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Technical and Environmental Feasibility Study on the Implementation of Commercial On-Grid Solar Photovoltaic (PV) Power Plants in Zambia

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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 embarked on constructing solar PV mini-grid power plants connected to the national grid for the purpose of reducing the constraint on the hydropower system. Two solar PV power plants were used as a benchmark to investigate the technical feasibility of deploying other solar photovoltaic (PV) power plants in Zambia. The technical performance of the two solar PV power plants was evaluated using PVsyst software. The results were compared with the analysis of the actual data obtained from the two solar PV power plants. Performance ratios (PR) for Ngonye and Bangweulu solar power plants were found to be 83% and 84%, respectively, which are above the internationally acceptable value of 75%. The yearly average daily peak sun hours for both plants were found to be 5 hours 23 minutes. The Capacity Utilization Factor (CUF), was found to be 18.8% and 19.8% respectively. According to Zambia Electricity Supply Corporation Limited (ZESCO), the Zambian utility grid can absorb an additional 816 MW of solar PV power, translating into an annual energy production of 1.6×10^6 MWh. The annual production of 150 GWh of energy from the two solar PV power plants would save the environment from pollution by about 1.5 million tons of carbon dioxide (CO_2) equivalent of greenhouse gases (GHGs) per year as compared to coal power production.

Keywords

Solar Photovoltaic (PV) System, On-Grid Power Plants, Technical Feasibility, Performance Ratio (PR), Climate Change Mitigation

1. Introduction

Climate change has proved to be one of the world's biggest developmental challenges [1]. Global warming has particularly contributed to climate change due to the utilization of fossil fuels for electricity generation, causing rapid environmental degradation and leading to global warming [2]. Globally, climate change has produced significant destruction to the environment and human life at large [1]. Zambia's hydropower production has not been spared by climate change, leading to reduced amounts of electricity being fed into the nation's grid. Population increase, combined with industrial development, has put pressure on Zambia's power demands.

Zambia has been striving to develop sustainable and appropriate programmes for Renewable Energy Sources (RES) to meet the energy demand. One of the main focuses is the introduction of solar energy initiatives with an attractive bidding environment for on-grid solar photovoltaic system developers. Zambia's main consumers of electricity are mining, residential, commercial, and other industrial sectors with mining accounting for the largest share due to its high energy demands. As the country's population increases, coupled with industrial development, there is a need to increase the supply of electricity to consumers. More hydro power stations with different capacities have been constructed, and others have been expanded to meet the country's increasing energy demand. Until 2016, almost the entire electricity generation in Zambia was from hydropower. With increased demand, hydropower still remains the mainstay, followed by coal, Heavy Fuel Oil (HFO), on-grid solar PV power, diesel, and mini-grid solar PV power as the least contributor. The installed capacities of the above-mentioned power systems are: 2398 MW, 300 MW, 110 MW, 88 MW, 84 MW, and 1.17 MW, respectively. The total installed capacity of Zambia is 2981 MW, with a power deficit of 850 MW. 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. Adapting to the impacts of climate change through changes in national power systems is key to mitigating these impacts. The purpose of climate change policies is to lessen greenhouse gas (GHG) emissions from electric power production by encouraging the production of electricity with no carbon emissions, as well as supplementing the electricity supply [3]. A switch to RES distributed power generation is considered to be a prospective passage for attaining several sustainability goals [3].

2. Literature Review

The U.S. Energy Information Administration under the Environmental Investigations Agency (EIA) has indicated that 2.21 pounds/kWh (~1.00 Kg/kWh) carbon dioxide equivalent of GHGs is released from the coal power generation process. The implication of this is that generation of 1 kWh of energy from coal power production is coupled with a discharge of about 1 kg CO_2 eq/kWh of GHG. Zambia is endowed with good renewable energy resources and is therefore suitable for exploiting solar energy as a sustainable source of energy. The solar energy sector can therefore benefit from the effects of climate change with reduced cloud cover and days of rainfall [4]. Zambia has therefore embarked in recent years on installing on-grid solar PV systems to supplement the nation's power supply.

