STUDY OF MAJOR ON-GRID SOLAR ENERGY INITIATIVES IN ZAMBIA

BY

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A Dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science in Physics

UNIVERSITY OF ZAMBIA

Author's Declaration

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Abstract

Climate change has greatly affected Zambia's hydropower production. This has contributed to reduced amounts of electricity being injected into the utility grid. Zambia has therefore embarked on igniting different solar energy initiatives. However, no critical study has been done to document the technical details and social, economic and environmental implications to provide strengths and weaknesses, lessons learnt and best practices of the existing on-grid solar photovoltaic (PV) systems for future solar energy entrepreneurs.

This dissertation provides a study of the *Bangweulu*, *CEC* and *Ngonye* solar PV power plants in Zambia. National Renewable Energy policies and institutional framework together with information and data from the two solar power plants were used in the study of their technical performance, financial viability, strengths and weaknesses from which lessons learnt and best practices were drawn. Technical performances of the existing solar PV power plants were evaluated using PVsyst and financial viability by using RETScreen RE softwares. Data from *Maamba* coal power plant was used as a benchmark for financial viability.

Performance ratios (PR) for *Ngonye*, *CEC* and *Bangweulu* solar power plants were found to be 83%, 86% and 84%, respectively which are above the internationally acceptable value of 75%. The yearly average daily peak sun hours for the three solar PV power plants were found to be 5.29 (5 hours 17 minutes). The Capacity Utilisation Factor (CUF), were found to be 18.8%, 16.6% and 19.8% respectively.

According to Zambia Electricity Supply Corporation (ZESCO), the Zambian utility grid can absorb an additional 816 MW of solar PV power translating into an annual energy production of 1.61×10^6 MWh. When compared with same amount of coal generated power as the benchmark, solar energy initiatives give rise to an aggregated cost saving of US$2.86 billion over a period of 25 years. Computations from actual and simulated values produced grid parities of 11.3 years and 11.6 years for *Ngonye* and *Bangweulu* solar PV power plants respectively. Additionally, the environment would be saved from being polluted by about 2 million tons of carbon dioxide (CO_2) equivalent of greenhouse gasses (GHGs) per year as compared to coal power production from *Maamba* coal plant. This shows that solar PV technology is the cheapest source of energy, environmentally friendly and financially viable to the government.

Dedication

I dedicate this research to my children Natasha, Lutanda and Kachimfya.

Acknowledgement

I wish to express my profound gratitude to my supervisors Prof. Prem Jain and Dr. S. Hatwaambo for their guidance and support throughout the research project. Their indispensable guidance and support were very encouraging and provided a smooth path that led to fine tuning of the dissertation.

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Profound thanks goes to the Ministry of Energy, Energy Regulations Board, Office for Promoting Private Power Investment and Industrial Development Corporation for providing me with information regarding Renewable Energy technologies.

Sincere thanks are presented to Bangweulu, Copperbelt Energy Corporation and Ngonye solar PV power plants for making it possible to have access to their facilities. Their warm welcome made me feel at home and provided me with confidence to carry out the research.

I would also like to thank my colleagues Mr. C. Chipalabela, Mr. F. Kapole and Miss. R. Pearce for their jovial encouragement even when things seemed tough.

Lastly but not the least, I thank God the almighty for his grace to make it possible for me to complete my research and be able to formulate the dissertation.

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Acronyms

AC – Alternating Current

AM – Air Mass

AREIP – Alternative Renewable Energy Investment Programme

ATI – African Trade Insurance

BOS – Balance of Systems

CdTe – Cadmium Telluride

CEC – Copperbelt Energy Corporation

CF – Capacity Factor

CUF – Capacity Utilisation Factor

CO_2 -Carbon dioxide

CU – Conversion Unit

DC – Direct Current

DiffHor – Horizontal Diffuse Irradiation

EArray – Effective radiation at the output of the array

EIA – Environmental Investigations Agency

EIB – European Investment Bank

eq – Equivalent

ERB – Energy Regulations Board

ESMAP – Energy Sector Management Assistance Program

GET FiT – Global Energy Transfer Feed-in Tariffs

GHG – Green House Gas

GHI – Global Horizontal Irradiance

GlobEff – Effective Global Irradiation

GlobHor – Global Horizontal Irradiation

GlobInc – Global incident in collector plane

GSA – Global Solar Atlas

GTI – Global Tilted Irradiance

GW – Giga Watt

HFO – Heavy Fuel Oil

HT – High Tension

IA – Implementation Agreement

IDC – Industrial Development Corporation

IDM – Islanding Detection Methods

IEA – International Energy Agency

IEEE – Institute of Electrical and Electronics Engineers

IFC – International Finance Corporation

ILR – Inverter Load Ratio

IPP – Independent Power Producer

IRENA – International Renewable Energy Agency

IRR – Internal Rate of Return

KfW – Kreditanstalt fü Wiederaufbau (“Credit Institute for Reconstruction”)

kW – Kilo Watt

kWh – Kilo Watt Hour

kW_p – Kilo Watt peak

Lc – Collection Loss

LCOE – Levelised Cost of Electricity

Lcr – Collection Loss Ratio

Ls – System loss

LSMFEZ – Lusaka South Multi-Facility Economic Zone

Lsr – System Loss Ratio

LT – Low Tension

m – metre

m^2 – square metre

MCR – Main Control Room

MIRR – Modified Internal Rate of Return

MoE – Ministry of Energy

MoU – Memorandum of Understanding

MPPT – Maximum Power Point Tracking

MW – Mega Watt

MW_{ac} – Mega Watt Alternating Current

MWh – Mega Watt Hour

NASA – National Aeronautics and Space Administration

NEP – National Energy Policy

NPV – Net Present Value

OPIC - Overseas Private Investment Corporation

OPPPI – Office for Promoting Private Power Investment

PBP – Pay Back Period

PCB – Programmable Computer Box

PCC – Point of Common Coupling

PLCC – Power Line Carrier Communication

PPA – Power Purchase Agreement

PR – Performance Ratio

PV – Photovoltaic

PVC – PolyVinyl Chloride

PVGIS – Photovoltaic Geographic Information System

PVOUT – Photovoltaic specific power output

PVsyst – Photovoltaic system software

PWM – Pulse Width Modulation

RE – Renewable Energy

RE – Renewable Energy

RES - Renewable Energy Source

RETScreen – Renewable Energy Project Analysis Software

RLSF – Regional Liquid Support Facility

RMU – Ring Main Unit

ROI – Return on Investment

SCADA – Supervisory Control and Data Acquisition

SO – System Operator

SAPP – Southern African Power Pool

SSA – Sub Saharan Africa

STC – Standard Test Conditions

S_y – Specific yield

T_Amb – Ambient Temperature

U.S – United States

US$ - United States Dollar

USc/kWh – United States cents per Kilo Watt Hour

WBG – World Bank Group

Ya – Normalised Array production

Y_f – Final yield

Y_r – Reference yield

ZESCO – Zambia Electricity Supply Corporation

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Chapter 1

1.0 Introduction

Climate change has evidently proved to be one of the world's substantial developmental challenges [1]. Global warming has particularly contributed to climate change. Utilisation of fossil fuels for electricity generation causes rapid environmental downgrading and leads to global warming [2]. Zambia's hydropower production has not been spared by climate change leading to reduced amounts of electricity being fed into the nation's grid.

The capacity of a nation to manage its vast developmental aims is greatly affected by access to dependable energy [3]. In response to this, Zambia is working to develop sustainable and appropriate programmes for Renewable Energy Sources (RES) to meet the energy demand. Following the extreme power deficit during 2017-20 induced by climate change, the Zambian Government adopted a solar energy strategy that enables the development of Independent Power Producers (IPPs) and outlines initiatives to accelerate the deployment of solar photovoltaic (PV) power plants. Alongside the strategy, the Zambian Government also emphasised on the need to supplement hydropower production in order to meet the country's energy demand. Solar energy initiatives looks to contribute to a Green House Gas (GHG)-free development passage and sustainable growth as well as diversification of Zambia's energy blend whilst making sure that cost-reflective, environmentally and socially sustainable projects increase worth for consumers.

1.1 Background

Zambia's main consumers of electricity are mining, residential and commercial industries with the main source being hydropower. The first hydropower station constructed in Zambia was the Victoria Falls in 1908 with a capacity of 108MW [4]**.** This was followed by the Kariba Dam and Kafue Gorge hydro power stations.

In 1955, the Kariba Dam hydro power station was designed to produce an energy output of 6720GWh per year but only gave an output of 6400GWh per year [5]. The capacity of the Kariba Dam hydro power station was 600MW [5].

The third power plant to come into operation was the Kafue Gorge hydro power station. The Kafue hydro power station was constructed in two stages**.** The first stage involved the construction of the Kafue Gorge in 1971 with an initial capacity of 600 MW. Due to the nature of the Kafue Flats, the storage capacity of the reservoir was not sufficient and a second dam was needed upstream so as to ensure a steady supply of water in the river to keep maximum power generation the whole year. In 1978, the Kafue Gorge hydro power plant had its capacity increased to 900 MW [6].

The Kafue Gorge and Kariba Dam hydro power stations were constructed to meet the country's energy demand. As the country's population increased coupled with industrial development, there was need to increase supply of electricity to consumers. More hydro power stations with different capacities were constructed and others expanded to meet the country's increasing energy demand. These plants include Kafue Gorge Upper with 990MW, Kafue Gorge Lower with 600MW, Kariba North Bank with 720MW, Kariba North Bank Extension with 360MW, Victoria Falls with 108MW, Lusiwasi with 15MW, Luanza with 14.5MW, Musonda Falls with 10MW, Chishimba Falls with 10MW and Shiwang'andu with 1MW. All these hydropower plants are under Zambia's power utility company Zambia Electricity Supply Corporation (ZESCO) [7]**.**

There are several other privately owned hydropower stations and which include Itezhi-tezhi with capacity of 120MW under Itezhi-tezhi Power Corporation, Mulungushi with 32MW and Lunsemfwa with 24MW under Lunsemfwa Hydro Power Company and Ikelengi with 0.75MW under Zengamina Limited. This gives a total of 2398.25MW of hydropower installed capacity [7]**.**

The country has one coal power plant called Maamba Coal Power plant with a production capacity of 300MW and privately owned by Maamba Collieries Limited [7]**.**

Privately owned diesel generated power stations are Bancroft Diesel with 20MW, Luano Diesel with 40MW, Luanshya Diesel with 10MW, Mufulira Diesel with 10MW under Copperbelt Energy Generation Plants. ZESCO has six diesel power plants and these are Kabompo Diesel with 2MW, Zambezi Diesel with 1.36MW, Mufumbwe Diesel with 0.8MW, Luangwa Diesel with 2.6MW, Lukulu Diesel with 0.32MW, Chavuma Diesel with 0.8MW, Shango'mbo Diesel with 1MW. Therefore, diesel power stations contribute 88.88MW to the total installed power generation capacity. Ndola Energy Power Generation plant has a 110MW capacity of Heavy Fuel Oil (HFO) power plant [7]**.**

This led to the nation's hydro power installed capacity to increase to 2,398.25MW, with coal at 300MW, diesel at 88.88MW, HFO at 110MW and solar Photovoltaic (PV) at 1.1MW [7]**.** The total installed capacity was 2,898.23MW in the year 2018 with solar only accounting for 0.04% [7]**.**

In 2019, Zambia Electricity Supply Corporation (ZESCO) decommissioned five diesel power plants; Kabompo with 2MW, Zambezi with 1.36MW, Mufumbwe with 0.8MW, Lukulu with 0.32MW and Chavuma with 0.8MW giving a total of 5.28MW [8]. This was in the quest to connect the five towns to the utility grid [8]. Zambia's installed capacity increased to 2981.32MW in 2019 after commissioning two grid connected solar power plants [8]. These are Bangweulu and Ngonye solar power plants with installed capacities of 54.3MW and 34MW respectively [8]. Furthermore, standard solar micro-grids were installed with the capacity of 0.067MW [8]. The total installed capacity for diesel generating power plants is 83.6 MW. Table 1.1 summarises Zambia's total installed power capacity.

However, despite having a huge contribution towards Zambia's power generation, hydropower generation systems are not operating at their installed capacities due to low water levels in their reservoirs induced by climate change. Water levels in reservoirs have a direct effect on hydro power production which in turn dictates the amount of electricity to be injected into the grid in case of a deficit to meet the demand. Hence, the knowledge about water levels in hydropower production reservoirs is necessary with regard to solar power production.

In order to maintain and monitor levels of one of the main reservoirs for hydroelectric production, that is the Kariba Dam, the Zambezi River Authority was formulated as a body in October 1987 by the Zambian and Zimbabwean parliaments. The body monitors and makes sure that water levels in Kariba Dam water reservoir is maintained at 475.50m. The body also measures water flow rates. The water levels in the Kariba Dam have not been spared by climate change leading to low water levels. The Kariba Dam is designed to operate between levels of 475.50m and 488.50m (with 0.70m freeboard) for hydropower generation [9]. Energy sectors such as hydro, wind and nuclear are negatively affected by climate change to various decreased levels of efficiency of supply [10]**.** The most affected amongst the three is hydro followed by wind and the least is nuclear [10]**.**

Table 1.1 Zambia's Installed Generation Capacity as at 2019

Undertaking	Station	Type	Installed Capacity (MW)
	Kafue Gorge Upper Hydro	Hydro	990.00
	Kariba North Hydro	Hydro	720.00
	Kariba North extension Hydro	Hydro	360.00
ZESCO	Victoria Falls Hydro	Hydro	108.00
	Lunzua River Hydro	Hydro	14.50
	Lusiwasi Hydro	Hydro	12.00
	Chishimba Falls Hydro	Hydro	6.00
	Musonda Falls Hydro	Hydro	10.00
	Shiwang'andu Hydro	Hydro	1.00
Itezhi-tezhi Power Corporation	Itezhi-tezhi Hydro	Hydro	120.00
Zengamina Limited	Ikelengi	Hydro	0.75
Lusemfwa Hydro Power Company	Mulungushi	Hydro	32.00
	Lunsemfwa Hydro	Hydro	24.00
	Total Hydro		**2,398.25**
Maamba Collieries Limited	Maamba Power Plant Coal	Coal	300.00
	Total Coal		**300.00**
Copperbelt Energy Generation Plants	Bancroft Diesel	Gas Turbine	20.00
	Luano Diesel	Gas Turbine	40.00
	Luanshya Diesel	Diesel	10.00
	Mufulira Diesel	Diesel	10.00
ZESCO Generation Plants	Luangwa Diesel	Diesel	2.60
	Shango'mbo Diesel	Diesel	1.00
	Total Diesel	Diesel	**83.60**
Ndola Energy Generation Plants	Ndola	Heavy Fuel Oil	110.00
	Total HFO		**110.00**
Off-grid Solar PV Power Plants	Muhanya Solar Limited Sinda Village Solar	Solar	0.03
	Mugurameno Chirundu Solar	Solar	0.01
	Additional Standard Micro-grids	Solar	0.07
	Total Solar		**0.11**
	Ngonye Solar Power Company	Solar	34.00
Grid Connected Solar PV Power Plants	Bangweulu Solar Power Company	Solar	54.30
	Copperbelt Energy Corporation	Solar	1.00
	Total solar	Solar	**89.30**
	Grand Total		**2,981.32**

The purpose of climate change policies is to lessen greenhouse gas (GHG) emissions from electric power production by encouraging production of electricity with no carbon content and supplement electricity supply [11]. Therefore, selecting appropriate RES with reduced climate change impacts can bring social, economic and other environmental satisfaction. A switch to RES distributed power generation is considered to be a prospective passage for attaining several sustainability goals [11].

Production of power from coal thermal power plants can emit 1.129Kg of carbon dioxide equivalent per kilowatt - hour (CO_2 eq/kWh) [12] which is hazardous to the environment. In India it has been found that 0.8-0.9Kg/kWh is discharged to the atmosphere in coal power plants [13]. The U.S. Energy Information Administration under the Environmental Investigations Agency (EIA) has indicated that 2.21 pounds/kWh (~1.00Kg/kWh) [14] carbon dioxide equivalent of GHGs is released from coal power generation process. The implication of this is that generation of 1kWh of energy from coal power production is coupled with a discharge of 1kg CO_2 eq/kWh of GHG. Energy produced from fossil fuels such as coal have a negative impact on the environment as production of electricity is coupled with emissions of GHGs that contribute to global warming.

Zambia has therefore embarked on installing on-grid solar PV system to supplement the nation's power supply. There are three categories of solar PV systems in Zambia. These are on-grid, off-grid and mini-grid.

1.1.1 On-grid PV System

On-grid solar PV system is a power generation system that is connected to the grid [15]. It is connected to the local utility company's grid or nation's grid. On-grid PV power systems do not need a battery bank [16]. Once a PV power generation system produces power, it is injected into the national utility grid for further distribution and supply to consumers [17]. Power generated from on-grid PV systems supplements the nation's power supply. On-grid solar PV power systems do not generate electricity during the night and depend on power from the grid to keep equipment alive.

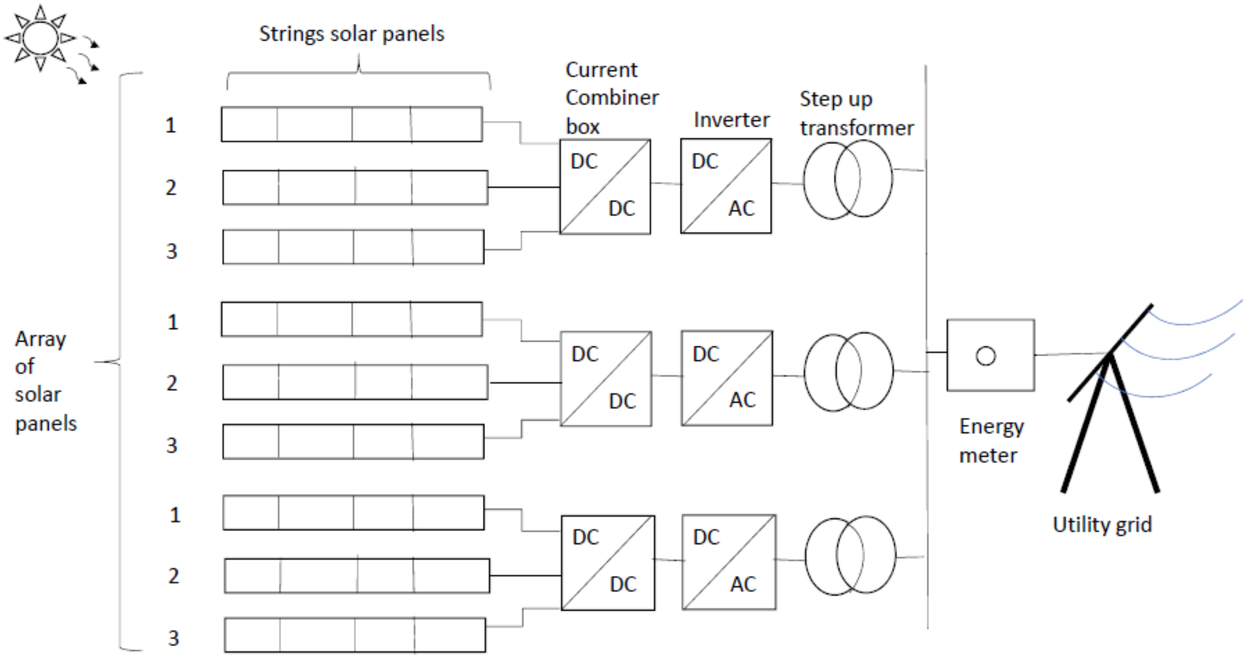

Figure 1.1 On-grid Solar PV system schematic diagram

1.1.2 Off-grid PV System

Off-grid solar PV system is a standalone system that is not connected to the grid [18] and require an energy storage system in form of batteries for the power produced [19]. The radiation from the sun is converted into energy during the day when there is sunlight. This prompts for an off-grid system to have a storage system in form of batteries. Off-grid solar PV power systems are best suited for home use or standalone buildings.

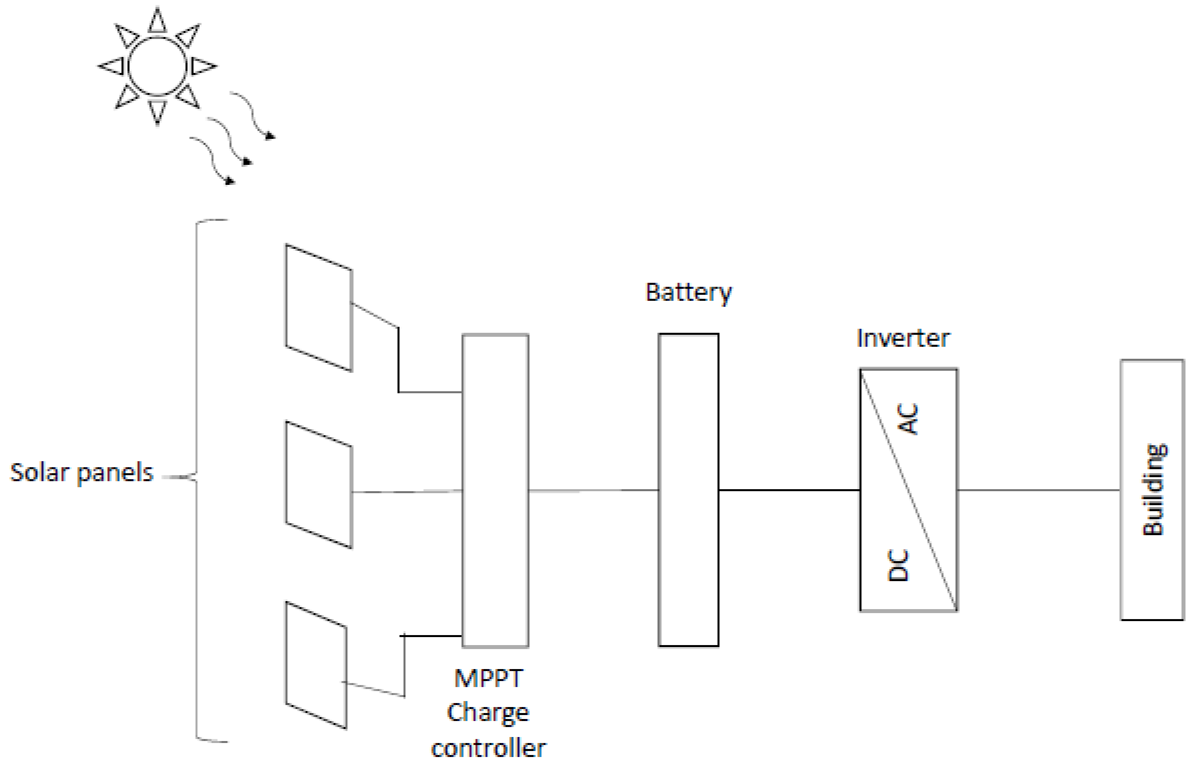

Figure 1.2 Off-grid solar PV system schematic diagram

1.1.3 Mini-grid PV System

A mini-grid is a small centralised PV power generation system that supplies electricity to a cluster of households and businesses in small area that do not require high consumption of power [20]. A mini grid is equipped with a battery bank and is not connected to the grid [21]. Mini-grids are mostly used to distribute and supply electricity in rural areas [22].

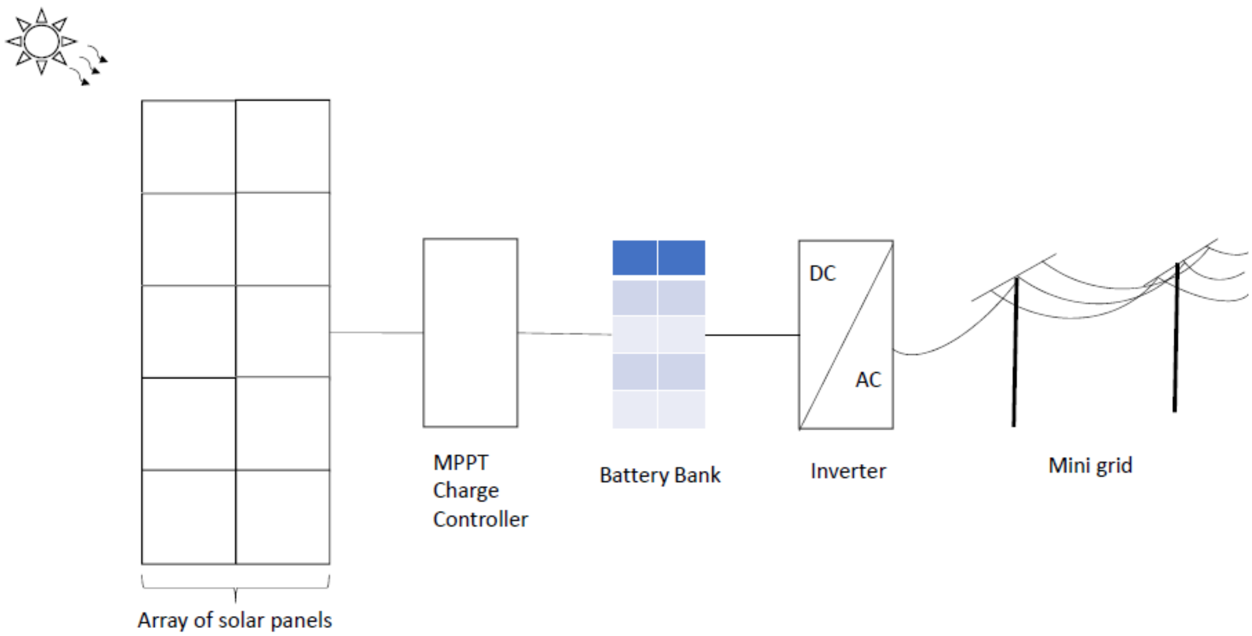

Figure 1.3 Mini-grid solar PV system schematic diagram

1.2 Statement of the Problem

Zambia is experiencing impacts of climate change including decreased hydropower generation. Diversification is needed in the country's energy mix by increasing the use of alternative energy sources.

This study is therefore aimed at gathering information on technical details of the installed plants and to evaluate technical performance as well as social, economic and environmental benefits. The other information to be collected is operational parameters, construction and operational challenges, energy import and export, tariff structure and revenue for the existing solar PV power plants.

No critical study has been done in Zambia to provide weaknesses, strengths, lessons learnt and best practices of the existing on-grid solar energy systems for future solar energy entrepreneurs.

1.3 Aim

The aim of this research is to study the major on-grid solar energy initiatives in Zambia.

1.4 Objectives

The objectives of the study were to:

i. provide detailed and up to date information and comprehensive documentation on on-grid solar energy systems in Zambia.
ii. critically analyse the strengths and weaknesses of the existing on-grid solar energy systems and their impact on Zambia's energy security, financial viability and environmental sustainability.
iii. identify and list good practices, lessons learnt and recommendations for on-grid solar energy initiatives for use in future solar energy investments in Zambia.

1.5 Hypothesis

The Zambian on-grid solar PV power systems will be technically feasible and financially viable with a plant performance ratio (PR) above 75 % leading to a meaningful break-even point and negligible Green House Gas (GHG) emission.

1.6 Significance of the Study

Zambia's energy sector has suffered immensely due to the adverse effect of climate change. Low rainfalls resulted in low water levels in hydropower stations reservoirs in 2015 [4] and the main water reservoir, the Kariba Dam has never attained its maximum level since 2015 [9].

Kariba Dam hydropower station has never operated at full capacity since 2015 which has resulted in reduced power production capacity of Zambia with prolonged blackouts. The low capacity of power production has hence affected the mining and other economic sectors in Zambia. There is need therefore, to study on-grid solar energy initiatives to supplement the country's power supply. The study will avail entrepreneurs and other stakeholders with valuable information necessary to invest in on-grid solar PV systems.

1.7 Outline of the Dissertation

The first chapter gives the introduction, background, statement of the problem, aim of the research, objectives, hypothesis and significance of the study. The second chapter reviews the literature in line with the research objectives. Chapter three discusses the methodology by outlining how the research was conducted and avails the tools that were used to carry out the research. The fourth chapter gives the results and analysis of the information that was collected. The dissertation ends with a discussion about the research, recommendations for future use and implementation.

1.8 Scope of the Dissertation

This dissertation covers and provides technical details of three solar power plants in Zambia. These are *Ngonye* solar power plant, *Bangweulu* solar power plant and *Copperbelt Energy Corporation (CEC)* solar power plant. Technical and financial feasibility study has been assessed for *Ngonye* and *Bangweulu* solar power plants to determine the economic benefit to the country and profitability to the solar PV power plant developers. The performance of the grid connected solar PV power plants have been evaluated in a quest to assess their strengths and weaknesses as well as lessons learnt and good practices.

Chapter 2

Theoretical Background and Literature Review

2.0 Introduction

This chapter gives a review of the literature about on-grid solar PV systems based on the objectives of the research. The literature stresses on the work and technology of on-grid PV solar systems and their contributions to the nation's energy demand. This is followed by the factors affecting the output of the solar PV power systems. It further underlines on-grid solar energy initiatives and their contribution to the generation of solar power production in an enabling environment with good economic, social and environmental policies. The chapter ends with policies and institutional framework governing the on-grid solar energy systems as well as the procedures for obtaining license to produce, transmit and supply of electricity.

2.1 On-grid PV System

Solar energy is the most prominent amongst the RES due to its global availability and advancement in technology [23]. The application of solar energy in the course of peak load moments minimises the load on hydropower generators to meet the nation's demand [23]. The only obstacle for on-grid PV power systems is the high initial capital investment as opposed to conventional energy sources [24]. On-grid PV integrated system permits huge amounts of electricity generated from PV system to be injected into the available utility grid [25]. PV power generation system has different components including solar panels, current combiner boxes, inverters, transformers, low-tension (LT) high-tension (HT) panels, capacitor bank, current differential relay, meters and cabling system.

The inverter has a cardinal role of converting direct current (DC) to alternating current (AC) with the desired operating frequency. The size of the inverter to be used in on-grid PV power systems is determined with reference to the amount of DC produced by solar panels [26]. Simulation softwares help in selecting the appropriate available inverter [27] to the solar PV system.

In PV power systems, there are fluctuations in voltage and frequency because of atmospheric conditions. Constant voltage and frequency are important in grid-connected systems to avoid disturbances in the utility grid. Inverters are needed to supply constant voltage and frequency by absorbing or supplying reactive power including synchronisation of the systems and feed PV power into the utility grid with the highest attainable efficiency [25].

2.2 On-grid Integration System

On-grid integration system incorporates ultra-modern inverter, anti-islanding, grid-plant protection and solar-grid forecasting technologies. Nevertheless, a successful incorporation of the capacitor bank into the existing solar energy system is cardinal for voltage support purposes.

2.2.1 Inverter System

An inverter system is the coordinating centre of processes of a PV power system [25]. It is an electronic device that converts DC to AC. Inverters have features that enable them to be the central manipulation unit of the PV power generation system. Inverters do not produce their own power but depend on the incoming DC power.

There are three main types of inverter systems. These are sine wave also known as pure sine wave, modified sine wave or modified square wave in actual sense and a square wave. Figures 2.1, 2.2 and 2.3 show sine wave, modified sine wave and square wave voltage outputs from inverters.

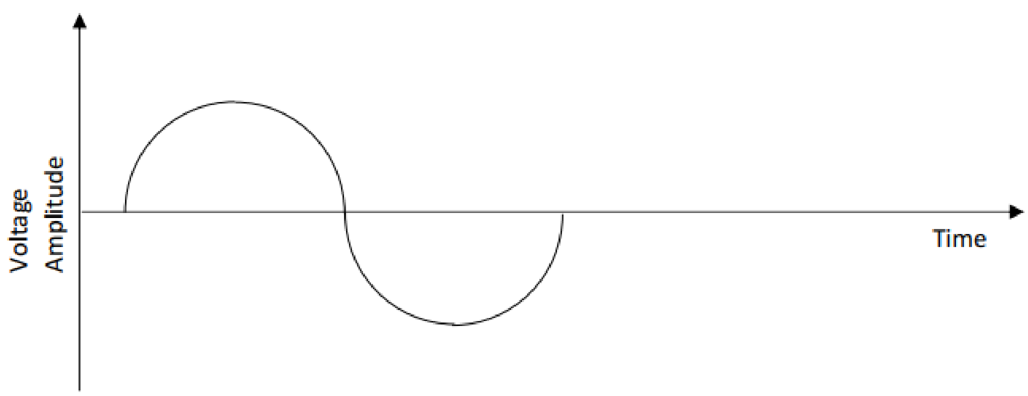

Figure 2.1 Sine wave voltage

Sine wave inverters are used for widespread or general applications. This is actually what is obtained from the utility grid for general purposes [28].

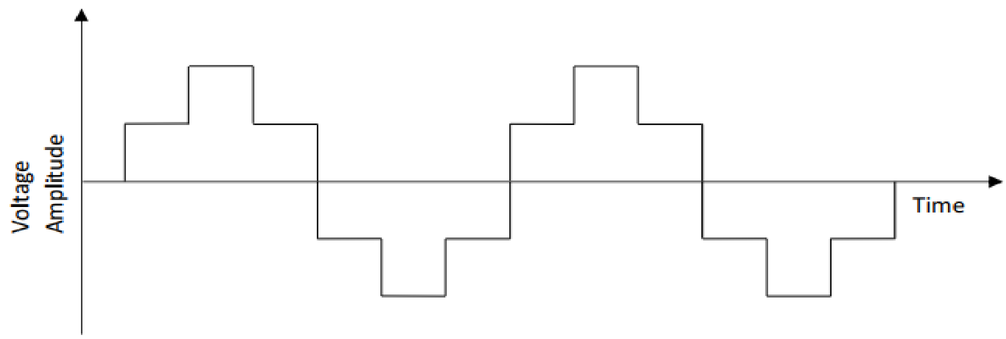

Figure 2.2 Modified sine wave voltage

Modified sine wave inverters are used for resistive, capacitive and inductive loads [28].

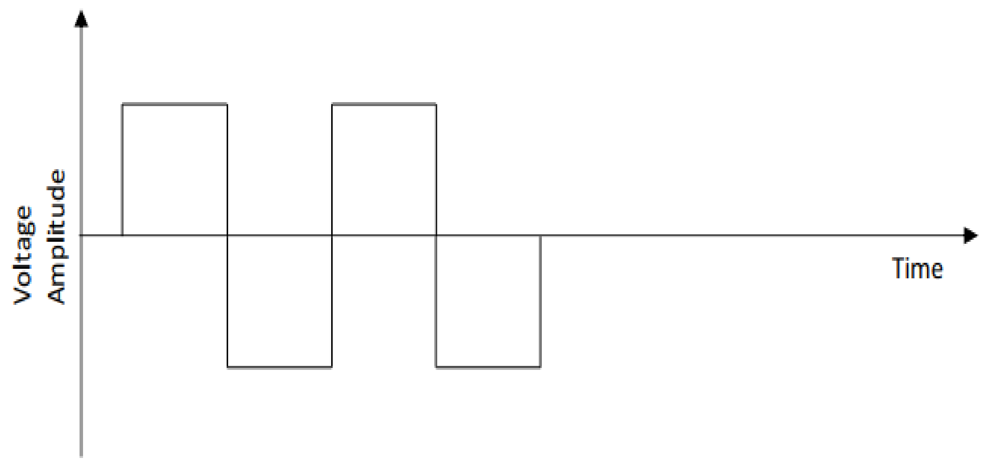

Figure 2.3 Square wave voltage

Square wave inverters are used for supporting motors alone. Square wave inverters produce a “humming” noise in electrical appliances where they are employed.

The selection of an inverter for a particular solar PV system is based on the DC size of the solar power plant. The DC size of the solar PV power plant dictates the size and number of inverters to be used to convert DC to AC. There should be a voltage match between the DC size and the installed inverters. Inverters’ voltage size might be slightly lower than the DC size as this can be compensated through losses encountered by solar panels. There are two types of inverter systems that are mainly used in on-grid solar power systems, namely, string inverters and central inverters.

2.2.2 Central Inverter

In central inverters, current from several strings of solar panels is connected to the inverter in parallel through a DC combiner box [29]. A combiner box is a device that aggregates current from several strings of solar panels. In commercial or huge solar PV power plants, several solar panels are connected in series to add up voltage. Several strings of solar panels are then connected in parallel to add up the current. The use of a combiner box is suitable for solar PV systems with the same solar panels and do not need too many Maximum Power Point Trackings (MPPTs) [30]. The purpose of an MPPT is to optimise the energy obtainable from the array of solar panels at any particular moment or under any condition. Solar panels produce non-identical values of voltage and current though not to a greater extent. The MPPT is employed to obtain the maximum possible power and it does this by varying the resistance hence adjusting voltage and current [31]. A central inverter receives aggregated current from several strings of solar panels with the help of a combiner box. Figure 2.4 show the connection of the central inverter.

