	60	53
5.0	86382	70723	58053	152	123	107
7.5	129573	106085	87079	224	182	160
10	172764	141447	116103	304	244	211

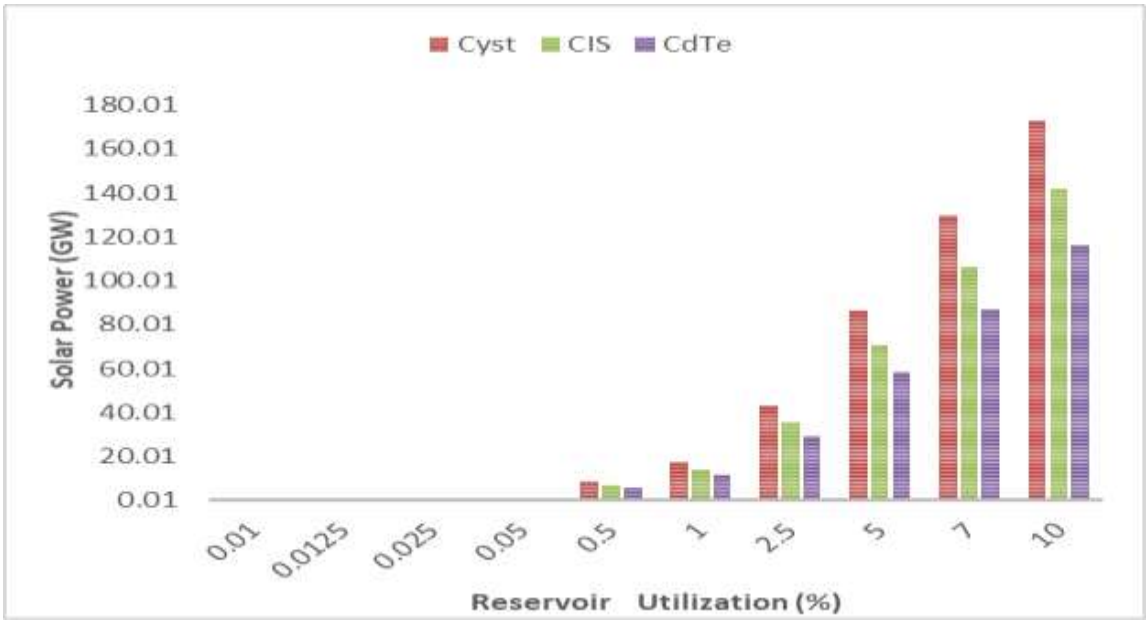


Figure 4.13 Solar Power Technical Potential for all the water reservoirs

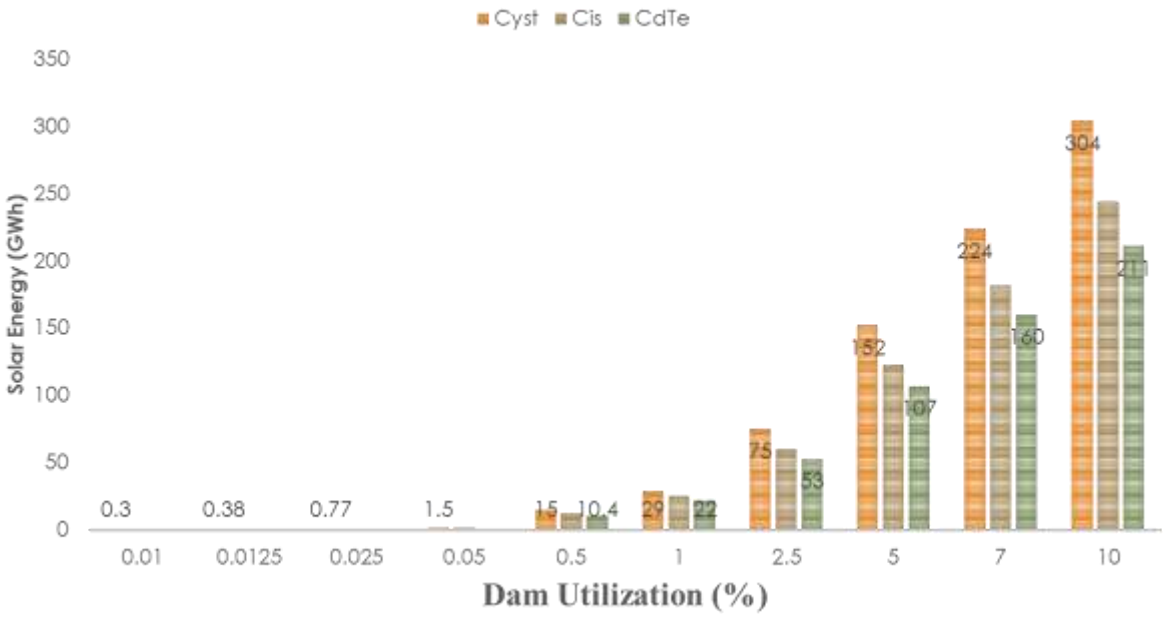


Figure 4.14 Solar Electricity Generation Potential of all the Reservoir

4.9 Technical Potential Considering Existing Grid Infrastructures

The summary of the technical information from the power stations is shown in Table 4.13.

Table 4.13 Hydropower Plants and Substation Parameters

Sn	Parameters	Kafue Gorge Hydro	Kariba Hydro	Mulungushi Hydro	Itezhi-Tezhi Hydro
1	Generator Capacity (MW)	165	180	31.3	60
2	Number of Generators	6	6	1	2
3	Plant Capacity (MW)	990	1080	31.3	120
4	Transformer Capacity (MVA)	135	200	41.9	71
5	Number of Transformers	10	6	1	2
6	Power factor	0.9	0.9	0.9	0.9
7	Substation Capacity (MVA)	1350	1200	41.9	142
8	Substation Capacity (MW)	1215	1080	37.71	127.8

Table 4.15 show plant and substation parameters which was used in simulation of technical power potential of all the four reservoirs. In this table, power was used to calculate substation capacity. MVA and MW are the parameters that became useful when coming up with scenarios which allowed simulation for technical power and energy in order to get the desired results of the study.

Tables 4.14 to Table 4.17 show how each power plant capacity can generate energy using three solar technologies. These power plant also show how each technology usage utilizes the reservoirs surface area and the total reservoirs utilization per plant capacity. Utilization capacity is the coverage of water reservoir with solar technology in relation to the total surface area. The findings of the study for all the three technologies were that generation of power and reservoir utilization in all the study areas was increasing as you increase on reservoir coverages. It was also shown that of all the solar technologies used, CdTe solar technology generated more energy than the other two reasons being that its efficiency is good when the system is loaded where system loses are also taken into account. It should also be noted that all the three solar technologies are incorporated into the simulation software PVGIS and it automatically gives out performance of each technology at any level of loading.

Note: that Table 4.14 to Table 4.17 show energy generation in relation to reservoir coverages by individual solar technologies and these results of solar coverages is given out by PVGIS as it gives out the generated energy.

Table 4.14 Technical Potential for Mulungushi Reservoir

Case	Capacity	Annual Electricity Generation (TWh)			Reservoir Surface Area Coverage (%)			Substation Utilization
	(MW)	Crystalline	CIS	CdTe	Crystalline	CIS	CdTe	(%)
1	1	1.77	1.65	1.85	0.0002	0.0002	0.0002	3
2	2	3.55	3.50	3.70	0.0003	0.0004	0.0004	5
3	3	5.32	4.95	5.55	0.0005	0.0005	0.0007	8
4	4	7.09	7.00	13.3	0.0006	0.0007	0.0009	11
5	5	8.86	8.75	9.24	0.0008	0.0009	0.0011	13
6	9	159.53	157.52	166.4	0.0013	0.0016	0.0020	24
7	19	336.79	334.84	351.29	0.0028	0.0034	0.0042	50
8	28	496.32	439.82	517.69	0.0042	0.0051	0.0062	74

Note that from Table 4.14 to Table 4.17, reservoirs surface area are the coverages in percentage form. This represents how much each solar technology would cover which is in direct relation to water savings. Substation utilization is the total surface area you would use if you used any of the stated solar technologies in percentage form. These values are generated by the simulating software.

Table 4.15 Technical Potential for Kariba Reservoir

Case	Capacity	Annual Electricity Generation (TWh)			Reservoir Surface Area Coverage (%)			Substation Utilization
	(MW)	Crystalline	CIS	CdTe	Crystalline	CIS	CdTe	(%)
1	18	31	31	31	0.0021	0.0025	0.0031	2
2	33	57	56	60	0.0039	0.0047	0.0057	3
3	45	77	77	81	0.0053	0.0064	0.0077	4
4	78	134	133	141	0.0091	0.011	0.0134	7
5	83	143	141	151	0.0097	0.0117	0.0143	8
6	90	155	153	163	0.0105	0.0127	0.0155	8
7	135	216	230	245	0.0158	0.0191	0.02342	13
8	165	283	281	304	0.0193	0.0233	0.0284	15
9	195	347	344	367	0.0228	0.0275	0.0335	18
10	248	426	422	450	0.0289	0.0350	0.0427	23
11	390	666	663	707	0.0455	0.0551	0.0671	36
12	585	1004	996	1061	0.0683	0.0826	0.1006	54

Table 4.16 Technical Potential for Kafue Reservoir

Case	Capacity	Annual Electricity Generation (TWh)			Reservoir Surface Area Coverage (%)			Substation Utilization
	(MW)	Crystalline	CIS	CdTe	Crystalline	CIS	CdTe	(%)
1	36	63	62	66	0.03	0.04	0.04	3
2	42	68	72	77	0.03	0.04	0.05	3
3	90	157	155	164	0.07	0.09	0.11	7
4	91	159	157	156	0.07	0.09	0.11	7
5	105	183	181	191	0.09	0.01	0.13	8
6	180	314	310	328	0.15	0.18	0.22	13
7	210	366	362	383	0.17	0.21	0.25	16
8	227	396	391	414	0.18	0.22	0.27	17
9	270	471	465	492	0.22	0.26	0.32	20
10	315	550	542	574	0.26	0.31	0.13	23
11	455	768	783	830	0.37	0.45	0.54	34
12	682	1190	1169	1244	0.55	0.67	0.81	51

Table 4.17 Technical Potential for Itezhi-Tezhi Reservoir

Case	Capacity	Annual Electricity Generation (TWh)			Reservoir Surface Area Coverage (%)			Substation Utilization
	(MW)	Crystalline	CIS	CdTe	Crystalline	CIS	CdTe	(%)
1	1	3	2	2	0.002	0.002	0.002	1
2	2	4	3	4	0.003	0.004	0.005	2
3	4	7	7	7	0.007	0.008	0.010	3
4	6	11	10	11	0.010	0.012	0.015	5
5	7	12	12	13	0.012	0.014	0.017	5
6	9	16	14	16	0.015	0.018	0.022	7
7	13	23	22	24	0.022	0.026	0.032	10
8	18	31	31	33	0.030	0.036	0.044	14
9	36	63	62	66	0.060	0.072	0.088	28
10	55	96	95	100	0.091	0.111	0.135	43

4.10 Technical Solar Power Potential: Substation Power scenarios

Figure 4.15 to Figure 4.18 show the results of the study when installed power scenarios were developed and summarized. The findings of the study show that Kafue Gorge had the highest solar installation power capacity in all the scenarios (Best, Optimal and Worst). Figure 4.17 and Table 4.18 show the summarized results of all the installation scenarios and from the figure it is seen that there are more power installations during the worst-case scenario. This is so because under this scenario, all power plants have got wider reserve margins hence increasing chances of solar power installation. Tables containing detailed data at 75%, 50%, and 10% are in Appendix 3 in Tables 7.15 to 7.17 and 7.18 as the summary of all the scenarios.