Scaling Solar Energy Initiative

Scaling 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 [5]. 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 ensures the developer against the default risk of ZESCO.

2.1. On-Grid Solar PV Power Plants

On-grid solar PV system is a power generation system that is connected to the grid [6]. It is connected to the local utility company's grid or the nation's grid. On-grid PV power systems do not need a battery bank [7]. Once a PV power generation system produces power, it is injected into the national utility grid for further distribution and supply to consumers [8]. 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 shows the schematic diagram for an on-grid solar PV power plant. It shows the main components of an on-grid solar PV power plant.

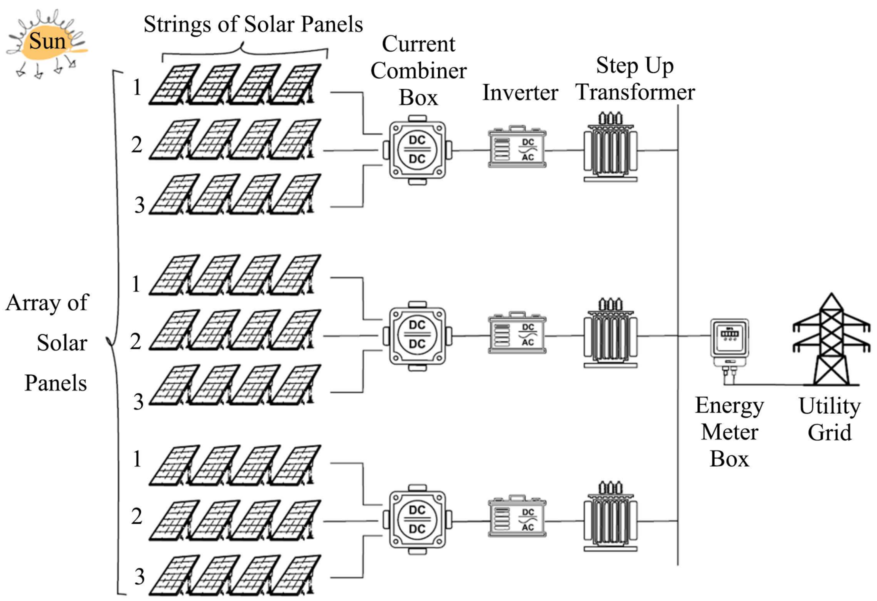

Figure 1. On-grid solar PV system schematic diagram.

2.2. Tools for Technical Evaluation of Utility-Scale Solar PV Power Plants

2.2.1. Final Yield (Y_f)

The closing or 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 arrangement [9]. Final yield does not account for losses concerning the inverter inefficiency, solar panel's temperature, wiring, variations in irradiance, dust accumulation or snow, and failure of other components. 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 [9] as produced for a defined period. It is used to compare energy generated by PV systems of different sizes [10].

$$Y_f = \frac{\text{Final energy yield}(\text{kWh})}{\text{Nominal DC power}(\text{kW})} \quad (1)$$

2.2.2. Reference Output (Y_r)

The reference yield is the conceptual attainable energy yield of the solar PV power system [11]. It is a representation of the maximum attainable energy for a PV power system at a particular location found at reference irradiance at STC. 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 [12]. The standard PV reference irradiance is 1000 W/m² [13]. This is given by [10]

$$Y_r = \frac{\text{Total in-plane irradiance}\left(\frac{\text{kWh}}{\text{m}^2}\right)}{\text{PV reference irradiance}\left(\frac{\text{kW}}{\text{m}^2}\right)} \quad (2)$$

This gives a standardized solar irradiance value used for comparing PV system performance. It provides a consistent baseline to normalize solar energy input across different locations and times.