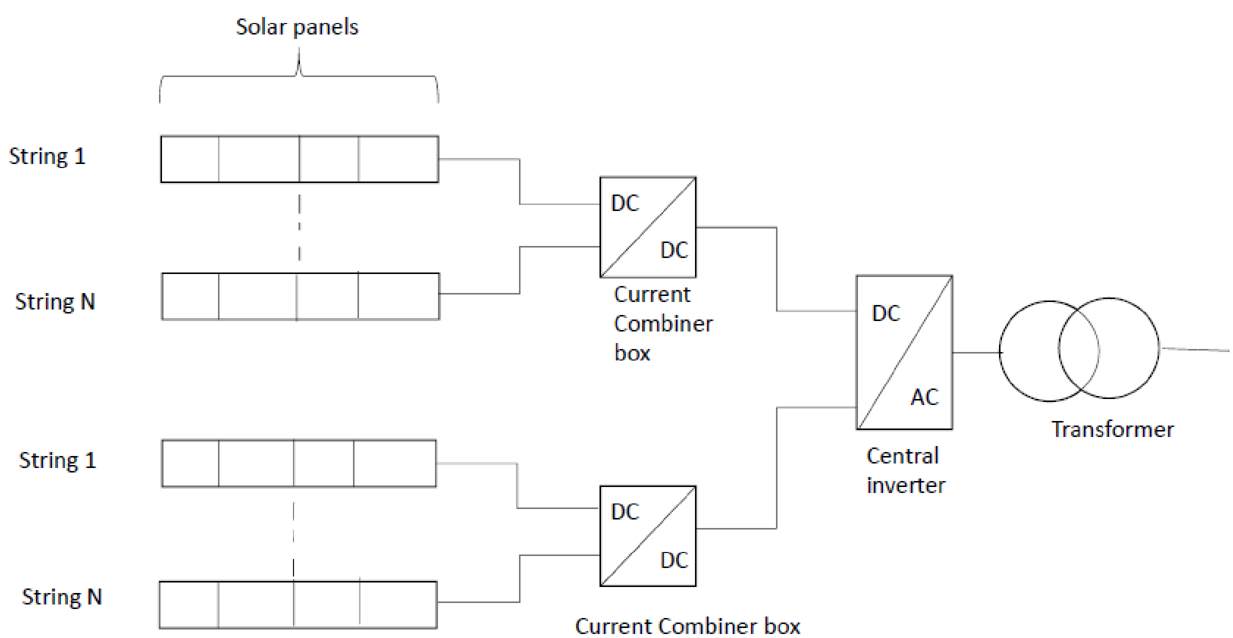

Figure 2.4 Schematic diagram showing the central inverter in an on-grid solar PV system

2.2.3 String Inverter

In string inverters, a string of solar panels is connected straight to the inverter without the use of DC combiner boxes with the help of numerous Maximum Power Point Trackers (MPPTs) as shown in Figure 2.5. This is suitable for a solar PV system with different solar panels and specifications [30]**.** The string inverter has the DC and AC sides integrated in it and conversion of DC to AC occurs within the inverter [27].

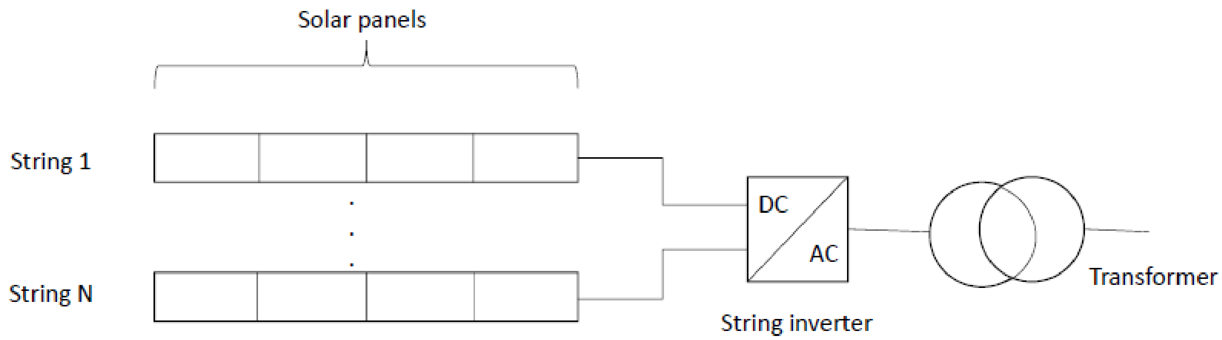

Figure 2.5 Schematic diagram showing a string inverter in an on-grid solar PV system

2.2.4 Anti-islanding Technology

An on-grid solar PV power system plays an important role to satisfying energy demand for end users. Nevertheless, the technology of grid connected system has set backs with regard to unexpected islanding occurrence that give rise to utility grid protection concerns and therefore risking the safety of workers [32]. It is therefore important to have a system in place that will guarantee the safety of utility workers and equipment.

Islanding is a phenomenon in which solar PV power plant keeps on supplying power to the utility which is isolated. In accordance with the Institute of Electrical and Electronics Engineers (IEEE) 1547 Section 4, it is mandatory for a PV solar power plant to disconnect from the utility grid inside two seconds when an island is formed [25]. Therefore, a PV power plant should be equipped with a system that must sense the formation of an island and disconnects from the grid within the minutest interval of time [33]. Therefore anti-islanding system disconnects the solar PV power plant from the grid immediately an island is formed. When the grid is reinstated, the inverter must not bridge inside one minute of grid reinstating after isolation or blackout. An important feature of anti-islanding protection is that a grid connected PV power generation system will only operate when grid power is active. On-grid inverters undergo anti-islanding examinations in the course of manufacturing to scrutinise if they are able to connect and disconnect [25].

2.2.5 Islanding Detection Methods (IDMs)

There are two methods usually employed in islanding detection system in grid connected PV systems. These are remote technique and local technique. The local technique is split into passive, active and hybrid techniques [25].

2.2.6 Passive Method

Passive method detects variables at the point of connection between a PV system and the grid for the purpose of detecting islanding. There is a relay in the islanding protection system that disconnects the PV solar power plant from the grid upon detecting disparities. Parameters that are monitored include variations in voltage, frequency, rate of change of power, total harmonic distortion and impedance [32].

2.2.7 Active Method

Active islanding detection method is done intentionally to observe effects of the disruptions on the grid [34]. This method monitors and stops islanding by detecting changes created by the interference. Active method has a core concern in that injection of small disturbance may compromise on power quality and bring about instability. Another problem is that this method needs additional equipment to inject the signal of disturbance [35]. Parameters that are monitored include frequency, voltage and phase [32].

2.2.8 Hybrid Method

A combination of passive and active methods produce an anti-islanding system referred to as hybrid method. Hybrid method incorporates both active and passive IDMs.

2.2.9 Remote Technique Method

This is a telecommunication-based method that depends on the exchange of signals in the middle of the PV power plant and the grid. The condition of the grid circuit breakers is the basis for detection in this method. The PV power plant is equipped with a receiver and circuit breakers connected between the PV power plant and the grid have transmitters. In case of islanding, a signal is conveyed to trip the PV power plant upon monitoring the condition of the grid circuit breaker. This method is extremely reliable but very expensive to put into practice. Standard utility telephone wires are required to implement this system and with advancement in technology, optic fibres can now be used [36]. The most commonly used methods in remote technique are; Power Line Carrier Communication (PLCC) and Supervisory Control and Data Acquisition (SCADA) [37].

2.2.10 Capacitor Bank

Solar panels have a longer lifespan as compared to inverters and this poses a challenge in PV solar power plants especially that inverters have the responsibility for many plant downtimes regarding PV power generation [38]. Therefore, inverters are connected in parallel with capacitors for voltage support and stability.

Several capacitors are connected in parallel with the PV power plant to avoid voltage changes and hence PV power output. Voltage changes are usually caused by variations in insolation which can lead to quick variations in voltages at the Point of Common Coupling (PCC).

The problem of voltage changes can be solved by operating a PV power plant with a leading power factor coupled with a capacitor bank connected in parallel to the PV power plant or the inverters for the purposes of compensating reactive power absorbed by inverters [39]. The reactive power of the capacitor bank is chosen in such a way that it compensates the reactive power absorbed by the inverter.

Figure 2.6 is a schematic diagram showing the capacitor bank connected by a single circuit breaker through to PCC and parallel to the PV system. The selection of the reactive power ***jC*** is done in such a way that it compensates the reactive power ***C*** absorbed by inverters in the system. Therefore, the capacitor bank controls the reactive power from the inverters in the PV power system. Upon producing its rated active power ***P***, there is a flow of the reactive power to the PCC that is given by jC-C and it is very close to zero. On account that there is an unexpected fall in PV power output owing to fast change in irradiance, the unexpected power change at PCC is ***P-jC*** [39].

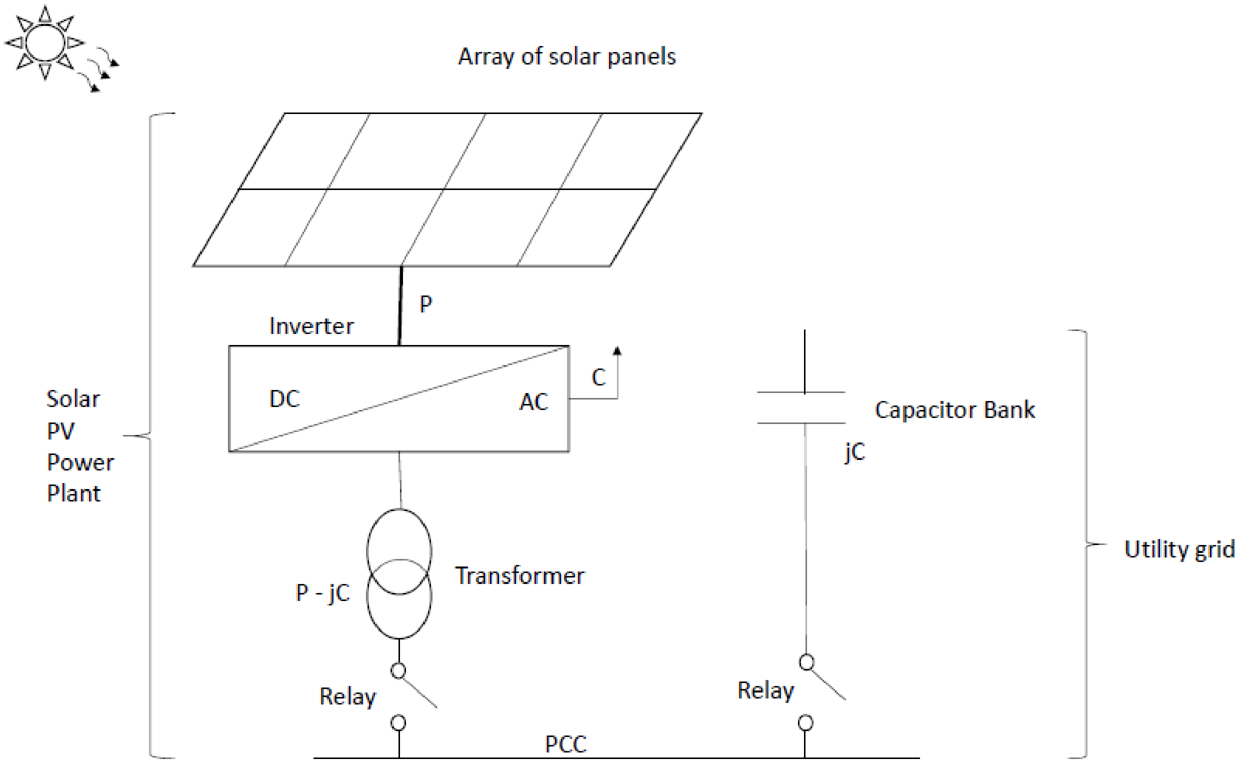

Figure 2.6 Connection of a capacitor bank in parallel to PV plant [39]

The capacitor is the source for reactive power generation. The size of the DC link capacitor can be determined from equation 2.1 [40] and is selected in accordance with the minimum possible capacitance needed coupled with the maximum acceptable ripple current [38].

$$C = \frac{2P_{max}}{[fV_{dc}^{2}(1 - k^{2})]} \tag{2.1}$$

where P_{max} is the maximum DC power out, f represents frequency, V_{dc} is the DC voltage and k is the ripple factor.

Capacitance can also be computed as presented in equation 2.2 below [41].

$$C = \frac{P}{2\omega_g V_{dc} V_r} \tag{2.2}$$

where P is the power rating for the inverter, ω_g is the grid frequency and is equal to $2\pi f_g$, V_{dc} is the input voltage for DC, whereas V_r is the maximum allowed ripple voltage.

2.2.11 Current Differential Relay

PV power plants have a unidirectional flow of current. During the day when generation of electricity is in process, current flows from the PV power plant to the grid. During the night when PV power generation is not in process, current flows from the grid to the PV power plant to keep equipment running. Therefore, a current differential relay is necessary in that it protects the PV power plant from over current during the night. In case of over current, the relay disconnects the PV power plant from the grid.

2.2.12 Energy Meters

These are meters that monitor the amount of energy being exported to the grid. Besides recording exported energy, energy meters record imported energy at night from the grid. It is essential to monitor the amount of energy being exported and imported for purposes of accounting.

2.3 Factors affecting PV Power Output: Atmospheric Conditions, Geographic Location and Orientation of Solar Panels

The output of solar panels is largely dependent on atmospheric state and location of the area where solar panels are mounted. The efficiency of solar panels is an important factor with regard to PV power output. The efficiencies and other ratings of solar panels are given at Standard Test Conditions (STC) of the solar panels. Measurements are performed in a clean laboratory with PV panel temperature of 25°C, solar irradiance of 1000 W/m^2 and air mass (AM) of 1.5 [42]. The efficiency of solar a panel is affected by weather conditions and particles deposited on surfaces of solar panels.

2.3.1 Atmospheric Conditions

The state of the atmosphere with regard to its composition in terms of temperature, wind, clouds, humidity and precipitation has an effect on the performance of solar panels.

Efficiency of a solar panel varies inversely as the temperature [43]. When the temperature is low, solar panels produce high voltage leading to increased efficiency. On a sunny and hot day, high temperature and solar radiation are likely to be experienced.

A windy day has an effect on the performance of solar panels with regard to dust deposition. At low wind speed, the deposition of dust is high as compared to high wind speed but excluding times with dust storms [44]. Deposition of particles on surfaces of solar panels reduces light transmittance hence affecting the amount of PV output negatively [45].

Rainfall is usually accompanied by thick clouds that reduce the amount of light reaching the panels hence reducing the output power of solar panels. The only advantage of rainfall is that it brings about a cleaning effect by removing dust accumulation from surfaces of solar panels and has a cooling effect which decreases the temperature of the panels. The amount of water vapour in the atmosphere reduces the intensity of solar radiation reaching the solar panels. Light from the sun is either absorbed or reflected by the water vapour in the atmosphere [46].

2.3.2 Geographic Location

Insolation is defined as the amount of solar energy received per unit area per unit time on a surface. Insolation is also referred to as solar irradiation. The amount of insolation affects the output of a solar panel. When insolation is high, the output of the solar panels is high and when insolation is low, the output of solar panels is low. The average insolation in Zambia is about 5.5kWh/m^2/day with about 3,000 sunshine hours per year [47][48]. The western part of Zambia has a vast area with very high insolation figures but unfortunately, the distance from potential PV sites to the grid connection point is long.

Solar radiation is the fuel for solar PV power production. Therefore, an accurate assessment of the solar radiation is important for estimation of PV power production at any place. Measured values of solar resource do not exist in many parts of the world especially developing countries. Therefore solar resource is estimated using different modelling techniques. Solargis recently prepared high accuracy global solar resource maps under contract obligations of the World Bank [49].

This work was funded by Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund managed by the World Bank under a global initiative of the Renewable Energy

Resource Mapping. The purpose of the solar maps is to give swift and uncomplicated access to solar information and maps worldwide [49]. Shown in Figures 2.7, 2.8 and 2.9 are Global Horizontal Irradiance (GHI) for long-term mean daily and yearly totals, Global Tilt Irradiance (GTI) at optimum tilt for long-term mean daily and yearly totals and Photovoltaic power Output potential (PVOUT) for an open space with fixed mounted PV system for long-term mean daily and yearly totals.

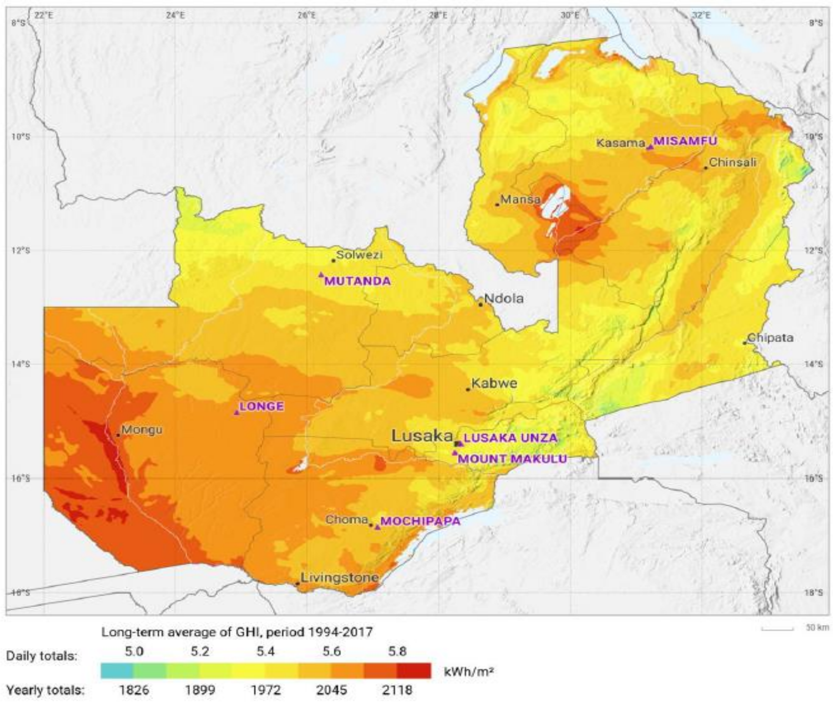

Figure 2.7 GHI for long-term mean daily and yearly totals [49]

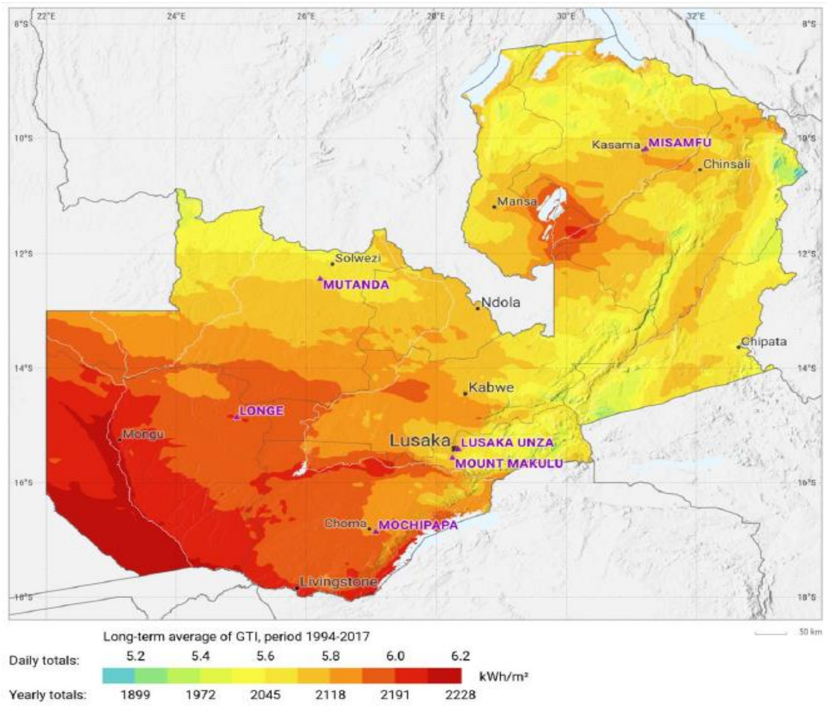

Figure 2.8 GTI at optimum tilt for long-term mean daily and yearly totals [49]

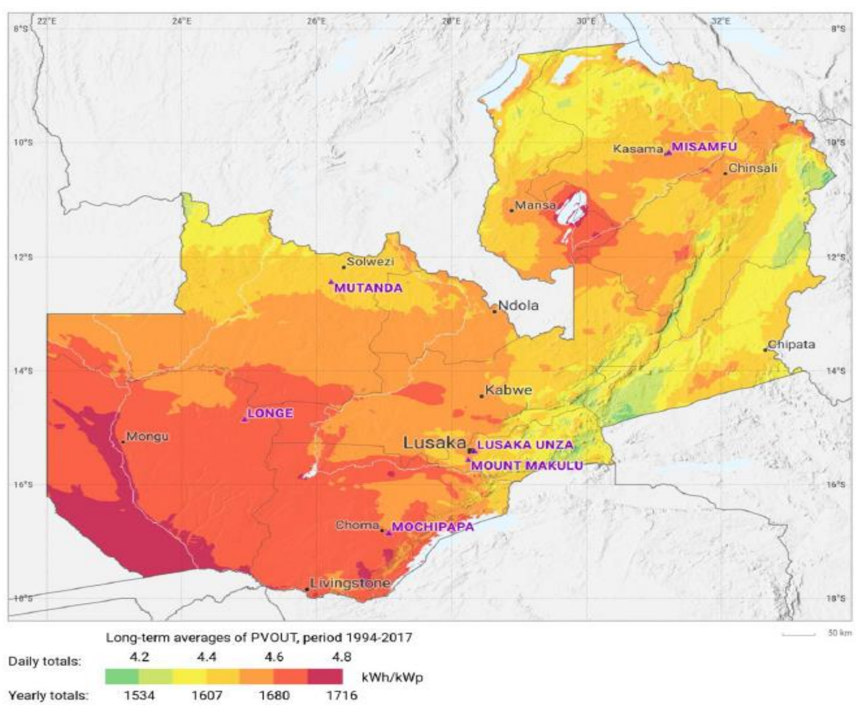

Figure 2.9 PVOUT for an open space with fixed mounted PV system for long-term mean daily and yearly totals [49]

2.3.3 Orientation and Angle of Tilt of Solar Panels

In order to maximize the incident irradiation on solar PV panels, the angle of inclination and orientation of solar panels is selected optimally with reference to the geographical location of an area [50]. As a rule of thumb, the angle of inclination of the panel is taken to be equal to the latitude of the place. On the other hand, Solar panels are oriented to face the North in the Southern hemisphere and South in the Northern hemisphere [51].

A solar PV panel receives the maximum solar radiation from the sun when light hits it at right angles [52]. It is therefore of great importance to track the Sun so that light hits solar panels at right angles during the day to maximise power generation. When solar trackers are used, there is a power gain of about 20% [52]. However a tracking system is costlier. The tracking system comprises the tracking tool, sensing element, driving system, tracking algorithm, control unit and the positioning mechanism [53].

2.4 On-grid Solar Energy Initiatives in Zambia

Zambia recently embarked on some on-grid solar PV power initiatives in cooperation with cooperating partners in order to meet the county's energy demand.

2.4.1 Scaling Solar

Scaling up solar is an on-grid solar energy initiative driven by the World Bank Group (WBG) that has a transparent and competitive tender process that enables the development of Independent Power Producers (IPPs) in sub-Saharan Africa [54]. In Zambia, scaling solar is implemented by the Zambian Government with the aid of the World Bank Group through the International Finance Corporation (IFC). The IFC finances the programme by lending money to IPPs or solar developers**.** The secretariat of scaling solar insures the developer against the default risk of ZESCO.

The purpose of scaling solar is to show through pilot programmes the social, economic and environmental viability of GHG-free RES in the quest to create viable markets for solar power in each participant country [54]. The programme envisages to procure about 600 MW of power to be fed into the grid.

2.4.2 Alternative Renewable Energy Investment Programme (AREIP)

AREIP is a substitute yet supportive programme to scaling solar which reviewed offers that were not solicited along with prior qualification of solar developers on grounds of the standards presented in the scaling solar initiative. Three solar projects were selected regarding this initiative.

2.4.3 Global Energy Transfer Feed-in Tariffs (GET FiT)

GET FiT is an on-grid solar energy initiative that promotes the development of GHG-free RES for purposes of diversifying the energy generation mix and sustainable growth. GET FiT Zambia is implemented by the Zambian government with the support from the German Government through Kreditanstalt fü Wiederaufbau (KfW) Bank and the African Trade Insurance (ATI). The main goal of GET FiT Zambia is to implement the Renewable Energy Feed-in-Tariff (REFiT) strategy.

The main objective of the GET FiT Zambia programme is to procure 120MW of solar power and integrate it into the grid in the quest to implement the REFiT strategy. The GET FiT program also aimed to contribute to diversification of Zambia’s energy blend whilst making sure that cost-reflective and environmentally and socially sustainable projects increase worth for consumers. It also aims at establishing paper work that is standard for IPPs as well as upgrade regulatory and licensing processes and encourage competition along with independent sector involvement in the Zambian energy sector.

KfW helps the German government to attain its objectives through development of policies and global growth collaboration. It also plays a vital role in making the growth capacity of African countries firm and alleviating climate change globally. With regard to GET FiT Zambia, KfW collaborates closely with the Government of Zambia through the Ministry of Energy.

In case the off-taker (the utility company operating the grid) delays in paying tariffs or defaults, the ATI help IPPs to get the cash they need. ATI has a Regional Liquidity Support Facility (RLSF) that helps IPPs in case the off-taker delay or defaults tariff payments [55].

2.5 Policies Governing On-grid Solar Energy Initiatives and Systems

2.5.1 National Energy Policy (NEP)

National Energy Policy (NEP) is a programme in which the government addresses matters related to energy production, transmission, distribution and usage. In order to achieve satisfaction with regard to economic, social and environmental benefits, it is important to manage the energy sector in an effective and sustainable way. Therefore, a vigorous National Energy Policy (NEP 2019) is important in making it easy to have access to energy services.

The main purpose of NEP is to accelerate development of the energy sector and supply electricity to all areas in the country as well as protecting the interest of consumers and other stakeholders [47].

2.5.2 Renewable Energy Feed-in Tariff (REFiT) Strategy

The REFiT Strategy is an execution strategy on grounds of consulting all main participants in the renewable energy (RE) sector. The purpose of REFiT strategy is to increase the country's generation output by means of independent sector investment in RE technologies. REFiT strategy targets small and medium projects of not more than 20 MW. Therefore, this will eventually add to a variety of energy systems for the sake of enhancing energy security. This will enable the strategy to give direction to the functioning of various institutions in the energy section that are subsets of the RE sub sector. For unity purposes, the strategy will make sure all levels included in the subsector take part in the execution of the strategy [56].

2.6 Institutional Framework for On-grid PV Systems

2.6.1 The Ministry of Energy (MoE)

Formulating and implementing policies is important to the energy sector. Formulating of policies is not enough to improve the energy sector but implementation is of great importance. The Ministry of Energy (MoE) is in charge of formulating and implementing policies in the energy sector [56]. The MoE supervises all units that are attached to the ministry and provide guidance where necessary.

2.6.2 The Energy Regulation Board (ERB)

The Energy Regulation Board (ERB) is a quasi-governmental institution that plays a vital role in regulating the energy sector by making adjustments with regard to energy prices, handling complaints, generating codes of standards, approving energy infrastructures and providing guidelines in the energy sector [47]. Operational licences issued by ERB to IPPs are infrastructural based. The implication of this is that the facility to be used by the IPP should comply with ERB's laid down infrastructure standards.

2.6.3 Zambia Electricity Supply Corporation (ZESCO)

ZESCO is a government owned utility company that generates, distributes and supply power to consumers. All on-grid independent power producers (IPPs) feed power into the ZESCO grid which is the national utility grid. ZESCO has challenges in that it is the only off taker of power produced by IPPs.

2.6.4 Office for Promoting Private Power Investment (OPPPI)

OPPPI is a unit of the Ministry of Energy whose main role is to promote investment in the development of GHG emission-free power projects. The main objectives of OPPPI are to identify projects; carry out feasibility studies; to come up with a suitable solicitation approach along with paper work for solar developers, secure solar developers and to negotiate for Implementation Agreements (IA) [47].

2.6.5 Industrial Development Corporation (IDC)

The Industrial Development Corporation plays a vital role in solar energy development as it is mandated to procure 600MW of power from IPPs through different on-grid solar energy initiatives. The IDC has criteria for selecting solar energy developers and has shares of 20% in any developed solar power plant. The IDC does not handle any technical or operational aspects. The president of Zambia chairs the board of IDC. Being a shareholder in IPPs, the IDC evaluates, determines price and lowers the input risk [57].

2.7 Legal Framework for On-grid PV Systems

A legal framework has a set of rules that governs the way in which all players in the energy sector should carry out their operations. The Zambian Government has rules to follow in the energy sector. These include Electricity Act, Chapter 433 of the legal codes of Zambia and the ERB Act, Chapter 436 of the legal codes of Zambia [56].

The Energy Regulation Act created the ERB, as an organisation, whose main function is to license and regulate institutions that plan to carry out operations in the energy sector. The Electricity Act regulates the production, distribution, transmission and supply of electricity.

2.8 Power Purchase Agreement (PPA)

A power purchase agreement is an agreement between an independent power producer (IPP) that generates electricity for sale and the company owning the utility grid, usually called an off-taker that buys electricity at an agreed tariff in USD c/kWh. The idea of PPA is to provide guarantee to the IPP that its generated power will be bought so that its investment is not stranded. In Zambia, the off taker is ZESCO. Another off-taker by the name of Greenco has come on board recently. Greenco supply power to Southern African Power Pool (SAPP). This will be a relief to ZESCO where procurement of power from IPPs is concerned [58]. PPAs for on-grid power plants in Zambia currently run for a period of 25 years. The tarrif under the PPAs can be fixed for the duration of the PPA or it can escalate at an agreed rate.

2.9 Tools for Technical and Economic Evaluation of Utility-scale Solar PV Power Plants in Zambia

The investment in an on-grid solar PV power system of any capacity or technology should yield results that will be profitable to the investor and of economic benefit to the country [59]. The analysis of technical, economical, policy and environmental factors is very cardinal with regard to evaluating the performance of the solar PV power system. It is prudent to carry out technical and financial feasibility analysis for purposes of determining or predicting the viability of an on-grid solar PV power system. There are several parameters (tools) used to analyse financial and technical feasibility of solar PV power plants. Figure 2.10 summarises important evaluation factors to consider when investing in a solar PV power system.

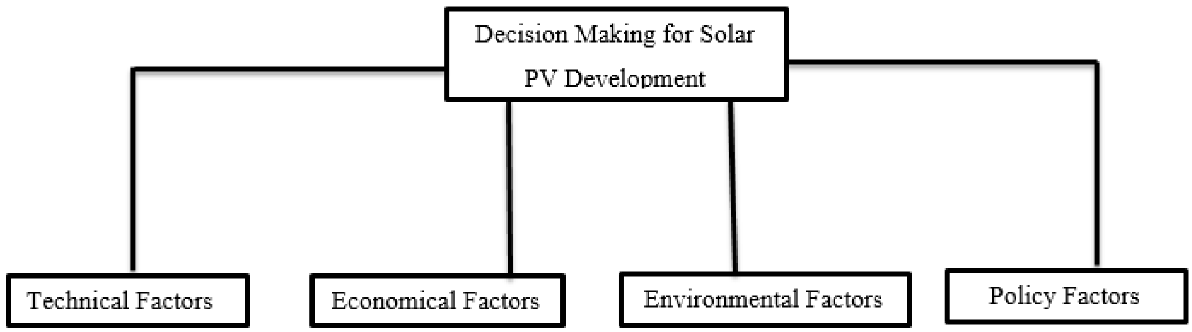

Figure 2.10: Evaluation factors for investment in a solar PV power system

2.10 Technical Parameters

2.10.1 Final Yield

The final yield (Y_f) of the solar PV system is the net output of energy for a specific period (day, month, year) per unit power of the DC nameplate of the PV installed system. Final yield does not account for losses with regard to the inverter inefficiency, solar panel's temperature, wiring, variations in irradiance, dust accumulation or snow and failure of other components.

$$Y_f = \frac{Final\ energy\ yield(kWh)}{Nominal\ DC\ power\ \ (kW)} \tag{2.3}$$

It is a representation of the time (number of hours) that the PV system arrangement would work at its power rating to supply the same energy as produced for a defined period. It is used to compare energy generated by PV systems of different sizes[60][61]

2.10.2 Reference Output

The reference yield is the conceptual attainable energy yield of the solar PV power system [62]. It is a representation of the maximum attainable energy for a PV power system at a particular location found at reference irradiance at STC.

$$Y_r = \frac{Total\ in - plane\ irradiance\ (\frac{kWh}{m^2})}{PV\ reference\ irradiance\ (\frac{kW}{m^2})} \tag{2.4}$$

Reference output or yield (Y_r) is the ratio of in-plane irradiance to solar PV reference irradiance and represents peak sun-hours of a particular location [63]. The standard PV reference irradiance is 1000W/m^2 [64].

2.10.3 Plant Performance Ratio (PR)

Plant performance ratio is the ratio of the measured or actual PV plant output to the expected output for a specific period under ideal conditions as found on the PV system nameplate. This is the ratio of the final yield (Y_f) to the reference yield (Y_r). PR measures the end result of the solar PV system with reference to the rated yield owing to inefficiency of the inverter, wiring, solar panel's temperature, variations in irradiance, dust accumulation or snow and failure of other components [60]. PR is an international accepted metric for assessing the performance of the solar PV power plant in accordance with the International Electrotechnical Commission (IEC). The European commission guidelines advocates for plant investigations when PR is below 0.75 (75%). According to European Union performance project for PV systems, a plant with PR of 0.8 (80%) and in excess, is considered to be outstanding [63].

$$PR = \frac{Y_f}{Y_r} \tag{2.5}$$

PR is not dependent on the location of the solar PV power plant and it is used to compare solar PV power plants in different areas. PR can also be calculated as;

$$PR = \frac{Actual\ plant\ ouput\ energy}{Calculated\ nominal\ output\ energy} \tag{2.6}$$

Nominal energy output is given by [65]

$$Energy\ output = Irradiance\ \times module\ efficiency\ \times effective\ module\ area \tag{2.7}$$

For nominal power, irradiance is considered for a specific period and the effective area of the modules forming a solar PV array.

2.10.4 Specific Yield (Sy)

Specific yield is defined as the ratio of the total of yearly energy produced to that of the installed capacity of the PV system [60].

$$S_y = \frac{Energy\ produced\ per\ year\ (kWh)}{Installed\ capacity\ (kW_p)} \tag{2.8}$$

It evaluates the actual or practical solar PV power potential.

2.10.5 Capacity Utilisation Factor (CUF)

Capacity Utilisation factor (*CUF*) is the ratio of the energy produced per year to the yield if the PV system had operated at nominal power the whole year [60].

$$CUF = \frac{Energy\ produced\ per\ year\ (kWh)}{8760\ \left(\frac{hours}{year}\right) \times\ installed\ capacity\ (kW_p)} \tag{2.9}$$

Therefore the relationship between Capacity Utilisation Factor and Specific Yield is,

$$CUF = \frac{S_y}{8760} \tag{2.10}$$

Capacity factor for solar PV power plants generally ranges between 12 and 24% [60].

2.2 Economic Parameters

2.2.1 Levelised Cost of Electricity (LCOE) of a Solar PV System

This is the cost associated with electricity generation of a generating power system taking into account all costs over the system's lifetime including investment, operational and maintenance and fuel costs. Thus, LCOE is an unchanging unit cost with the same present-day value insofar as the aggregated cost of constructing and running a generating power system over its entire lifecycle. In simple terms, LCOE changes different yearly costs to unchanging present cost and permits an exclusive cost value as an indication for resource cost.

The most important parameters that control LCOE are investment costs and rate of discount. The investment costs rank the most important as compared to the discount rate. The capital cost can be divided into module and Balance of System (BOS) costs. The module part includes costs of solar panels of the solar PV system array and assembly. BOS is inclusive of structural, electrical and electronic system and computer programming costs. LCOE is given by [66]

$$LCOE = \frac{Total\ Lifetime\ Costs}{Total\ Lifecycle\ Energy\ Generation} \tag{2.11}$$

Therefore, LCOE can be summarised as; [60]

$$LCOE = \frac{\left\{\frac{\sum_{t=1}^{n} C_t}{(1+r)^t}\right\}}{\left\{\frac{\sum_{t=1}^{n} E_t}{(1+r)^t}\right\}} \tag{2.12}$$

where; C_t is the total investment in time t (year),

E_t is the energy produced in time t (year),

n is the closing year for power generation,

r is the discount rate and,

t is the year number.

and $C_t = I_t + O_t + M_t$

$$E_t = S_1(1-d)^t \tag{2.13}$$

Where; d *is* the percentage degradation rate of solar panels,

I_t is the investment cost,

O_t and M_t are operations and maintenance costs, respectively, in year t denoted as O & M,

S_1 is energy generated for year 1.

2.2.2 Payback Period (PBP) or Grid Parity

Payback period is the period that is required for an investment to recuperate its costs. For PBP to be attained, the amount of revenue should be equal to the total cost of investment [60].

Payback period is calculated as

$$Grid\ parity = \frac{Total\ investment\ cost}{Annual\ revenue\ generation} \tag{2.14}$$

Payback period is also known as grid parity [66].