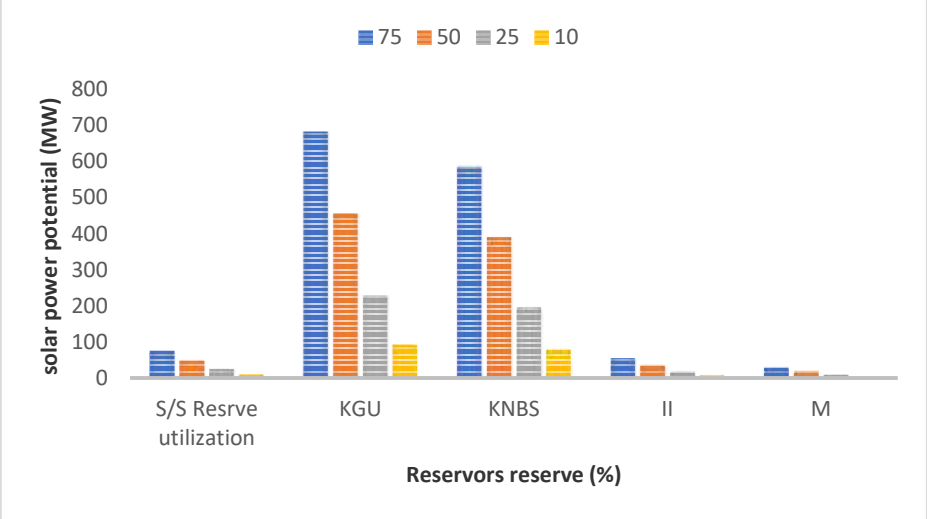


Figure 4.15 Power Potential under Optimal Scenario

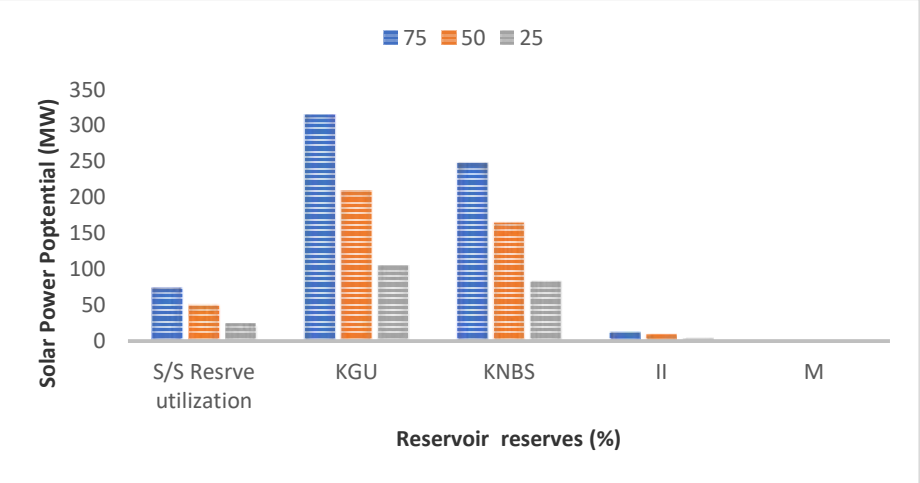


Figure 4.16 Power Potential under Worst Scenario

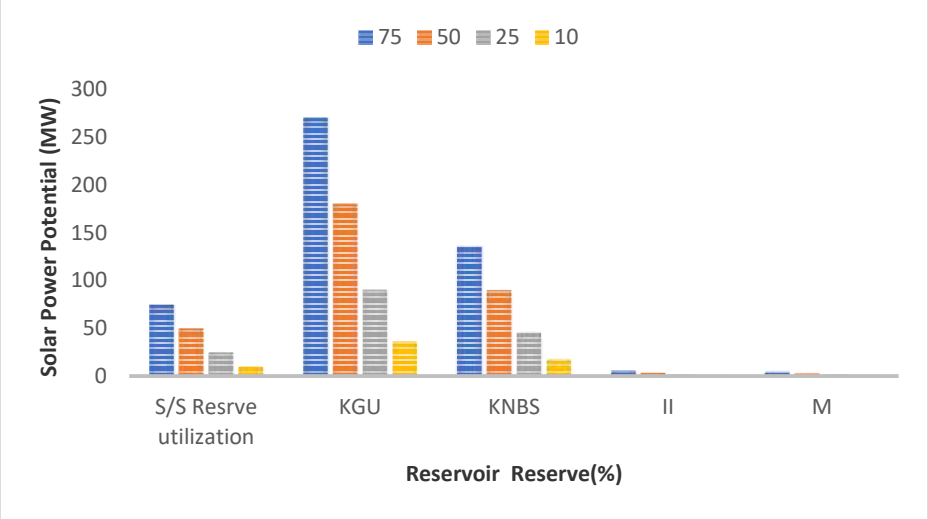


Figure 4.17 Power Potential under Best Scenario

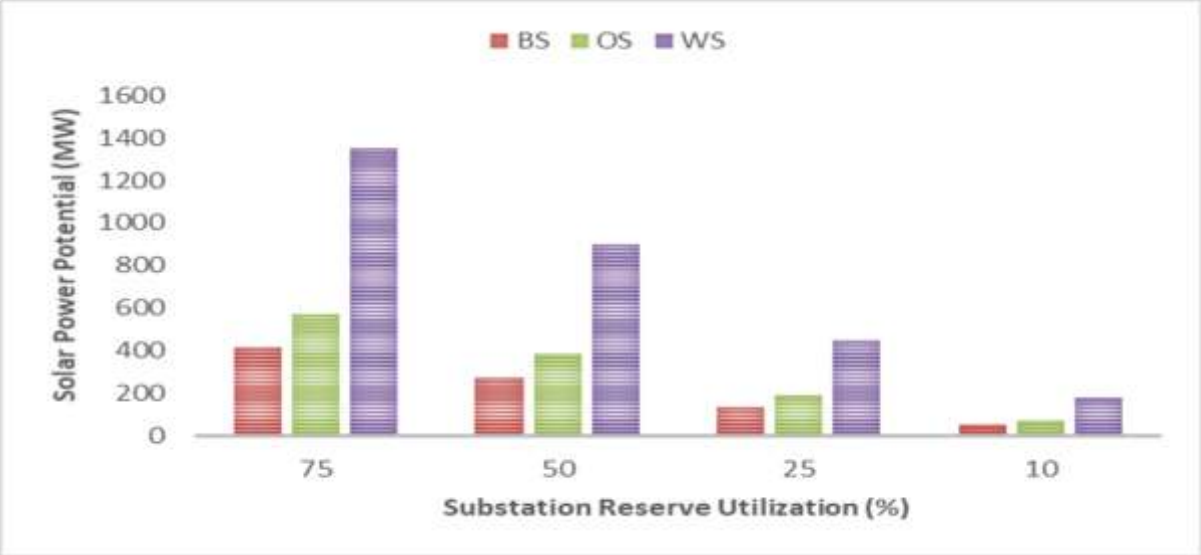


Figure 4.18 Power Potential for all Scenarios

Table 4.18 Technical Floating Solar PV power potential of the three scenarios

Scenarios	Capacity (MW)	Reservoir Area (Km^2)	Daily solar radiation (KWh/m^2-day)	Floating Photovoltaic Power (MW) At the Percentage Below			
				75%	50%	25%	10%
Best	2221.3	11146	5.91	416	277	139	56
Optimal	2221.3	11146	5.91	576	384	192	77
Worst	2221.3	11146	5.91	1350	900	449	180

Table 4.19 Floating Solar PV Electricity Generation Potential of all Scenarios

Scenarios	Capacity (MW)	Reservoir Area (Km^2)	Daily Solar Radiation (KWh/m^2-day)	Floating Photovoltaic Electricity (GWh)											
				75%			50%			25%			10%		
				Mono	CIS	Cdte	mono	Cis	Cdte	mono	Cis	Cdte	Mono	CIS	Cdte
Best	2221.3	11146	9.51	706.96	713.75	757.4	481.2	474.95	503.55	412.55	241.55	252.7	98.77	96.65	100.85
Optimal	2221.3	11146	9.51	999	986	1048	665	657	703	333	329	349	129	131	141
Waste	2221.3	11146	9.51	2786.3	2700	2923	1834	1843	1954.3	934	924	980.4	312	309	319.24