2.2.3. Plant Performance Ratio (PR)

Plant performance ratio (PR) 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) [12]. PR measures the final result of the solar PV system with reference to the rated yield, taking into consideration the inefficiency of the inverter, wiring, solar panel's temperature, variations in irradiance, dust accumulation, or snow, and failure of other components [9]. PR is an internationally accepted metric for assessing the performance of the solar PV power plant as per the International Electro technical Commission (IEC), that is, IEC 61724-1 "Photovoltaic System Performance Monitoring-Guidelines for Measurement, Data Exchange and Analysis". The European Commission guidelines advocate for plant investigations when PR is below 0.75 (75%). According to the European Union performance project for PV systems, a plant with a PR of 0.8 (80%) and in excess, is considered to be outstanding [12]. PR is given by [9];

$$PR = \frac{Y_f}{Y_r} \tag{3}$$

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;

$$PR = \frac{\text{Actual plant ouput energy}}{\text{Calculated nominal output energy}} \tag{4}$$

Nominal energy output is given by

$$\text{Energy output} = \text{Irradiance} \times \text{module efficiency} \times \text{effective module area} \tag{5}$$

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

2.2.4. Specific Yield (S_y)

Specific yield is defined as the ratio of the total yearly energy produced to that of the installed capacity of the PV system [9]. It evaluates the actual or practical solar PV power potential. This is given by;

$$S_y = \frac{\text{Energy produced per year}\left(\text{kWh}\right)}{\text{Installed capacity}\left(\text{kW}_\text{p}\right)} \tag{6}$$

This reflects how efficiently the installed capacity converts sunlight into electricity over a year, and allows for easy comparison between systems of different sizes or locations.

2.2.5. Capacity Utilisation Factor (CUF)

Capacity Utilization 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 [9].

$$CUF = \frac{\text{Energy produced per year}\left(\text{kWh}\right)}{8760\left(\frac{\text{hours}}{\text{year}}\right) \times \text{installed capacity}\left(\text{kW}_\text{p}\right)} \tag{7}$$

Therefore,

$$CUF = \frac{S_y}{8760} \tag{8}$$

8760 is represents the total number of hours in a year.

The capacity factor for solar PV power plants generally ranges between 12% to 24% [9].

3. The Power Plants

3.1. Ngonye Solar PV Power Plant

Ngonyesolar PV power plant is a 34 MW_p 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 plant covers an area of 56 hectares and is owned by Enel Green Power of Italy. The plant is divided into two parts, the

Eastern and the Western. 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 the 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 as described below.

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 size of the plant. The total number of solar panels is 104,580, giving a 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 of 3486 trackers, and each tracker has an actuator (230 V, 6 A) that tilts the solar panels to track the Sun. The actuators are energized by solar power through auxiliary transformers. To enable the solar trackers to track the position of the Sun, the plant has pyranometers installed in all seven (7) blocks of the plant. The pyranometers sense the position of the Sun and send signals to the Programmable Computer Box (PCB) in the control room that in turn stimulates the actuator to move 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 tilt angle for solar panels is set between −46.5˚ and +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 the process of the photovoltaic effect. However, a tracking system increases the cost of the plant.

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. In case of severe wind, the anemometer records wind speed, sends the signal to the Programmable Computer Box (PCB), which in turn stimulates the actuator to tilt solar panels into safe mode protection, that is, at 180˚.

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 cells. Therefore, the amount of dust on the surfaces of the panels has to be monitored daily to maintain a high performance ratio. To monitor dust and particle accumulation on solar panels, the plant is equipped with three (3) soiling monitoring systems. The systems 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 QPPI (Quick Power Parallel Integration) 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 feed power into conversion units (CU) where DC is converted into AC by inverters rated 1.41 MW, yielding a total of 33.84 MW of AC power. The AC output of 28.2 MW is what has been agreed with the System Operator (SO)-ZESCO. The amount of power fed into the grid is achieved by employing the Power Plant Controller (PPC), which controls the output power.

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 the DC and AC sides in case of a fault. 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 a total number of twenty-four (24) inverters. The inverters are used in the plant 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. Each of the conversion modules is connected in parallel with capacitors rated 50 μF, 550 V. The inverters give an output of 550 V of AC power.