2.2.3 Net Present Value (NPV)

This concept focuses on the time value or current value of money over the project's applicable life. All expected market prices are discounted up to the current time and are treated as the current worth of the market price [60]. Equation 3.13 show that a sum *M* is paid every year for *n* number of years.

$$NPV = \sum_{t=1}^{n} \frac{M}{(1+r)^t} \tag{2.15}$$

where; *M* is the amount of money spent in year t.

r is the discount rate

t is the number of years in future

2.2.4 Operations and Maintenance Costs (O & M)

Operations and maintenance costs differ from one solar PV power developer to the other. They also differ from one region to the other globally. Maintenance costs include cleaning of solar panels, clearing of vegetation under or near solar panels and other equipment, wages, repairs on inverters, replacing of stolen modules and repairs and replacing of parts of trackers or none functioning ones. Solar PV power projects that are developed in Organisation for Economic Co-operation and Development (OECD) member countries, O & M costs are assumed to be US$18.3/kW/year and for solar PV power projects developed in countries that are not member states of OCED, O & M costs are assumed to be US$9.5/kW/year [67]. Since Zambia is not a member country of OCED, O & M costs for *Ngonye*, *Bangweulu* and *CEC* solar PV power plants are assumed to be US$9.5/kW/year.

Chapter 3

Methods, Data Collection and Materials

3.0 Introduction

This chapter gives an outline of how the research was carried out and the instruments that were used. The chapter is divided into four parts. The first part gives the information on low water levels for hydropower production obtained from Zambezi River Authority. The second part gives details about the contribution of solar energy towards the nation's energy supply and the third part outlines the technical details and operational parameters of solar PV power plants. The fourth part gives the economic and technical analysis of the on-grid solar energy systems in Zambia and their financial viability.

3.1 Data collection and Procedure

3.1.1 Status of Water Levels in Kariba Dam

The data on water levels for the Kariba Dam were obtained from 2014 to 2019 to assess the performance of the hydropower plant. Actual levels for the Kariba Dam water reservoir were collected from Zambezi River Authority on request from management. The data is shown in Table 4.1.

3.1.2 Installed Capacity by Power Generation Technology

The contribution of solar PV power towards the nation's energy supply was determined by considering all power generation technologies in the country and by taking note of the current total installed capacity of power generation. The current installed capacities were obtained from ERB's energy sector report for 2019. The results were recorded as shown in Table 4.2

3.1.3 Technical Details of On-grid Solar PV Power Systems in Zambia

The technical details of the solar PV power systems were obtained by visiting and working closely with the technical personnel in solar PV plants and getting illustration on how different components perform their respective tasks for plant operations. Essential components of the solar PV power plants were observed and their technical specifications recorded for purposes of analysing their execution with regard to solar PV power process. Technical details of the components were recorded in Tables 4.3, 4.4 and 4.5 for *Ngonye, Bangweulu* and *CEC* solar PV power plants respectively.

3.1.4 Estimated Yearly Energy Output using World Bank Global Solar Atlas (GSA)

The estimated annual energy outputs for *Ngonye, Bangweulu* and *CEC* solar PV power plants were calculated with the aid of GSA provided by the World Bank. The photovoltaic power output potential (PVOUT) for Lusaka, where the *Ngonye* and *Bangweulu* solar PV power plants are located were obtained from GSA. At the same time, the PVOUT for Copperbelt University was recorded for purposes of estimating the annual energy output for CEC solar PV system. The annual PVOUT for LSMFEZ (*Ngonye* and *Bangweulu* solar PV power plants) was found to be 1749 kWh/kW_p and for Copperbelt University 1760 kWh/kW_p. Copperbelt University was used as it is the nearest location to CEC solar PV power plant on GSA. Estimated energy outputs were computed using equation 3.1 and results recorded in Table 4.8 of the results and analysis chapter. The GSA computed values were compared to the actual values obtained from respective solar PV power plants and percentage deviations computed.

$$Estimated\ output = \ PVOUT\ from\ GSA\ (kWh/kWp)\ X\ Plant\ capacity\ (kWp) \tag{3.1}$$

The actual energy outputs from the *CEC*, *Ngonye* and *Bangweulu* solar PV power plants were recorded and compared to GSA energy outputs.

The percentage deviation between the two values of energy outputs were calculated as shown in equation 3.2 and results recorded in Table 4.8

$$Percentage\ deviation = \frac{(GSA\ computed\ value - PV\ energy\ value)}{GSA\ computed\ value} \times 100\% \tag{3.2}$$

3.2 Technical Feasibility of Solar PV Power Plants

Technical feasibility of *CEC, Ngonye* and *Bangweulu* solar power plants were evaluated based on the computed values of their respective *PR* and capacity utilisation factors. The evaluation was carried out by making use of irradiance values, energy outputs, efficiency of solar panels and plant installed capacities. Dimensions of solar panels were taken to calculate the effective surface area of the solar PV array.

Equation (2.5) was used to compute *PRs* of respective plants whilst equation (2.9) was used to compute the capacity utilisation factor. The total number and dimensions of the solar panels for all the three solar PV power plants under review were collected and recorded in table 4.9 to determine the effective surface area of the solar PV array. Results for *PRs* were recorded in Tables 4.10, 4.11 and 4.12 for *Ngonye*, *Bangweulu* and *CEC* solar plants, respectively. *Bangweulu* solar power plant has two types of solar panels (120 and 117.5MW) installed. Therefore, two different values of annual nominal energy outputs were computed and their ratios used to split their respective actual energies. Capacity factors were computed by first calculating the specific yield (S_y) using equation (2.8) and equation (2.10) to compute the capacity factor. Capacity factors for respective solar PV power plants were analysed as shown in Table 4.13. The final PV system yields (Y_f) were determined by calculating daily net energy outputs and employing equation (2.3) and results recorded in Table 4.14. The reference yields (Y_r) for *Ngonye*, *Bangweulu* and *CEC* solar PV systems were determined using equation (2.4) after computing their respective daily average irradiances. 1000W/m^2 was used as PV reference irradiance. Results were recorded in Table 4.15. The *PRs* with respect to Y_f and Y_r were calculated by employing equation 3.3 and results recorded in Table 4.16.

3.2.1 Solar PV Energy Output with Varying Irradiance and Temperature for Ngonye and CEC Solar PV Power Plants.

The relationship between solar PV energy output and irradiance was determined by plotting their respective graphs for different months of the year. The dependence of energy output on irradiance was deduced after analysing their respective graphs as shown in figures 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12 of the results in chapter 4. A major challenge faced during the research was non-disclosure of partly essential information such as irradiance data from *Bangweulu* solar PV power plant.

3.2.2 Energy Generated with Respect to Degradation Rate

The estimated energy generated for the life cycle of *Ngonye*, *Bangweulu* and *CEC* solar PV power plants were computed using equation (2.13). This was worked out as shown below.

From equation (2.13)

$$E_t = S_1(1-d)^t$$

For the life cycle of t = 25 years as per PPA.

$$E_t = S_1[1 + (1 - d) + (1 - d)^2 + (1 - d)^3 + \dots\dots\dots\dots + (1 - d)^{24}] \quad (3.3)$$

Equation (4.4) yields

$$E_t = S_1\left[\frac{1 - (1 - d)^t}{1 - (1 - d)}\right] \quad (3.4)$$

Equation (4.5) was used to calculate lifetime energy (25 years) outputs for *Ngonye* and *Bangweulu* solar PV power plants. The degradation rate for *Ngonye* solar power plant was calculated using the figure 3.1 as provided by the manufacturer. Degradation rate was computed as in equation (3.5).

$$Degradation = \frac{Max.efficiency\ in\ year\ 1 - efficiency\ in\ year\ 25}{25} \quad (3.5)$$

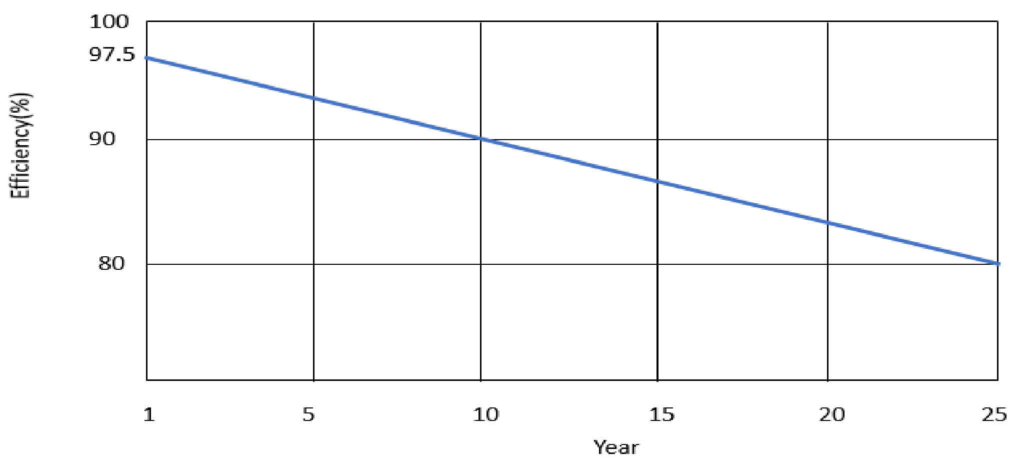

Figure 3.1 Ngonye solar PV plant manufacturer's degradation rate for solar panels [68]

3.3 Economic Feasibility of Solar PV Power Plants

The economic feasibility or financial viability of the solar PV power plants was determined by computing the net profit in exporting power to the national utility ZESCO. First and foremost, the annual energy produced was computed and used to calculate the estimated lifetime energy for 25 years. The other factor that was taken into consideration was the M & O costs. M & O costs were subtracted from the total revenue to find the net profit. The investment costs should be recuperated within a shortest possible time for the project to be viable.

3.3.1 Estimated Revenue (ER) from Ngonye and Bangweulu Solar PV Power Plants

The energy imports (energy received from the grid during the night when there is no generation of electricity from solar PV power plants) per year from ZESCO were taken into consideration when calculating revenue by subtracting annual energy imports from the annual energy outputs to come up with net annual energy output.

The estimated revenue for *Ngonye* and *Bangweulu* solar power plants were computed as shown in equation (3.6) and recorded in Table 4.17. The revenue for *CEC* solar PV power plant was not computed because it does not supply electricity at any tariff rate to power off-takers in the country.

$$ER = tariff\,\frac{US\$}{kWh} \times\ net\ estimated\ energy\ generated\ kWh \tag{3.6}$$

The net present value of O and M costs were calculated using eqn (3.7).

$$NPV\ =\ \frac{M}{1+r}\left[\frac{1-(\frac{1}{1+r})^{n}}{1-(\frac{1}{1+r})}\right] \tag{3.7}$$

where *M* is the money spent in year n

n is the year number and

r is the discount rate

The net lifetime revenue was calculated by subtracting lifetime O & M from the lifetime revenue and results recorded in Table 4.18.

The initial investment and O & M were also converted to their respective net present worth for purposes of computing the net profit of the project in order to determine the financial viability of the plant. Net profits of respective plants were computed and recorded in Table 4.18.

3.3.2 Economic Analysis of Solar Energy Initiative PV Power Plants compared to the Benchmark plant

In this sub section, *Maamba* coal power plant was taken as the benchmark for comparison. To determine the economics of power from utility-scale solar power plants in Zambia, the energy generated by the selected two solar PV power plants in Zambia were collected and aggregated. The cost of supplying solar PV power to ZESCO was computed and compared to the cost of supplying the same amount of power from the benchmark plant. The difference was calculated and analysed as presented in Table 4.20.

The economic benefit of the GET FiT solar energy initiative was analysed based on the tariffs agreed in the tenders that were added. The estimated annual energy outputs were calculated based on GSA parameters and by utilising equations 3.1 and 3.6. The results were tabulated in Table 4.21. The results from Table 4.21 were compared to those of *Maamba* coal power plant (benchmark) and recorded in Table 4.22.

3.4 Computation of Grid Parity for Ngonye and Bangweulu Solar PV Power Plants

Grid parities for *Ngonye* and *Bangweulu* solar PV power plants were computed using equation 3.12 and results recorded in Table 4.19 of the results and analysis section. The grid parity for *CEC* solar PV power plant was not computed because it does not supply electricity at any tariff rate to power off-takers in the country.

3.5 Solar PV Power Absorption Capacity

The amount of solar PV power that the grid can absorb was obtained from ZESCO and results analysed in Tables 4.23, 4.24 and 4.25. NPV for the cost saving from solar PV power that can be absorbed by the utility grid was computed and results recorded in Table 4.26.

3.6 Technical and Financing Model of Solar PV Power Plants

The technical and financing model of solar PV power plants were done by utilising RETScreen and PVsyst softwares, respectively. With regard to technical feasibility, PR was used as the key indicator for technical feasibility of the plant with NPV as the key indicator for economic feasibility. The results for technical feasibility of *Ngonye* solar PV power plant are presented in Tables 4.27 and 4.28 with figures 4.10 to 4.16. The results for technical feasibility of *Bangweulu* solar PV power plant are presented in Tables 4.29 and 4.30 with Figures 4.17 to 4.23. The results for economic feasibility of *Ngonye* solar PV power plant are presented in Tables 4.36 to 4.38 and Figures 4.28 and 4.29. The results for economic feasibility of *Bangweulu* solar PV power plant are presented in Tables 4.39 to 4.41 and Figures 4.30 and 4.31. Actual annual energy outputs were compared with annual energy yields from PVsyst software.

3.7 Comparison of Theoretical, Actual and Simulated values of Technical Parameters for Ngonye and Bangweulu solar PV Power Plants.

The values of PR and annual energy generation for *Ngonye* and *Bangweulu* solar PV power plants were collected, compared and analysed as tabulated in Tables 4.32 and 4.33.

Actual and PVsyst simulated values of final, reference, and specific yields were compared, analysed and their results recorded in Tables 4.33, 4.34 and 4.35 respectively. The values of actual and RETScreen simulated values of grid parities for *Ngonye* and *Bangweulu* solar PV power plants were collected, compared and analysed as tabulated in Table 4.42.

3.8 Strengths and Weaknesses, Lessons Learnt and Good Practices of On-grid Solar PV Power Systems

Strengths and weaknesses were obtained by evaluating the performance of the existing on-grid solar PV systems in Zambia. The evaluation was done by putting into consideration the technical, economic, social and environmental sustainability. The institutions in the energy subsector were engaged to further explore strengths and weaknesses of on-grid solar energy initiatives. This was accomplished by arranging meetings with the main participants in the RE sector and through questionnaires. Annual power generation and consumption as well as on-grid solar PV power absorption capacity were provided by ZESCO and results recorded in Table 4.23.

Chapter Four

Results and Discussion

4.0 Introduction

In this chapter results, computations and simulations of the data collected are presented. The presentation is in graphs, figures, tables, numbers and bar charts

4.1 Status of Water Levels in Kariba Dam

This shows that the Kariba Dam has never attained its full capacity of 487.71 m since 2015.

Table 4.1: Kariba Dam hydro power station water levels

Month	Water level (m) 2014/15	Water level (m) 2015/16	Water level (m) 2016/17	Water level (m) 2017/18	Water level (m) 2018/19	Water level (m) 2019/20
Oct	484.22	479.03	478.80	481.80	484.86	477.77
Nov	483.39	478.36	478.18	481.16	483.83	477.11
Dec	482.68	477.77	477.73	480.75	482.84	476.87
Jan	482.82	477.28	478.06	480.58	482.06	476.71
Feb	482.62	477.18	479.32	480.99	481.48	476.91
Mar	482.32	477.71	480.66	482.81	480.97	477.36
Apr	482.16	478.79	481.64	484.15	480.44	478.64
May	482.02	479.68	482.72	485.54	480.07	480.24
Jun	481.68	480.25	483.16	486.65	479.66	481.16
Jul	481.15	480.16	483.07	486.85	479.12	481.20
Aug	480.37	479.78	482.67	486.50	478.63	480.79
Sep	479.63	479.32	482.24	485.82	478.18	480.44

Figure 4.1 shows the variation of water levels of the Kariba Dam water reservoir for different years in Zambia. During 2015/16, 2016/17 and 2019/20 rain seasons, there was an increase in water levels in the reservoir from February to June due moderate rainfall. In addition, during 2017/18 rain season, there was an increase in water levels in the reservoir from February to July due to an improved rainfall pattern. During 2014/15 and 2018/19 rain seasons, there was a reduction in water levels for one year due to drought caused by adverse effects of climate change. This is attributed to poor rainfall patterns caused by climate change. Figures 4.1 and 4.2 show that the Kariba Dam

water reservoir has never attained its capacity with regard to water levels for all the six seasons under review.

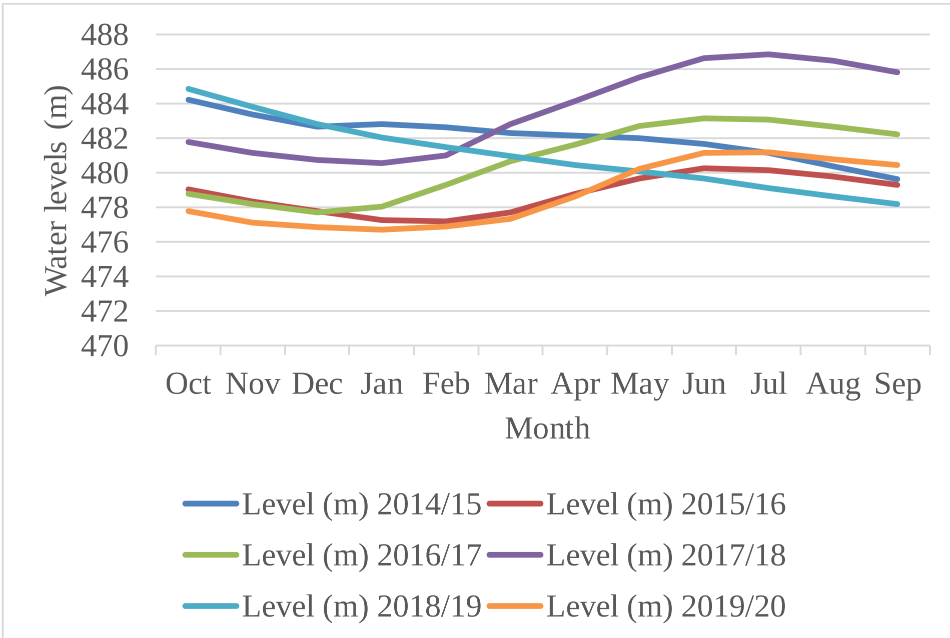

Figure 4.1 Kariba Dam hydropower reservoir water levels for six seasons

Figure 4.2 shows Kariba Dam daily reservoir water levels defined by the rule curve. The rule curve is a curve that splits the storage capacity of a water reservoir in sections where different plans for demand and supply will be applied and the limits for respective sections differ. The rule curve in Figure 4.2 shows that the water reservoir is far from attaining favourable water levels for hydropower generation. This calls for the country to consider other energy sources to meet the energy demand.

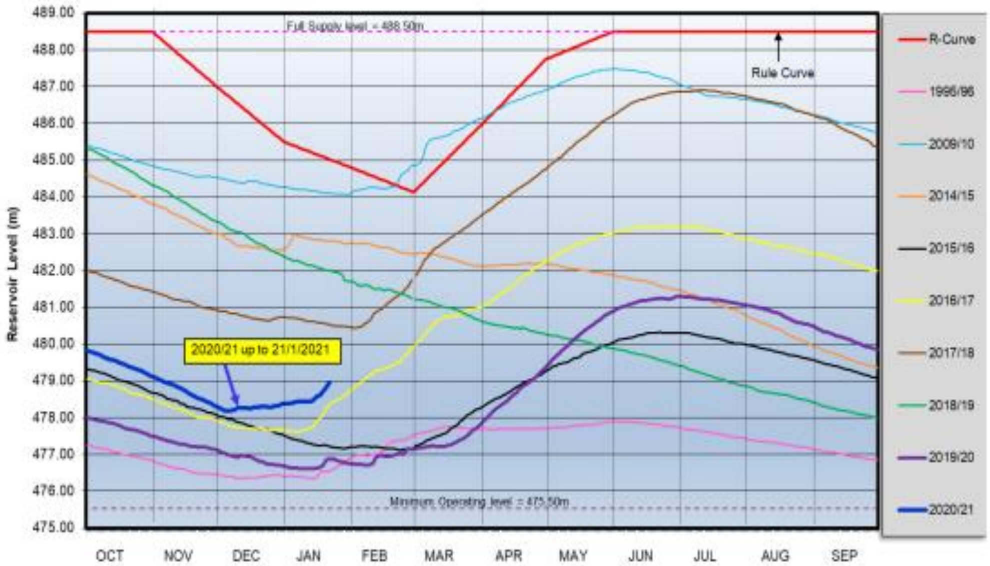

Figure 4.2 Kariba Dam water reservoir rule curve coupled with daily water levels [9]

The contribution of solar PV power towards the nation's energy supply was determined by considering all power generation technologies in the country and by taking note of the current total installed capacity of power generation. The current installed capacities were obtained from ERB's energy sector report for 2019. The results were recorded as shown in Table 4.2.

Table 4.2: Power generation installed capacities by technology

Technology	**Installed capacity (MW)**		**Installed capacity (%)**	
	2018	**2019**	**2018**	**2019**
Hydro	2398.25	2398.25	82.75	80.44
Coal	300.00	300.00	10.35	10.06
Diesel	88.88	83.60	3.07	2.80
HFO	110.00	110.00	3.80	3.69
Solar	1.10	89.47	0.04	3.00
Total	2898.23	2981.32	100.00	100.00

Figure 4.3 shows that Zambia's main source of electricity is hydropower. This is seconded by coal driven electrical power system and with solar PV technology the least.

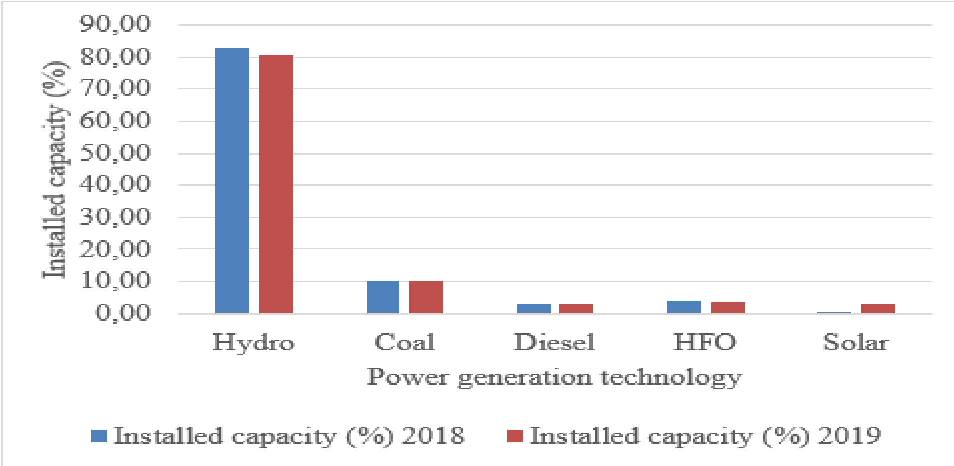

Figure 4.3 Zambia's electricity installed capacity by technology for the year 2018 and 2019

Coal has significantly contributed to supplement the nation's supply of electricity. The generation of electricity from coal is coupled with carbon emissions and this calls for implementation of GHG free power generation technologies.

4.2 Technical Details of Ngonye, Bangweulu and CEC solar PV Systems

4.3 Ngonye Solar PV System

Ngonye solar PV power plant is a 34 MW_p solar PV power plant situated at the Lusaka South Multi-Facility Zone (LSMFEZ) and was commissioned in May 2019 under the World Bank's Scaling Solar initiative. The cost of constructing the solar PV power plant was US$ 46m. The debt to equity ratio for constructing the plant was about 75% to 25% respectively. The debt to equity ratio shows how much money is invested in the company (project) by creditors to the amount of money invested by the company (owners). The debt providers were International Finance Corporation (IFC) and the European Investment Bank (EIB). The plant covers an area of 56 hectares and is owned by Enel Green Power of Italy.

4.3.1 Technical Details of Ngonye solar PV Power Plant

The technical details of the solar PV power systems were obtained by visiting and working closely with the technical personnel in solar PV plants and getting illustration on how different components perform their respective tasks for plant operations. Essential components of the solar PV power plants were observed and their technical specifications recorded for purposes of analysing their execution with regard to solar PV power process. Technical details of the components were recorded in Table 4.3.

The DC installed capacity of all the three solar PV power plants were calculated with reference to the rating of the solar panels and the AC outputs of the solar PV power plants were calculated with reference to inverter ratings.

Table 4.3: Technical details of the Ngonye solar PV power plant

No.	Description	Specific Description	Quantity	Capacity/Specifications
1	Plant capacity	Direct Current (DC)		34MW
2	Plant capacity	Alternating Current (AC)		33.84MW
3	System Operation	AC output		28.2MW
4	PV solar panels	Eastern part	60656	325W
5	PV solar panels	Western part	43924	325W
6	Solar trackers	Actuators	3486	230V, 60A
7	DC combiner box		145	
8	Auxillary transformers		14	70kVA, 550/380V
9	PCB		10458	
10	Dust monitoring system (Dust IQ)		3	
11	Block Pyranometers		7	
12	3 Weather stations	Pyranometer	4	
		Anemometer	1	
		Thermometer	1	
		Hygrometer	1	
		Barometer	1	
13	Current paralleling system (QPPI)		12	
14	Conversion units (CU) (Inverters)		7	1.41MW
15	Step up/down Transformers		12	2,82MVA, 550/33000V
16	Delivery cabin (MCR)		1	
17	Power quality analyser		1	
18	Current differential Relay		1	
19	CEWE pyrometers (Energy meter)		2	
20	Capacitors		240	50 micro F, 550V

The plant comprises two sides, that is, the direct current (DC) and alternating current (AC). The DC side comprises solar panels that produce DC and AC side incorporates inverters that convert DC to AC hence the name AC side. The solar PV system produces DC and AC by employing equipment and instruments listed in Table 4.3.

The Western part of the solar PV power plant has 43,924 polycrystalline solar panels, each 325 W, representing 42% of the total DC size of the plant and the Eastern part has 60,656 polycrystalline solar panels, each 325 W, representing 58% of the total DC side of the plant. The total number of solar panels is 104,580 giving DC power output of 33,839,975 W (33.84 MW). The plant is further divided into seven (7) blocks. The solar panels are connected in series and mounted on trackers in strings of 30. There are a total number of 3,486 trackers and each tracker has an actuator (230 V, 6 A) that tilts the solar panels to track the Sun. The actuators are energised by solar power through auxiliary transformers. To enable the solar trackers track the position of the Sun, the plant has pyranometers installed in all the seven (7) blocks of the plant. The pyranometers sense the position of the Sun and send signal to the Programmable Computer Box (PCB) in the control room that in turn stimulates the actuator to make a movement to tilt the solar panels. PV solar trackers adjust the direction that a solar panel is facing according to the position of the Sun in the sky. The trackers are limited to elevation angle ranging between -46.5° to +46.5°. By keeping the panel perpendicular to the sun, more sunlight strikes the solar panel, less light is reflected and more energy is absorbed and converted into current through a process called photovoltaic effect.

Weather conditions (wind speed, irradiance, air pressure, humidity and temperature) in the plant are taken care of by three (3) weather stations within the plant. These are connected to the control room where necessary parameters are monitored. The anemometer records wind speed, there is a threshold at which it activates the actuator to tilt solar panels into safe mode (180°) protection by sending a signal to the PCB.

The performance of the solar panels is affected by accumulated dust on their surfaces because the amount of accumulated dust lowers the amount of light reaching the solar panels. Therefore, the amount of dust on the surfaces of the panels has to be monitored on a daily basis to maintain a high performance ratio. To monitor dust and particle accumulation on solar panels, the plant is equipped with three (3) dust monitoring system (DustIQs). The DustIQs measure the amount of accumulated dust on the solar panels.

Strings of panels are connected to current combiner boxes and current in each combiner box is monitored from the main control room. Each combiner box is fed with 24 strings of panels and is protected from over current by fuses that are integrated within the box. Power from combiner boxes is fed into current paralleling system (QPPI) panels. The plant has 12 QPPI panels and each panel is fed with power from six (6) combiner boxes through PV steel collector cables. The QPPIs feeds power into conversion units (CU) where DC is converted into AC by inverters rated 1.41 MW yielding a total of 33.84 MW AC power. The AC output of 28.2 MW is what has been agreed with the public system operator (SO), which is, ZESCO. This is achieved by employing the Power Plant Controller (PPC) where the output power is controlled.

The QPPI panel is used for paralleling different combiner boxes before power is fed into inverters. The connection between the inverters and the QPPI has a breaker to disconnect DC and AC side in case of a fault. There are seven CUs and each CU is equipped with a Pyranometer that senses the position of the Sun. The plant has seven (7) CUs in accordance with the number of blocks. There are two types of CUs in the plant. Type-one has two (2) inverters and type-two has four (4) inverters. There are five (5) type-two CUs and two (2) type-one CUs giving the total number of twenty-four (24) inverters. The CUs are connected from one to the other by polyvinyl chloride (PVC) steel collector cables of different sizes depending on the amount of current being conducted.

Inverters are modular, that is, they have ten (10) conversion modules integrated in them and each conversion module is rated 141 kW giving the total rating of 1.41 MW for each inverter. The system has been designed such that two inverters should feed one transformer bringing the total number of transformers to twelve (12). Each of the conversion modules is connected in parallel with capacitors rated 50 µF, 550 V. Inverters give an output of 550V of AC power.

The transformers then step up 550 V from the inverters to 33 kV. The 33kV voltage from the 12 transformers is fed into the delivery cabin through collector cables, that is, collector east (400mm^2) for the eastern plant and collector west (300mm^2) for the western plant. The delivery cabin is the point of power export to the nation's grid. The delivery cabin is equipped with a SCADA room where all the signals and information regarding processes of the plant is collected and monitored.

The delivery cabin is also equipped with ELSPEC G4400 power quality analyser that monitors power quality, voltage and frequency. It is a requirement by ERB that each solar PV power plant must have a power quality monitor installed before power is injected into the national utility grid. After power quality inspection, 33 kV is then transmitted to the grid using three phase system.

The delivery cabin has two CEWE pyrometers, an electronic instrument that record the amount of energy imported to the nation's grid and it is a requirement by ERB that two energy meters for monitoring energy being exported be installed.

During the night when solar power is unavailable, the plant is kept live by 33 kV power from ZESCO that is stepped down by transformers to 220 V and during the day when solar power production begins, the plant synchronises AC and DC power to continue with solar PV power generation process. At night, the delivery cabin is programmed to work in reverse mode to accommodate power from ZESCO. The plant is protected by the current differential relay in case of over-current from ZESCO

The plant is equipped with interlocking key system to avoid human error with regard to equipment isolation in case one intends to work on or carry out maintenance on plant equipment. Interlocking keys are used for sequential control of equipment to ensure safe operation.

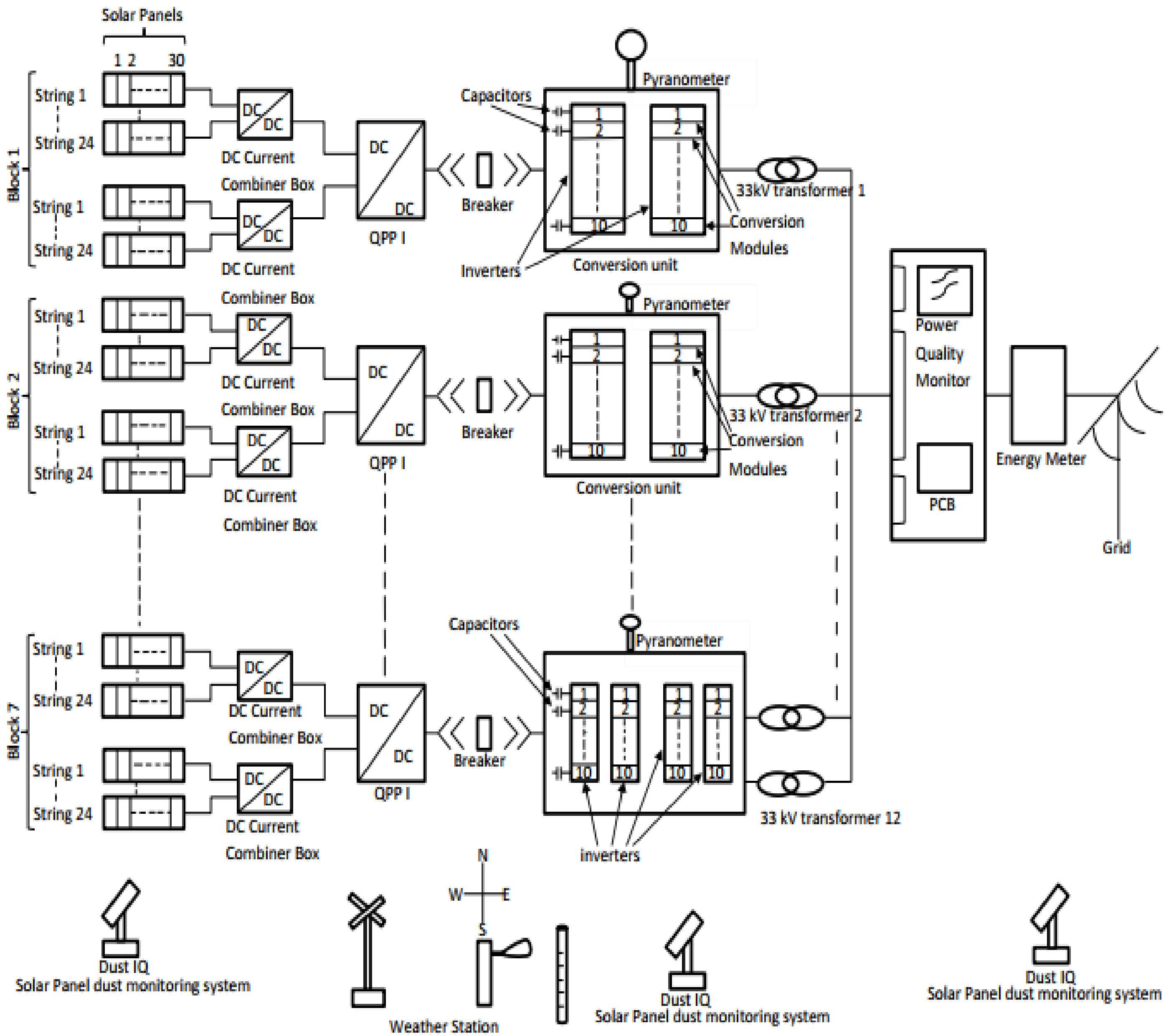

Figure 4.4: Schematic diagram of the Ngonye solar PV power plant

4.3.2 Tariffs Structure and Payment

Ngonye solar power plant exports power to ZESCO at the rate of 7.84 c/kWh [69]. ZESCO has the mandate to pay *Ngonye* solar PV power company (Enel Green Power) every month. In case of payment default by ZESCO, scaling solar initiative has the provision of insurance to provide the solar PV power companies with funds needed to operate the power plant.

4.3.3 Construction Challenges

i. The area is rocky and this proved to be a challenge when drilling holes for mounting steel structure supporters for solar panels and when drilling trenches for laying of PVC steel collector cables.
ii. The area became very slippery during rainy season such that construction work almost stalled.
iii. Expertise was mostly focussed on foreigners.

4.3.4 Operational Challenges

i. The plant has lost 50 solar panels through theft since the plant was commissioned and each solar panel cost US$ 115.
ii. There is too much vegetation (grass) in rainy season and this calls for additional manpower to manage vegetation that may cause shading on solar panels if not controlled.
iii. Actuators get jammed during the process and this leads to unplanned maintenance work.
iv. The plant has thousands of modules that poses as a challenge where cleaning is concerned
v. Expenses on washing solar panels, vegetation control and replacing solar panels.

4.4 Bangweulu Solar PV System

Bangweulu solar PV power plant is a 54.3 MW_p solar PV plant situated at the Lusaka South Multi-Facility Economic Zone (LSMFEZ) and was commissioned in March, 2019 under the IFC/World Bank Scaling Solar initiative. The cost of constructing the solar PV power plant was US$ 60m. The debt to equity ratio for constructing the plant was about 68% to 32% respectively. The debt providers were International Finance Corporation (IFC) and Overseas Private Investment Corporation (OPIC). The plant covers an area of 52 hectares and is owned by Neoen of South Africa.

4.4.1 Technical Details of the Plant

The plant comprises two sides, that is, the direct current (DC) and alternating current (AC). The solar PV system produces DC and AC by employing equipment and instruments as tabulated in Table 4.4.