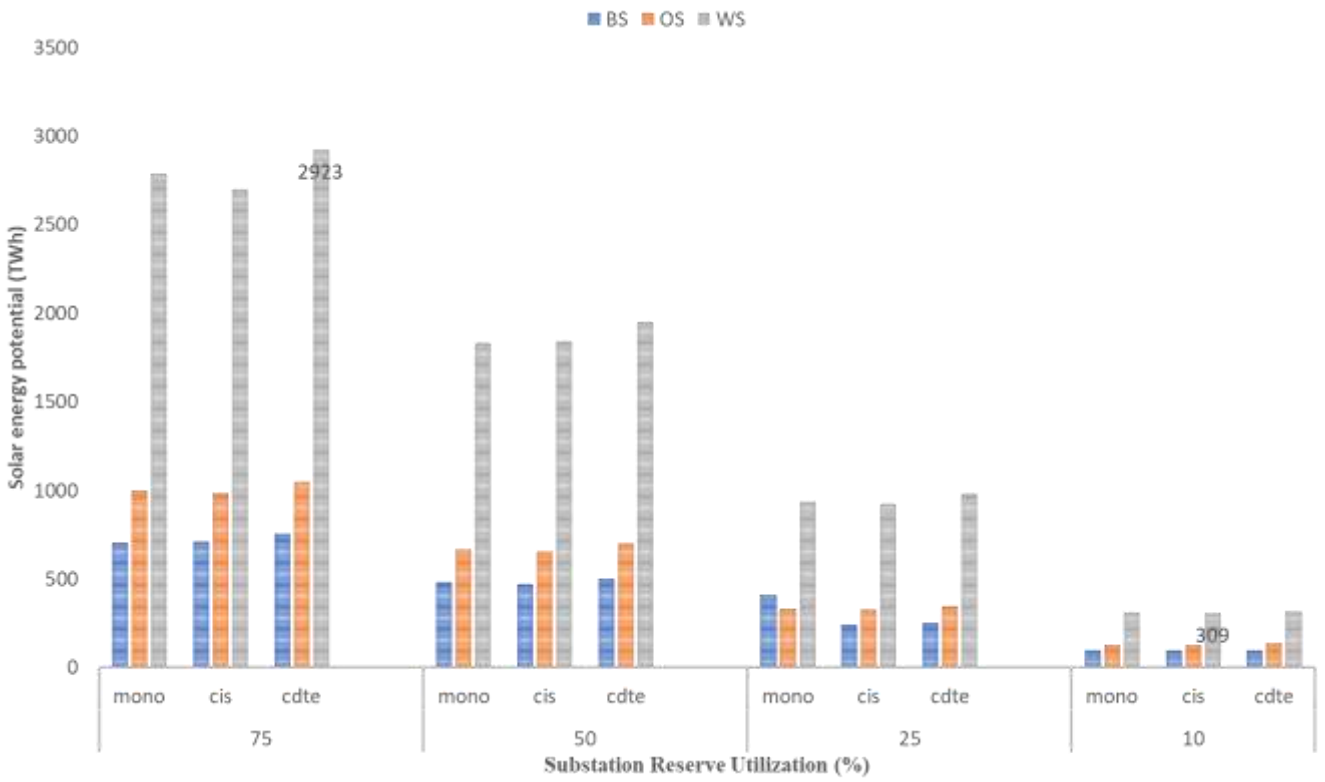


Figure 4.19 Floating Solar PV Electricity Generation Potential of all Scenarios

4.11 Technical Solar Energy Potential: Substation Parameters

4.11.1 Generation scenarios

Technical potential was evaluated considering hydropower plant installed and available power capacity including generation deficit during dry or drought seasons. This also considered the substation installed capacity including substation reserve margins during normal and abnormal operation periods of the hydropower plants. In this part, 12 scenarios were considered by varying substation utilization. The variations involved the power plants energy generation under normal and abnormal operation periods as shown in Table 4.20 and Table 4.21. The following were the results at 2.28% coverage of the total surface area of the four-hydro reservoir with solar installation of 56 MW: the Mono crystalline solar technology generated 98.77 GWh, CIS generated 96.65 GWh while the CdTe solar technology generated 100.85 GWh coming out as the highest with total surface area coverage of 0.0453 km^2. Its good performance was as a result of its good efficiency when compared with the other two solar technologies. At 15.61% coverage of the total surface areas of the floating solar system with an installation of 384 MW of solar CdTe technology generated 641 GWh of energy with 0.2904 km^2 surface area coverage while CIS and Mono crystalline generated 604 GWh and 594 GWh with surface area coverage of 0.2431 km^2 and 0.1978 km^2 respectively. At 54.87% total coverage of the four reservoir, CdTe solar technology generated the highest energy 2922.69 GWh with the overall surface area coverage of 1.0518 km^2 of the four-water reservoir's while CIS and Mono crystalline technology generated 2786.32 GWh and 2699.82 GWh with the total surface area coverage of 0.2143 km^2 and 0.2613 km^2 respectively of the total surface areas of the four-hydro reservoir. The results stated above show that CdTe solar technology performed well in terms of energy generation despite occupying relatively smaller areas than these other two solar technologies mono crystalline and CIS.

Table 4.20 Technical Potential of floating solar PV systems

Substation Utilization (%)	Solar PV Capacity (MW)	Annual Solar Electricity Generation Potential (GWh)		
		MONO	CIS	CdTe
2.28	56	98.77	96.65	100.85
3.12	77	132.55	134.5	144.7
5.64	139	243.32	239.95	254.55
7.32	180	308.86	304.0	317.3
7.80	192	333.0	329.0	349
11.26	277	480.0	473.0	502
15.61	384	594.0	604.0	641
16.91	416	695.0	686.0	734
18.25	449	848.09	839.75	892.24
23.41	576	1166.53	1152.52	1223.4
36.58	900	1833.79	1842.84	1954.29
54.87	1350	2786.32	2699.82	2922.69

Table 4.21 Technical potential and Reservoir Surface area coverage of floating solar PV systems

Substation Utilization (%)	Solar PV Capacity (MW)	Reservoir Surface Area Coverage (KM^2)		
		MONO	CIS	CdTe
2.28	56	0.0343	0.0627	0.0453
3.12	77	0.0372	0.0851	0.0611
5.64	139	0.0786	0.1369	0.1234
7.32	180	0.0869	0.1817	0.2243
7.80	192	0.1067	0.1917	0.2443
11.26	277	0.1705	0.2047	0.2505
15.61	384	0.1978	0.2431	0.29042
16.91	416	0.2143	0.2613	0.3204
18.25	449	0.2654	0.3144	0.3866
23.41	576	0.3202	0.3826	0.3987
36.58	900	0.4783	0.5805	0.6993
54.87	1350	0.7135	0.8687	1.0518

Figures 4.19 and 4.20 show electricity generated and integrated into the system using three scenarios (Best, Optimum and Worst case Scenario). The results of the three scenarios from all the (4) large water reservoirs show that at 10% of Substation reserve margins, the worst case scenario generated 180TWh, the Optimum generated 77TWh and at Best case scenario generated 56TWh . At 75%, the highest substation reserve margin, worst case scenario energy generated was 1350TWh while at Optimum and Best-case scenarios generation was 576TWh and 416TWh respectively.