Table 4.4: Technical details of the Bangweulu solar PV power plant

No.	Description	Specific Description	Quantity	Capacity/Specifications
1	Plant capacity	Direct Current (DC)		54.3
2	Plant capacity	Alternating Current (AC)		57.8MW
3	System Operation	AC output		47.5MW
4	PV solar panels	120W panels	400,000	120W
5	PV solar panels	117.5W panels	53,600	117.5W
6	Auxiliary transformer		8	
7	Dust monitoring system		5	
8	Weather station		5	
9	Block pyranometers		12	
10	AC combiner box		615	
11	Inverters	9-string	1,140	47kVA
		12-string	90	47kVA
12	LT panels		12	2400kVA
13	Step up/down transformers		12	4.8MW 33/0.480kV
14	RMU		7	
15	Capacitor Bank		1	5MVAr, 33kV
16	MCR	9 HT panels	1	630A, 33kV, 40kA
17	Power Quality Monitor		1	
18	Current differential relay		1	
19	Energy meters		2	

The DC side of the plant is made up of 400,000 (120 MW) and 53,600 (117.5 MW) Cadmium Telluride (CdTe) thin film solar panels bringing the total number of panels to 453,600 and giving DC output of 54,227,500 W (54.3 MW). The solar panels are inclined at an angle of 13^0 and facing true north. The DC side of the plant is partitioned into 12 blocks and each block is connected to 102 string inverters. There are two types of string inverters, the 9-string and 12-string inverters. Four strings of 90 solar panels each feed the 9-string inverters bringing the total number of panels feeding one inverter to 360. Four strings of 120 solar panels each feed the 12-string inverters bringing the total number of panels feeding one inverter to 480.

The 9-string inverter solar panels have ten (10) solar panels in series that forms one string, and nine (9) strings of these solar panels are connected in parallel to form a one 9-string of solar panels. This gives a total number of 90 solar panels in a one 9-string inverter solar panels. Then four 9-string inverter solar panels are fed into one inverter and hence the name 9-string inverters. This gives a total number of 360 solar panels feeding a one 9-string inverter.

The 12-string inverter solar panels have ten (10) solar panels in series that forms one string, and 12 strings of these solar panels are connected in parallel to form a one 12-string of solar panels. This gives a total number of 120 solar panels in a one 12-string inverter solar panels. Then four 12-string inverter solar panels are fed into one inverter and hence the name 12-string inverters. This gives a total number of 480 solar panels feeding a one 9-string inverter.

The 9-string inverters are 1 140 and the 12-string inverters are 90 bringing the total number of inverters to 1,230 and each with power rating of 47 kVA. Inverters are connected to AC combiner boxes with current rating of 160 A that are equipped with bus bars where inverters feed the power. The plant has 615 AC combiner boxes and each combiner box is fed with two inverters and has a manual switch inside to disconnect or isolate the DC from the AC side of the plant. The designed AC output of the plant is 57,810 kW but the agreed AC output with the system public operator is 47.5 MW. This is achieved by employing the Power Plant Controller (PPC) where the output power is controlled. The inverters give an output of 480 V of AC power.

AC combiner switches from each block are connected to Low Tension (LT) collection and distribution panels that are equipped with switch gears at the connection point with transformers. LT panels collect power from AC combiner boxes and feed transformers rated at 4.8 MW 33/0.480 kV. There are twelve (12) transformers in total and each transformer has a role to step up 480V to 33 kV of power collected from AC combiner switches.

The plant has a capacitor bank rated 5 MVAr, 33 kV. The capacitor bank is connected parallel to the plant for voltage support purposes. The capacitor bank is connected to the bus bar where AC generated power is offloaded.

Power from transformers is fed into Ring Main Units (RMUs). A RMU is a voltage cabinet used to integrate transformers to form a power distribution network. The solar plant has seven (7) RMUs, and each RMU has feeder panels in accordance with the number of transformers feeding it. Five of the seven RMUs are fed with two transformers each except block 4 and 5 transformers that have separate RMUs. RMU's panels are SF_6 gas filled equipment, that is, they are insulated by SF_6.

Collector cables collect power from AC combiner boxes to LT panels, from LT panels to transformers, from transformers to RMUs and from RMUs to the MCR.

The plant has five (5) weather stations equipped with anemometers, pyranometers, thermometers, barometers and hygrometers. These are connected to the control room where necessary parameters are monitored.

Each of the twelve blocks, has a pyranometer installed and inclined at 13°. This means block pyranometers are inclined at the same inclination angles as that of solar panels. This increases the accuracy of irradiance measurement received by solar panels.

The performance of the solar panels is affected by accumulated dust on their surfaces and the amount of dust on the surfaces of the panels has to be monitored on a daily basis to maintain a high performance ratio. Test and reference panel system have been installed for dust monitoring purposes. There are five (5) dust-monitoring systems in the plant. The reference panel is cleaned everyday whilst the test panel is only cleaned when solar panels for the whole plant are cleaned. Both panels are connected to the smart logger then to the control room.

The 33 kV power lines from the seven (7) RMUs, that is, from the 12 transformers are fed into the Main Control Room (MCR) through collector cables. The MCR is equipped with a Gas Insulated Substation (GIS) with nine (9) High Tension (HT) panels rated 630 A, 33 kV, 40 kA. The MCR is equipped with a SCADA room where all the signals and information regarding processes of the plant is collected and monitored. The MCR is also equipped with the Power Quality Monitor that monitors power quality. It is a requirement by the Energy Regulations Board (ERB) that each solar power must have a power quality monitor installed before power is injected into the ZESCO grid. There is an interconnector between the solar power plant and ZESCO grid and it is equipped with a protection unit that protects both plants from current overloads. After power quality inspection, 33 kV is then transmitted to the grid using three phase system through collector cables.

The MCR has two energy meters which records the amount of energy imported to the nation’s grid and it is a requirement by ERB that two meters for monitoring energy should be installed. This is the basis for billing and recording of energy imports and exports.

During the night when solar power is unavailable, the plant is kept live by 33 kV power from ZESCO which is stepped down by transformers to 220 V and during the day when solar power production begins, the plant synchronises AC and DC power to continue with solar PV power generation process. At night the delivery cabin is programmed to work in reverse mode to accommodate power from ZESCO.

The plant has a lock-in lock-out procedure that ensures that plant personnel can only work on plant equipment that is de-energised.

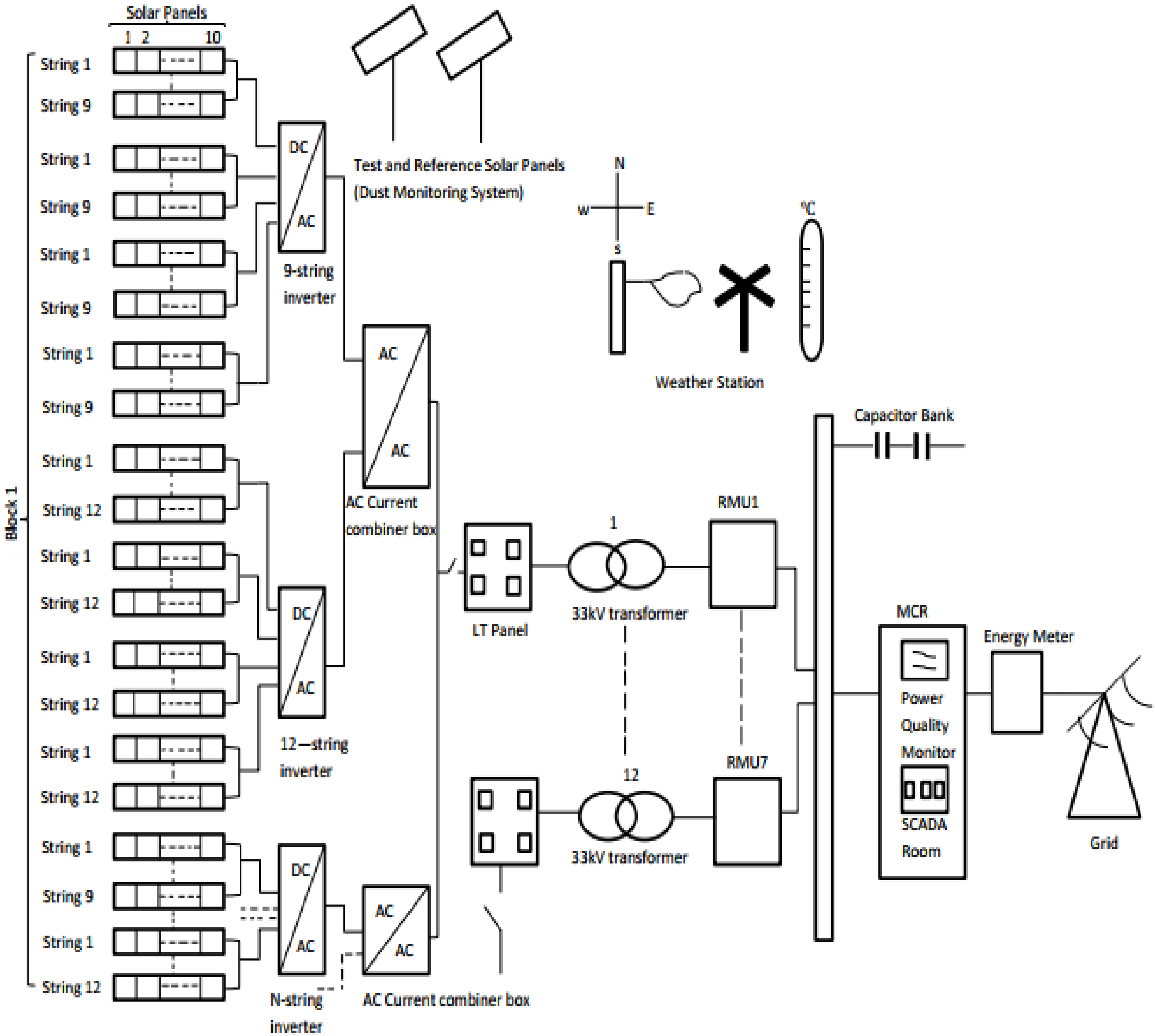

Figure 4.5: Schematic diagram of the Bangweulu solar PV power plant

4.4.2 Tariffs Structure and Payment

Bangweulu solar power plant exports power to ZESCO at a rate of 6.02 c/kWh [70]. ZESCO has the mandate to pay Bangweulu solar power company (Neoen South Africa) every month. The agreement with regard to tariff payments has a provision for the guarantor or Insurance Company (Bank).

4.4.3 Construction Challenges

- The area is rocky and this proved to be a challenge when drilling holes for mounting steel structures supports for solar panels and when drilling trenches for laying of PVC steel collector cables.
- The area became very slippery during rainy season such that construction work almost stalled.
- Expertise mostly lay with foreigners.

4.4.4 Operational Challenges

- Attempts have been made to steel power collector cables.
- There is too much vegetation (grass) in rainy season and this calls for additional manpower to manage vegetation that may cause shading on solar panels if not controlled.
- Cleaning of solar panels. The solar power company has hired a water tanker for purposes of cleaning solar panels.
- Expenses on washing solar panels, vegetation control and replacing solar panels.

4.5 CEC Solar PV System

CEC solar PV power is a 1 MW_p solar PV plant situated in Kitwe and was commissioned in March, 2018 at a cost of US$ 1.3 m. All logistics required to put up the plant was done within 12 months and the plant was constructed in 21 days. These logistics include license to manufacture and install solar power plant, feasibility study, decision letter from ZEMA, zoning approval from council and implementation strategy and agreement. The power plant was mainly for capacity building purposes in readiness for bigger power plants to be constructed in the future.

4.5.1 Technical Details

The plant comprises of two sides, that is, the direct current side (DC) and the alternating current (AC) side. The DC side has 3864 solar panels with power rating of 270 W producing DC power of 1,043,280 W. The solar panels are inclined at 15° and technical details of the components were recorded in Table 4.5.

Table 4.5: Summary of technical details of the CEC solar PV power plant

No.	Description	Specific Description	Quantity	Specifications
1	Plant capacity	Direct Current (DC)		1MW
2	Plant capacity	Alternating Current (AC)		0,864MW
3	PV solar panels		3,864	270W
4	DC combiner box		8	
5	Weather station	Pyranometer	1	
6		Anemometer	1	
7		Ambient temperature sensor	1	
8		Module temperature sensor	1	
9	Inverters		24	36-40kW
10	Step up/down transformers		1	1MVA, 0.4/ 11kV
11	PQ meter		1	
12	Energy meter		1	
13	Energy Check meter		1	

The AC side has 24 inverters rated at 36 kW with the maximum rating of 40 kW producing maximum and minimum power of 960 kW and 864 kW respectively. Each inverter has eight (8) inputs and seven (7) of the eight (8) inputs are connected to strings of panels in series. The seven strings connected to the inverter are in parallel. Each string has twenty-three (23) solar panels that are connected in series and the current from each string is fed into a single input of the inverter. This means each inverter is connected to 161 solar panels. There are twenty-four (24) inverters in total. The power from the inverters is fed into AC current combiner boxes and into the transformer. Each combiner box is fed with power from three (3) inverters giving a total number of eight (8) combiner boxes. The eight lines from the combiner boxes feed 400 V into the transformer which steps up the voltage to 11 kV. 11 kV is then transmitted to the grid using three phase system through an evacuation distance of 1.2 km.

The inverters used have been programmed such that they are compatible with the Zambian grid code. The inverters have an anti-islanding system that protects the solar power plant in case there is a blackout. The system disconnects the solar plant in case of a black out and should there be any fault on the three phase, the system can disconnect the plant from the grid. The plant has a control room where all operational parameters are monitored.

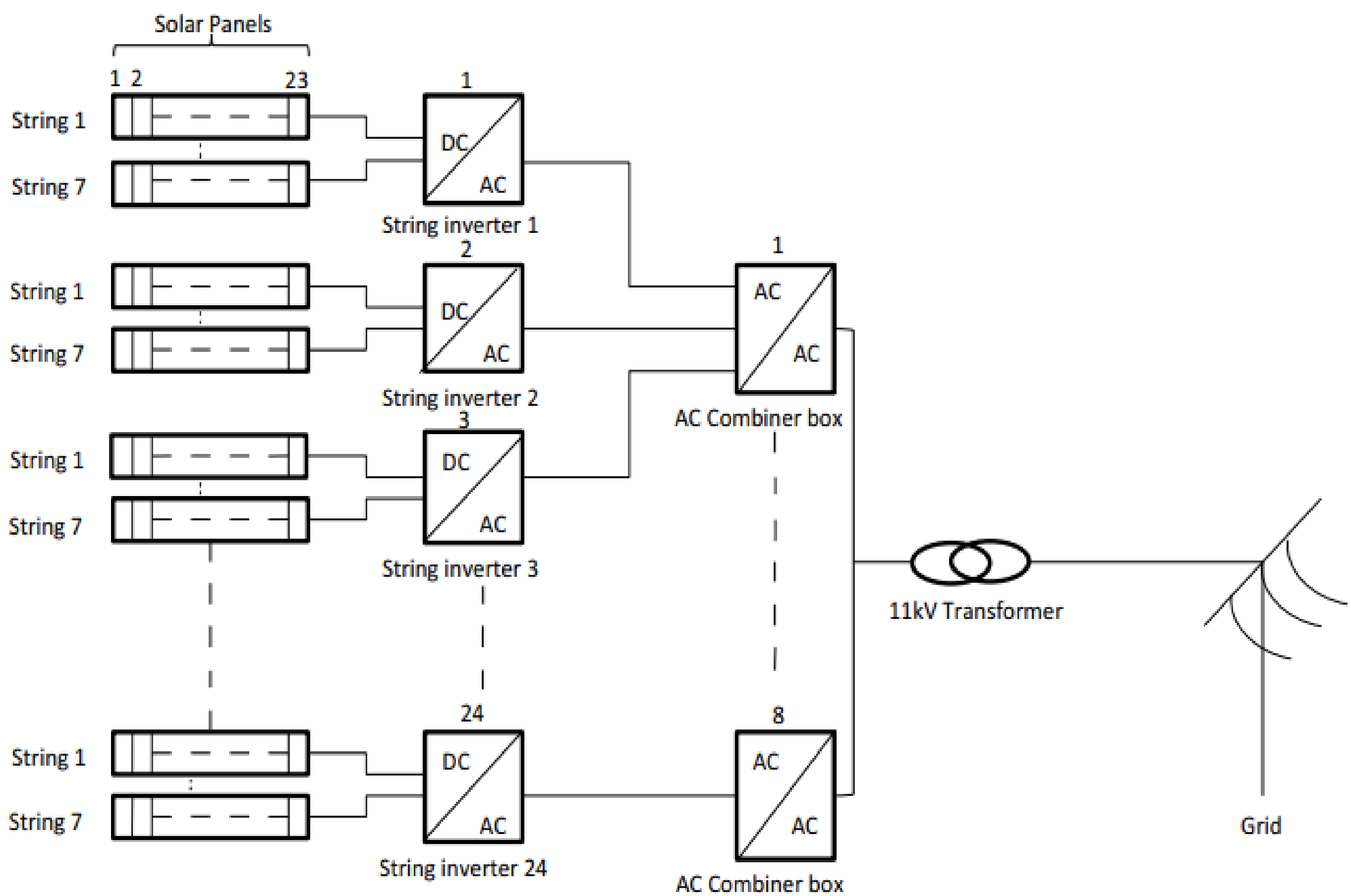

Figure 4.6: Schematic diagram of the CEC solar PV power plant

4.5.2 Upcoming Modifications

- CEC is considering to construct a battery bank for learning and/or education purposes.
- CEC is considering to install a solar panel's water cooling system to increase the efficiency of the plant.

4.5.3 Environmental Challenges before Commissioning the Plant

- ZEMA charged CEC for relocation of animals from proposed site.
- The trees on site were cut down and ZEMA instructed CEC to replant the trees at Copperbelt University
- License and other logistical requirements were unnecessarily delayed for approval.
- CEC carried out an impact assessment on transmission lines.
- CEC carried out an impact assessment of the solar plant on the grid. CEC had to use software called Etap system to assess the impact of the Solar PV system on the grid. This was done by replicating the solar plant when connected to the grid.

4.6 Operating Frequency

The Zambian grid code is designed to operate at a frequency of 50 Hz with a tolerance of ±2.5 Hz. Therefore, the solar PV power plants operate with frequency in the range of 47.5 to 52.5 Hz failure to which the solar PV power plant will be disconnected from the grid by the anti-islanding protection system.

4.7 Technical Feasibility of Solar PV Power Plants

4.7.1 Measurements of Irradiance, Module Temperature and Monthly Energy Outputs

Irradiance values and monthly energy outputs were utilised in calculating *PR* of solar PV power plant whilst PV solar panel's temperature was used to determine the effect of temperature on energy output. A major challenge faced during the research was non-disclosure of partly essential information from *Bangweulu* solar PV power plant. This records as a limitation to the study. Measurement of in-plane global irradiance PV module temperatures and monthly net energy output for Ngonye solar power plant are presnted in Table 4.6.

Table 4.6: Measurement of in-plane global irradiance PV module temperatures and monthly net energy output for Ngonye solar power plant

Month	Monthly average values				
	In-plane global irradiance (kWh/m^2)	**PV solar panel temperature (deg.cel)**	**Generated energy (MWh)**	**Imported energy (MWh)**	**Net energy output (MWh)**
Oct-19	6.60	41.61	4713.49	19.60	4693.89
Nov-19	5.20	36.25	4163.96	19.40	4144.56
Dec-19	5.60	36.20	4960.96	19.20	4941.76
Jan-20	4.40	32.59	4123.35	19.10	4104.25
Feb-20	4.30	32.15	3830.81	18.60	3812.21
Mar-20	5.20	34.72	5066.36	20.50	5045.86
Apr-20	5.62	35.68	5279.57	20.50	5259.07
May-20	5.86	32.99	5646.34	21.20	5625.14
Jun-20	4.45	27.41	3549.12	21.30	3527.82
Jul-20	5.20	28.17	4487.22	22.60	4464.62
Aug-20	6.06	34.09	5082.39	21.90	5060.49
Sep-20	6.24	36.64	5435.90	20.40	5415.50
Total			56339.47	244.30	56095.17

Table 4.7 shows determination of average daily energy yields from monthly energy yields for CEC solar PV system. Radiation in Wh/m^2 yields monthly average daily energy in kWh/m^2. The result of the monthly average radiation is an essential parameter in determining PR by using equations 2.6 and 2.7.

Table 4.7: Determination of average daily energy yields from monthly energy yields for CEC solar PV system

Month	Radiation yield/month (Wh/m^2)	Energy yield/month (kWh)	Average daily cell temperature (°C)	Monthly average daily radiation (kWh/m^2)	Monthly average daily energy yield (MWh)
Oct-19	182666.36	157885.92	33.18	5.89	5.09
Nov-19	165692.20	132422.03	32.27	5.52	4.41
Dec-19	145918.77	126983.53	30.43	4.71	4.10
Jan-20	123565.67	103714.15	29.51	3.98	3.35
Feb-20	85590.49	75544.41	29.51	2.95	2.60
Mar-20	103729.28	91886.77	30.09	3.35	2.96
Apr-20	183151.36	150581.67	29.88	6.10	5.02
May-20	124897.60	102343.54	27.53	4.03	3.30
Jun-20	102208.25	83751.74	22.28	3.41	2.79
Jul-20	151201.12	127031.65	22.58	4.88	4.10
Aug-20	139795.20	112368.17	26.52	4.51	3.62
Sep-20	176990.62	154720.04	29.73	5.90	5.16
Total energy yield		1452598.46			47.61

The results in Table 4.8 give small errors when GSA computed energy values are compared with actual solar PV power plant's annual energy outputs. *Ngonye*, *Bangweulu* and *CEC* solar PV power plants gave marginal errors of 6%, 1% and 17% respectively. These errors can be attributed to irradiance fluctuations and equipment downtimes. Inverter downtime was found to be the main contributor to PV power plant downtimes.

Table 4.8 Comparison of annual power generation between GSA Computations and actual plant outputs

Solar PV plant	*Ngonye*	*Bangweulu*	*CEC*
GSA PVOUT (kWh/kWp)	1749.00	1749.00	1760.00
PV power plant capacity (MW)	34.00	54.30	1.00
Annual energy imports (MWh)	244.30	-	-
Actual annual energy output (MWh)	56339.47	94417.13	1452.60
Net annual total energy output (MWh)	56095.17	-	-
GSA annual total energy output (MWh)	59466.00	94970.70	1760.00
Percentage Deviation	6%	1%	17%

Figure 4.7 shows variation of in-plane irradiance for one year from October 2019 to September 2020.

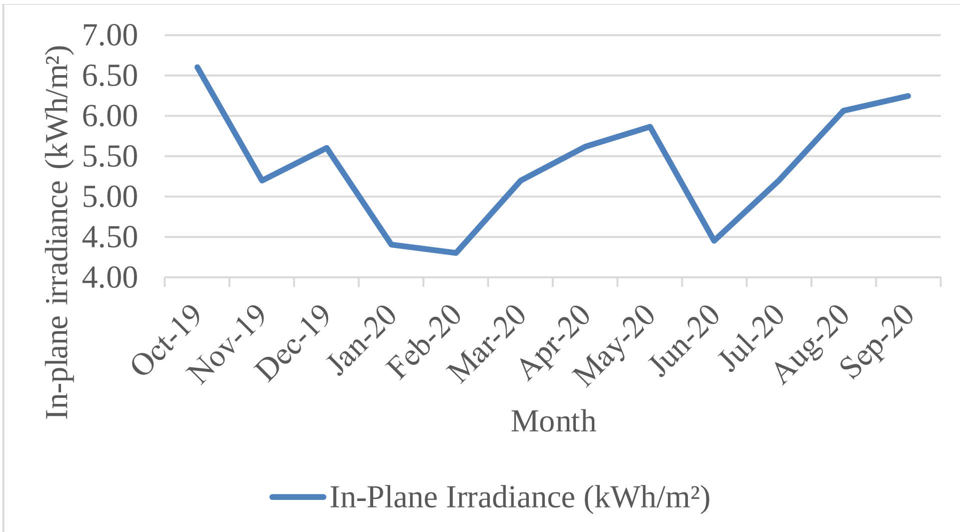

Figure 4.7 Ngonye PV system variation of in-plane irradiance for different months of the year for a period of twelve months

Figure 4.8 shows variation of module temperature for different months of the year. October 2019 recorded the highest module temperatures due to high ambient temperatures whilst June recorded the lowest temperatures due to low ambient temperatures.

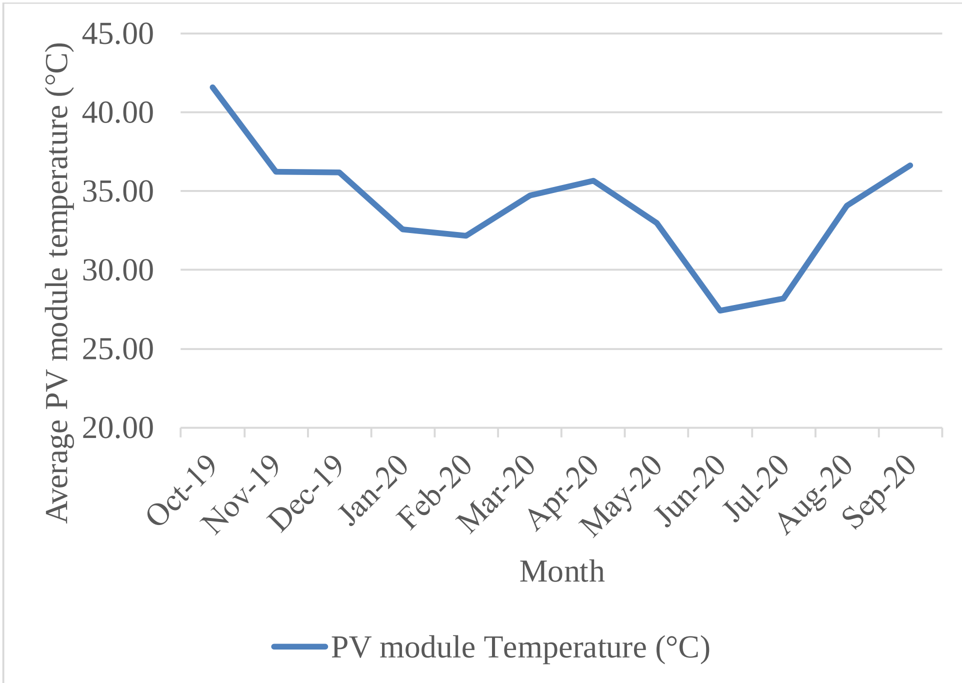

Figure 4.8 Ngonye PV system variation of module temperature for different months of the year for a period of twelve months

Figure 4.9 shows variation of energy output for different months of the year for *Ngonye* solar PV power plant. Comparing Figures 4.7, 4.8 and 4.9, the highest irradiance of 6.60 kWh/m^2 and module temperature of 41.61°C were recorded in the month of October whilst the highest energy output of 5646.34 MWh was recorded in the month of May. Despite irradiance being high in the month of October, the highest energy output was recorded in the month of May. This is attributed to the fact that higher module temperatures result in lower voltage output that in turn lowers the energy output. Every one degree Celsius rise in temperature for silicon PV cells results in about 0.6% decrease in output voltage.

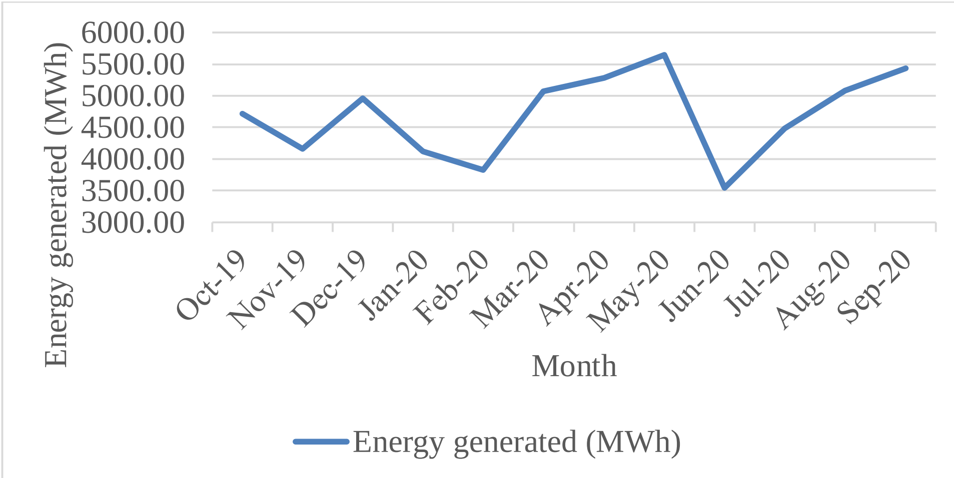

Figure 4.9 Ngonye PV system variation of energy output for different months of the year for a period of twelve months

Figure 4.10 shows variation of in-plane irradiance for one year from October 2019 to September 2020 for *CEC* solar PV power plant. Irradiance varies from month to month due to weather changes. The highest value of irradiance was recorded in October that was accompanied. The least value of irradiance was recorded in February.

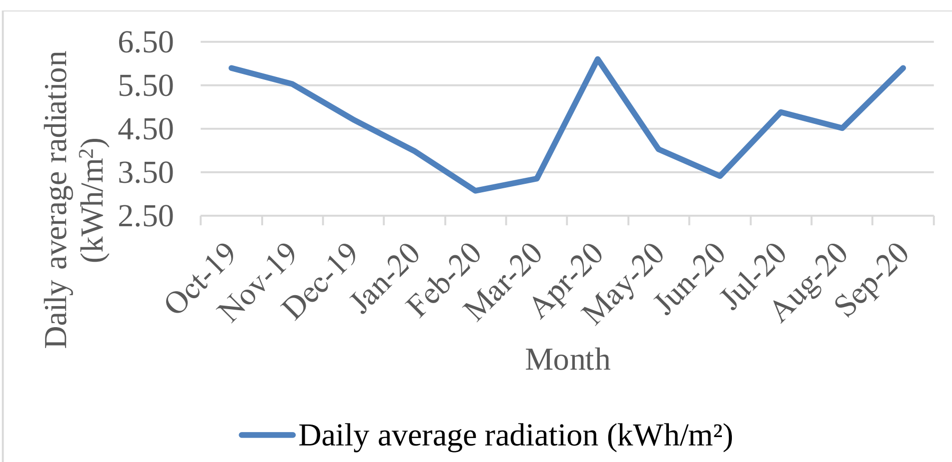

Figure 4.10 CEC PV system variation of in-plane irradiance for different months of the year for a period of twelve months

Figure 4.11 shows variation of module temperature for different months of the year for *CEC* PV power plant. October recorded the highest module temperatures due to high ambient temperatures whilst June recorded the lowest temperatures due to low ambient temperatures. The recorded temperatures are a representation of daily average temperatures.

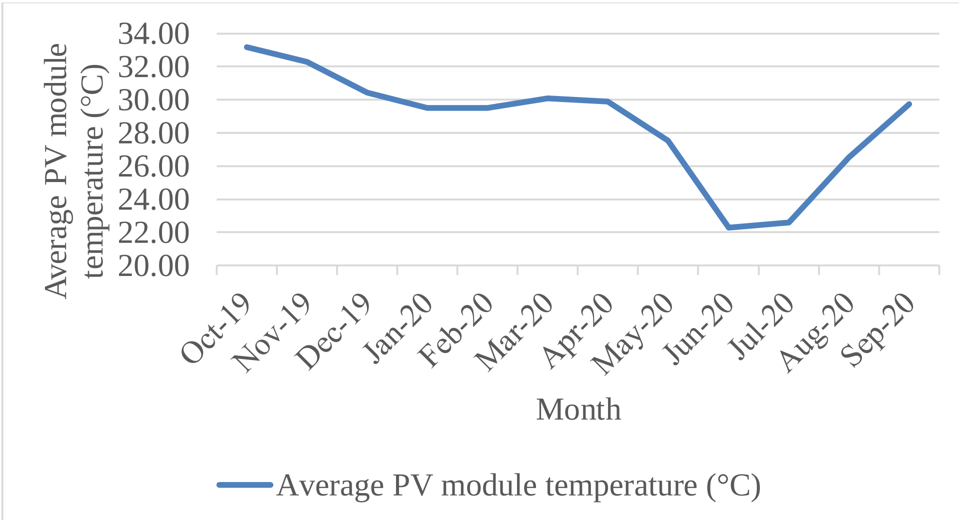

Figure 4.11 CEC PV system variation of module temperature for different months of the year for a period of twelve months

Figure 4.12 shows variation of energy output for different months of the year for *CEC* PV power plant. Figures 4.10, 4.11 and 4.12 show that the highest average daily radiation of 5.90 kWh/m^2 was recorded in the month of September with highest daily average energy of 5.16 MWh recorded in the same month. October recorded the highest PV module temperature of 33.18 °C. September and October recorded almost the same average values of irradiance of 5.90 kWh/m^2 and 5.89 kWh/m^2 respectively but September recorded the highest amount of energy due to lower PV module temperature of 29.73 °C.

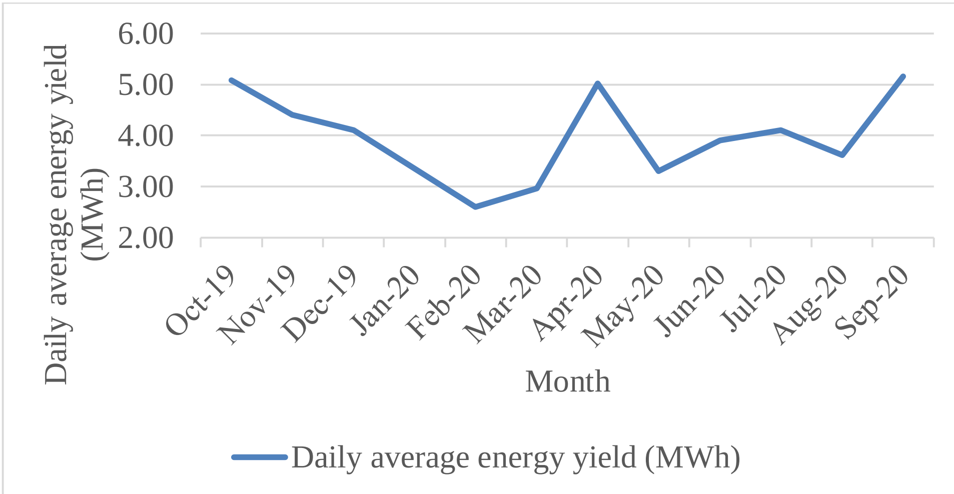

Figure 4.12 CEC PV system variation of energy output for different months of the year for a period of twelve months

Table 4.9 gives computations of effective surface areas of the PV array for *Ngonye, Bangweulu* and *CEC* solar power plants. Effective surface of the solar panels and not the area of the plant is important as it is one of the factors to consider when calculating PR with respect to effective surface area of a solar PV power plant.

Table 4.9 Determination of module effective surface area of the three solar PV power plants

Solar PV power plant	**Dimensions (m)**	**Module rating (W)**	**Module area (m^2)**	**Module number**	**Effective surface area (m^2)**
Ngonye	0.996x1.979	325.000	1.971	104,580.000	206127.180
Bangweulu	0.600x1.200	120.000	0.720	400,000.000	288000.000
	0.600x1.200	117.500	0.720	53,600.000	38592.000
CEC	0.991x1.650	270.000	1.635	3,864.000	6317.640

Table 4.10 summarises the *PR* of Ngonye solar PV power system. The average *PR* was found to be 84.18%. The optimal *PR* for a solar PV system is 75%. This entails that the PV power plant has a high performance. The *PR* of 67.73% recorded in October is due to breakdown of power conversion units.

Table 4.10 Computation of plant performance ratio for Ngonye solar PV power plant

Month	Days	In-Plane Irradiance (kWh/month-m²)	Effective area (m²)	Module Efficiency	Nominal Energy (MWh)	Actual Energy (MWh)	*PR* (%)
Oct-19	31	204.600	206,127.180	0.165	6,958.647	4,713.490	67.730
Nov-19	30	156.000	206,127.180	0.165	5,305.714	4,163.960	78.481
Dec-19	31	173.600	206,127.180	0.165	5,904.307	4,960.960	84.023
Jan-20	31	136.400	206,127.180	0.165	4,639.098	4,123.350	88.882
Feb-20	29	124.700	206,127.180	0.165	4,241.170	3,830.810	90.324
Mar-20	31	161.200	206,127.180	0.165	5,482.571	5,066.360	92.408
Apr-20	30	168.600	206,127.180	0.165	5,734.252	5,279.570	92.071
May-20	31	181.660	206,127.180	0.165	6,178.435	5,646.340	91.388
Jun-20	30	133.500	206,127.180	0.165	4,540.466	3,549.120	78.166
Jul-20	31	161.200	206,127.180	0.165	5,482.571	4,487.220	81.845
Aug-20	31	187.860	206,127.180	0.165	6,389.303	5,082.390	79.545
Sep-20	30	187.200	206,127.180	0.165	6,366.856	5,435.900	85.378
Mean PR							84.187

Table 4.11 gives the PR of Bangweulu solar PV power system. An average of 82.98% was computed and this shows that the solar PV system's performance is very good as compared to the optimal literature value of 75%.

Table 4.11 Computation of plant performance ratios for Bangweulu solar PV power plant

Module rating (W)	GHI (kWh/m²)	Effective surface area (m²)	Module Efficiency	Annual nominal Energy (MWh)	Total annual nominal energy (MWh)	Total annual actual energy (MWh)	*PR* (%)
120.000	2,092.000	288,000.000	0.167	100,616.832	113,776.550	94,417.125	82.980
117.500	2,092.000	38,592.000	0.163	13,159.718			

Table 4.12 shows monthly computed values of plant performance ratio. The average PR is above the international acceptable value of 75%.

Table 4.12 Computation of Plant performance ratio for CEC solar PV power plant

Month	**Days**	**In-Plane Irradiance (KWh/month-m²)**	**Effective area (m²)**	**Module Efficiency**	**Nominal Energy (MWh)**	**Actual Energy (MWh)**	***PR* (%)**
Oct-19	31	182.666	6317.640	0.165	190.413	157.886	82.918
Nov-19	30	165.692	6317.640	0.165	172.719	132.422	76.669
Dec-19	31	145.919	6317.640	0.165	152.107	126.983	83.483
Jan-20	31	123.566	6317.640	0.165	128.806	103.714	80.519
Feb-20	29	85.590	6317.640	0.165	89.220	75.544	84.671
Mar-20	31	103.729	6317.640	0.165	108.128	91.887	84.980
Apr-20	30	183.151	6317.640	0.165	190.918	150.582	78.873
May-20	31	124.898	6317.640	0.165	130.195	102.343	78.607
Jun-20	30	102.208	6317.640	0.165	106.543	83.751	78.608
Jul-20	31	151.201	6317.640	0.165	157.613	127.032	80.597
Aug-20	31	139.795	6317.640	0.165	145.724	112.368	77.110
Sep-20	30	176.991	6317.640	0.165	184.497	154.720	83.860
Mean PR							80.908

Table 4.13 summarises the performance of *Ngonye*, *Bangweulu* and *CEC* solar PV power plants. Their CUFs are within acceptable range in accordance with research findings. The acceptable range of values for CF values for good performance of a solar PV system is 12% to 24%.

Table 4.13 Analysis of specific yield (Sy) and capacity factor (CUF) for Ngonye, Bangweulu and CEC solar PV power plants

Solar PV power plant	*Ngonye*	*Bangweulu*	*CEC*
Installed capacity (MW_p)	34.00	54.30	1.00
Net annual energy generation (MWh)	56095.17	94417.12	1452.60
S_y (kWh/kW_p)	1649.86	1738.80	1452.60
CUF (%)	18.83	19.85	16.58

Table 4.14 gives the daily average number of hours that the PV solar system would need to operate at its power rating for purposes of providing the same amount of energy. The final PV yields were found to be 4.52, 4.76 and 3.97 hours for *Ngonye*, *Bangweulu* and *CEC* solar PV systems.

Table 4.14 Determination of final PV system yield for three on-grid PV solar systems under review

Solar PV power plant	**Average daily net energy output (MWh)**	**Nominal DC power (MW)**	Y_f **(hours)**
Ngonye	153.58	34.00	4.52
Bangweulu	258.50	54.30	4.76
CEC	3.97	1.00	3.97

Table 4.15 gives the average number of sunshine hours in a year for a solar PV system. The reference yields were found to be 5.39, 5.39, and 4.61 for *Ngonye*, *Bangweulu* and *CEC* solar PV systems. The average number of sunshine hours for the three solar PV power plants is 5.13 hours. Reference yields for *Ngonye*, *CEC* and *Bangweulu* solar PV power plants gives the number of hours in which the intensity of solar irradiance reaches an average of 1000 W/m^2.

Table 4.15 Determination of reference yield for the three on-grid solar PV systems under review

Solar PV power plant	**Daily average in-plane global irradiance (kWh/m^2)**	**PV reference irradiance (W/m^2)**	Y_r **(hours)**
Ngonye	5.39	1000	5.39
Bangweulu	5.39	1000	5.39
CEC	4.61	1000	4.61

Table 4.16 gives *PRs* of the solar PV power system with respect to Y_f and Y_r. This is an alternative way of determining the *PR* of the solar PV power system. It is theoretically reliable method of determining *PR* of a PV solar power plant.

Table 4.16 Determination of PR with respect to Yr and Yf

Solar PV power plant	Y_f **(hours)**	Y_r **(hours)**	***PR*** **(%)**
Ngonye	4.52	5.36	84.33
Bangweulu	4.76	5.36	88.81
CEC	3.97	4.61	86.12

4.8 Economic Feasibility of Ngonye and Bangweulu Solar PV Power Plants

Table 4.17 gives lifetime energy outputs taking into account solar panel's degradation rate for a period of twenty-five (25) years. Degradation reduces the actual generation of energy of a solar PV power plant.

Table 4.17 Computation of lifetime energy production for Ngonye and Bangweulu solar PV power plants

Solar PV plant	Annual energy output (MWh)	Degradation rate (%/year)	lifecycle (years)	Lifetime energy generated (MWh)
Ngonye	56,095.17	0.70	25	1,290,664.92
Bangweulu	94,417.13	0.50	25	2,224,085.33

Table 4.18 summarises the profitability of *Ngonye* and *Bangweulu* solar PV power plants. The estimated lifetime revenue has been computed.

Table 4.18 Computation of estimated lifetime revenue for Ngonye and Bangweulu solar PV power plants

Solar PV plant	*Ngonye*	*Bangweulu*
Lifetime energy generated (MWh)	1,290,664.92	2,224,085.33
Tariff (US$c/kWh)	7.84	6.02
Estimated lifetime revenue (US$)	101,188,129.70	133,889,936.90
O & M costs	8,075,000	12,825,000
Net revenue	93,113,129.70	121,064,936.90

4.8.1 Computation of Grid Parity for Ngonye and Bangweulu Solar PV Power Plants

Table 4.19 shows simple payback periods of 11.29 years and 11.60 years for Ngonye and Bangweulu solar PV power plants, respectively.

Table 4.19 Computation of grid parity for Ngonye and Bangweulu solar PV power plants

Solar PV power plant	Investment cost (US$)	Revenue/year (US$)	O&M costs/year (US$)	Net revenue/year (US$)	Grid parity (years)
Ngonye	46,000,000.00	4,397,861.33	323,000.00	4,074,861.33	11.29
Bangweulu	60,000,000.00	5,683,911.23	513,000.00	5,170,911.23	11.60

4.8.2 Economics of Power from Utility-scale Solar Power Plants in Zambia

Table 4.20 shows the results of the cost of producing 3,514,750.25 MWh of energy from the two on-grid solar PV power plants in Zambia. The results show that it is cheaper to generate power from the two on-grid solar PV power plants as compared to Maamba coal power plant. The difference in costs of power generation is US$ 126,941,209.20. This can be of economic and environmental benefit to the country as US$ 126,941,209.20 can be saved for a period of 25 years if solar PV power that is GHG free is utilised.

Table 4.20 Comparison of the cost of energy generated from Ngonye and Bangweulu solar PV power plants to that of same amount of energy from the Maamba Coal power plant (Benchmark)

Power plant	*Ngonye*	*Bangweulu*
Amount of life-time energy (MWh)	1,290,664.92	2,224,085.33
Cost of power (US$)	101,188,129.70	133,889,936.90
Total life-time energy from Ngonye and Bangweulu (MWh)	3,514,750.25	
Total cost of power (US$)	235,078,066.60	
Power plant	Maamba coal	
Amount of energy (MWh)	3,514,750.25	
Tariff (US$c/kWh)	10.3	
Total cost of power (US$)	362,019,275.80	

Difference in cost between energy over 25 year period from Maamba and solar power plants

Power plant	**Cost (US$)**
Maamba	362,019,275.80
Ngonye and *Bangweulu*	235,078,066.60
Difference in cost (saving)	126,941,209.20

4.9 Simulation Analysis of Technical Feasibility and Financial Viability of Ngonye and Bangweulu Solar PV Power Plants

4.9.1 Economic Analysis of the GET FiT Solar Energy Initiative

Table 4.21 show anticipated energy output from GET FiT solar PV power plants for a period of 25 years. The aggregated annual energy output is 359 GWh and lifetime energy of 8975 GWh.

Table 4.21 Computation of lifetime energy generation for GET FiT solar PV power plants

Solar PV plant	**Annual energy output (GWh)**	**Degradation rate (%/year)**	**lifecycle (years)**	**Lifetime energy generated (GWh)**
Belemu East and West	126.00	N/A	25	3150
Sola 1 and 2	120.00	N/A	25	3000
Garneton North and South	113.00	N/A	25	2825

Table 4.22 shows the cost of supplying 359 GWh of energy from the three GET FiT solar PV power plants to be constructed and comparing it to the cost of supplying the same amount of energy from Maamba coal power plant taken as the benchmark.

The difference in costs of power generation is US$ 527,540,000.00. This can be of economic and environmental benefit to the country as US$ 527,540,000.00 can be saved for a period of 25 years if GET FiT solar PV power plants are implemented.

Table 4.22 Comparison of the cost of same amount of energy generated from GET FiT solar PV power plants to that of Maamba coal power plant (Benchmark)

Solar PV power plant	**Capacity (MW_{ac})**	**Estimated annual energy generation (GWh)**	**Tariff (US$c/kWh)**	**Annual revenue (US$)**	**Lifetime revenue (US$)**
Belemu East and West	40.00	126.00	3.99	5,027,400.00	125,685,000.00
Sola 1 and 2	40.00	120.00	4.52	5,424,000.00	135,600,000.00
Garneton North and South	40.00	113.00	4.80	5,424,000.00	135,600,000.00
Aggregated cost (US$)					396,885,000.00

Cost of producing the same amount of energy from Maamba coal (Benchmark)

Coal power plant	**Amount of energy (GWh)**	**Tariff (US$c/kWh)**	**Annual cost (US$)**	**Lifetime cost (US$)**
Maamba	359.00	10.30	36,977,000.00	924,425,000.00

Difference in energy cost between Maamba coal and GET FiT solar PV power plants

Power plant	**Cost (US$)**
Maamba	924,425,000.00
GET FiT	396,885,000.00
Difference in cost	527,540,000.00

Table 4.23 shows the nation’s current annual energy generation and consumption. It further show the total installed solar power and the amount of solar power the utility grid can absorb for year 2022 horizon. The amount of installed on-grid solar PV power differs with the value mentioned under Figure 4.2 because what has been agreed with the service operator (SO), that is, ZESCO is 28.2 MW and 47.5 MW from *Ngonye* and *Bangweulu* solar PV power plants respectively.

Table 4.23 Power generation, consumption and grid solar PV power absorption study

Current annual energy production (GWh)	**Current annual energy consumption (GWh)**	**Current power deficit (MW)**	**Total installed solar power (MW)**	**Capability of utility grid solar PV power absorption (MW)**
11,957.00	18,396.00	850.00	76.00	816.00

Table 4.24 shows the solar PV grid absorption capacity power for solar PV power converted into useful energy based on the average annual sunshine hours. Lifetime of operation has been taken to be 25 years as per the average PPA for solar PV power plants.

Table 4.24 Conversion of 'grid absorption power capacity of solar PV power' into useful energy for technical and financial analysis

Capability of utility grid solar PV power absorption (MW)	Average number of sunshine hours (hours)	Average annual energy (MWh)	Lifetime energy (MWh)
816.00	5.39	1,606,457.16	40,161,429.00

Table 4.25 shows cost of energy that can be generated from solar PV grid absorption capacity power of 816 MW to that of Maamba Coal power as the benchmark. The tariff used is Zambia's current worst case scenario tariff of 4.80 c/kWh obtained with reference to GET FiT solar energy initiative. Computations show that the government through ZESCO can save about US$ 2,208,878,595.00 for a period of 25 years.

Table 4.25 Comparison of the cost of energy generated from 'solar PV grid absorption capacity power' to that of the same amount of Maamba coal power (Benchmark)

Power plant	Lifetime energy (MWh)	Tariff (USc/kWh)	Total expenditure (US$)
Solar PV power	40,161,429.00	4.80	1,927,748,592.00
Maamba coal power	40,161,429.00	10.30	4,136,627,187.00
Difference in cost			2,208,878,595.00

Table 4.26 shows that the government through ZESCO, can save about US$ 2,863,359,804.20 within a period of 25 years. This amount can be channeled to other developmental projects.

Table 4.26 Cost saving from solar PV projects at 25 years' life span

Energy Initiative name or product description	Current saving (US$)
Scaling solar	126,941,209.20
GET FiT	527,540,000.00
Anticipated total grid solar power	2,208,878,595.00
Total savings from Solar PV power	2,863,359,804.20

4.9.2 Technical Analysis of Ngonye Solar PV Power Plant using PVsyst Software

Table 4.27 represents the main results of PVsyst simulation. The parameters recorded includes Global Horizontal irradiation (*GlobHor*), Diffuse Horizontal irradiation (*DiffHor*), Ambient temperature (*T_Amb*), Global irradiation incident in collector plane (*GlobInc*), Effective global irradiation (*GlobEff*), Effective energy at the output of the array (*EArray*) and Plant perfomance ratio (*PR*).

Table 4.27 Main results for Ngonye PV solar power plant using PVsyst simulation

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	ratio
January	159.7	84.60	22.50	164.7	159.5	4633020	4523523	0.808
February	143.9	76.60	21.20	144.5	140.0	4123722	4025861	0.819
March	160.8	83.20	21.20	163.5	158.2	4582286	4473004	0.805
April	165.6	51.20	20.20	186.8	182.7	5244673	5119454	0.806
May	156.3	50.60	18.50	196.0	192.6	5612903	5481989	0.823
June	147.6	38.10	16.60	201.7	198.8	5749826	5616240	0.819
July	154.1	40.10	16.60	204.1	201.1	5793659	5656595	0.815
August	179.1	46.00	20.10	214.7	211.0	6105684	5962291	0.817
September	182.4	58.20	22.90	193.2	188.9	5351997	5224675	0.795
October	197.2	68.80	25.20	200.0	194.3	5537636	5408892	0.795
November	181.1	80.60	23.50	187.4	182.1	5242546	5120636	0.804
December	161.4	81.20	20.59	168.4	163.6	4779167	4666983	0.815
Year	1989.2	759.19	20.75	2225.0	2172.8	62757119	61280144	0.810

Table 4.28 shows plant performance ratio (*PR*) with normalised performance coefficients. The other parameters analysed include reference yield radiation (Y_r), normalised array losses (L_c), normalised array production (Y_a), normalised system losses (L_s), normalised system production or final yield (Y_f), array loss ratio (L_{cr}), and system loss ratio (L_{sr}).

Table 4.28 Normalised performance coefficients for Ngonye solar PV power plant using PVsyt software

	Yr kWh/m²/day	Lc ratio	Ya kWh/kWp/day	Ls ratio	Yf kWh/kWp/day	Lcr ratio	Lsr ratio	PR ratio
January	5.31	0.916	4.40	0.104	4.29	0.172	0.020	0.808
February	5.16	0.830	4.33	0.103	4.23	0.161	0.020	0.819
March	5.27	0.925	4.35	0.104	4.24	0.175	0.020	0.805
April	6.23	1.086	5.14	0.123	5.02	0.174	0.020	0.806
May	6.32	0.997	5.33	0.124	5.20	0.158	0.020	0.823
June	6.72	1.086	5.64	0.131	5.51	0.162	0.019	0.819
July	6.58	1.088	5.50	0.130	5.37	0.165	0.020	0.815
August	6.93	1.132	5.79	0.136	5.66	0.164	0.020	0.817
September	6.44	1.193	5.25	0.125	5.12	0.185	0.019	0.795
October	6.45	1.199	5.25	0.122	5.13	0.186	0.019	0.795
November	6.25	1.108	5.14	0.120	5.02	0.177	0.019	0.804
December	5.43	0.898	4.53	0.106	4.43	0.165	0.020	0.815
Year	6.10	1.039	5.06	0.119	4.94	0.170	0.020	0.810

Figure 4.13 shows the reference incident radiation (Y_r). This is the incident radiation as received by the tilted collector with an assumption that there are no PV array losses. The interpretaion of this is that, 6.096 kWh/m^2/day is received with an assumption that there are no losses.

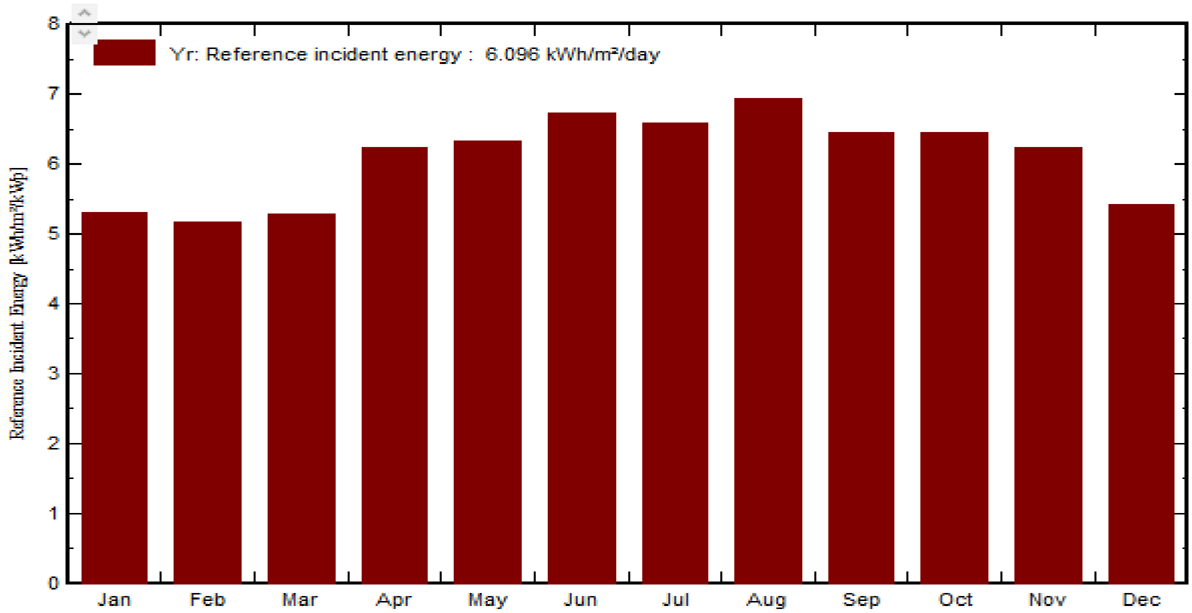

Figure 4.13 Reference incident radiation in collector plane using PVsyst software

Figure 4.14 shows that of the 6.092 kWh/m^2/day of radiation received, about 1.16 kWh/m^2/day is not converted into electrical energy due to system losses by inverters, array losses (losses from solar panels) and other plant components. Therefore, out of the 6.092 kWh/m2/day, only about 4.94 kWh/m2/day is converted to useful energy.

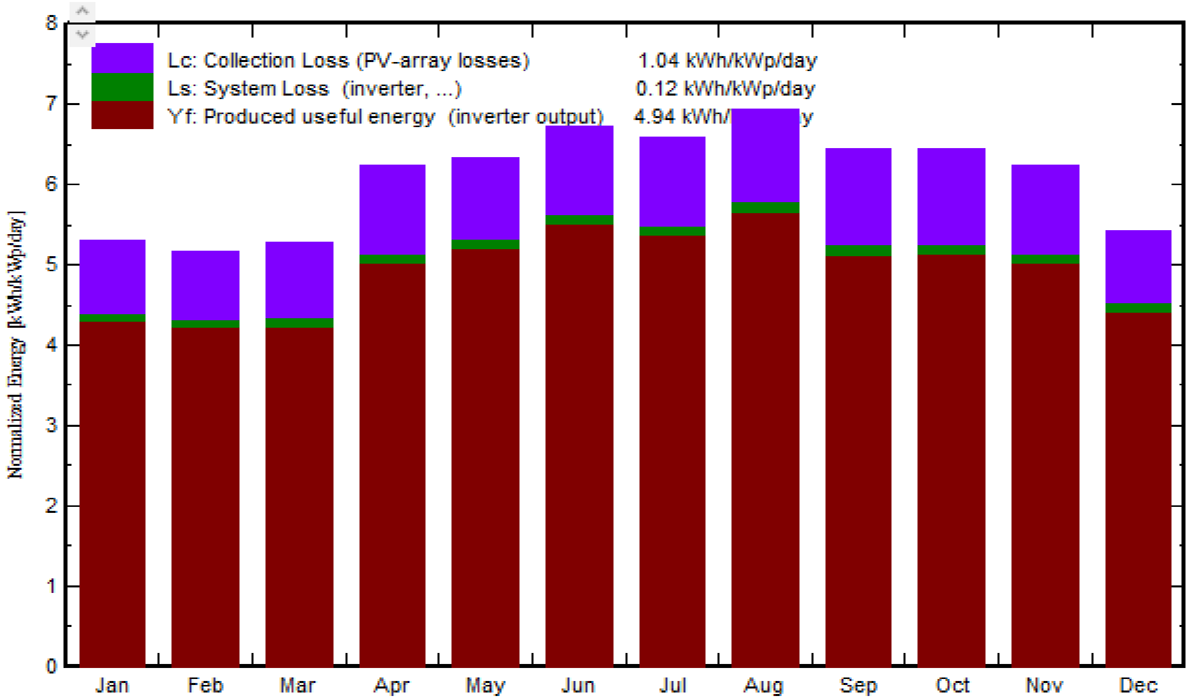

Figure 4.14 Normalised productions (per installed kWp) for Ngonye solar PV power plant: Nominal power 34 MW_p

Figure 4.15 indicates that, 19% of solar resource received by *Ngonye* solar PV power plant in the assessed period was not converted into electrical energy owing to factors including inverter downtimes, module efficiency, losses due to loose contacts, and plant component defects.

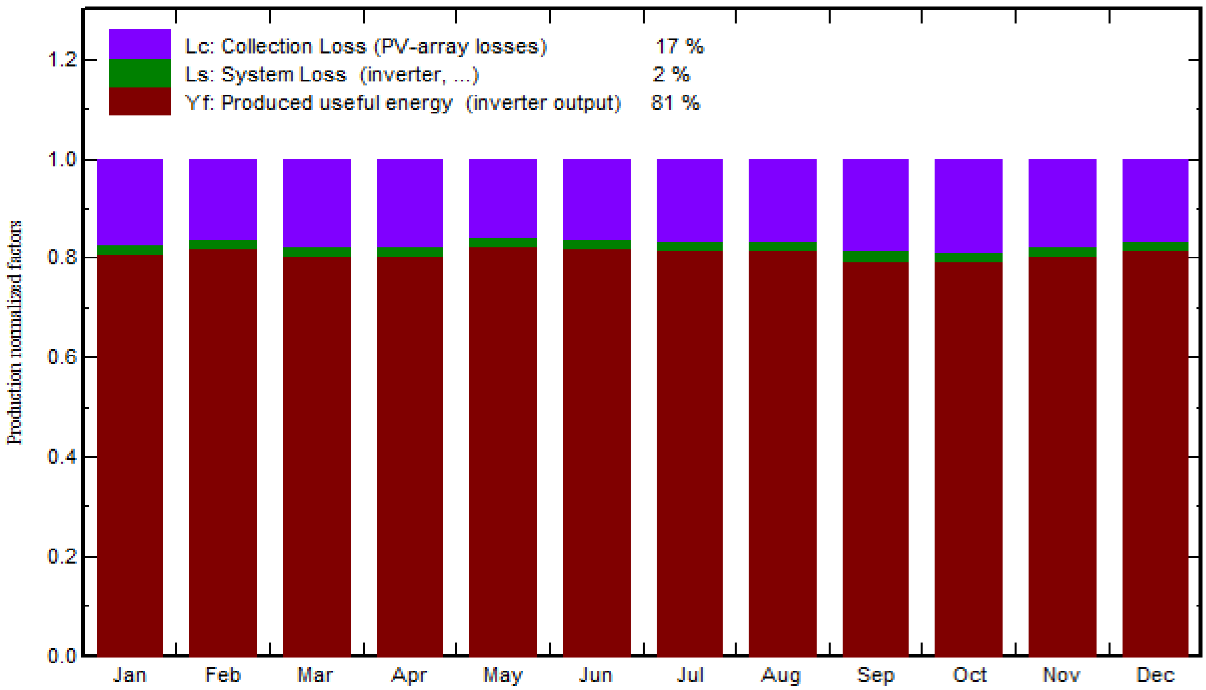

Figure 4.15 Normalised production and loss factors for Ngonye PV solar powe plant: Nominal power 34 MW_p

Figure 4.16 represents the plant perforformance ratio (*PR*) after factoring out the losses caused by the system (L_s) and array losses (L_c). Sytem losses are mainly caused by the inverter downtimes. Array losses are caused by energy losses from solar panels. This mainly incude shading, soiling and cloud cover. Therefore PR represents the proportion of energy that is available for export to the utility grid.

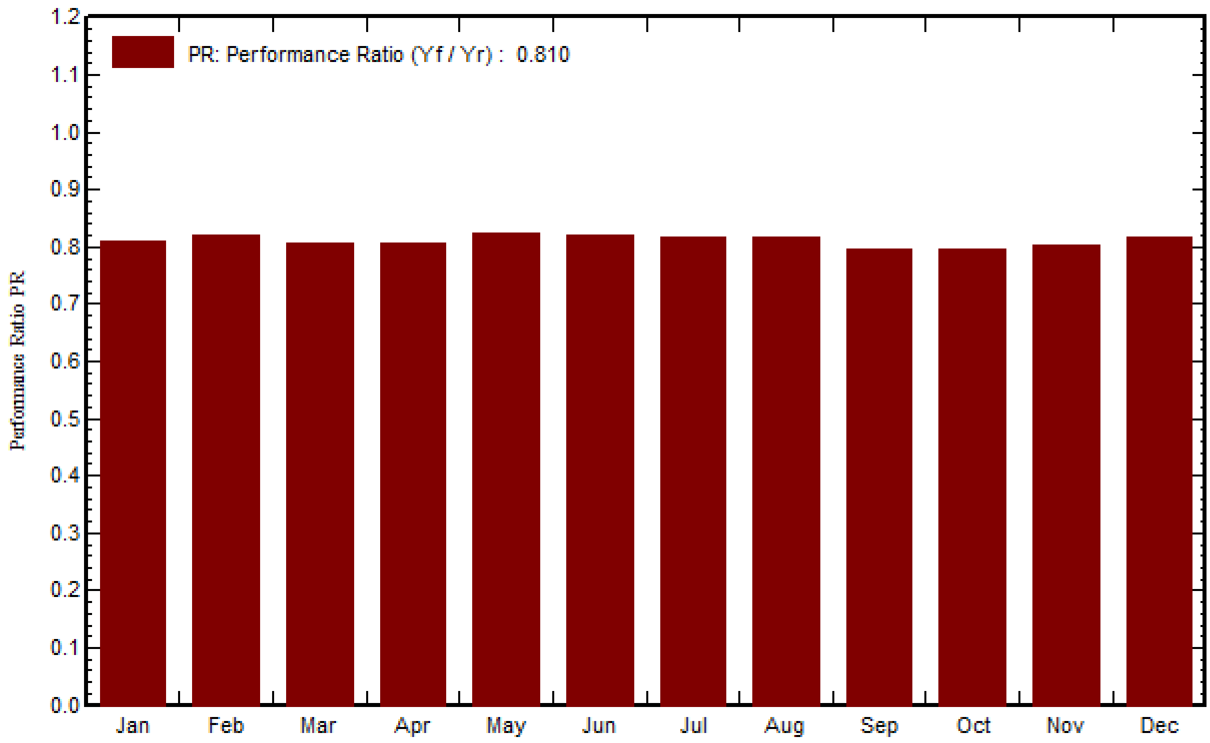

Figure 4.16 Plant performance ratio for Ngonye solar PV power plant using PVsyst software

Figure 4.17 shows the amount of energy that can be injected into the grid with respect to different illumination levels. The horizontal-axis shows the daily irradiation in the collector plane [kWh/m^2/day]. The vertical-axis shows the system's production [kWh/day]. For Grid-connected systems, this is usually linear (points below correspond to days with special losses like shadings or system unavailability). There is often a curvature in the upper part, corresponding to higher operating temperatures in summer.

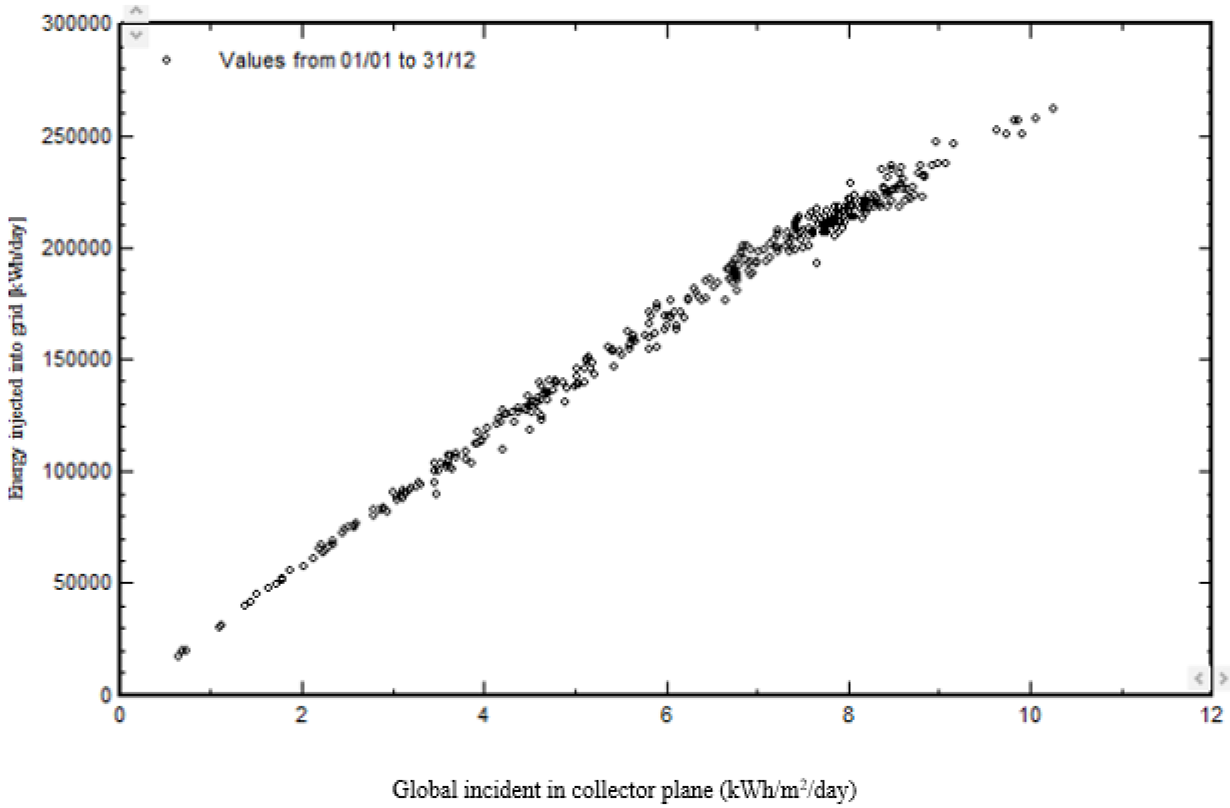

Figure 4.17 Daily input and output for Ngonye solar PV power plant using PVsyt software

Figure 4.18 shows the simulated pattern of energy injection into the grid with sharp spikes and troughs due to variation in irradiance. Solar PV power is directly proportional to the amount of solar resource available and hence the irradiance. The amount of energy injected into the grid is not uniform at any particular time. This is the reason why a capacitor bank is needed to compensate for active and reactive power.

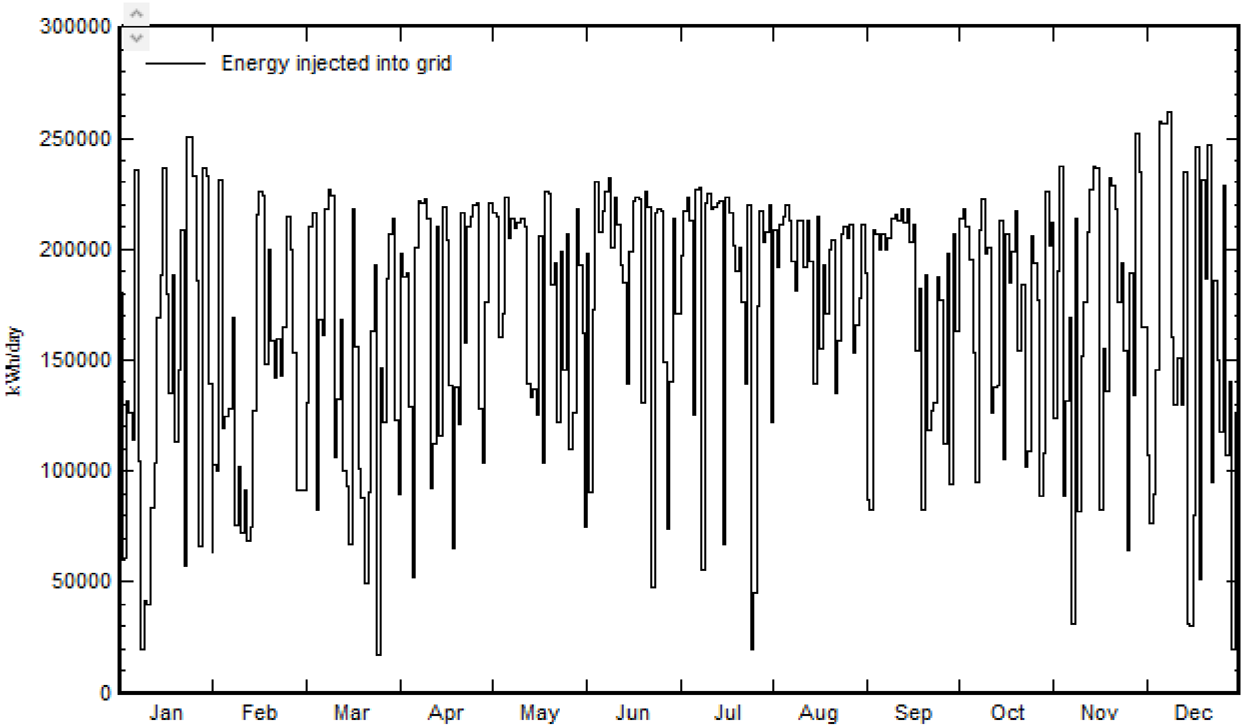

Figure 4.18 Daily simulated system output energy for Ngonye solar PV power plant using PVsyt software

Figure 4.19 shows operating temperatures of PV modules under different illumination, in comparison with the STC conditions. Each dot represents a module at a give illumination level. The dots show the relationship between the irradiation and the module temperature. This can be compared to the red dot (STC) and shows real world performance of the module.

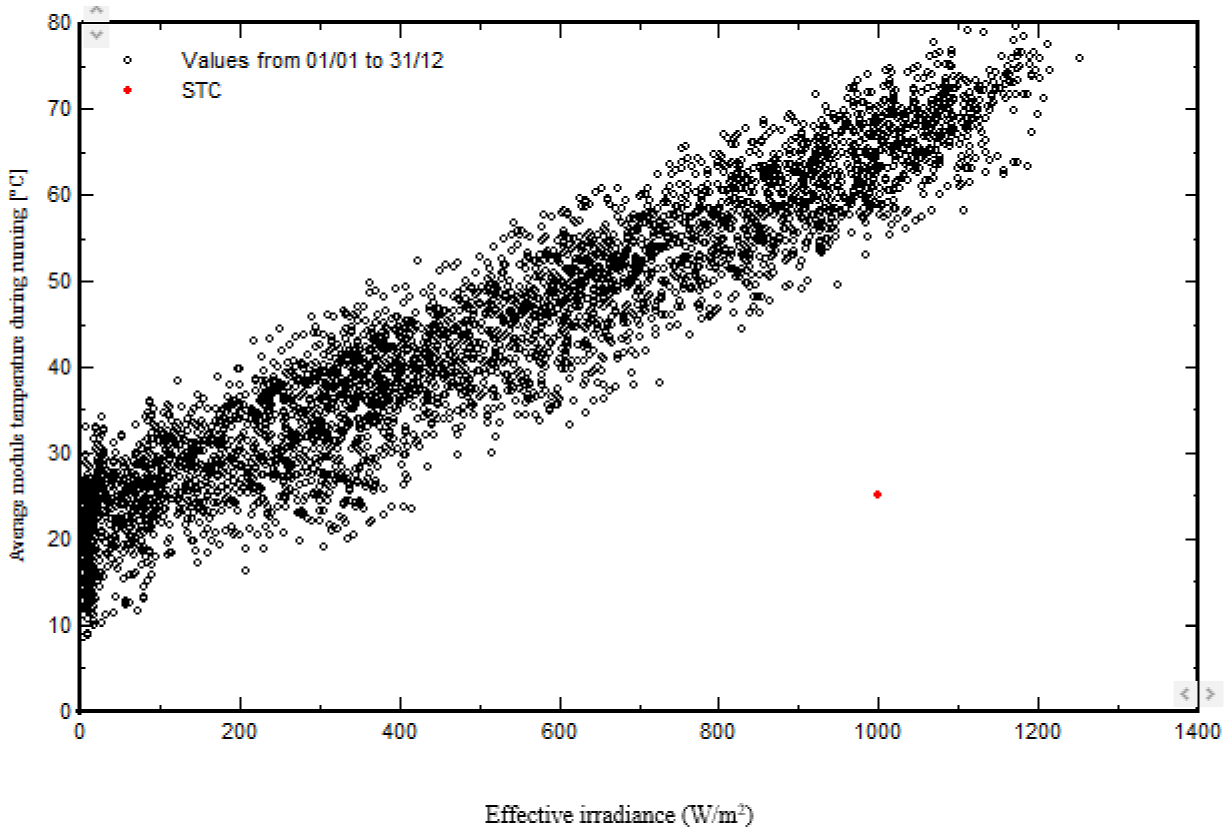

Figure 4.19 Array module temperature vs simulated effective irradiance for Ngonye solar PV power plant using PVsyst software

4.9.3 Technical Analysis of Bangweulu Solar PV Power Plant using PVsyst Software

Table 4.29 represents the main results of PVsyst simulation. The parameters recorded includes Global Horizontal irradiation (*GlobHor*), Horizontal Diffuse irradiation (*DiffHor*), Ambient temperature (*T_Amb*), Global incident in collector plane (*GlobInc*), Effective global irradiation (*GlobEff*), Effective energy at the output of the array (*EArray*) and Plant perfomance ratio (*PR*).