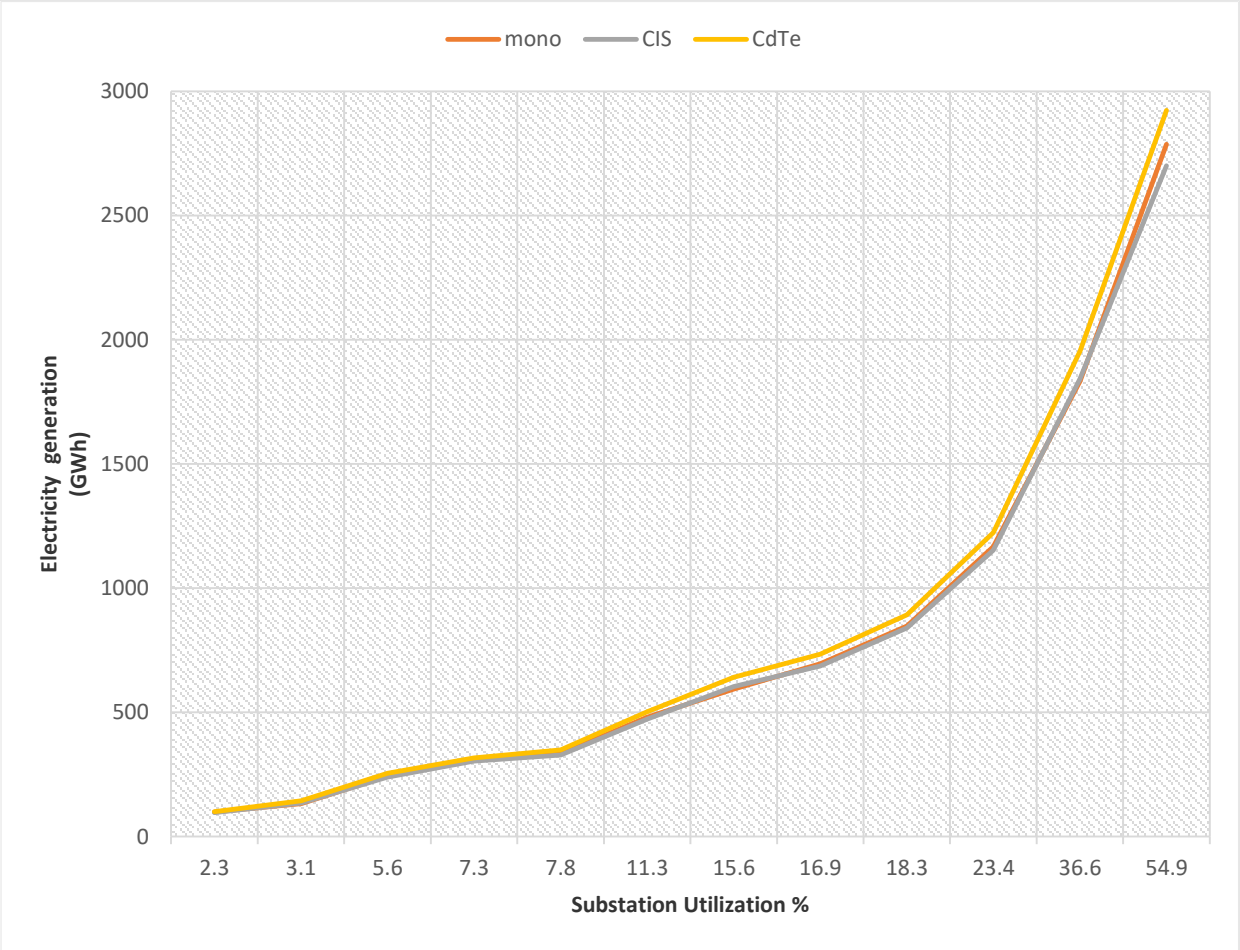


Figure 4.20 Technical Potential of floating Solar PV systems

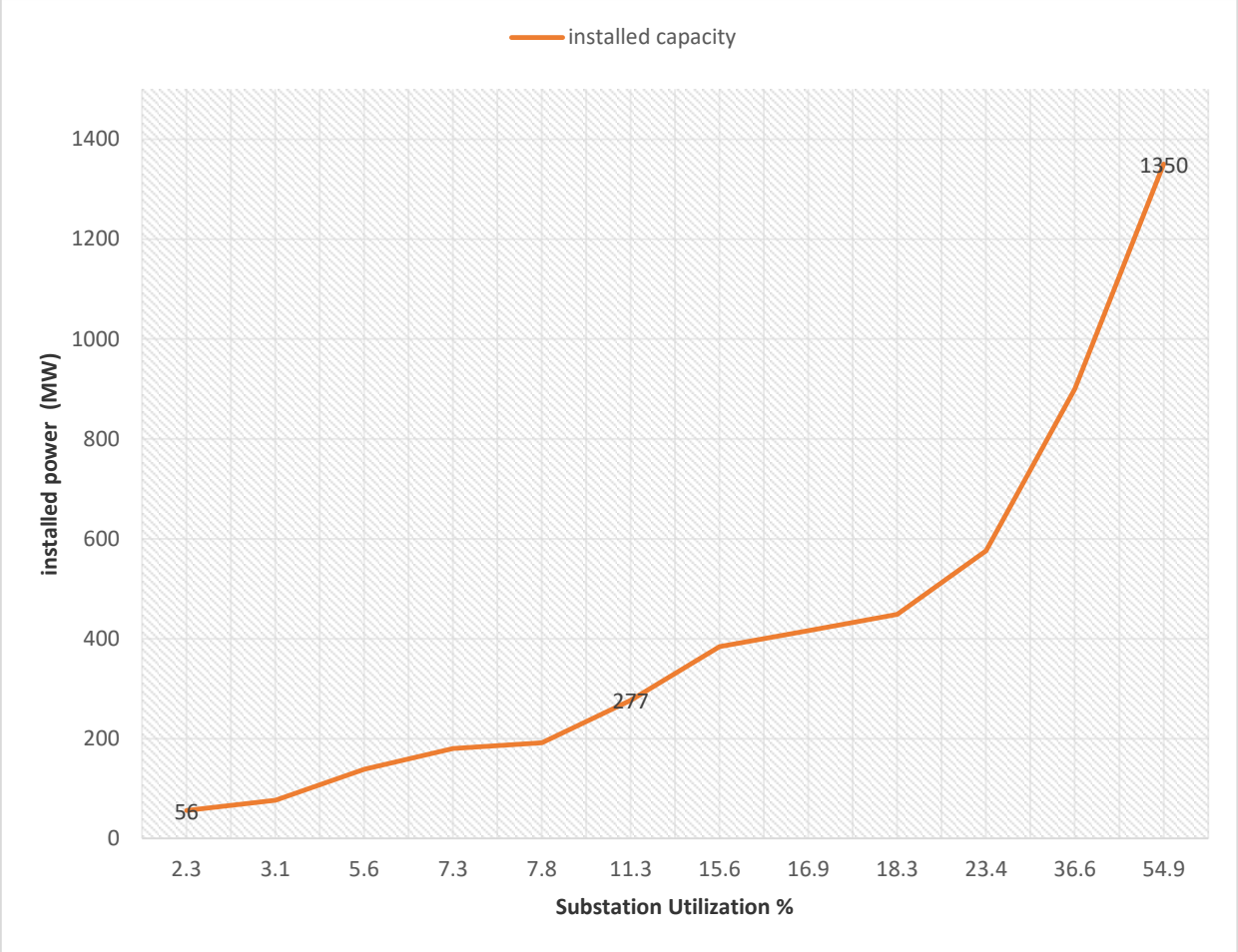


Figure 4.21 Installation of Technical Potential of floating Solar PV systems

These results show that there is more energy generation and contribution into the grid from floating solar system during the worst case scenario followed by Optimum and Best case scenario. This is shown both at highest and lowest substation reserve margins and is in line with existing literature which indicates that when there is less water for electricity generation, there is a wider reserve margin within the substation. The low hydro energy generation makes it possible for floating solar to contribute more energy. subsequently, at Best case scenario, less solar energy is contributed as the hydro system is still working normally and only requires less power contribution to raise energy profiles for the system to stabilize and operate at full capacity.

4.11.2 Scenarios Generation Potential

From the energy generated and contributed into the system after accounting for all the losses as shown in Figure 4.21 to 4.22, it is clear and possible that Zambian's energy profiles could be raised by introducing floating solar photovoltaic systems which operate mainly during the day making the country meet its national energy demand for domestic and industrial use while

prolonging the life span of the reservoir during water savings and allow it to be used for other economical use. Technical FSPV system under worst case scenario generated 1350TWh of energy enough to supply to the nation during adverse climatical conditions that might affect the energy sector. From the findings of the study, FSPV system can supply energy into the grid. The injected energy into the grid during normal supply could be exported for financial earnings while during bad conditions could be used to compensate the shortfalls hence help stabilize power flow in the system.

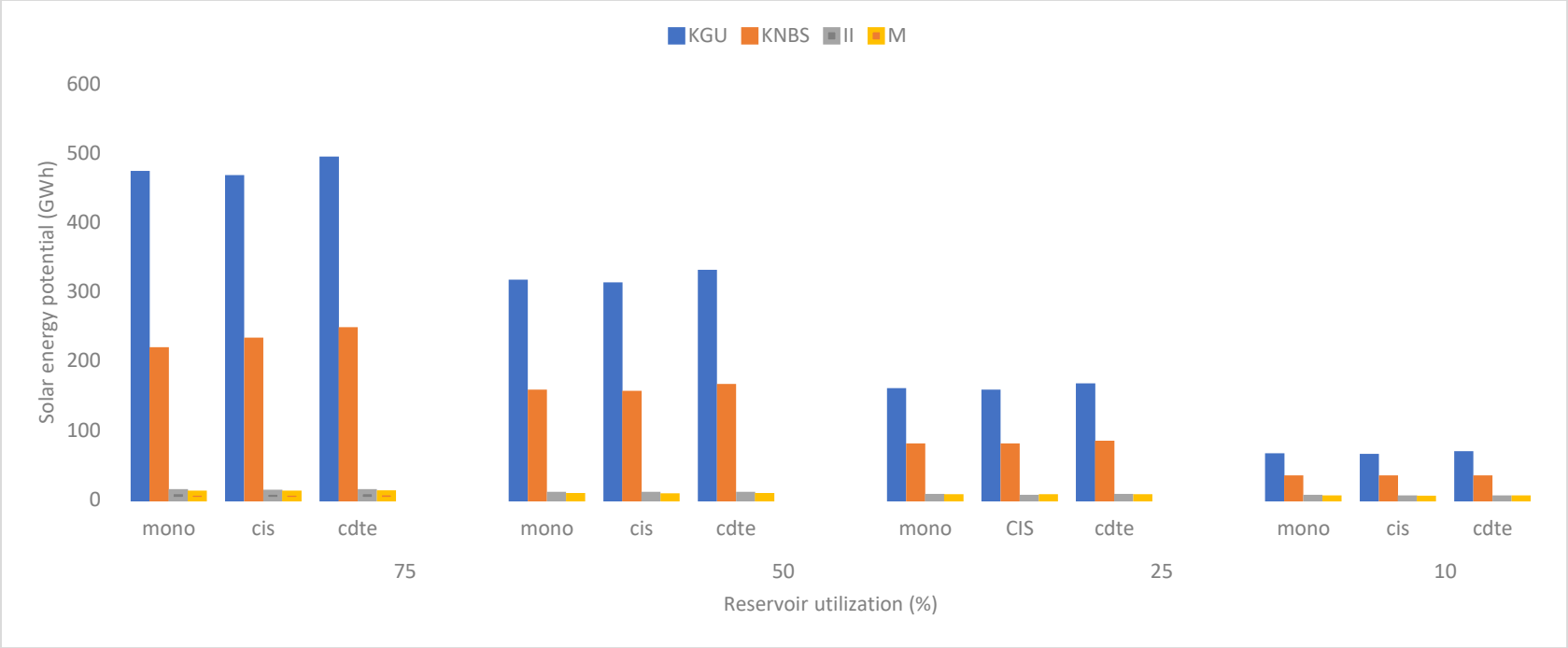


Figure 4.22 Solar Energy at Best Case Scenario

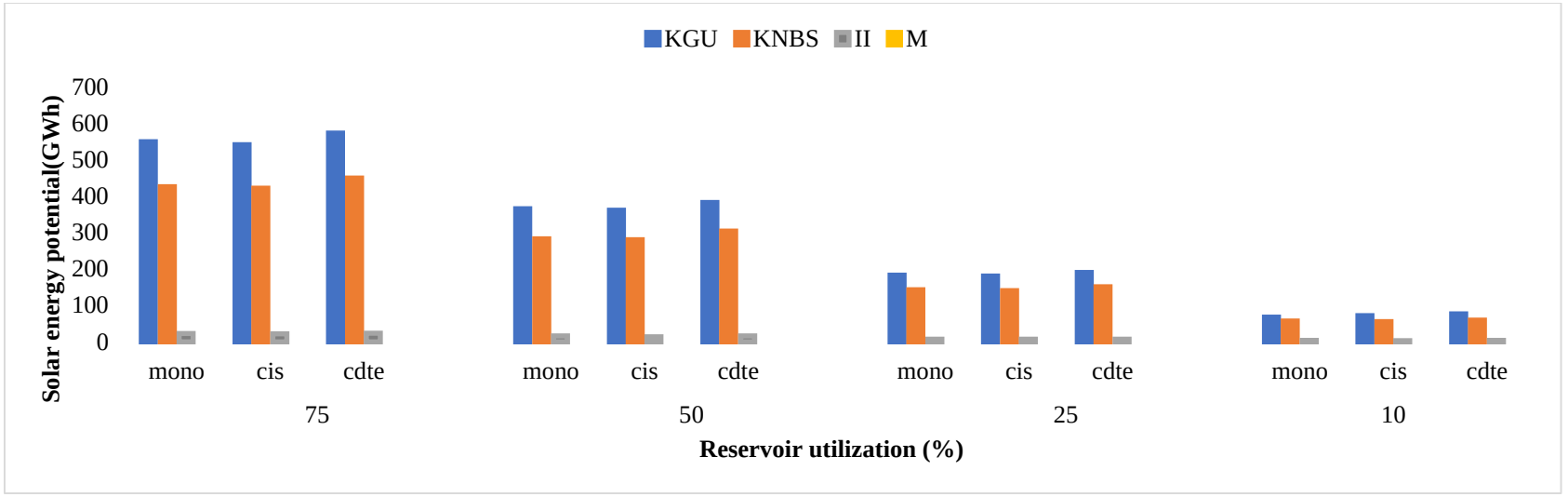


Figure 4.23 Solar Energy at Optimal Case Scenario (GWh)

4.11.3 Evaporation Loss Savings

According to Table 4.22 loss of water through vapor can be minimized by covering a large portion of water reservoirs. Three solar technologies were used to cover the reservoirs and performance was based on the size of each solar technology. CIS Is big in size and covered a bigger surface area while the smallest is CdTe solar technology which covered a relatively smaller area than the other two technologies. From Table 4.22 it is noted that reservoir utilization increased as solar installation increased translating to water saving depending on the largest solar technology which covers more area. In this case, CIS solar technology was the biggest. The major findings of the study is that reservoirs utilization increases with solar installation increase and huge volumes of water could be saved if wider areas of any water reservoir are covered with solar. This would prolong the period of reservoir use under water shortage conditions and save water for other economical use like: Fishing, irrigation and hydropower generation. Table 4.22 shows water loss savings by use of three different solar technologies.

Table 4.22 Technical Potential and Evaporation Loss Savings of floating solar PV System

Substation Utilization (%)	Solar PV Capacity (MW)	Annual Evaporation Loss Water Saving (km^3)		
		MONO	CIS	CdTe
2.28	56	3.46E-10	6.33E-10	4.58E-10
3.12	77	3.76E-10	8.60E-10	6.17E-10
5.64	139	7.94E-10	1.38E-09	1.25E-09
7.32	180	8.78E-10	1.84E-09	2.27E-09
7.80	192	1.08E-09	1.94E-09	2.47E-09
11.26	277	1.73E-09	2.07E-09	2.53E-09
15.61	384	2.00E-09	2.46E-09	2.93E-09
16.91	416	2.16E-09	2.64E-09	3.24E-09
18.25	449	2.68E-09	3.18E-09	3.90E-09
23.41	576	3.23E-09	3.86E-09	4.03E-09
36.58	900	4.83E-09	5.86E-09	7.06E-09
54.87	1350	7.21E-09	8.77E-09	1.06E-08

4.12 Environmental responsibility to the Reservoirs of the study areas

The findings of this study show that if 10% of the total surface area of the four large reservoirs is covered by FSPV systems, not only enough solar energy (2393.5TWh/year) can be captured for conversion into electricity but also a total of 505.9 million m3 per year of water can be saved which is 1.04 times more than the 2010 water used for both irrigation and water supply for consumption in Zambia (UN-water, 2010). Additionally, a total of 1,114.6 km2 of land could be preserved, thus, reducing environmental impact and supporting sustainable development. Promotion of renewable energy enhances clean energy which has no bad effect to the environment. According to the study conducted by Château et al. (2019). They performed a mathematical analysis Model where they compared different FSPV coverage–20%, 40% and 60%–and assessed the ecosystem change. They concluded that it is possible to cover up to 60% of the water body and still maintain a 70% of fish production and aquatic life found in the water rreservoirs.The analyses for the current study covered water resevoirs at only 0.01% up to 10% which is way too small as compared to the percentages of 20%, 40%and 60% where 60% coverage only disturbs the ecosystem by 30%. Hence floating solar photovoltaic system for electricity generation would not have an impact to the environmental. The system will also help to enhance clean in reservoirs where floating solar system can be implemented as the growth of algae will reduce to an extent due to cover from sunlight. A lot of heat during solar energy generation is dissipated hence cooling effects from the water increases good performance of solar energy generation hence a good promotion to clean energy generation which is environmentally friendly

4.13 Implementation Challenges of Floating Solar PV Systems in Zambia

Though floating solar photovoltaic system for electricity generation in Zambia seems to be an alternative energy source that is viable and attainable, there are still some challenges that are tied to its implementation in Zambia and these are:

1. Huge initial investment capital challenges.
2. Operating procedures and regulations that rely on high-inertia power generators continue to hold the belief that low-inertia renewable energy sources are unable to provide the initial energy needed to operate the system.

3. Low-inertia renewable energy sources are still unable to supply the initial energy required to start the system, according to operating procedures and standards that depend on high-inertia power generators.

4.14 Summary of the results

The study showed that enough energy could be injected into the grid in order to stabilize power whenever water levels meant for power generation go down. This has been seen from a huge contribution that can happen at worst case scenario of the power plant in which 2923 GWh of energy through CdTe solar technology can be injected into the system after accounting for all the power system losses. This was only possible for this technology as it can operate under intense conditions and exposure to too much heat caused by losses.

CHAPTER FIVE

5 CONCLUSIONS AND RECOMENDATIONS

This chapter provides the conclusions and recommendations arising from the study. The chapter also gives insight on further research to be undertaken in order to increase installation of floating solar system on Zambian's water reservoirs and integrate it with hydropower in order to stabilize the country's energy sector. For the study, the following were the specific objectives considered;

a. To quantify the theoretical and geographical solar potential on the useable surface areas of the reservoirs for implementation of floating solar photovoltaic system.
b. To determine the substation reserve margins of the larger hydro power plants of Zambia.
c. To determine the technical power and electricity generation potential of floating solar photovoltaic systems on the selected hydro reservoirs.

5.1 Conclusions

The main aim of this research was to assess the technical potential of floating solar photovoltaic systems in Zambia on selected larger hydropower plant water reservoirs for electricity generation. The reason for this research was because literature showed that there was a knowledge gap promoting the current investigation and the summary of the key findings are shown here under.

5.1.1 Quantifications of the Theoretical and Geographical solar potential on the useable surface areas of the four largest reservoirs of Zambia

i. Theoretical power potential: (actual energy received by each study sites)

The findings of the study shows that the total surface area of the four largest water reservoirs is 11,146 km^2 with the total installed hydropower capacity of 2221.3 MW.

These water reservoirs have the capability of generating total annual theoretical solar energy potential of the 25,610 TWh**.**

ii. Geographical power potential: (Energy generated according to reservoir utilization percentages).

Geographical potential of the four reservoirs was simulated and analyzed at ten different reservoirs percentages levels between 0.01% and 10%. The results show that between 0.01% and 10% reservoirs coverage, Geographical annual solar energy potential ranging from 2.4TWh and 2393.5TWh could be generated. Furthermore, it should be noted that only 0.20% of largest hydro Reservoir surface area is required to implement all the eight (8) solar PV projects current underway (1122MW_P) which will result in annual evaporation water loss saving amounting to 0.0101km^3 (10.1million m^3) representing 3.74% of the total water supply consumption and 4.8% of total water used for irrigation for 2010 of Zambia (UN-Water,2012). Additionally, utilization of 0.5% of the total rreservoirs surface areas, would result in 119.7TWh of annual solar energy geographical potential. This potential translates to annual water saving from evaporation loss of approximately 0.0253 km^3 (25.3million m^3)

5.1.2 Determination of substation reserve margins of hydro power plants

Substation reserve margins of all the four largest water reservoirs were calculated and simulated using the three solar technologies incorporated into PVGIS simulation software. In order to know the available actual free space of the substation at any instance ready for solar energy injection and also to ascertain the type of solar technology that will do well for this deployment and performance was only known through the results given.

Annual solar technological performance was grouped in order to know the best performing solar technology at any adopted power scenario.

5.1.3 Determination of technical power and electricity generation potential of floating solar photovoltaic systems from the study sites

The process of assessing the technical potential involved considering the electrical grid infrastructure availability from the largest four (4) hydropower plant for integration of floating solar PV technology within the defined hydropower reservoir boundaries considering the estimated

geographical surface area and technical characteristics of PV generation systems to convert solar energy to electrical energy while taking into consideration of the local conditions. The technical potential was also evaluated considering Hydropower plants' installed capacity, generation deficit and substation reserve margins.

According to data collected from the power plants, the substation reserve margin was found to be 270 MW for Kafue Gorge, 135 MW for Kariba North, 5 MW for Mulungushi, and 6 MW for Itezhi-Tezhi at best power plant operation period. However, during dry seasons, it was noted that some of the generators at the power plants are usually removed from operation or operated at reduced capacity thereby, reducing available power plant capacity, thus increasing substation reserve margins.

Therefore, for optimal case and worst case the substation reserve margin was found to be; Optimal Case (315 MW for KG, 248MW for Kariba North bank, and 13MW for Itezhi Tezhi) and Worst Case (682 MW for Kafue Gorge upper, 585 MW for Kariba North bank, 28MW for Mulungushi, and 55MW for Itezhi Tezhi). Thus, for each of the scenarios (best, optimal and worst cases), the substation reserve margin utilization was varied between 10% and 75% considering three (3) solar PV technologies; Monocrystalline, CIS, and CdTe. Hence, 48 scenarios were developed.

5.2 Research impacts; Practical implications and contribute to the body of knowledge:

The assessment of floating solar photovoltaic systems for electricity generation in Zambia was conducted, and based on the study, from my point of view, solar systems will supply energy to the consumers during the day while hydropower generation is on standby, conserving water for other useful, cost-effective uses and extending the life of water reservoirs. Hydropower takes over during the night as solar power production stops. This system will significantly improve Zambia's overall energy industry

5.3 Academic value and additions to the research community and other energy users:

From the materials and methods that have been used in this study, my perspective is that the research community will greatly benefit from this study and will help other researchers to replicate

the methods used and use them in other research areas while domestic and industrial energy users will enjoy energy that is sustainable and be energy secure at all times.

5.4 Suggestions for future research works:

1. When a floating solar photovoltaic system is technically connected into the main grid system, taking into account the existing infrastructure and anticipated loads of the Zambian network, more research can be done on the stability of the electrical power system.
2. Future studies should be conducted to obtain the optimal technical and economics of floating solar PV potential that can be injected into the existing power grid.

5.5 Proposed Recommendations

1 Installation of floating photovoltaics (FPV) in existing hydropower Reservoirs, would provide solar electricity and help compensate hydropower generation deficit during dry season and minimize on evaporation losses of water while helping to sustainably satisfy the current and future energy needs of the fast-growing economy of Zambia.

2 There is need to urgently for Zambia to adopt floating solar as a new means of generating clean and reliable energy as in the near future, floating photovoltaics system will surpass the known traditional way of generating electricity which are (Hydropower, Nuclear, Geothermal and Biomass).

3 There is need to take advantage of already existing policy shift towards implementation of renewable energy by worlds developed organizations financial lending institutions through their sustainable development policies that are aimed at prioritizing renewable energy hence an advantage of financial aid.

4 There is need for Zambia to revisit and realign its policies in order to speed up the implementation of floating solar photovoltaic system and integrate it with the existing hydropower network.

5 The grid code which was designed to cater for the traditional hydropower should be adjusted to suit renewable energy as it is an upcoming world's biggest source of energy.

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APPENDICE

Appendix 1 Types of Solar Energy

Background

Appendix 1 gives some of the technologies and solar types employed in solar power systems and how floating solar technology may be integrated with the existing grid.

Types of Solar Panels

1. **Monocrystalline solar panel;**
   A monocrystalline solar panel is a solar panel comprising monocrystalline solar **cells**. The panel derives its name from a cylindrical silicon ingot grown from single-crystal silicon of high purity in the same way as a semiconductor

2. **CIS**; A copper indium gallium selenide solar cell is a thin-film solar cell used to convert sunlight into electric power. It is manufactured by depositing a thin layer of copper indium gallium selenide solution on glass or plastic backing, along with electrodes on the front and back to collect current.