Table 4.29 Main results for Bangweulu PV solar power plant using PVsyst simulation

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	159.7	84.60	22.50	151.7	148.2	7040412	6925995	0.846
February	143.9	76.60	21.20	141.1	138.4	6613500	6507605	0.854
March	160.8	83.20	21.20	163.0	160.0	7472713	7352179	0.835
April	165.6	51.20	20.20	179.5	177.0	8273502	8138178	0.840
May	156.3	50.60	18.50	176.9	174.6	8421321	8285336	0.867
June	147.6	38.10	16.60	172.8	170.5	8264704	8132033	0.871
July	154.1	40.10	16.60	178.3	176.0	8470418	8332768	0.865
August	179.1	46.00	20.10	199.4	197.1	9396010	9240460	0.858
September	182.4	58.20	22.90	191.4	189.0	8699163	8552625	0.828
October	197.2	68.80	25.20	196.5	192.9	8966050	8816406	0.831
November	181.1	80.60	23.50	172.5	168.7	7961154	7830582	0.841
December	161.4	81.20	20.59	151.6	148.0	7090325	6978207	0.852
Year	1989.2	759.19	20.75	2074.7	2040.5	96669273	95092377	0.849

Table 4.30 shows (Plant performnce ratio (*PR*) with normalised performance coefficients. The other parameters analysed include reference yield radiation (Y_r), normalised array losses (L_c), normalised array production (Y_a), normalised system losses (L_s), normalised system production or final yield (Y_f), array loss ratio (L_{cr}), and system loss ratio (L_{sr}). The table defines the performance of Ngonye solar PV power plant.

Table 4.30 Normalised performance coefficients for Bangweulu solar PV power plant using PVsyt software

	Yr kWh/m²/day	Lc ratio	Ya kWh/kWp/day	Ls ratio	Yf kWh/kWp/day	Lcr ratio	Lsr ratio	PR ratio
January	4.89	0.687	4.21	0.068	4.14	0.140	0.014	0.846
February	5.04	0.666	4.37	0.070	4.30	0.132	0.014	0.854
March	5.26	0.795	4.46	0.072	4.39	0.151	0.014	0.835
April	5.98	0.875	5.11	0.084	5.02	0.146	0.014	0.840
May	5.71	0.677	5.03	0.081	4.95	0.119	0.014	0.867
June	5.76	0.659	5.10	0.082	5.02	0.114	0.014	0.871
July	5.75	0.692	5.06	0.082	4.98	0.120	0.014	0.865
August	6.43	0.820	5.61	0.093	5.52	0.128	0.014	0.858
September	6.38	1.009	5.37	0.090	5.28	0.158	0.014	0.828
October	6.34	0.982	5.36	0.089	5.27	0.155	0.014	0.831
November	5.75	0.835	4.91	0.081	4.83	0.145	0.014	0.841
December	4.89	0.655	4.24	0.067	4.17	0.134	0.014	0.852
Year	5.68	0.780	4.90	0.080	4.82	0.137	0.014	0.849

Figure 4.20 shows the reference incident radiation (Y_r). This is the incident radiation as viewed by the tilted collector with an assumption that there are no PV array losses. The interpretaion of this is that, 5.684 kWh/m^2/day is assumed to be received with an assumption that there are no losses

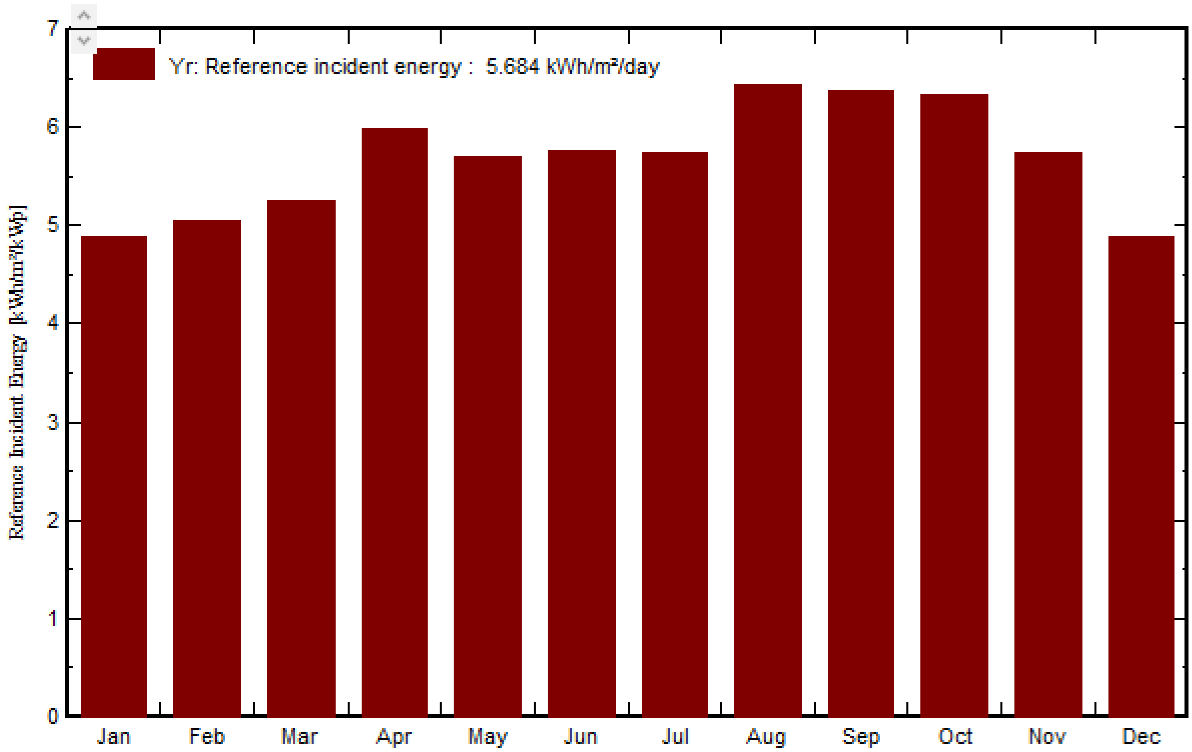

Figure 4.20 Reference incident radiation in collector plane using PVsyst softaware for Bangweulu solar PV power plant

Figure 4.21 shows that of the 5.684 kWh/m^2/day of radiation received, about 0.86 kWh/m^2/day is not converted into electrical energy due to system losses by inverters array losses (losses from solar panels) and other plant components. Therefore, of the 5.684 kWh/m^2/day, only about 4.82 kWh/m^2/day is converted to useful energy.

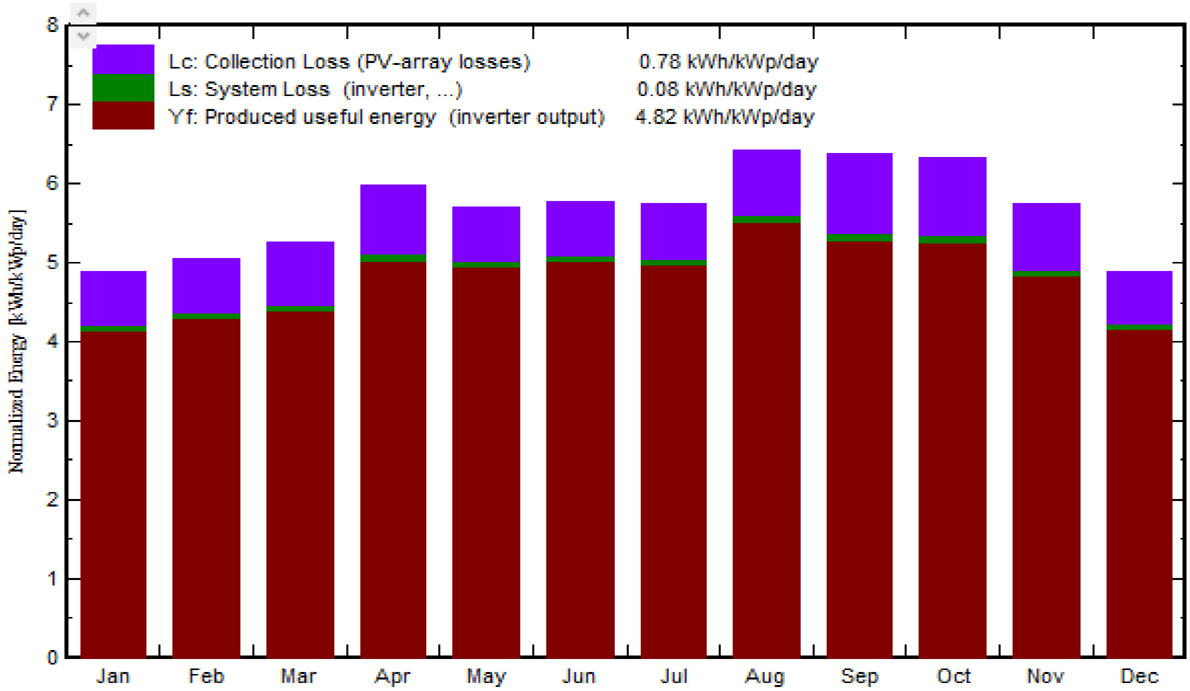

Figure 4.21 Normalised productions (per installed kWp) for Bangweulu solar PV power plant: Nominal power 54MW_p

Figure 4.22 indicates that, 15.1% of solar resource received by *Bangweulu* solar PV power plant in the assessed period was not transformed into electrical energy owing to factors such as conduction losses, inverter downtimes, module efficiency, losses due to loose contacts, and plant component defects.

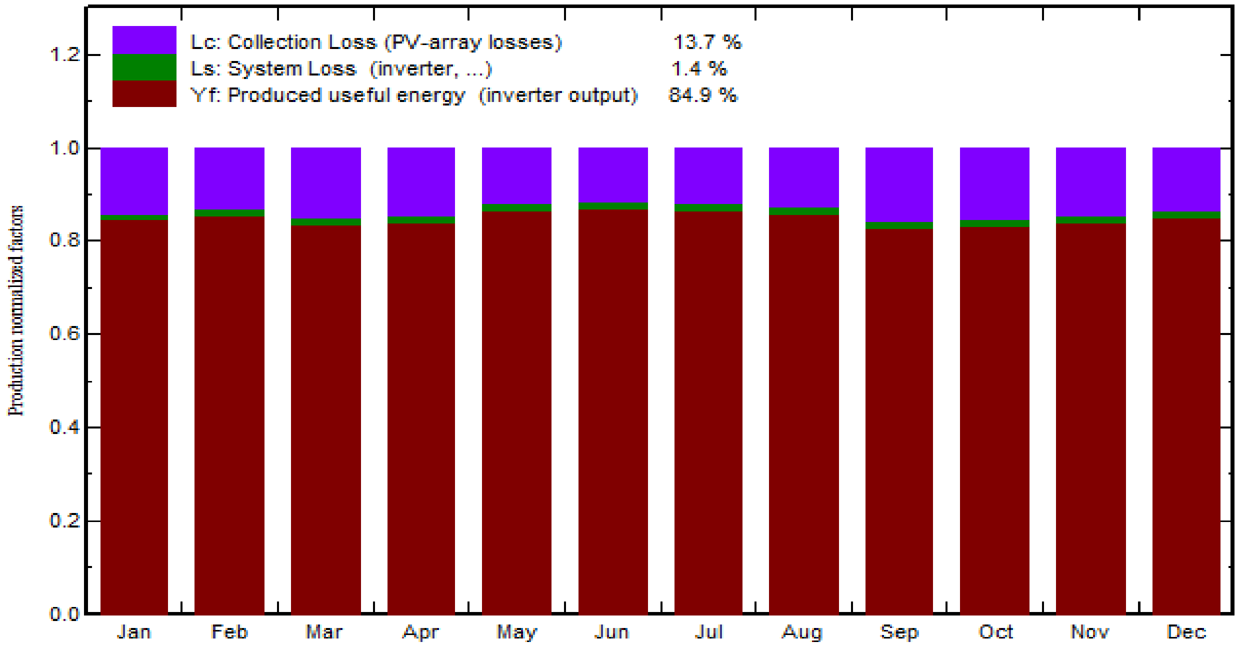

Figure 4.22 Normalised production and loss factors for Bangweulu solar PV power plant: Nominal power 54MW$_p$

Figure 4.23 shows the plant performance ratio (*PR*) which represents the proportion of energy that is available for export to the utility grid after factoring out the losses caused by inverter (L_s) and array losses (L_c). Sytem losses are mainly caused by the inverter and conduction heat losses. Array losses are caused by energy losses from solar panels.

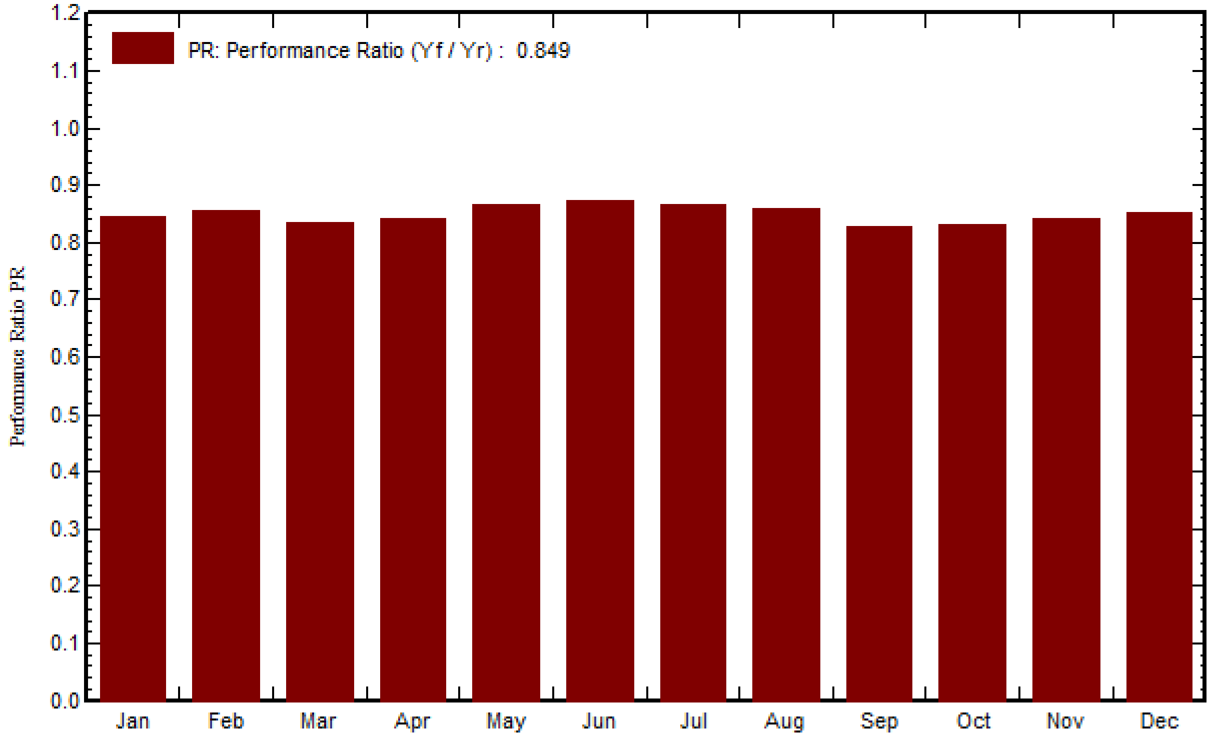

Figure 4.23 Plant performance ratio for Bangweulu solar PV power plant using PVsyst software

Figure 4.24 shows the amount of energy that can be injected into the grid with respect to different illumination levels. Each point of the graph represents the production of one day. The horizontal-axis shows the daily irradiation in the collector plane [kWh/m^2/day]. The vertical-axis shows the system's production [kWh/day]. For Grid-connected systems, this is usually linear (points below correspond to days with special losses like shadings or system unavailability). There is often a curvature in the upper part, corresponding to higher operating temperatures in summer.

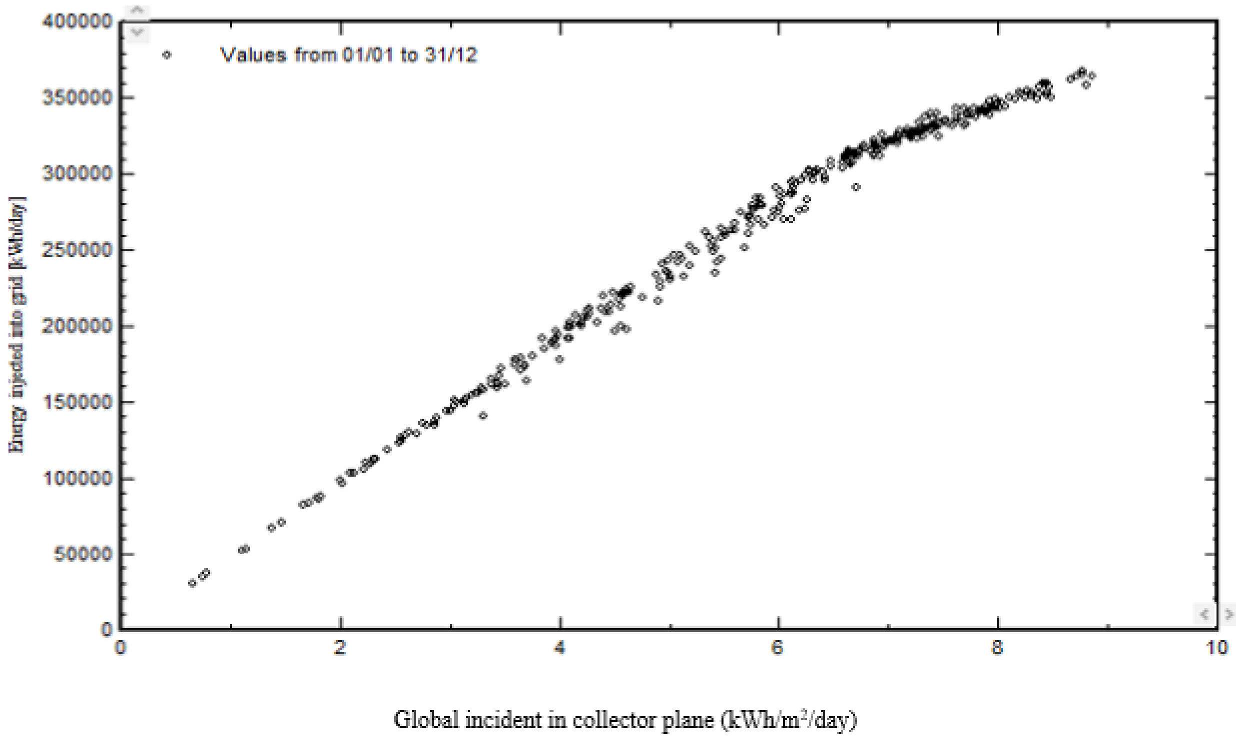

Figure 4.24 Daily input and output for Bangweulu solar PV power plant using PVsyt software

Figure 4.25 shows the pattern of energy injection into the grid with sharp spikes and troughs due to variation in irradiance. Solar PV power is directly proportional to the amount of solar resource available and hence the intense in irradiance. The amount of energy injected into the grid is not uniform at any particular time. This is the reason as to why the capacitor bank is needed to compenate for active and reactive power.

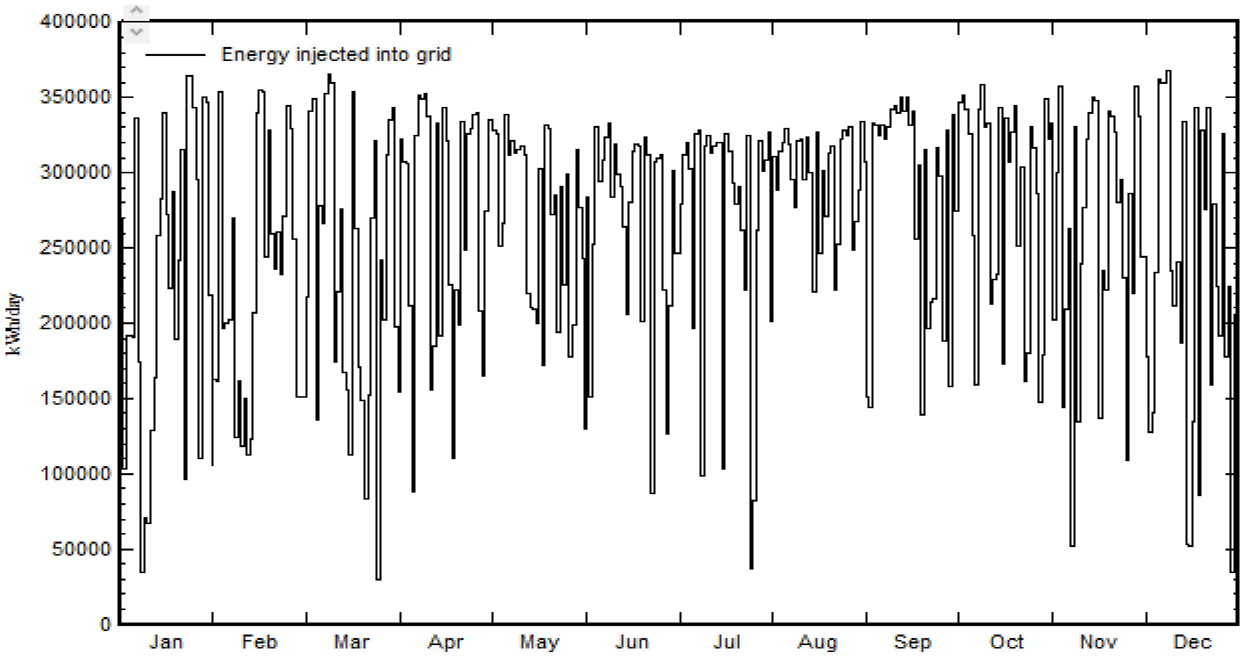

Figure 4.25 Daily system output energy for Bangweulu solar PV power plant using PVsyt software

Figure 4.26 shows operating temperatures of PV modules under different illumination, in comparison with the STC conditions. Each dot represents a module at a give illumination level. The dots show the relationship between the irradiation and the module temperature. This can be compared to the red dot (STC) and shows real world performance of the module.

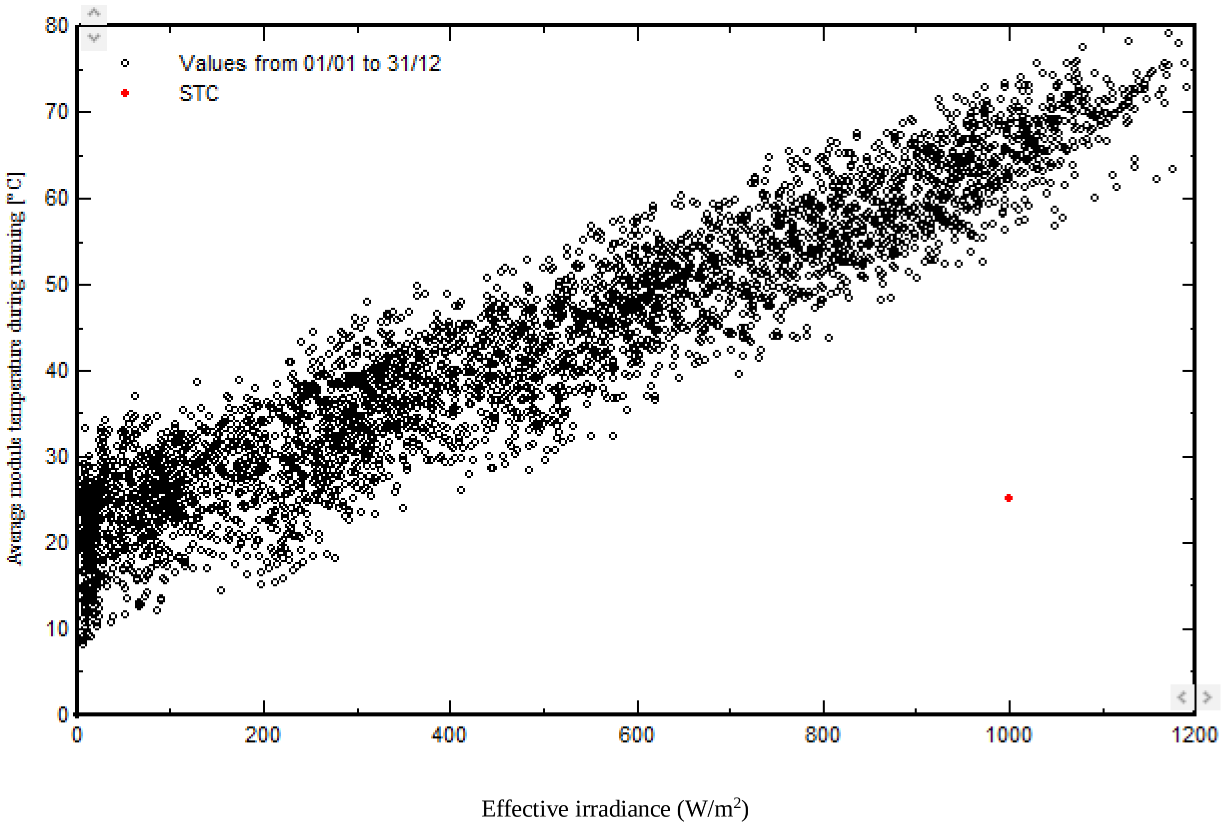

Figure 4.26 Array temperature vs effective irradiance for Bangweulu solar PV power plant using PVsyst software

Table 4.31 shows comparison of plant performance ratios for *Ngonye, bangweulu* and *CEC* solar PV power plants with reference to actual, theoretical and simulation values. Theoretical values are higher than actual and simulated values due to plant downtimes, scheduled maintenance and systematic errors.

Table 4.31 Comparison of PR with respect to theoretical, actual and simulation values

PV power plant	**PR from actual nominal and actual energy yields (%)**	**PR from theoretical values Y_r and Y_f (%)**	***PR* from PVsyst software (%)**
Ngonye	84.19	84.33	81.00
Bangweulu	82.98	88.81	84.90
CEC	80.91	86.12	N/A

Table 4.32 shows comparison of annual energy generated values between actual and simulated values for *Ngonye* and *Bangweulu* solar PV power plants. Actual values deviate from simulated values due to plant downtimes, scheduled maintenance and systematic errors.

Table 432 Comparison of annual power generation between PVsyst simulated values and actual plant outputs

Solar PV power plant	Actual energy generated (MWh/year)	PVsyst simulated energy generated (MWh/year)	Deviation (%)
Ngonye	56,095.17	61,280.00	9.24
Bangweulu	94,417.13	95,092.00	0.71

Table 4.33 shows daily average final yields for *Ngonye* and *Bangweulu* solar PV power plants to be 4.73 and 4.79 hours respectively. This represents the number of hours that the two solar PV power plants would work to produce the same amount of energy generated per day.

Table 4.33 Comparison of final yield (Yf) between actual value and PVsyst simulated value for Ngonye and Bangweulu solar PV power plants

Solar PV power plant	Y_f-PVsyst (hours)	Y_f-Actual (hours)	Y_f-Average (hours)	Deviation (%)
Ngonye	4.94	4.52	4.73	9.20
Bangweulu	4.82	4.76	4.79	6.00

Table 4.34 shows daily average reference yields for *Ngonye* and *Bangweulu* solar PV power plants to be 5.73 and 5.52 hours respectively. This represents average peak sun hours for the two solar PV power plants.

Table 4.34 Comparison of reference yield (Yr) between actual and PVsyst simulated value for Ngonye and Bangweulu solar PV power plants

Solar PV power plant	Y_r-PVsyst (hours)	Y_r-Actual (hours)	Y_r - Average (hours)	Deviation (%)
Ngonye	6.10	5.36	5.73	13.81
Bangweulu	5.68	5.36	5.52	5.97

The deviations in table 4.35 are as a result of plant stoppages, inverter downtimes and preventive maintenance. The deviations for *Ngonye* solar PV power plant are higher than that of *Bangweulu* owing to reduced plant downtimes necessitated by jammed actuators for solar trackers.

Table 4.35 Comparison of Specific yield (Sy) between actual value and PVsyst simulated value for Ngonye and Bangweulu solar PV power plants

Solar PV power plant	**Actual S_y (kWh/kW$_p$)**	**Simulated S_y (kWh/kW$_p$)**	**Deviation (%)**
Ngonye	1649.86	1802.00	9.22
Bangweulu	1738.80	1761.00	1.28

4.9.4 Financial Analysis of Ngonye Solar PV Power Plant using RETScreen Software

Table 4.36 shows the resulting calculations as produced by RETScreen for equity and debt ratio 75% to 25% with the total investment of US$ 46,000,000.00 based on the given financial parameters; inflation rate, discont rate, reinvestment rate and debt interest rate.

Table 4.36 Equity analysis and annual debt payment for Ngonye solar PV power plant

Financial parameters		
General		
Fuel cost escalation rate		0%
Inflation rate	%	2%
Discount rate	%	9%
Reinvestment rate	%	9%
Project life	yr	25
Finance		
Incentives and grants	$	0
Debt ratio	%	75%
Debt	$	34 500 000
Equity	$	11 500 000
Debt interest rate	%	7%
Debt term	yr	15
Debt payments	$/yr	3 787 915

Table 4.37 shows the amount of investment in the solar PV system project, total costs of operating the plant, total annual savings and net yearly cash flows.

Table 4.37 Investment and O&M costs for Ngonye solar PV power plant

Costs | Savings | Revenue			
Initial costs			
Investment Costs	100%	$	46 000 000
Total initial costs	**100%**	$	**46 000 000**
Yearly cash flows - Year 1			
Annual costs and debt payments			
O&M		$	323 000
Debt payments - 15 yrs		$	3 787 915
Total annual costs		**$**	**4 110 915**
Annual savings and revenue			
Savings		$	4 397 861
GHG reduction revenue		$	0
Other revenue (cost)		$	0
Total annual savings and revenue		**$**	**4 397 861**
Net yearly cash flow - Year 1		**$**	**286 946**

Table 4.38 shows pre-tax equity and assets. Pre-tax IRR-equity, that is, Pre-tax Internal Rate of Return-equity shows the return on the investment of 12.20% excluding the taxes that the solar PV power developer is mandated to pay tax authorities. Pre-tax MIRR-equity, that is, Modified Internal Rate of Return undertakes positive cashflows of 10.90% are reinvested at the power plant's cost of investment. Pre-tax IRR and MIRR-assets were generated to be 2.80% and 4.90% respectively. The table futher shows that the simple payback period for Ngonye PV power plant is 11.30 years with a positive NPV of US$ 6,046,512.00 depicting that the project is financially viable.

Table 4.38 Analysis of NPV for Ngonye solar PV power plant

Quantity	Description	Value
Pre-tax IRR- Equity	Percentage (%)	12.20
Pre-tax MIRR- Equity	Percentage (%)	10.90
Pre-tax IRR- Assets	Percentage (%)	2.80
Pre-tax MIRR- Assets	Percentage (%)	4.90
Simple payback	Years	11.30
Equity payback	Years	12.80
NPV	US Dollar	6,046,512.00
Annual life-cycle savings	US Dollar/year	615,573.00
Benefit-cost (B-C) ratio		1.50
Debt service coverage		1.10

Figure 4.27 shows cumulative pre-tax and cash flows for a 25 year period. The negative value of pre-tax in the first year depicts an equity investment cost. The negative values of cumulative cash flows from year 0 to about year 11, depict the net yearly cash flows until the break-even point (simple pay back) is attained in about 11.3 years. Positive cash flows show cumulative revenue from the project whilst positive pre-tax shows the return on the investment excluding the taxes that the solar PV power developer is mandated to pay tax authorities.

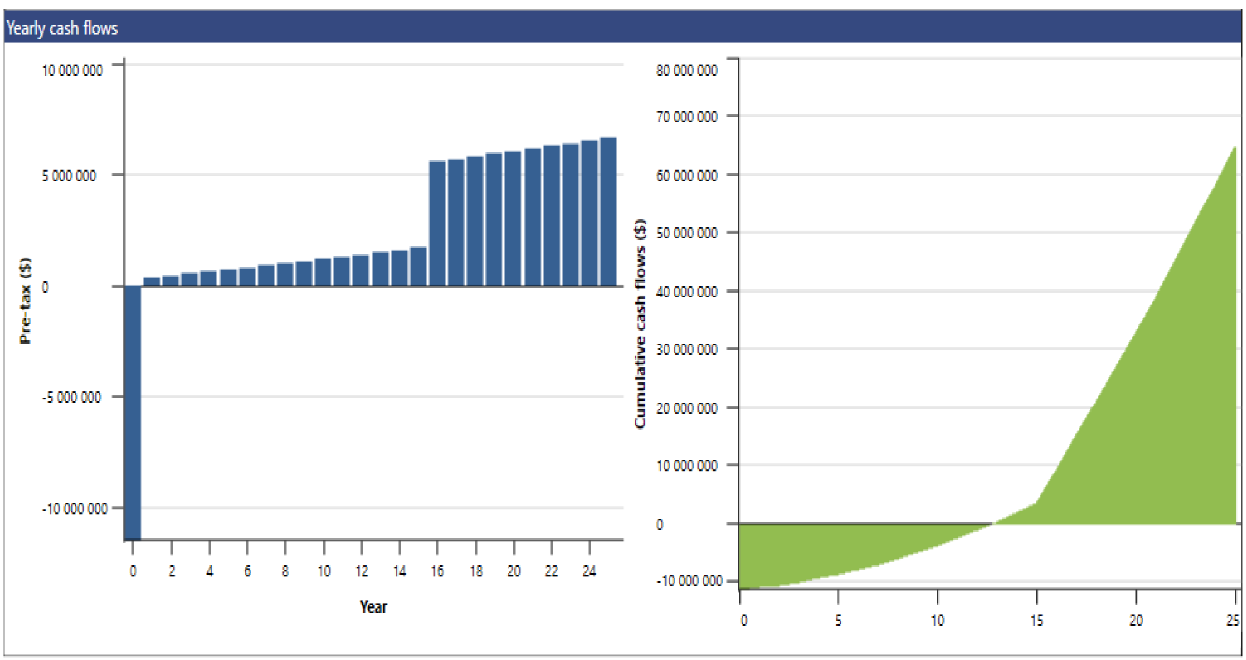

Figure 4.27 Cumulative pre-tax and cash flows for Ngonye solar PV power plant

4.9.5 Financial Analysis of Bangweulu Solar PV Power Plant using RETScreen Software

Table 4.39 shows the resulting calculations as produced by RETScreen for equity and debt ratio 68% to 32% with the total investment of US$ 60.000,000.00 based on the given financial parameters; inflation rate, discont rate, reinvestment rate and debt interest rate.

Table 4.39 Equity analysis and annual debt payment for Bangweulu solar PV power plant

Financial parameters		
General		
Fuel cost escalation rate		0%
Inflation rate	%	2%
Discount rate	%	9%
Reinvestment rate	%	9%
Project life	yr	25
Finance		
Incentives and grants	$	0
Debt ratio	%	68%
Debt	$	40 800 000
Equity	$	19 200 000
Debt interest rate	%	7%
Debt term	yr	15
Debt payments	$/yr	4 479 621

Table 4.40 shows the amount of investment in the solar PV system project, total costs of operating the plant, total annual savings and net yearly cash flows.

Table 4.40 Investment costs, O&M costs and revenue for Bangweulu solar PV power plant

Costs | Savings | Revenue			
Initial costs			
Investment costs	100%	$	60 000 000
Total initial costs	**100%**	$	**60 000 000**
Yearly cash flows - Year 1			
Annual costs and debt payments			
Annual O&M costs		$	513 000
Debt payments - 15 yrs		$	4 479 621
Total annual costs		**$**	**4 992 621**
Annual savings and revenue			
Revenue		$	5 683 911
GHG reduction revenue		$	0
Other revenue (cost)		$	0
Total annual savings and revenue		**$**	**5 683 911**
Net yearly cash flow - Year 1		**$**	**691 290**

Table 4.41 shows pre-tax equity and assets. Pre-tax IRR-equity, that is, Pre-tax Internal Rate of Return-equity shows the return on the investment of 11.10% excluding the taxes that the solar PV power developer is mandated to pay tax authorities. Pre-tax MIRR-equity, that is, Modified Internal Rate of Return undertakes positive cashflows of 10.10% are reinvested at the power plant's cost of investment. Pre-tax IRR and MIRR were generated to be 3.10 and 5.20% respectively. The table futher shows that the simple payback period for Ngonye PV power plant is 11.60 years with a positive NPV of US$ 5,703,293.00.