3. **CdTe;** Cadmium telluride (CdTe) photovoltaics is a photovoltaic (PV) technology based on the use of cadmium telluride in a thin semiconductor layer designed to absorb and convert sunlight into electricity.

Appendix 2; Theoretical Potential of the four largest hydro Reservoir

Theoretical Potential

Kariba North Hydropower Station Theoretical Solar Potential

Table 7.1: Theoretical Potential of Kariba Hydro reservoir (Surface Area 5580km^2)

Month	Number of Days	Solar Radiation at Optimum $(22)^0$		Solar Energy (TWh)	
		Daily	Monthly	Daily	Monthly
January	31	5.83	188.01	32.52	1049.10
February	28	5.03	162.16	28.05	904.85
March	31	5.09	164.23	28.41	916.40
April	30	5.32	171.77	29.71	958.48
May	31	6.15	198.28	34.30	1106.40
June	30	6.12	197.49	34.16	1101.99
July	31	6.12	197.44	34.15	1101.72
August	31	6.62	213.43	36.92	1190.94
September	30	7.08	228.38	39.51	1274.36
October	31	6.93	223.39	38.64	1246.52
November	30	5.11	164.87	28.52	919.97

Table 7.1: Continues

December	31	4.91	158.42	27.40	883.98
AVERAGE	30	5.86	188.99	32.69	1054.56
ANNUAL	365	5.86	2267.87	392.28	12654.72

Mulungushi Hydropower Station Theoretical Solar Potential

Table 7.2: Theoretical Solar Energy Potential for Mulungushi Hydropower (Surface Area 4369km^2)

Month	Number of Days	Solar Radiation at Optimum Angle $(15)^0$		Solar Energy (TWh)	
		Daily	Monthly	Daily	Monthly
January	31	5.17	166.63	22.57	728.01
February	28	4.51	160.93	19.69	703.10
March	31	5.52	178.18	24.13	778.47
April	30	5.31	177.05	23.21	773.53
May	31	6.64	214.26	29.02	936.10
June	30	6.36	211.86	27.77	925.62
July	31	6.56	211.48	28.64	923.96
August	31	6.77	218.3	29.57	953.75
September	30	6.83	227.74	29.85	995.00
October	31	6.73	217.14	29.41	948.68
November	30	5.20	173.43	22.73	757.72
December	31	5.22	168.35	22.80	735.52
AVERAGE	30	5.90	193.78	25.78	846.62
ANNUAL	365	5.90	2325.35	309.36	10159.5

Kafue upper gorge Hydropower Station Theoretical Solar Potential

Table7. 3: Theoretical Solar Energy Potential for Kafue Hydropower (Surface Area 805km^2)

Month	Number of Days	Solar radiation at Optimum $(22)^0$		Solar Energy (TWh)	
		Daily	Monthly	Daily	Monthly
January	31	6.10	196.67	4.91	158.32
February	28	4.54	162.19	3.66	130.56
March	31	5.12	165.08	4.12	132.89
April	30	5.59	186.33	4.50	150.00
May	31	6.58	212.38	5.30	170.97
June	30	6.10	203.31	4.91	163.66
July	31	6.46	208.53	5.20	167.70
August	31	6.81	219.68	5.48	176.84
September	30	6.90	229.96	5.55	185.12
October	31	7.06	227.89	5.69	183.45
November	30	4.90	163.36	3.95	131.50
December	31	4.95	159.76	3.99	128.61
AVERAGE	30	5.93	194.60	4.77	156.65
ANNUAL	365		2335.14	57.24	1879.79

Itezhi-Tezhi Hydropower Station Theoretical Solar Potential

Table7.4: Theoretical Potential for Itezhi -Itezhi Hydro reservoir (Surface Area 392km^2)

Month	Number of Days	Solar Radiation at Optimum Angle $15)^0$		Solar Energy (TWh)	
		Daily	Monthly	Daily	Monthly
January	31	5.60	180.58	2.19	70.79
February	28	4.62	164.83	1.81	64.61
March	31	5.22	168.24	2.04	65.95
April	30	5.79	192.91	2.27	75.62
May	31	6.55	211.36	2.57	82.85
June	30	6.39	212.89	2.50	83.45
July	31	6.62	213.53	2.59	83.70

Table7.4: Continues

August	31	7.00	225.81	2.74	88.52
September	30	6.74	224.77	2.64	88.11
October	31	6.70	216.14	2.63	84.73
November	30	4.90	163.18	1.92	63.97
December	31	5.02	161.80	1.97	63.43
AVERAGE	30	5.93	194.67	2.32	76.31
ANNUAL	365	71.16	2336.04	27.84	915.73

Table 7.5 annual Theoretical Potential VS annual hydro generation of the four-power station

Power Station	Hydro Installed Capacity (MW)	Reservoir Area (km^2)	Daily Average Solar Radiation (kWh/m^2-day)	Annual Total Solar Energy (TWh)	Annual Hydro Energy Generation (GWh)	E_{Hyd}/E_{Solar} (%)
Kariba North	1080	5580	5.86	12,654.72	4,925.0	0.039
Mulungushi	31.3	4369	5.90	10,159.5	172.4	0.002
Kafue	990	805	5.93	1,879.79	6,027.0	0.321
Itezhi- Tezhi	120	392	5.93	915.73	772.18	0.084
Total	2221.3	11146	5.91	25,609.74	11,896.58	0.046

Table 7.6 shows the location and size of the study areas

Hydro reservoirs	Districts	Province	Capacity (MW)	Latitude /Longitude	Solar Radiation Kwh/M^2	Surface Area (Km^2)
Kariba	Siavonga	Southern	1080	-16.522 /28.762	5.86	5580
Mulungushi	Kabwe	Central	31.3	-14.700/28.821	5.90	4963
Kafue	Kafue	Lusaka	990	-15.807 /28.421	5.93	805
Itezhi – Tezhi	Itezhi - Tezhi	Southern	120	-15.760 /26.021	5.93	392

Appendix 3 TECHNICAL POTENTIAL

Technical Power Potential of the Four Water Reservoir (Crystalline Technology**)**

Table 7.7 Summarized results of technical power potential of the four water Reservoirs using crystalline technology.

Power Stations	Hydro Installed Capacity (Mw)	Reservoir Surface Area (Km^2)	Crystalline Floating Solar PV Power (MW) at The Following Percentage Reservoir Coverages									
			0.01	0.125	0.025	0.05	0.5	1	2.5	5	7	10
Kariba	1080	5580	86	108	216	432	4,325	8,649	21,623	43,245	64,868	86,490
Mulungushi	31.3	4369	68	85	169	339	3,386	6,772	16,930	33,860	50,790	67,720
Kafue Gorge	990	805	12	16	31	62	624	1,248	3,119	6,239	9,358	12,478
Itezhi-Tezhi	120	392	6	8	15	30	304	608	1,519	3,038	4,557	6,076
Total	2221.3	11146	172	217	431	863	8,639	17,277	43,191	86,382	129,573	172,764

Table 7.8 Summarized results of Technical Energy potential of the four water Reservoirs using crystalline solar technology.

Power stations	Hydro Installed Capacity (MW)	Reservoir Surface Area(km^2)	Crystalline energy generation (TWh) at the following percentage coverages									
			0.01	0.0125	0.025	0.05	0.5	1	2.5	5	7	10
Kariba	1080	5580	0.15	0.19	0.38	0.74	7	14	37	77	111	152
Mulungushi	31.3	4369	0.12	0.15	0.31	0.60	6	12	30	59	89	119
Kafue GU	990	805	0.02	0.03	0.05	0.11	1	2	5	11	16	22
Itezhi- tezhi	120	392	0.01	0.01	0.03	0.05	1	1	3	5	8	11
Total	2221.3	11146	0.30	0.38	0.77	1.5	15	29	75	152	224	304

Table 7.9 Summarized results of technical power potential of the four water Reservoirs using CIS solar technology.

Power Stations	Hydro Installed Capacity (MW)	Reservoir Surface Area(km^2)	CIS Floating Solar PV Power (MW) At the following percentage Reservoir coverages									
			0.01	0.125	0.025	0.05	0.5	1	2.5	5	7	10
Kariba	1080	5580	71	89	177	354	3,541	7,081	17,703	35,406	53,109	70,812
Mulungushi	31.3	4369	55	69	139	277	2,772	5,544	13,861	27,722	41,583	55,444
Kafue Gorge	990	805	10	13	26	51	511	1,022	2,554	5,108	7,662	10,216
Itezhi- Tezhi	120	392	5	6	12	25	249	497	1,244	2,487	3,731	4,975
Total	2221.3	11146	141	177	354	707	7,073	14,144	35,362	70,723	106,085	141,447

Solar energy technical potential of the Four Water Reservoir (CIS technology**)**

Table 7.10 Summarized results of Technical Energy potential of the four water Reservoirs using CIS solar technology

Power Stations	Installed Capacity (MW)	Reservoir Surface Area (Km^2)	CIS Floating Solar PV Energy Generation (TWh) At the Following Reservoir Percentage Coverages									
			0.01	0.125	0.025	0.05	0.5	1	2.5	5	7	10
Kariba North	1080	5580	0.13	0.16	0.31	0.60	6	12	30	62	90	120
Mulungushi	31.3	4369	0.10	0.12	0.24	0.48	5	10	24	48	73	97
Kafue Gorge	990	805	0.02	0.03	0.04	0.09	1	2	4	9	13	18
Itezhi- Tezhi	120	392	0.01	0.01	0.02	0.04	0.43	1	2	4	6	9
Total	2221.3	11146	0.26	0.32	0.61	1.21	12.43	25	60	123	182	244

Table7.11 Summarized results of technical power potential of the four water Reservoirs using CdTe solar technology.

Power Stations	Installed Capacity (MW)	Reservoir Surface Area(km^2)	CdTe Floating Solar PV Power (MW) At the following percentage Reservoir coverages									
			0.01	0.125	0.025	0.05	0.5	1	2.5	5	7	10
Kariba	1080	5580	58	73	145	291	2906	5813	14531	29063	43594	58125
Mulungushi	31.3	4369	46	57	114	228	2279	4551	11378	22755	34133	45510
Kafue GU	990	805	8	10	21	42	419	839	2096	4193	6289	8385
Itezhi- tezhi	120	392	4	5	10	20	204	408	1021	2042	3063	4083
Total	2221.3	11146	116	145	290	581	5808	11611	29026	58053	87079	116103

Table7.12 Summarized results of Technical Energy potential of the four water Reservoirs using CdTe solar technology

Power Stations	Installed Capacity (MW)	Reservoir Surface Area(km^2)	CdTe Floating Solar PV energy generation (TWh) At the following Reservoir percentage coverages									
			0.01	0.125	0.025	0.05	0.5	1	2.5	5	7	10
Kariba	1080	5580	0.01	0.13	0.26	0.53	5	11	26	53	79	105
Mulungushi	31.3	4369	0.09	0.11	0.21	0.42	4	8	21	42	63	84
Kafue GU	990	805	0.01	0.02	0.04	0.08	1	2	4	8	12	15
Itezhi- Tezhi	120	392	0.01	0.01	0.02	0.04	0.37	1	2	4	6	7
Total	2221.3	11146	0.12	0.27	0.53	1.07	10.4	22	53	107	160	211

Table7.13 Summarized Technical power potential of the four Reservoirs using three solar technologies

Solar PV Technology	Installed Capacity (MW)	Reservoir Surface Area(km^2)	Floating Solar PV Power generation (MW) at the following Reservoir percentage coverages									
			0.01	0.125	0.025	0.05	0.5	1	2.5	5	7	10
Crystalline	2221.3	11,146	172	217	431	863	8,639	17,277	43,191	86,382	129,573	172,764
CIS	2221.3	11,146	141	177	354	707	7,073	14,144	35,362	70,723	106,085	141,447
CdTe	2221.3	11,146	116	145	290	581	5,808	11,611	29,026	58,053	87,079	116,103

Table7.14 Summarized Technical Energy potential of the four Reservoirs using three solar technologies

Solar PV Technology	Installed Capacity (MW)	Reservoir Surface Area(km^2)	CdTe Floating Solar PV energy generation (TWh) At the following Reservoir percentage coverages									
			0.01	0.0125	0.025	0.05	0.5	1	2.5	5	7	10
Crystalline	2221.3	11,146	0.30	0.38	0.77	1.5	15	29	75	152	224	304
CIS	2221.3	11,146	0.26	0.32	0.61	1.21	12.4	25	60	123	182	244
CdTe	2221.3	11,146	0.12	0.27	0.53	1.07	10.4	22	53	107	160	211

Appendix 3; Technical Solar Energy Potential: Substation Parameters Best Scenarios

Table 7.15 Best scenarios of power installation for all the four largest Reservoirs

Power Station	Capacity (MW)	Reservoir Area (Km^2)	Daily Solar Radiation (KWh/m^2-Day)	Floating Photovoltaic Power (MW) At the Percentage Below			
				75%	50%	25%	10%
KaribaNorth Bank	1080	5580	5.86	135	90	45	18
Mulungushi	31.3	4369	5.90	5	3	2	1
Kafue	990	805	5.93	270	180	90	36
Itezhi Tezhi	120	392	5.93	6	4	2	1
Total	2221.3	11146	5.91	416	277	139	56

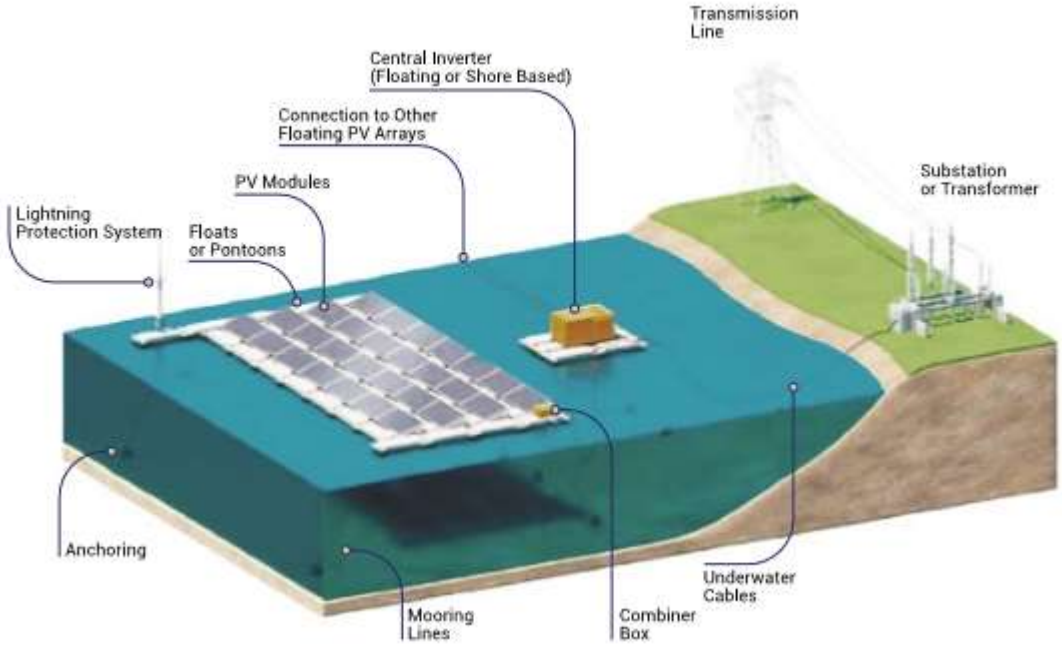

Figure 7.1 The illustration below shows the typical layout of floating solar photovoltaic system integrated with hydropower.

Optimal Scenarios

Table 7.16 Optimal scenarios of power installation for all the four largest Reservoirs

Power Station	Capacity (MW)	Reservoir area (Km^2)	Daily Solar Radiation (kWh/m^2day)	Floating Photovoltaic Power (MW) At The Percentage Below			
				75%	50%	25%	10%
Kariba North	1080	5580	5.86	248	165	83	33
Mulungushi	31.3	4369	5.90	-	-	-	-
Kafue Gorge	990	805	5.93	315	210	105	42
Itezhi Tezhi	120	392	5.93	13	9	4	2
Total	2221.3	11146	5.91	576	384	192	77

Worst Scenarios

Table 7.17 Worst scenarios of power installation for all the four largest Reservoirs

Power Station	Capacity (MW)	Reservoir Area (Km^2)	Daily Solar Radiation (KWh/m^2day)	Floating Photovoltaic Power (MW) At the Percentage Below			
				75%	50%	25%	10%
Kariba North	1080	5580	5.86	585	390	195	78
Mulungushi	31.3	4369	5.90	28	19	9	4
Kafue	990	805	5.93	682	455	227	91
Itezhi Tezhi	120	392	5.93	55	36	18	7
TOTAL	2221.3	11146	5.91	1350	900	449	180

Summary of all Power scenarios

Table 7.18 Technical Floating Solar PV power potential of the three scenarios

Scenarios	Capacity (MW)	Reservoir Area (Km^2)	Daily solar radiation (KWh/m^2-day)	Floating Photovoltaic Power (MW) At the Percentage Below			
				75%	50%	25%	10%
Best	2221.3	11146	5.91	416	277	139	56
Optimal	2221.3	11146	5.91	576	384	192	77
Worst	2221.3	11146	5.91	1350	900	449	180

Floating Solar PV Electricity Generation Potential

Table 7.19 Best Scenarios of electricity generation

Power Station	Capacity (Mw)	Reservoir Area (Km^2)	Daily Solar Radiation (Kwh/M^2day)	Floating Photovoltaic Electricity (Gwh)											
				75%			50%			25%			10%		
				Cry	Cis	Cdte	Cry	Cis	Cdte	Cry	Cis	Cdte	Cry	Cis	Cdte
Kariba North	1080	5580	5.86	216	230	245	155	153	163	77	77	81	31	31	31
Mulungushi	31.3	4369	5.90	8.96	8.75	9.24	5.32	4.95	5.55	3.55	3.50	3.70	1.77	1.65	1.85
Kafue	990	805	5.93	471	465	492	314	310	328	157	155	164	63	62	66
Itezhi Tezhi	120	392	5.93	11	10	11	7	7	7	4	3	4	3	2	2
Total	2221.3	11146	5.91	706.96	713.75	757.24	481.32	474.95	503.55	412.55	241.55	252.7	98.77	96.65	100.85

Table 7.20 Optimal Scenarios of electricity generation

Power Station	Capacity (Mw)	RESERVOIR Area (Km^2)	Daily Solar Radiation (Kwh/M^2-Day)	Floating Photovoltaic Electricity (Gwh)											
				75%			50%			25%			10%		
				Cry	Cis	Cdte	Cry	Cis	Cdte	Cry	Cis	Cdte	Cry	Cis	Cdte
Kariba North	1080	5580	5.86	426	422	450	283	281	304	143	141	151	57	56	60
Mulungushi	31.3	4369	5.90	-	-	-	-	-	-	-	-	-	-	-	-
Kafue	990	805	5.93	550	542	574	366	362	383	183	181	191	68	72	77
Itezhi Tezhi	120	392	5.93	23	22	24	16	14	16	7	7	7	4	3	4
Total	2221.3	11146	5.91	999	986	1048	665	657	703	333	329	349	129	131	141

Table 7.21 Worst Scenarios of electricity generation

Power Station	Capacity (MW)	Reservoir Area (km^2)	Daily Solar Radiation (Kwh/m^2day)	Floating Photovoltaic Electricity (Gwh)											
				75%			50%			25%			10%		
				Cry	Cis	Cdte	Cry	Cis	Cdte	Cry	Cis	Cdte	Cry	Cis	Cdte
Kariba North	1080	5580	5.86	1004	996	1061	666	663	707	347	344	367	134	133	141
Mulungushi	31.3	4369	5.90	496.32	439.8	517.7	336.8	334.8	351.3	159.5	157.5	166.4	7.04	7.00	9.24
Kafue	990	805	5.93	1190	1169	1244	768	783	830	396	391	414	159	157	156
Itezhi Tezhi	120	392	5.93	96	95	100	63	62	66	31	31	33	12	12	13
TOTAL	2221.3	11146	9.51	2786.3	2700	2923	1834	1843	1954.3	934	924	980.4	312	309	319.24

Table 7.22; Crystalline Technical Solar Potential of the four-water reservoir

SN	Capacity (Mw) /Hydro Power Station				Annual Electricity Generation (Gwh)				Reservoir Surface Area Percentage Coverage			
	Kafue gorge	Kariba	Mulungushi	Itezhi Tezhi								
1	36	18	1	1	63	31	1.77	3	0.03	0.0021	0.0002	0.002
2	42	33	2	2	68	57	3.55	4	0.03	0.0039	0.0003	0,003
3	90	45	3	2	157	77	5.32	4	0.07	0.0053	0.0005	0.003
4	91	78	5	4	159	134	8.86	7	0.07	0.0091	0.0008	0.007
5	105	83	-	4	183	143	-	7	0.09	0.0097	-	0.007
6	180	90	-	6	314	155	-	11	0.15	0.0105	-	0.010
7	210	135	-	7	366	216	-	12	0.17	0.0158	-	0.012
8	227	165	-	9	396	283	-	16	0.18	0.0193	-	0.015
9	270	195	4	13	471	347	7.09	23	0.22	0.0228	0.0006	0.022
10	315	248	9	18	550	426	159.53	31	0.26	0.0289	0.0013	0.030
11	455	390	19	36	768	666	336.79	63	0.37	0.0455	0.0028	0.060
12	682	585	28	55	1190	1004	496.32	96	0.55	0.0683	0.0042	0.091