Table 4.41 Analysis of NPV for Bangweulu solar PV power plant

Quantity	Description	Value
Pre-tax IRR- Equity	Percentage (%)	11.20
Pre-tax MIRR- Equity	Percentage (%)	10.10
Pre-tax IRR- Assets	Percentage (%)	3.10
Pre-tax MIRR- Assets	Percentage (%)	5.20
Simple payback	Years	11.60
Equity payback	Years	13.00
NPV	US Dollar	5,703,293.00
Annual life-cycle savings	US Dollar/year	580,631.00
Benefit-cost (B-C) ratio		1.30
Debt service coverage		1.20

Figure 4.28 shows cumulative pre-tax and cash flows for a 25 year period. The negative value of pre-tax in the first year depicts an equity investment cost. The negative values of cumulative cash flows from year 0 to about year 11, depict net yearly cash flows until the break-even point (simple pay back) is attained in about 11.6 years. Positive cash flows show cumulative revenue from the project whilst positive pre-tax shows the return on the investment excluding the taxes that the solar PV power developer is mandated to pay tax authorities.

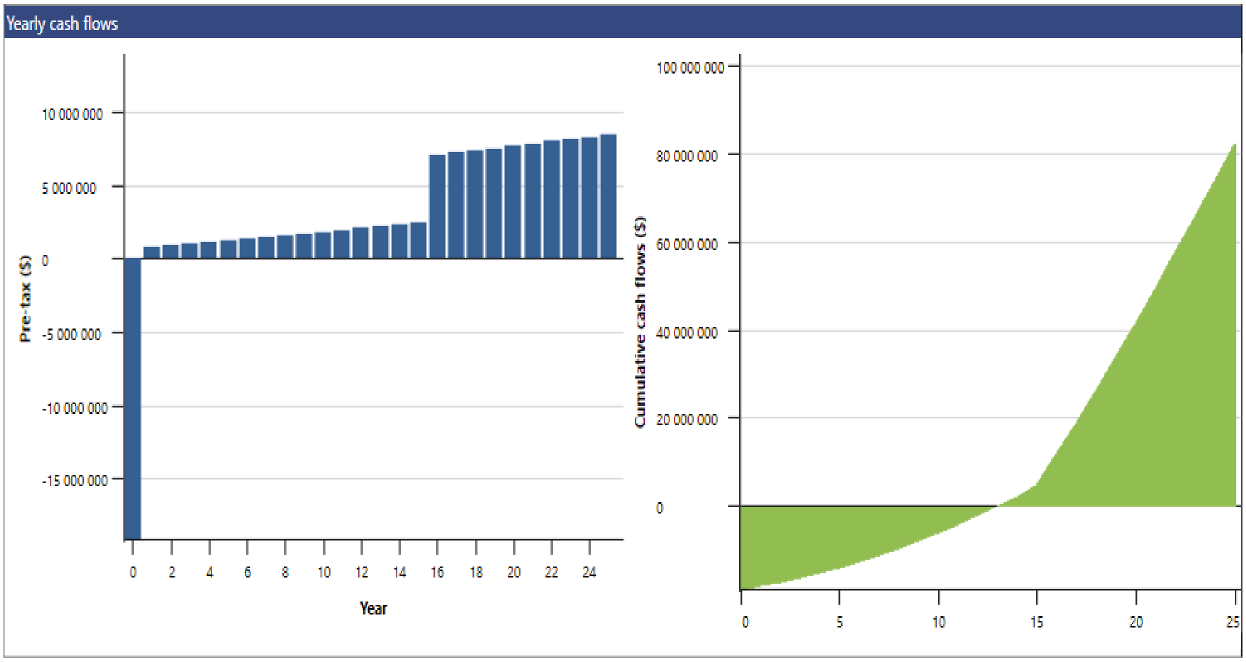

Figure 4.28 Cumulative pre-tax and cash flows for Bangweulu solar PV power plant

Table 4.42 compares grid parities from two different sources of analysis, that is, computation from actual plant values and RETScreen simulation values. The difference is very small with Bangweulu solar PV power plant recording the difference of zero.

Table 4.42 Grid parity comparison between actual values and RETScreen simulation values

Solar PV power plant	**Grid parity from actual values (years)**	**Grid parity from RETScreen simulation values (years)**	**Deviation (%)**
Ngonye	11.29	11.30	0.09
Bangweulu	11.60	11.60	0.00

Figure 4.29 show the variation of discount rate (debt interest rate) with equity pay back. It shows that the higher the discount rate, the longer the equity pay back and vice versa.

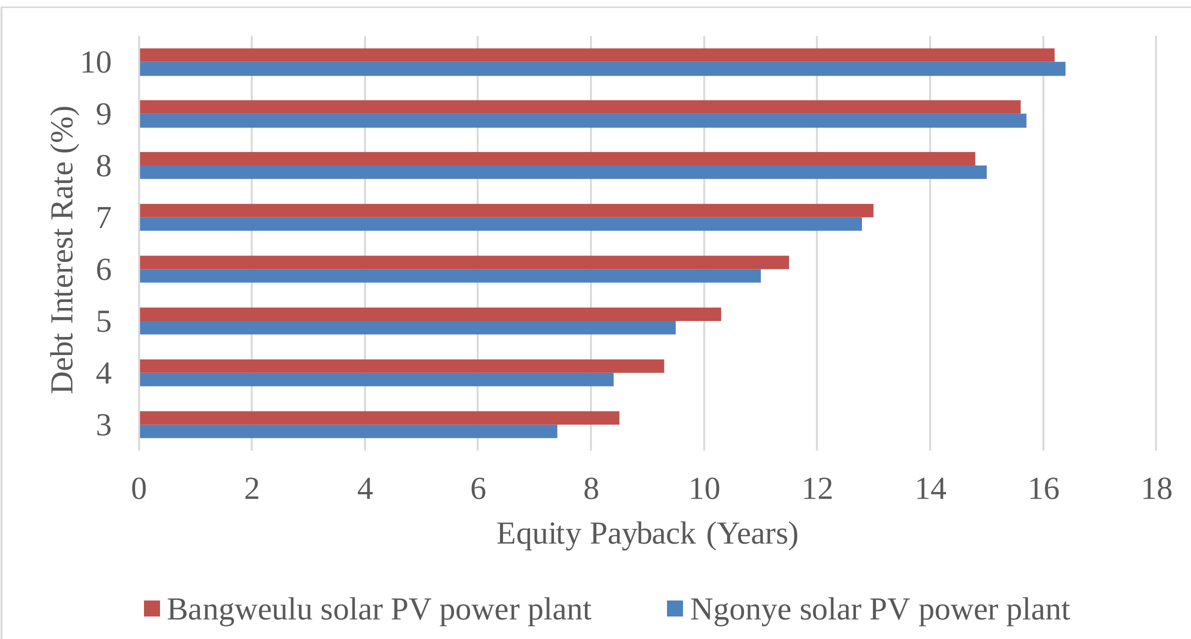

Figure 4.29: variation of discount rate (debt interest rate) with equity pay back

4.10 Strengths and Weaknesses, Lessons Learnt and Good Practices of On-grid Solar PV Power Systems

4.10.1 Strengths of On-grid solar PV Power Systems

i. On-grid solar PV power systems provide diversity and relieve pressure on hydropower generation that has been constrained due to low water levels because of climate change.
ii. Solar energy provide clean and sustainable energy.
iii. Solar energy is cheap

4.10.2 Weaknesses of Solar On-grid PV Power Systems

i. Operation for on-grid solar PV power systems shifts due to variability in energy generation caused by variations in irradiance. It is weather dependent and therefore solar PV plant efficiency drops during cloudy and rainy days.
ii. On-grid solar PV systems cannot supply base load power.
iii. The Solar plant cannot feed to the utility grid during a grid failure or blackout.
iv. Small and medium enterprises have a challenge in investing in solar energy due to high initial investment cost. Financial institutions demand for collateral from new investors.
v. Current financial position of the national utility and off taker (ZESCO) poses a risk that has the potential to cause developers bid in higher tariffs.
vi. Lack of one stop shop for permits and information.
vii. There is no guidance from Zambia Environmental Management Agency (ZEMA) on how to dispose off unwanted solar products such as solar panels after their life time.

4.10.3 Lessons Learned from On-grid Solar PV Power Systems

i. There is need to revise the national grid code and the subsequent System Operation procedures. The national grid code provides procedures and technical requirements for connecting and using of the national utility grid.
ii. Capacity building is very important before and during construction of the solar PV power system as it enlightens players with techno-economic requirements.

iii. Expertise in utility scale solar PV is scarce in Zambia. Learning institutions should take advantage of this opportunity and develop programs for Renewable Energy at all levels (Artisan to Graduate)
iv. Solar PV power systems are better developed in small capacities below 50MW and distributed in different locations of the country.
v. On-grid PV solar power requires adequate grid integration studies and readily available funding.

4.10.4 Good Practices for On-grid Solar PV Power Systems

i. Variable power generation are best developed in small quantities (below 50MW) distributed in different geographic location.
ii. Introduction of an intermediary power off-taker concept that provides for an alternative off-taker of power from renewable energy resources (IPPPs) in addition to ZESCO.
iii. The enactment of the new electricity act 2019 that provides for an open access regime enabling independent buyers of power and provision of wheeling and ancillary services by ZESCO.
iv. Procurement of solar PV power in phases depending on predictable load growth as it is advantageous to both the off taker and IPPs.

4.11 Impacts of On-grid solar PV power systems' Strengths and Weaknesses on Zambia's Energy Security, Financial Viability and Environmental Sustainability

i. Increases security of supply, diversifies energy mix, the competitive tender process enables price discovery and attracts lower prices. Lower prices guarantee the government of supply of energy with an incentive of cost saving hence financially sound to the Government through ZESCO.
ii. Solar PV power is an important resource in augmenting the now constrained hydropower generation. This increases energy security.
iii. Low O & M costs of solar PV power system increases the probability of profit-making of the system.
iv. Lack of standardised documentation hinders IPPs regarding direction and forecasting of the development procedures.

v. Financial instabilities of electricity generating companies might lead to insecurity of investors and might lead to financial unviability in case of consecutive tariff payment defaults. Consecutive tariff payment defaults might constrain the Insurer leading to collapse in business and hence the entire project.

vi. Lack of guidance on how to dispose off unwanted solar products poses as a risk and hazardous to the environment.

vii. On-grid solar PV power systems are climate friendly and this is environmentally sound to the country.

Chapter 5

Conclusion and Recommendations

5.0 Conclusion

i. The country is in need of GHG-free and economical alternative sources of energy such as solar in order to meet the nation's increasing energy demand. Currently power generation from on-grid solar PV systems in Zambia is 88.3 MWp out of the current total installed power capacity of 3,538.27 MWp with the inclusion of the newly commissioned Kafue lower hydro power station. *Ngonye*, *Bangweulu* and *CEC* solar PV power plants gave marginal errors of 6%, 1% and 17% respectively regarding annual power generation. Therefore, estimated values from GSA provide a thorough insight of the actual PV power to be generated. The plant performance ratio (PR) for *Ngonye*, *Bangweulu* and *CEC* solar PV power plants were found to be 83%, 86% and 84% respectively. These values are above the internationally acceptable standard value of 75%. Annual mean daily peak sun hours for *Ngonye*, *CEC* and *Bangweulu* solar PV power plants was found to be 5.29 hours. The Capacity Utilisation Factors (CUF), which is the percentage utilisation of the solar PV power plant against the installed capacity for *Ngonye*, *CEC* and *Bangweulu* solar power plants were found to be 18.8%, 16.6% and 19.8% respectively. Therefore the percentage utilisation of *Ngonye*, *CEC* and *Bangweulu* solar PV power plants are within acceptable range of 12 to 24%.

   In comparison with *Maamba* coal power production as the benchmark, the estimated cost saving for Scaling Solar is US$126.94Million for *Ngonye* and *Bangweulu* solar PV power plants while GET FiT programme estimated a cost saving of US$527.54Million. The anticipated solar PV grid absorption capacity power estimated a cost saving of US$2.21Billion. The total estimated cost saving from the three mentioned solar energy initiatives is US$2.86Billion for the period of 25 years. *Ngonye* and *Bangweulu* solar PV power plants can recuperate investment costs in 11 years 4 months and 11 years 7 months, respectively for a 25-year PPA making them financially sound.

ii. If GET FiT and anticipated solar PV power that can be absorbed by the grid are implemented, about 2,116 GWh of energy will be injected into the grid. Therefore the environment will be saved from being polluted with about 2.1Million tonnes CO_2 equivalent of GHGs per year if the same energy is generated through coal power production.

iii. Therefore on-grid solar PV power systems through solar energy initiatives provide diversity, energy security and relieve pressure on hydropower generation that has been constrained due to low water levels because of climate change. Additionally, the PR above 75%, CUF above 12%, an average peak sun hours of 5.29 hours, a total estimated saving of US$2.86Billion, an average grid parity of 11.6 years for a period of 25 years and the environment being saved from being polluted with about 2.1 Million tonnes CO_2 equivalent GHGs, shows that solar PV power technology is one of the cheapest sources of energy, environmentally friendly and financially sound to the Government.

iv. The study of Zambia's on-grid solar energy initiatives and PV power systems presents strengths, weaknesses, lessons learned, good practices and impacts of on-grid solar PV power systems' strengths and weaknesses on Zambia's energy security, financial viability and environmental sustainability as outlined in sections 4.10.1, 4.10.2, 4.10.3, 4.10.4 and 4.11 respectively.

5.1 Recommendations

i. For load management purposes (load shedding), ZESCO may adopt the following principle. During the day when on-grid solar PV power generation is high, the utility company may reduce production from conventional sources such as hydro and thermal such that in an unlikely fall in solar PV power generation, the utility company may have spinning reserves from conventional sources to quickly ramp up to match the demand. The automatic generators at hydropower stations can be set to "Auto-Mode" during the day to automatically vary hydro power production for purposes of accommodating intermittent weakness of solar PV power generation.

ii. There is need for doing accurate assessment of grid absorption capacity at different grid points/substations.

iii. In view that solar energy is one of the cheapest source of power, GRZ should prioritise use of solar energy over other power sources as long as the grid can absorb it.

iv. GET FiT's direction of installing solar PV power systems in small capacities of less than 50MW and distributed across the country, should be adopted.

v. Solar tax credits and rebates should be introduced to empower small and medium enterprises for the benefit of the country.

vi. An introduction of remuneration for consistent generation of good quality solar PV power should be introduced as this will ignite competition for production of high quality power amongst solar developers.

vii. Grid integration (grid transmission and distribution) should be implemented in North-Western province for purposes of installing solar PV systems. North-Western province has very good solar irradiance levels coupled with undeveloped vast land. This can be of economic benefit to the developer and the country.

viii. Solar PV power system developers may adopt the installation of CdTe thin film solar panels as they are cheap, their efficiency improved and degradation rate per year reduced with the incoming of high-tech solar panel production systems.

ix. In order to receive cheapest energy, Government should invite bids for solar energy projects in a manner similar to Scaling Solar and GET Fit solar programs.

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Appendix A: Copperbelt Energy Corporation (CEC) Solar Power Plant Questionnaire

Study of the major on-grid solar energy initiatives in Zambia

This is a Physics MSc academic research questionnaire aimed at providing detailed and up to date information and documentation on on-grid solar energy systems in Zambia, providing critical analysis of the strengths and weaknesses of the existing on-grid solar energy system and its impact on Zambia's energy security, financial viability and environmental sustainability, identifying and listing good practices, lessons learnt and recommendations for on-grid solar energy initiatives for use in future solar initiatives and investments in Zambia.

Copperbelt Energy Corporation (CEC)

Questionnaire by Walusa Francis

07/01/2021

Question	Response
Current Status (General)	
Solar Power (Operational and Technical)	
Kindly avail us with monthly recorded irradiance values from October 2019 to September 2020.	Find in the attached excel sheet
Kindly avail us with monthly energy outputs from October 2019 to September 2020.	Find in the attached excel sheet
What is the efficiency and degradation rate of installed solar panels?	Solar Panel Efficiency -18.51% Degradation Rate cannot be calculated because of incomplete data needed to calculate the rate. However, an estimate can be calculated from the given data in the excel sheet attached.
What are the dimensions of the solar panels?	Solar Panel Dimensions -Length - 1650 mm -Width - 991 mm -Thickness - 35 mm -Module area 1.635 m^2
What is the rating of the transformer?	Transformer Station Rating -1 MVA -0.4/ 11 kV

What instruments are found at the weather station?	Weather Station comprises of the following: -1 Pyranometer -1 Anemometer -1 Ambient Temperature Sensor -1 Module Temperature Sensor

Solar Power General/Others	
What are the strengths and weaknesses of the existing on-grid solar energy projects/systems in Zambia?	**Key Strengths** 1. The inverter Anti-islanding Protection feature enables safe operation of the Solar Plant. 2. Inverter smart grid integration feature allows safe connection of the Solar Plant to the grid without needing synchronization equipment 3. Inverters can be used to improve voltage profile in the utility grid as they are capable of injecting and absorbing reactive power. 4. Relatively low operating and maintenance cost. 5. Adds to diversification of power sources in Zambia **Weaknesses** 1. Weather dependent – Solar Plant efficiency drops during cloudy and rainy days. 2. Cannot supply baseload power 3. Takes up to much land. Approximately 1 ha per MWp 4. The Solar plant cannot feed to the utility grid during a grid failure or blackout. 5. High installation costs leading to high energy tariffs compared to grid power.
What lessons have you learned regarding on-grid solar projects or systems in Zambia?	**Lessons learnt** 1. There is high resource potential in Zambia for solar development 2. Intelligence of inverters has significantly improved thereby reducing grid integration challenges 3. Expertise in utility scale solar PV is scarce in Zambia. Learning institutions should take advantage of this opportunity and

	develop programs for Renewable Energy at all levels (Artisan to Graduate)
What good practices have you identified regarding on-grid solar energy systems?	**Good Practices** 1. Regular online Solar Plant monitoring. 2. Capacity building and personnel training 3. Proper technical asset management 4. Regular module cleaning is key to plant performance
What recommendations would you make for the betterment of on-grid solar energy systems in Zambia?	**Recommendations** 1. Developers should add Energy storage to on-grid solar systems as it will improve the efficiency of the Solar Plant. 2. Electricity tariffs should migrate to cost reflectivity to increase solar power development 3. Net metering net should be implemented to increase solar PV uptake. Netmetering would improve return and encourage residential and commercial adoption of grid time solar PV
Any other comment/information regarding on-grid solar energy power plant in Zambia.	**Comment** 1. Collaboration between industry & academia required to include renewable energy in curricula and support implementation 2.
What is the **total monthly** expenditure for the solar power plant?	**Expenditure** Between \$1500 and \$2000 /month

Attachment

1. **Monthly Solar Data**

Irradiation and Energy Yields.xlsx

Copperbelt Energy Corporation Solar Power Plant Excel Sheet

	Monthly Irradiation and Energy Yields	
Date	Radiation Yield [Wh/m²]	Energy Yield [kWh]
Jan-19	-	-
Feb-19	38,963,61	31,784,40
Mar-19	162,535,61	68,664,72
Apr-19	76,788,14	29,699,10
May-19	-	-
Jun-19	-	-
Jul-19	31,557,22	26,478,84
Aug-19	155,575,75	129,372,19
Sep-19	158,890,28	134,209,11
Oct-19	189,231,89	159,772,67
Nov-19	150,613,96	132,422,03
Dec-19	145,918,77	126,983,53
Jan-20	123,565,67	103,714,15
Feb-20	85,590,49	75,544,41
Mar-20	103,729,28	91,886,77
Apr-20	183,151,36	150,581,67
May-20	124,897,60	102,343,54
Jun-20	102,208,25	83,751,74
Jul-20	151,201,12	127,031,65
Aug-20	139,795,20	112,368,17

Sep-20	182,039,15	154,720,04
Oct-20	190,380,54	161,564,72
Nov-20	173,493,00	147,733,98
Dec-20	132,420,30	115,391,48

Appendix B: Ministry of Energy (MoE) Questionnaire

Study of the major on-grid solar energy initiatives in Zambia

This is a Physics MSc academic research questionnaire aimed at providing detailed and up to date information and documentation on on-grid solar energy systems in Zambia, providing critical analysis of the strengths and weaknesses of the existing on-grid solar energy system and its impact on Zambia's energy security, financial viability and environmental sustainability, identifying and listing good practices, lessons learnt and recommendations for on-grid solar energy initiatives for use in future solar initiatives and investments in Zambia.

Ministry of Energy

Questionnaire by Walusa Francis

26/07/2020

Solar Energy Initiative	Response
General	
Does the government have a policy document on Solar/Renewable Energy? If yes, please provide details.	Yes. The Energy Policy and Renewable Energy Feed In Tariff (REFIT) Stratergy
Does the government intend to adopt increased use of solar energy in future? If so, what main reasons or advantages does it perceive in this?	YES. Increased security of supply, diversification of energy mix…refer to REFIT strategy and Energy Policy
Does the government have any specific targets for solar and other renewable energy?	No
Is there any law or Statutory Instrument (SI) that compels or requires the utility company to generate a certain percentage of electricity from renewable energy (solar energy)?	No
Is the Ministry planning to introduce any incentives such as tax rebates with regard to on-grid solar power systems?	No. Taxes and rebates are not the Jurisdiction of the Ministry of Energy. However, Zambia Development Agency (ZDA) through Ministry of Commerce has investment incentives for a certain threshold on investment. Refer to ZDA
Does the Ministry have solar tax credit?	No
When is the Ministry going to introduce and implement solar standards?	Most of the standards related to Solar are already in place. Those related to Solar home systems are pending approval.

	Check with Nchimunya Mwiinga from UNZA Physics department who is part of this committee.
Is the Ministry planning to introduce remuneration for consistent production of good quality solar power	No plans at the moment
Do you have any role to play when it comes to controlling tariffs? Do you leave it entirely to ERB?	No role. Entirely left to the ERB
Solar Energy Initiative	**Response**
Scaling solar	
What is the current status of Scaling Solar initiative?	Round one completed and two solar power plants are operational. Plans are still underway for round 2
Does the government perceive the Scaling Solar as a good initiative? Please give reasons.	Yes. Increases security of Supply, Diversifies energy mix, the competitive tender process enables price discovery and attracts lower prices,
Why has the Scaling Solar not moved beyond the LSMFEZ?	Lack of sponsor to provide financial guarantee. Current financial position of the national utility and off taker (ZESCO) poses a risk that has the potential to cause developers bid in higher tariffs.
Why has the World Bank deferred its support towards scaling solar? As a government, what are you doing about it to retain faith from the World Bank for continued support?	Answer to the why question TBA. But note that the Ministry of Energy is Just a component of Government and cannot answer on behalf of the whole Government. Finance related challenges and retention of faith from the WB are under the Jurisdiction of MoF
What measures have you put in place to avoid such occurrences in future?	Introduction of intermediary Power Off taker Concept that provides for an alternative offtaker of power from renewable energy Sources in addition to ZESCO and Enactment of the New Electricity Act 2019 which provides for an Open Access regime enabling independent buyers of power and provision wheeling an ancillary services by ZESCO
Will scaling solar initiative under the World Bank Group be 'resurrected'? Will there be phase 2 of scaling solar?	No. Instead, a new program called Alternative Renewable Energy Programme is being developed by IDC. Kindly note that Scaling Solar is under the Jurisdiction of the

	Industrial Development Corporation and not the Ministry of Energy.
How much money does ZESCO owe IPPs and other institutions?	The Ministry of Energy does not keep this information and would not disclose it in any event. Such information can be obtained from ZESCO by the interviewer. Consider Citing public sources for approximate figures.
When will the 'ARIEP' scaling solar complementary programme commence?	Check with IDC
Has the Ministry secured solar developers (IPPs) for 'ARIEP'?	ARIEP is an IDC programme
If not, why?	N/A
What other alternatives do you have apart from ARIEP in implementing scaling solar presidential directive to secure 600MW seeing that only 88MW has been secured so far?	600MW mandate was given to IDC. Ministry is doing a grid integration study to determine hoe much more renewable energy power can e integrated into the grid beyond the 600MW. Only after this study concludes with plans for new tenders commence.
Apart from Neoen RSA and Enel Green Power, which other companies were awarded tenders for the 600MW scaling solar project?	None. The two companies emerged winning bidders after an evaluation. Check IDC website for Scaling Solar round 1 tender information
What has happened to the other companies mentioned in response above after the World Bank deferred its support?	N/A
Does scaling solar have the provision for an insurance cover to protect solar developers against the risk of ZESCO to default?	Yes.
Please provide salient features of the PPAs with the two companies. Tariffs, duration, tariff escalation, etc. Can the copies of the PPAs be made available?	• Bangweulu Power Company (By Neon) tariff is 6.02 cents/KWh. • Ngonye Power limited (By Enel) is 7.84 cents/KWh • PPAs are for 25years and have no escalation. PPAs are between ZESCO and the respective companies. Copy can be obtained from the parties
What improvements have the installed solar power plants brought about with regard to power load management?	Best answered by ZESCO who are the system operators. But In terms of load shedding, this newly installed capacity has reduced the power deficit by the amount equivalent to their total installed capacity
How has been the government experience of the solar power? E.g. Costs, diversity of energy sources, meeting the shortfall, etc.	Positive - Increased generation capacity, lower tariffs than conventional sources

Solar Energy Initiative	Response
GET FiT	
What is the current status of the GET FiT program.	120MW Solar PV Power procured awaiting signing of PPAs with ZESCO and construction. 100MW small hydro tender under preparation.
How does the government perceive the cost of power under the GET FiT program?	Cheaper than other souces. At the time of award, the Tariffs from the GETFIT Solar tender were the cheapest in sub Saharan Africa outside south Africa.
Has the PPA been signed for the GET FiT programme? If not, at what stage of signing is the PPA?	No. at PPA negotiation stage
If the PPA has not been signed, where is the 'bottleneck' and what are you doing as a Ministry to resolve such bottlenecks or accelerate the process of signing the PPA?	Developers and their respective lenders are still at due diligence stage.
Has the tariff payment structure been agreed between solar developers and ZESCO?	Yes
Has GET FiT secretariat insured the developers against the risk of ZESCO to default?	Procurement of a Liquidity Support Facility from Africa Trade Insurance (ATI) that allow a few months of cover in case of default.
In the case where a developer withdraws from the programme, will the standby developer, who will take over the project, inherit all that was agreed with the previous developer?	No. Note that PPAs and other documents under GETFIT were standardized and similar for all developers. However, the peculiar details will be renegotiated with standby developer
Land disputes are very common and have proved to be a challenge where construction of solar plants is concerned. What are you doing as a Ministry to solve this problem?	The Ministry provides support letters to developers which can be presented to land owners during the land procurement phase. The Ministry also only proceeds with projects whose owners can prove they legally own the land the project will be sitting on. In certain tenders where it is possible for projects to be lumped together, the Ministry procures the land to lessen land procurement challenges.

Solar Energy Initiative	Response
China Solar Power	
Has ZESCO and China Solar Power reached an agreement to construct solar power plant(s)?	This is a project by ZESCO. Details have not yet been submitted to the Ministry. Consider obtaining information from ZESCO

What is the capacity and location of the solar power plant(s) to be constructed?	N/A
Has the exact modus operandi been structured?	N/A
Will China solar power embark on solar power plant construction or will it opt to only fund the project?	N/A
Other Initiatives	
What are the other on-grid solar initiatives on the cards?	TBA However, note that the Grid integration Study is underway to determine the capacity of RES the Zambian Grid can take up. Further planning will be based on the results of this study.
What is the status of the initiatives?	N/A TBA
Independent Power Producers	?
What is the Ministry's target for solar power procurement from IPPs?	No Target at the moment
What complaints (if any) do you receive from IPPs regarding the policies for solar power production?	• Lack of one stop shop for permits and information, • lack of standardized documents eg PPAs, Implementation Agreements, Grid Connection agreements • Targets on Renewable Energy
Don't you think that the dispute between CEC and the government might tarnish the image of Zambia where security of investors is concerned?	'Dispute' is subjective.
Is the Ministry involved in solving disputes arising from ZESCO and IPPs?	The Ministry only focuses of policy formulation, implementation and guidance. The ministry does not indulge in operational matters of ZESCO

Appendix C: Office for Promoting Private Power Investment (OPPPI) Questionnnaire

Study of the major on-grid solar energy initiatives in Zambia

This is a Physics MSc academic research questionnaire aimed at providing detailed and up to date information and documentation on on-grid solar energy systems in Zambia, providing critical analysis of the strengths and weaknesses of the existing on-grid solar energy system and its impact on Zambia's energy security, financial viability and environmental sustainability, identifying and listing good practices, lessons learnt and recommendations for on-grid solar energy initiatives for use in future solar initiatives and investments in Zambia.

Office for Promoting Private Power Investment (OPPPI)

Questionnaire by Walusa Francis

07/11/2020

Question	**Response**
How many on-grid solar initiatives/projects do you have on the cards?	There are numerous on-grid solar projects, across the country that are being implemented by various stakeholders such as ZESCO, Other Government Institutions, Private Sector etc.
How much on-grid solar energy do you intend to procure?	Governments role in power developments is merely facilitative. The facilitation is aimed at ensuring the security of supply for the country. The Zambian power market is liberalised and therefore market players such as ZESCO, CEC and the power producers determine how much power is procured.
How many developers have you engaged or do you wish to engage?	The engagement of developers is a continuous process. In its facilitative role, Government welcomes all prospecting developers including power earmarked for private sector offtakers.
How many areas have you identified through feasibility studies as potential for on-grid solar projects?	Feasibility assessments for Solar power projects are being done across the country by various stakeholders.

What made areas mentioned above as potential areas?	Selection of potential areas for power projects is dependent on many techno-economic and environmental factors such as: 1. Availability of energy resource 2. Availability of land 3. Availability and costs associated with power evacuation 4. Grid integration 5. Availability of appropriate technologies 6. Accessibility to site 7. Proximity to offtaker facilities etc
How do you develop an appropriate solicitation strategy and documents for developers?	Solicitation strategies and related documents are driven by the characteristic requirements of a given project. Project Documents for a private sector project are different from that of a project being implemented by a public entity, and documentation for a power project earmarked for a private sector offtaker is different for a project with power earmarked for a public offtaker.
Why was scaling solar assigned to IDC instead of the already existing OPPPI?	Government facilitates power projects using various strategies and the OPPPI provides support to such developments.
What challenges do you face when negotiating for implementation strategies?	Negotiation for an Implementation Agreement (IA) is a standard process whose challenges have been addressed.
What are the strengths and weaknesses of the existing on-grid solar energy projects?	Strength: enhancement of security of supply Weakness: Variable energy generation
What are the impacts of on-grid solar energy systems regarding energy security in Zambia?	Positive: Relief pressure on hydrogeneration that has been constrained due to low water as a result of climate change Negative: Operation shifts due to variability in energy generation causing challenges on system operations

What lessons have you learned regarding on-grid solar projects or systems in Zambia?	There is need to revise the National Grid Code and the subsequent System Operation Procedures
What good practices have you identified regarding on-grid solar energy systems?	Variable Energy Generators are best developed in small quantities (50 MW ±) distributed in different geographic location
What "mechanism(s)" do you use to attract investors?	Technical Assistance during the development of project. Developers can engage the OPPPI in developing the technical solutions, business case and environmental strategies for the projects. Facility the procurement of other government licenses, approvals, rights, easements etc. Incentives provided through the Ministry of Commerce and the Ministry of Finance
What other services do you offer to on-grid solar developers besides negotiating implementation agreements?	Technical Support to meet Prudent Utility Practices as the projects are being developed
How has been OPPPI experience of the solar power? e.g. Costs, diversity of energy sources, meeting the shortfall, etc.	Solar Power is an important resource in augmenting the now constrained legacy hydroelectric power generation
Any other comment/information regarding on-grid solar energy power plant in Zambia.	None

Appendix D: Zambia Electricity Supply Corporation (ZESCO) Questionnaire

Study of the major on-grid solar energy initiatives in Zambia

This is a Physics MSc academic research questionnaire aimed at providing detailed and up to date information and documentation on on-grid solar energy systems in Zambia, providing critical analysis of the strengths and weaknesses of the existing on-grid solar energy system and its impact on Zambia's energy security, financial viability and environmental sustainability, identifying and listing good practices, lessons learnt and recommendations for on-grid solar energy initiatives for use in future solar initiatives and investments in Zambia.

Zambia Electricity Supply Corporation (ZESCO)

Questionnaire by Walusa Francis

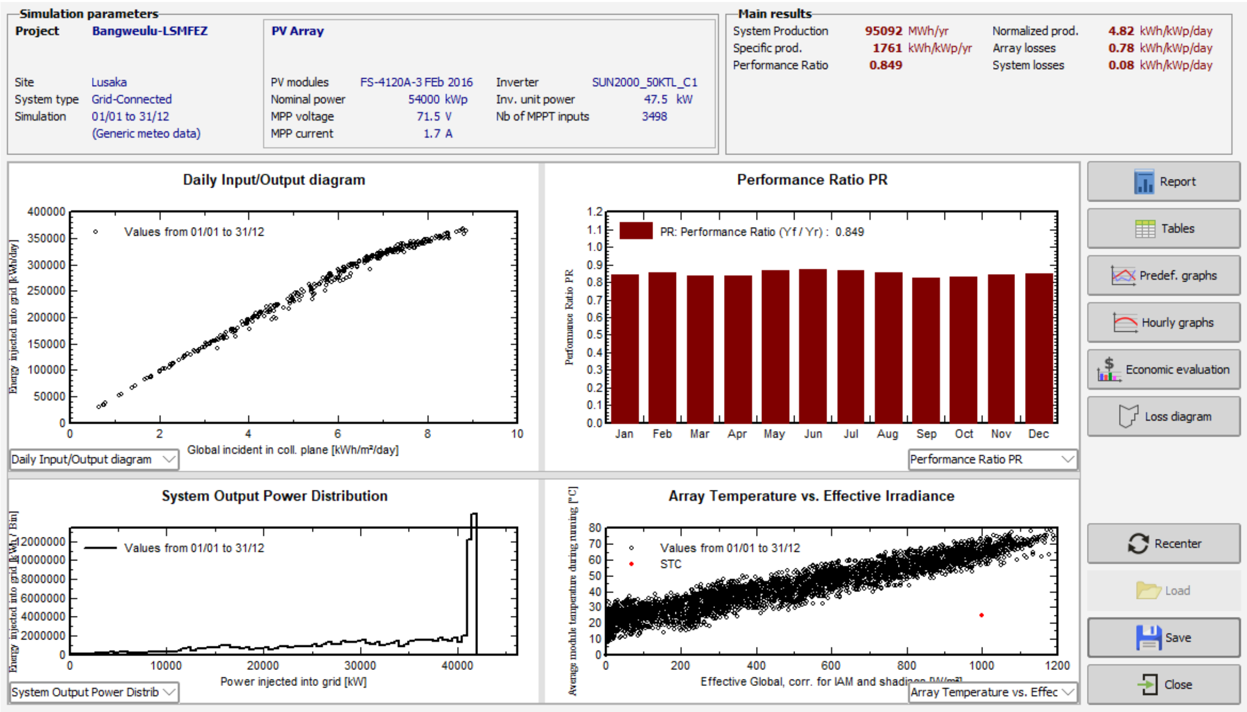
21/12/2020

Question	Response
Current Status (General)	
What is Zambia's current annual average power production?	11,957 GWh
What is Zambia's current annual average energy consumption?	18,396 GWh
How much power deficit does Zambia have currently?	850 MW
Solar Power (Current Status)	
How much total installed solar power does Zambia have currently?	76 MW
How much solar power can the Zambian grid absorb?	About 816 MW FOR YEAR 2022 HORIZON
How many on-grid solar energy initiatives/projects does ZESCO have on the cards at present?	ABOVE 5 (FIVE)
What is the status of the Scaling Solar Project?	PARTLY IMPLEMENT, OTHERS FINANCIAL CLOSURE NOT YET ATTAINED
What is the current status of the GET FiT project?	FINANCIAL CLOSURE NOT YET ATTAINED

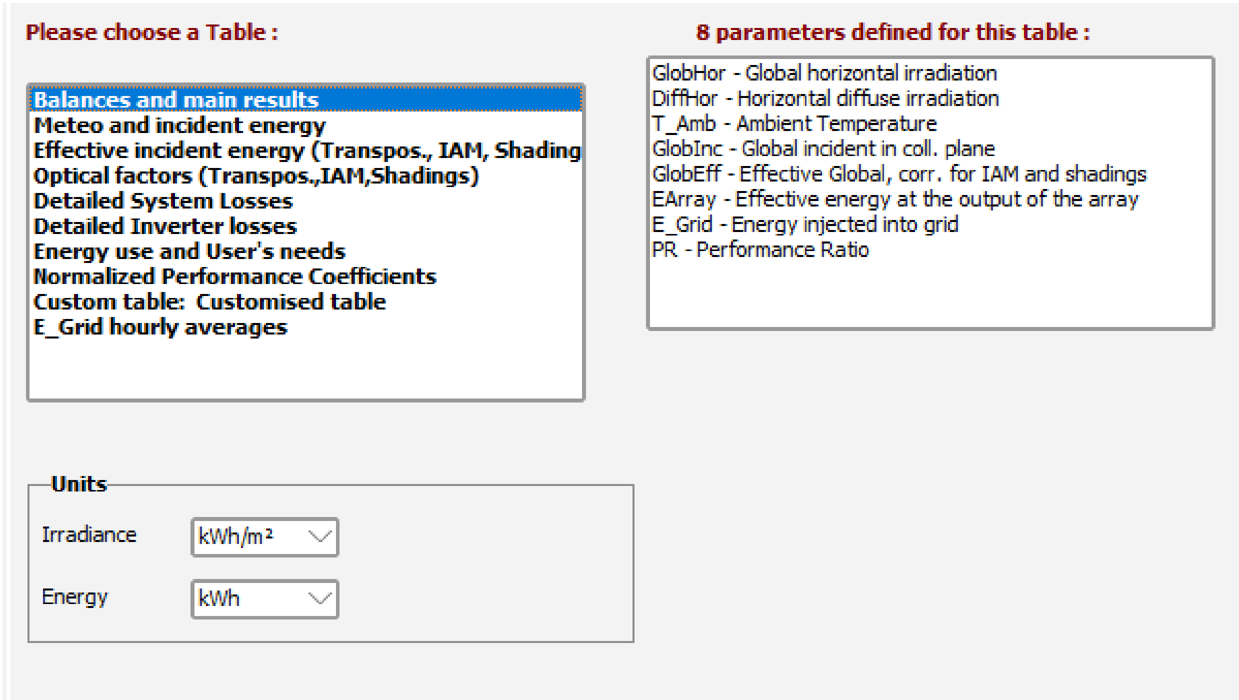
Solar Power General/Others	
How has been ZESCO's experience of solar power, e.g. costs, energy security, diversity of energy sources, environmental, etc.	PROJECTS NOT YET IMPLEMENTED, PENDING FINANCIAL CLOSURE
How much more solar power does ZESCO intend to procure?	IMPLEMENTATION WILL BE DONE IN PHASES DEPENDING ON PREDICTABLE LOAD GROWTH
What challenges do you face when negotiating for power purchase agreements (PPA) with independent power producers (IPPs)?	OVERPRICING OF ELECTRICITY TARRIFFS AND POWER PLANT PERFORMANCE GUARANTEES
What are the strengths and weaknesses of the existing on-grid solar energy projects/systems in Zambia?	- PROVIDE GENERATION MIX AS STRENGTH - RESOURCE INTERMITTENCE IS A CHALLENGE
What lessons have you learned regarding on-grid solar projects or systems in Zambia?	- THEY REQUIRE ADEQUATE GRID INTEGRATION STUDIES AND READY FINANCING
What good practices have you identified regarding on-grid solar energy systems?	- FAST DEPLOYMENT, STUDIES NOT COMPLICATED E.g GEOTECHNICAL, HYDROLOGICAL AND HYDROGEOLOGICAL
What is the tariff per kWh which ZESCO pays to buy power from the Mamba coal power plant. What is the duration of the PPA? Is the tariff constant over the period of the PPA? If not, how does it change?	THIS IS CONFIDENTIAL INFORMATION BUT THE TARRIFF RANGE IS BETWEEN 8 – 12 USD|kWh
What recommendations would you make for the betterment of on-grid solar energy systems in Zambia?	- MORE FUNDING AND SKILLS IS NEEDED FOR DEPLOYMENT OF THIS TECHNOLOGY
Any other comment/information regarding on-grid solar energy power plant in Zambia.	NIL

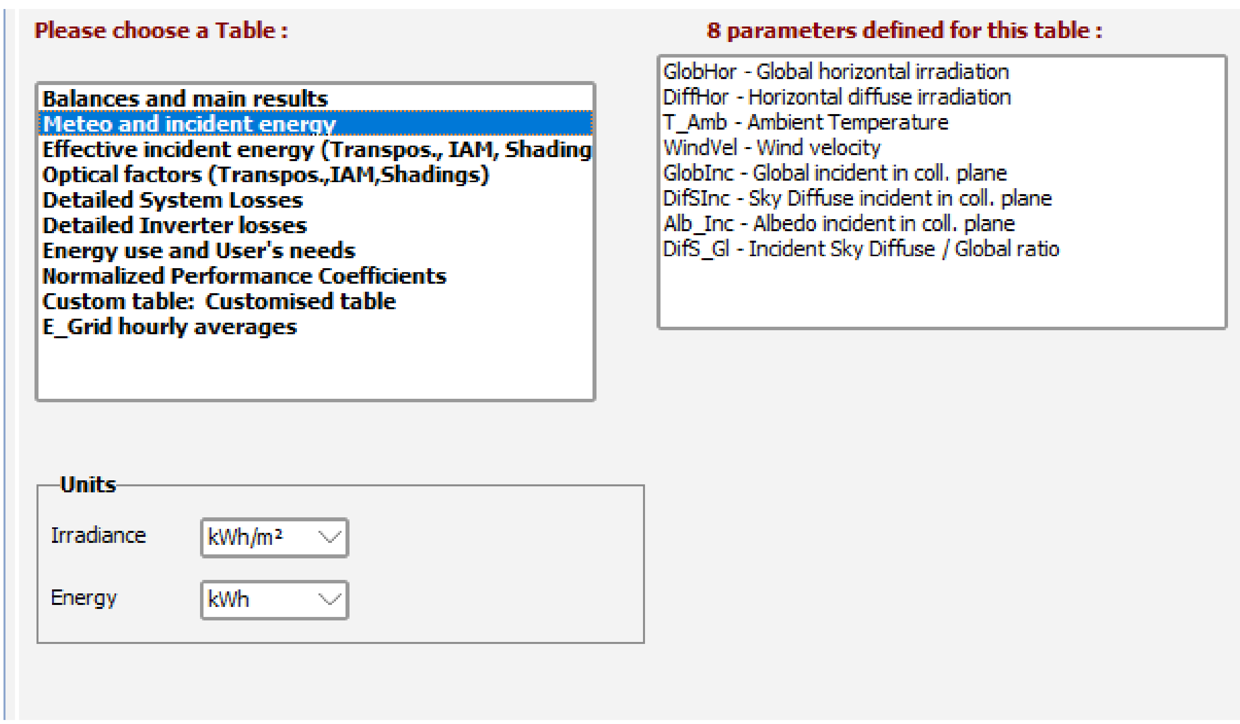
Appendix E: Bangweulu Solar PV Power Plant PVsyst Software Simulation Results

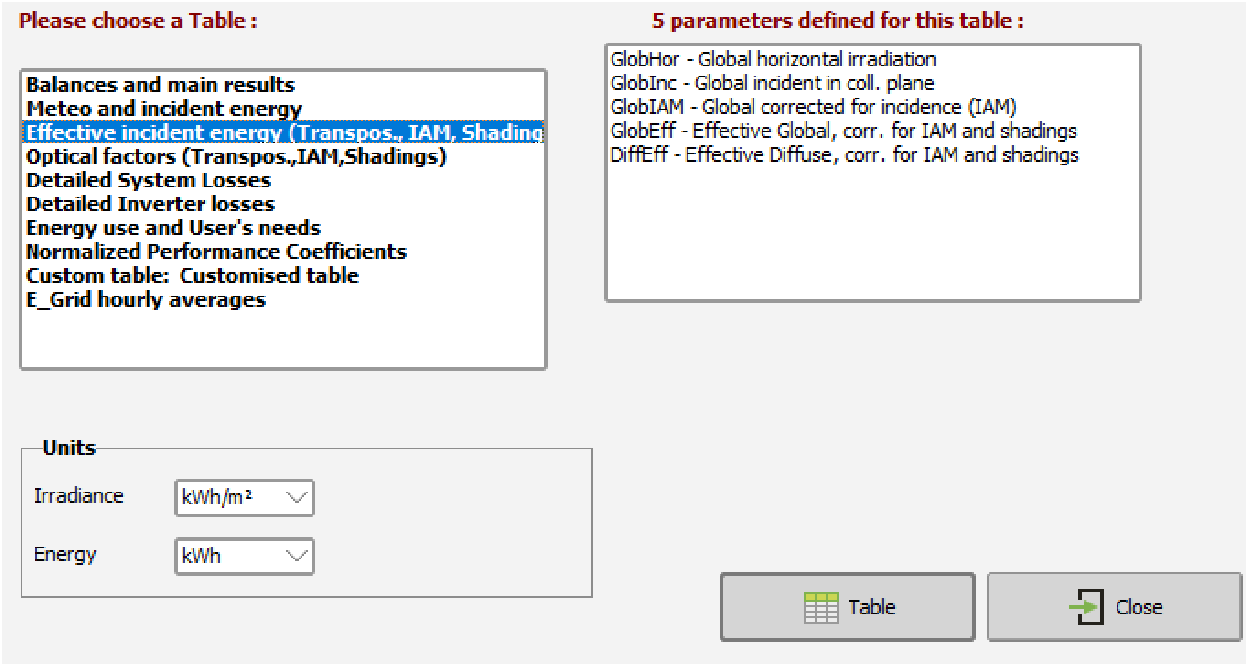
Bangweulu-PVSyst



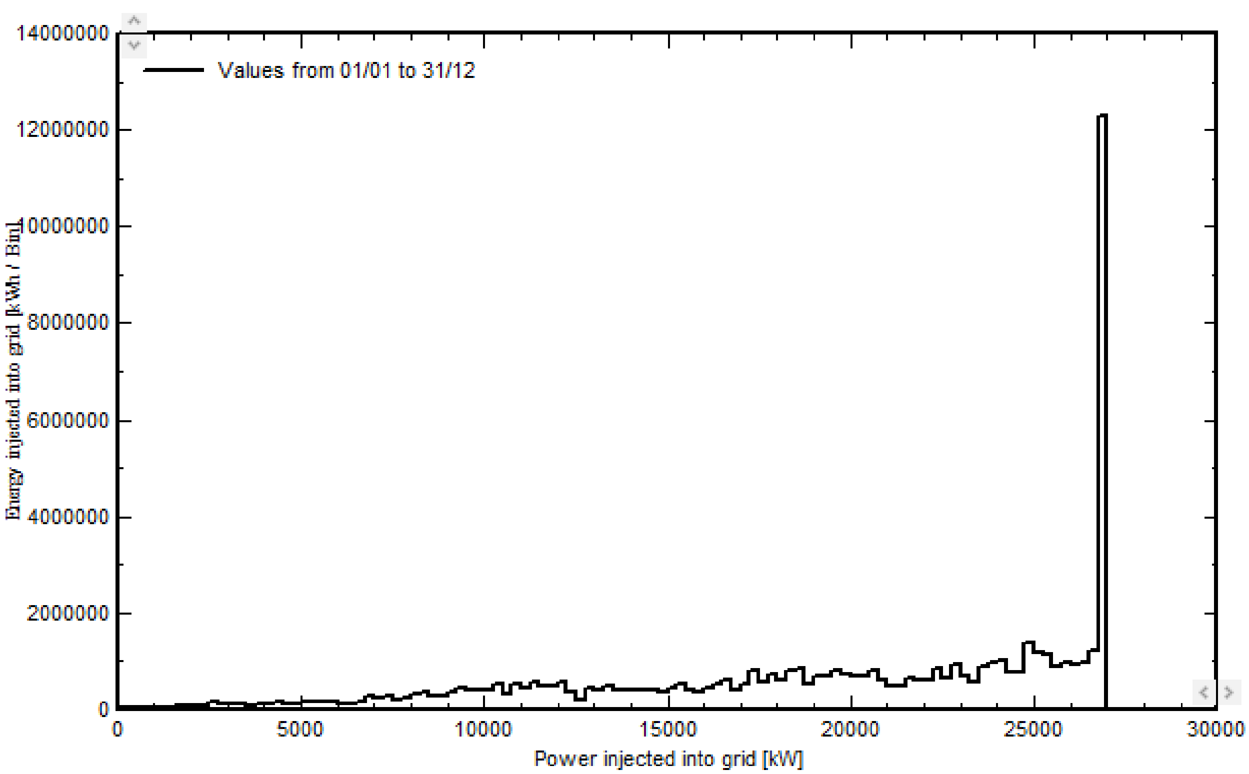
	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	ratio
January	159.7	84.60	22.50	151.7	148.2	7040412	6925995	0.846
February	143.9	76.60	21.20	141.1	138.4	6613500	6507605	0.854
March	160.8	83.20	21.20	163.0	160.0	7472713	7352179	0.835
April	165.6	51.20	20.20	179.5	177.0	8273502	8138178	0.840
May	156.3	50.60	18.50	176.9	174.6	8421321	8285336	0.867
June	147.6	38.10	16.60	172.8	170.5	8264704	8132033	0.871
July	154.1	40.10	16.60	178.3	176.0	8470418	8332768	0.865
August	179.1	46.00	20.10	199.4	197.1	9396010	9240460	0.858
September	182.4	58.20	22.90	191.4	189.0	8699163	8552625	0.828
October	197.2	68.80	25.20	196.5	192.9	8966050	8816406	0.831
November	181.1	80.60	23.50	172.5	168.7	7961154	7830582	0.841
December	161.4	81.20	20.59	151.6	148.0	7090325	6978207	0.852
Year	1989.2	759.19	20.75	2074.7	2040.5	96669273	95092377	0.849


Please choose a Table :
Balances and main results
Meteo and incident energy
Effective incident energy (Transpos., IAM, Shading
Optical factors (Transpos.,IAM,Shadings)
Detailed System Losses
Detailed Inverter losses
Energy use and User's needs
Normalized Performance Coefficients
Custom table: Customised table
E_Grid hourly averages
8 parameters defined for this table :
GlobHor - Global horizontal irradiation
DiffHor - Horizontal diffuse irradiation
T_Amb - Ambient Temperature
GlobInc - Global incident in coll. plane
GlobEff - Effective Global, corr. for IAM and shadings
EArray - Effective energy at the output of the array
E_Grid - Energy injected into grid
PR - Performance Ratio
Units
Irradiance
kWh/m²
Energy
kWh

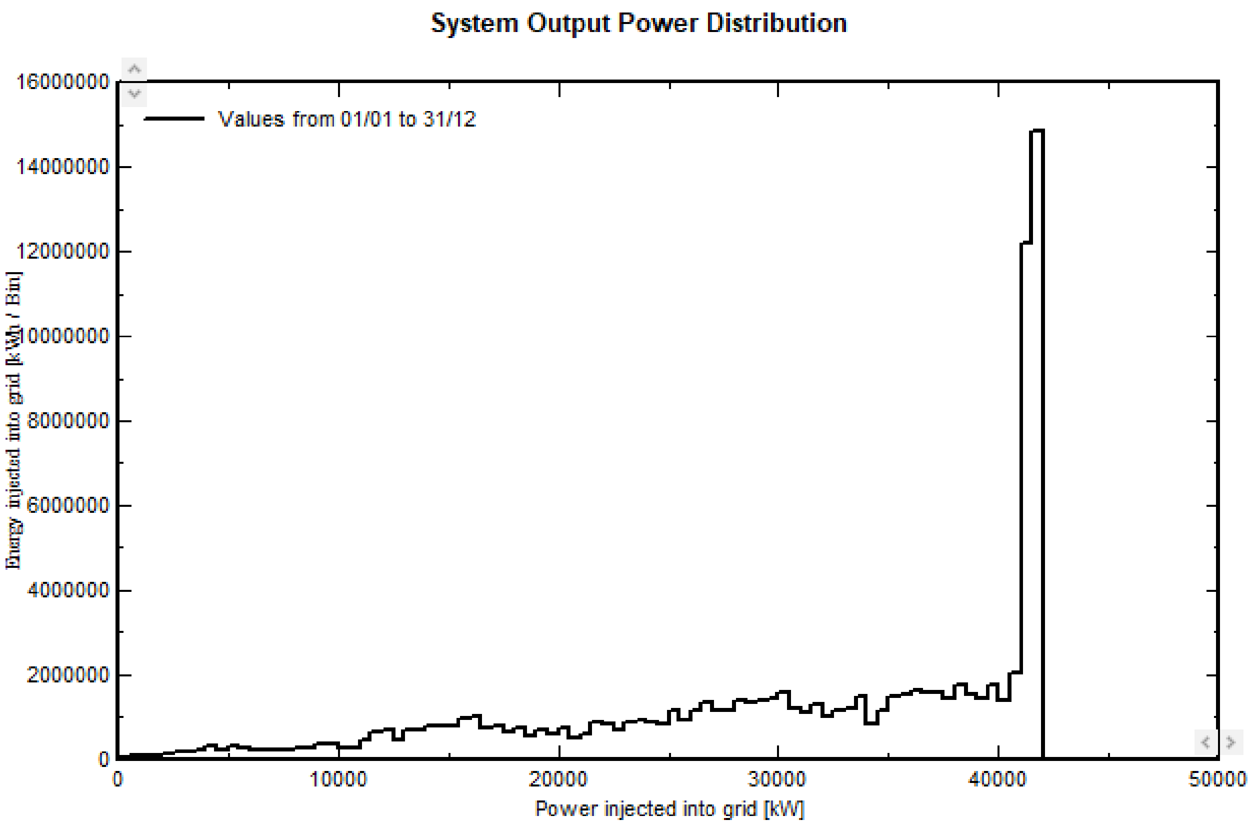

Please choose a Table :
Balances and main results
Meteo and incident energy
Effective incident energy (Transpos., IAM, Shading
Optical factors (Transpos.,IAM,Shadings)
Detailed System Losses
Detailed Inverter losses
Energy use and User's needs
Normalized Performance Coefficients
Custom table: Customised table
E_Grid hourly averages
8 parameters defined for this table :
GlobHor - Global horizontal irradiation
DiffHor - Horizontal diffuse irradiation
T_Amb - Ambient Temperature
WindVel - Wind velocity
GlobInc - Global incident in coll. plane
DifSInc - Sky Diffuse incident in coll. plane
Alb_Inc - Albedo incident in coll. plane
DifS_Gl - Incident Sky Diffuse / Global ratio
Units
Irradiance
kWh/m²
Energy
kWh



Please choose a Table :
Balances and main results
Meteo and incident energy
Effective incident energy (Transpos., IAM, Shading
Optical factors (Transpos.,IAM,Shadings)
Detailed System Losses
Detailed Inverter losses
Energy use and User's needs
Normalized Performance Coefficients
Custom table: Customised table
E_Grid hourly averages
5 parameters defined for this table :
GlobHor - Global horizontal irradiation
GlobInc - Global incident in coll. plane
GlobIAM - Global corrected for incidence (IAM)
GlobEff - Effective Global, corr. for IAM and shadings
DiffEff - Effective Diffuse, corr. for IAM and shadings
Units
Irradiance
kWh/m²
Energy
kWh
Table
Close



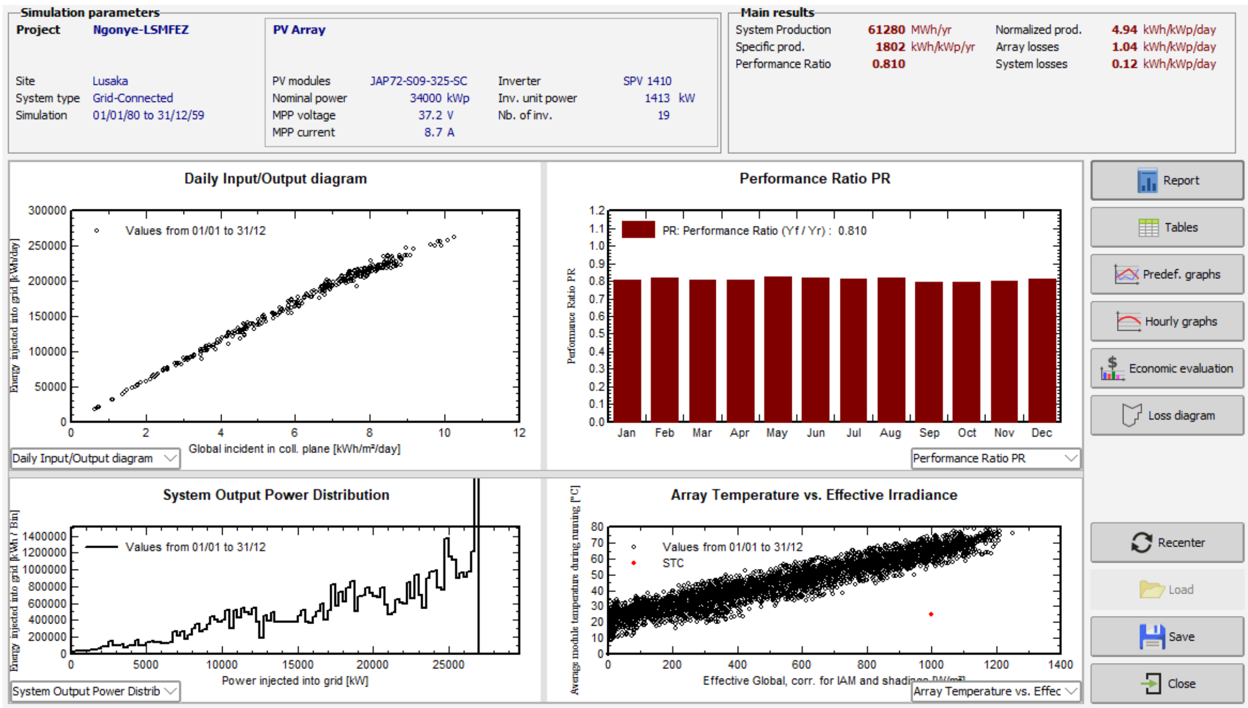
Values from 01/01 to 31/12
Energy injected into grid [kWh / Bin]
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
5000
10000
15000
20000
25000
30000
Power injected into grid [kW]



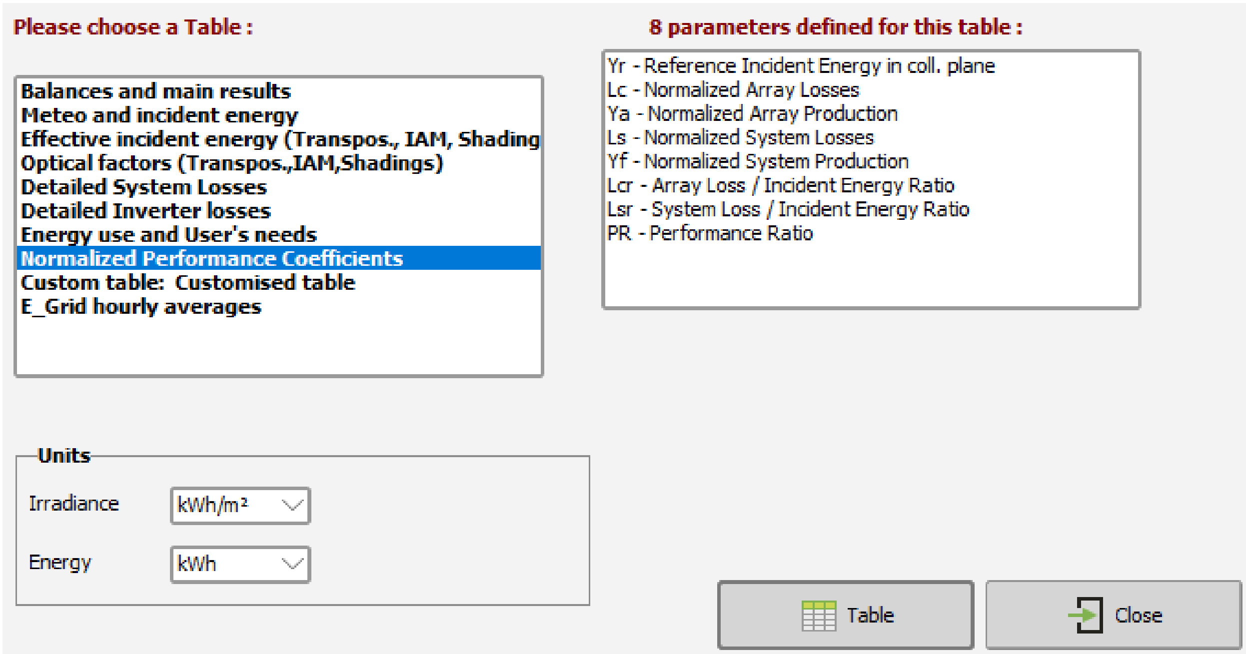
System Output Power Distribution
Values from 01/01 to 31/12
Energy injected into grid [kWh / Bin]
16000000
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
0
10000
20000
30000
40000
50000
Power injected into grid [kW]

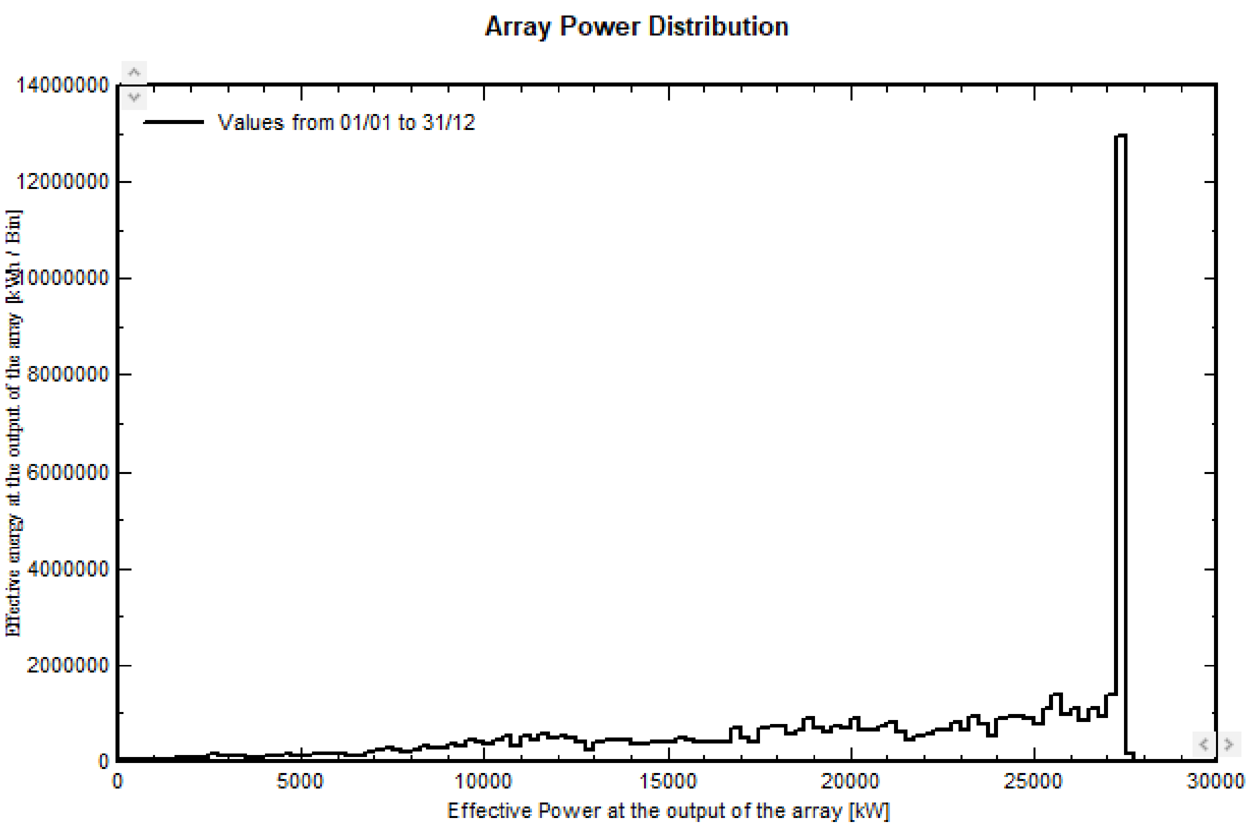
Appendix F: Ngonye Solar PV Power Plant PVsyst Software Simulation Results

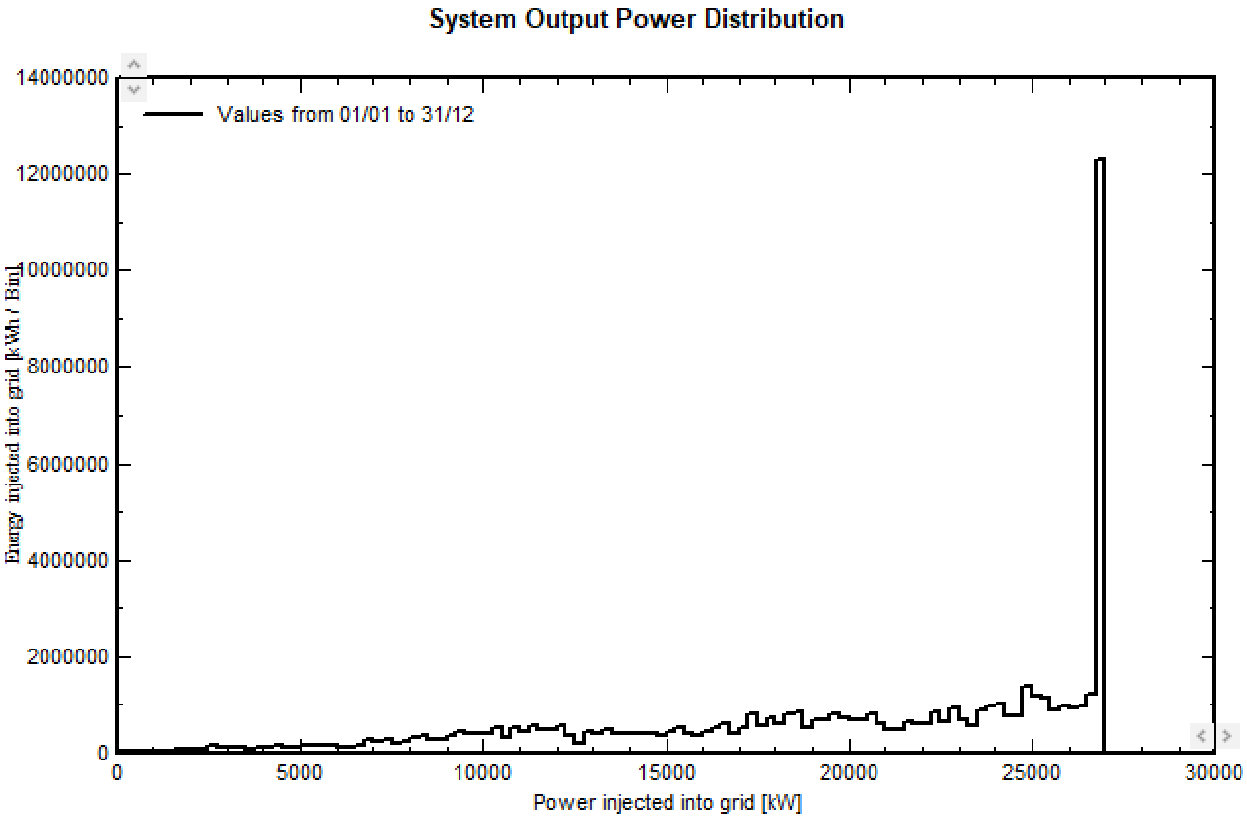
Ngonye-PVsyst



	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	159.7	84.60	22.50	164.7	159.5	4633020	4523523	0.808
February	143.9	76.60	21.20	144.5	140.0	4123722	4025861	0.819
March	160.8	83.20	21.20	163.5	158.2	4582286	4473004	0.805
April	165.6	51.20	20.20	186.8	182.7	5244673	5119454	0.806
May	156.3	50.60	18.50	196.0	192.6	5612903	5481989	0.823
June	147.6	38.10	16.60	201.7	198.8	5749826	5616240	0.819
July	154.1	40.10	16.60	204.1	201.1	5793659	5656595	0.815
August	179.1	46.00	20.10	214.7	211.0	6105684	5962291	0.817
September	182.4	58.20	22.90	193.2	188.9	5351997	5224675	0.795
October	197.2	68.80	25.20	200.0	194.3	5537636	5408892	0.795
November	181.1	80.60	23.50	187.4	182.1	5242546	5120636	0.804
December	161.4	81.20	20.59	168.4	163.6	4779167	4666983	0.815
Year	1989.2	759.19	20.75	2225.0	2172.8	62757119	61280144	0.810


Please choose a Table :
Balances and main results
Meteo and incident energy
Effective incident energy (Transpos., IAM, Shading
Optical factors (Transpos.,IAM,Shadings)
Detailed System Losses
Detailed Inverter losses
Energy use and User's needs
Normalized Performance Coefficients
Custom table: Customised table
E_Grid hourly averages
8 parameters defined for this table :
Yr - Reference Incident Energy in coll. plane
Lc - Normalized Array Losses
Ya - Normalized Array Production
Ls - Normalized System Losses
Yf - Normalized System Production
Lcr - Array Loss / Incident Energy Ratio
Lsr - System Loss / Incident Energy Ratio
PR - Performance Ratio
Units
Irradiance
kWh/m²
Energy
kWh
Table
Close


Array Power Distribution
Values from 01/01 to 31/12
Effective energy at the output of the array [kWh / Bin]
Effective Power at the output of the array [kW]
0
2000000
4000000
6000000
8000000
10000000
12000000
14000000
0
5000
10000
15000
20000
25000
30000


System Output Power Distribution
Values from 01/01 to 31/12
Energy injected into grid [kWh / Bin]
0
2000000
4000000
6000000
8000000
10000000
12000000
14000000
0
5000
10000
15000
20000
25000
30000
Power injected into grid [kW]

Appendix G: Bangweulu Solar PV Power Plant Basic Project Information

Basic Project Information

PPI and Sector Information

Primary sector: Energy

Subsector(s): Electricity

Segment(s): Electricity generation

Technology: Solar, PV

Type of PPI: Greenfield project

Subtype of PPI: Build, own, and operate

Sponsor Information

Sponsor	Amount of equity	% of ownership
Neoen	10.5	55
First Solar	4.8	25

Total equity: 19.1

Debt Provider Information

Year	Total debt funding	Debt:equity ratio
2017	39.9	68:32

Debt provider	Type	Local/International
IFC	Multilateral	International
OPIC	Bilateral	International

Government Support Information

Type of direct government support: Not Available

Value of direct government support: Not Available

Multilateral Support

Year	Agency	Support type
2017	IFC	Loan
2017	IFC	Risk Management (including Political Risk Insurance)
2017	IFC	Syndication
2017	IDA	Guarantee
Year	Name of bilateral	Subtype of PPI:
2017	Other OPIC	Loan

Appendix H: Ngonye Solar PV Power Plant Basic Project Information

Basic Project Information

Project name: Ngonye Solar PV Plant

Project id: 9436

Country: Zambia

Location: Lusaka South Multi-Facility Economic Zone, Lusaka Province

Financial Closure Year:2018

Company: NGONYE POWER COMPANY LIMITED

Status: Active

Update status date:06/20/2018

Other name(s):

PPI and Sector Information

Primary sector: Energy

Subsector(s): Electricity

Segment(s): Electricity generation

Technology: Solar, PV

Type of PPI: Greenfield project

Subtype of PPI: Build, own, and operate

Additional Contract Information

Contract period (years):25

Contract award method: License scheme

Government level granting contract: National

Public disclosure of the contract: No

Unsolicited proposal: Yes

Main revenue source(s): Purchase agreements or transmission fees with public entity(ies)

Sponsor Information

Sponsor	Amount of equity	% of ownership
Others	2.25	20
Enel SpA	9	80

Total equity: 11.25

Debt Provider Information

Year	Total debt funding	Debt:equity ratio
2018	33.75	75:25

Debt provider	Type	Local/International
EIB	Multilateral	International
IFC	Multilateral	International

Governtment Support Information

Type of direct government support: Not Applicable

Type of indirect government support: Not Applicable

Value of direct government support: Not Applicable

Value of indirect government support: Not Applicable

Multilateral Support

Year	Agency	Support type
2018	IFC	Loan
2018	EIB	Loan
2018	IDA	Guarantee
2018	IFC	Risk Management (including Political Risk Insurance)

PPI and Sector Information

Primary sector: Energy

Subsector(s): Electricity

Segment(s): Electricity generation

Technology: Solar, PV

Type of PPI: Greenfield project

Subtype of PPI: Build, own, and operate

Additional Contract Information

Contract period (years):25

Contract award method: License scheme

Government level granting contract: National

Public disclosure of the contract: No

Unsolicited proposal: Yes

Main revenue source(s): Purchase agreements or transmission fees with public entity(ies)

Sponsor Information

Sponsor	Amount of equity	% of ownership
Others	2.25	20
Enel SpA	9	80

Total equity:11.25

Debt Provider Information

Year	Total debt funding	Debt:equity ratio
2018	33.75	75:25

Debt provider	Type	Local/International
EIB	Multilateral	International
IFC	Multilateral	International

Government Support Information

Type of direct government support: Not Applicable

Type of indirect government support: Not Applicable

Value of direct government support: Not Applicable

Value of indirect government support: Not Applicable

Multilateral Support

Year	Agency	Support type
2018	IFC	Loan

Year	Agency	Support type
2018	EIB	Loan
2018	IDA	Guarantee
2018	IFC	Risk Management (including Political Risk Insurance