Table 7.23; CIS technical Solar Potential of the Four Water Reservoir

SN	Capacity (Mw) /Hydro Power Station				Annual Electricity Generation (Gwh)				Reservoir Surface Area Percentage Coverage (%)			
	Kafue gorge	Kariba	Mulungushi	Itezhi Tezhi								
1	36	18	1	1	62	31	1.65	2	0.04	0.0025	0.0002	0.02
2	42	33	2	2	72	56	3.50	3	0.04	0.0047	0.0004	0.04
3	90	45	3	2	155	77	4.95	3	0.09	0.0064	0.0005	0.04
4	91	78	5	4	157	133	7.00	7	0.09	0.011	0.0007	0.08
5	105	83	-	4	181	141	-	7	0.01	0.0117	-	0.08
6	180	90	-	6	310	153	-	10	0.18	0.0127	-	0.012
7	210	135	-	7	362	230	-	12	0.21	0.0191	-	0.014
8	227	165	-	9	391	281	-	14	0.22	0.0233	-	0.018
9	270	195	4	13	465	344	8.75	22	0.26	0.0275	0.0009	0.026
10	315	248	9	18	542	422	157.52	31	0.31	0.0350	0.0016	0.036
11	455	390	19	36	783	663	334.84	62	0.45	0.0551	0.0034	0.072
12	682	585	28	55	1169	996	439.82	95	0.67	0.0826	0.0051	0.111

Table7.24 CdTe technical Solar Potential of The Four Water Reservoir

SN	Capacity (Mw) /Hydro Power Station				Annual Electricity Generation (Gw)				Reservoir Surface Area Percentage Coverage (%)			
	Kafue Gorge	Kariba	Mulungushi	Itezhi-Tezhi								
1	36	18	1	1	66	31	1.85	2	0.04	0.0031	0.0002	0.002
2	42	33	2	2	77	60	3.70	4	0.05	0.0057	0.0004	0.005
3	90	45	3	2	164	81	5.55	4	0.11	0.0077	0.0007	0.005
4	91	78	5	4	156	141	13.3	7	0.11	0.0134	0.0009	0.10
5	105	83	-	4	191	151	-	7	0.13	0.0143	-	0.10
6	180	90	-	6	328	163	-	11	0.22	0.0155	-	0.015
7	210	135	-	7	383	245	-	13	0.25	0.02342	-	0.017
8	227	165	-	9	414	304	-	16	0.27	0.0284	-	0.022
9	270	195	4	13	492	367	9.24	24	0.32	0.0335	0.0011	0.032
10	315	248	9	18	574	450	166.4	33	0.13	0.0427	0.0020	0.044
11	455	390	19	36	830	707	351.29	66	0.54	0.0671	0.0042	0.088
12	682	585	28	55	1244	1061	517.69	100	0.81	0.1006	0.0062	0.135

Table 7.25 Installed generation mix capacity for electricity generation in Zambia

License's Name	Station	Technology	Installed capacity (MW)
Zesco Limited	Kafue Gorge	Hydro	990
	Kariba North Bank	Hydro	720
	Kariba North Extension	Hydro	360
	Victoria Fails	Hydro	108
	Lunzua River	Hydro	14.8
	Lusiwasi	Hydro	12
	Chishimba Falls	Hydro	6
	Musonda Falls	Hydro	10
	Shiwang'andu	Hydro	1
	Lusiwasi Upper	Hydro	6
	Kafue Gorge Lower	Hydro	300
Itezhi-Tezhi Power Corperation	Itezhi-Tezhi	Hydro	120
	Ikelengi	Hydro	0.7
	Mulungushi	Hydro	32
	Lunsemfwa	Hydro	24
	Total Hydro	Hydro	**2,704.50**
Maamba Collieries Limited	Maamba power Plant	Coal	300
Dangote Cement Zambia limited	Dangote Thermal power plant	Coal	30
	Total Coal		**330**
Copperbelt Energy Corporation Generation Plants	Luano	Diesel	40
	Bancroft	Diesel	20
	Kankoyo	Diesel	10
	Macrlaren	Diesel	10
	Shang'ombo	Diesel	1.6
ZESCO Limited Generation Plant	Lundazi	Diesel	1.75
	Chama	Diesel	1.45
	Total Diesel		**84.8**
Ndola energy Generation plant	Ndola	Heavy Fuel oil	110
Rural Electrification Authority Generation Plants	Samfya	Solar	0.06
Copperbelt Energy corporation	Kitwe	Solar	1
Muhanya Solar	Sinda Village	Solar	0.03
Ngonye Power company Ltd	LSMFEZ	Solar	34
Bangweulu	LSMFEZ	Solar	54
Solera Power	Luangwa bridge	Solar	0.01
Standard Microgrid	Kafue	Solar	0.02
Mugurameno	Chirundu	Solatr	0.01
	Total Solar		**89.13**
Grand Total			**3,318.43**

Appendix 4 Location Map View of Some 0f The Study Areas

Figure show map of Kafue gorge upper study area

Figure show map of Itezhi Tezhi power stations

Appendix 5: Certificate of Ethical Clearance

THE UNIVERSITY OF ZAMBIA

DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road | P.O. Box 32379 | Lusaka 10101 | **Tel:** +260-211-290 258/291 777
Fax: +260-1-290 258/253 952 | **Email:** director@drgs.unza.zm | **Website:** www.unza.zm

APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006465

30th June, 2022

REF NO. NASREC-2022-JUL-002

Chrispin Lumpote
The University of Zambia
School of Engineering
Department of Electrical and Electronics Engineering
P.O. Box 32379
LUSAKA

Dear Mr. Lumpote,

RE: "ASSESSMENT OF TECHNICAL POTENTIAL OF FLOATING SOLAR PHOTOVOLTAIC SYSTEM FOR ELETRICITY GENERATION IN ZAMBIA"

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	ORDINARY REVIEW	APPROVAL NO. NASREC-2022-JUL-002
Approval and Expiry Date	Approval Date: 8th July, 2022	Expiry Date: 7th July, 2023
Protocol Version and Date	Version - Nil.	7th July, 2023
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	• Version - Nil	To be provided
Recruitment Materials	• Nil	Nil
Other Study Documents	• Questionnaire.	

Excellence in Teaching, Research and Community Service

Appendix 6: Approval of access to the study sites

ZESCO

Powering the Nation & the Region

Ref: A200/HRD/1053/2021

22 September 2021

Mr Chrispin Lumpote
The University of Zambia
School of Engineering
P.O. Box 32379
LUSAKA

Dear Mr Lumpote

REQUEST TO CONDUCT RESEARCH – MR CHRISPIN LUMPOTE

Reference is made to your letter dated 27th May, 2021 wherein you requested ZESCO Management to grant you permission to carry out a research entitled ***"Analysis of Floating Solar Photovoltaic Technical Potential and its Implication to the System Stability"***.

This serves to inform you that permission has been granted for you to undertake *the* "Analysis of Floating Solar Photovoltaic Technical Potential and its Implication to the System Stability" research under the following terms and conditions:

1. That all information regarding the research should be handled with all the confidentiality it deserves and shall be used for academic purposes only.
2. The final report should be availed to the office of the undersigned before submission to your school for a go ahead in writing.
3. A copy of the final report shall be retained by ZESCO Limited for future reference.
4. You are only permitted to carry out a case study under Generation Directorate.

Please fill in the attached form to indicate whether or not you are agreeable to these Terms and Conditions and return a copy to the office of the undersigned.

Yours sincerely
ZESCO LIMITED

CHILESHE M LUPUTA (MRS)
SENIOR MANAGER – HUMAN RESOURCE DEVELOPMENT

CC: Director - Human Resource
Director - Generation
Power Station Manager – KGPS
Training File

CML/ck

All correspondence to be addressed to the Managing Director
ZESCO Limited, Stand No. 6949 Great East Road, P.O. Box 33304, Lusaka-Zambia
Tel: +260-211-361111, E-mail: zesco@zesco.co.zm
www.zesco.co.zm

Appendix 7: Proof of Manuscript Submission/Acceptance

chris mudeene <mudeenechris@gmail.com>

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Assessment of Technical Potential of Floating Solar Photovoltaic System for Electricity Generation in Zambia

Chrispin LUMPOTE, Mabvuto MWANZA

Dept. of Electrical & Electronic Engineering, School of Engineering, University of Zambia, P.O.Box32379, Lusaka, DOI: **https://doi.org/10.51584/IJRIAS.2023.8502**

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Abstract: Sustainable hydropower development provides a basis for a reliable and stable power source that is economical and environmentally friendly. Zambia is heavily dependent on hydropower whose hydrological pattern is facing serious threats from frequent droughts and severe weather conditions affecting power generation. However, Zambia's hydropower is characterized by larger water reservoirs (Mulungushi, Itezhi Tezhi, Kafue Gorge and Kariba North) receiving high solar energy exceeding 2000 kWh/m^2 per year. Hence, integration of floating solar PV systems with hydropower could help boost hydropower production during dry periods and save loss of water through vapor. The paper aims at assessing the technical potential of integrating floating solar PV systems for electricity generation on the existing larger hydropower water reservoirs. The findings indicate that larger hydropower reservoirs have a total surface area of 11,146 km^2 equivalent to an annual theoretical solar energy potential of 25,610TWh.At 10% of the total coverage of all the surface areas, the technical potential is estimated at 172.76 GW_P (Monocrystalline), 141.44 GW_P (CIS) and 116.10 GW_P (CdTe) equivalent to an annual solar electricity generation potential of 304 TWh, 244 TWh and 211TWh respectively. In short, Zambia has huge potential for integration of floating solar with hydropower using the existing power grid infrastructure to increase on the electricity generation for the nation. Additionally, the solar energy profile fits well with the electricity demand profile for Zambia which makes it a better alternative for the energy mix of the country. These findings are vital to providing a guide to decision-makers for the inclusion of floating solar energy in the future national energy mix and conservation of land.

Keywords: Substation Reserve Utilizations, Floating Solar PV, Electricity Generation, Photovoltaic, Renewable Energy, Hydro Reservoirs