The system has been designed such that two inverters should feed one transformer, bringing the total number of transformers to twelve (12).

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. The plant has three types of collector cables, that is, 200, 300, and 400 mm^2.

The transformers step up 550 V of voltage from the inverters to 33 kV. The 33 kV voltage from the 12 transformers is fed into the delivery cabin through collector cables, that is, collector east (400 mm^2) for the eastern plant and collector west (300 mm^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 Supervisory Control and Data Acquisition (SCADA)room where all the signals and information regarding processes of the plant are collected and monitored. The delivery cabin is also equipped with power quality analyzer that monitors power quality, voltage, and frequency. It is a requirement by Energy Regulation Board (ERB) that each solar PV power plant must have a power quality monitor installed before power is injected into the utility grid. After power quality inspection, 33 kV is then transmitted to the grid using three three-phase system.

The delivery cabin has two pyrometers, an electronic instrument that records 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 should be installed.

During the night, when solar power is unavailable, the plant is kept alive by 33 kV power from Zambia Electricity Supply Corporation (ZESCO) that is stepped down by transformers to 220 V and during the day when solar power production begins, the plant synchronizes AC and DC power to continue with the 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 an interlocking key system to avoid human error for equipment isolation in case one intends to work on or carry out maintenance on plant equipment.

3.2. Bangweulu Solar PV Power Plant

Bangweulu solar PV power plant is a 54.3 MW_p 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 plant covers an area of 52 hectares and is owned by Neoen company of South Africa.

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 described below.

The DC side of the plant is made up of 400,000 (120 W) and 53,600 (117.5 W) Cadmium Telluride (CdTe) thin film solar panels, bringing the total number of panels to 453,600, giving DC output of 54,298,000 W (54.3 MW). The solar panels are inclined at an angle of 13 degrees and facing north. The DC side of the plant is partitioned into 12 blocks with each block 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, giving the total number of panels feeding one inverter as 480.

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

The 12-string inverter solar panels have ten (10) solar panels in series that form one string, and 12 strings of these solar panels are connected in parallel to form a 12-string of solar panels. This gives a total number of 120 solar panels in a 12-string inverter solar panel. The 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 9-string inverter.

The 9-string inverters are 1140 and the 12-string inverters are 90, bringing the total number of inverters to 1230 and each with a power rating of 47 kVA. Inverters are connected to AC combiner boxes with a current rating of 160 A, which 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's 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 MVA 0.480/33kV. There are twelve (12) transformers in total, and each transformer has a role to step up 480 V to 33 kV of power collected from AC combiner switches.

The plant has a capacitor bank rated 5 MVAr (Mega Volt-Ampere Reactive) 33 kV. The capacitor bank is connected in 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). The solar plant has seven (7) RMUs, and each RMU has feeder panels based on the number of transformers feeding it. Five of the seven RMUs are fed with two transformers each, except blocks 4 and 5 transformers which have separate RMUs. RMU's panels are SF_6 gas-filled equipment, that is, they are insulated by SF_6.

Collector cables inject power from AC combiner boxes to LT panels, from LT panels to transformers, from transformers to RMUs, and from RMUs to the Main Control Room (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 degrees. This means block pyranometers are inclined at the same inclination angles as of solar panels. This inclination increases the accuracy of the 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 daily to maintain a high performance ratio. The test and reference panel system has-been installed for dust monitoring purposes. There are five (5) dust-monitoring systems in the plant. The reference panel is cleaned every day, whilst the test panel is only cleaned when the 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 the processes of the plant are collected and monitored. The MCR is also equipped with the Power Quality Monitor, which checks power quality. It is a requirement by the Energy Regulations Board (ERB) that each solar power system 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 the ZESCO grid, and it is equipped with a protection unit that protects both plants from current overloads. After power quality check by the power quality monitor, 33 kV is then injected into the grid using a three-phase system through collector cables.

The MCR has two energy meters that record 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 the billing and recording of energy imports and exports.

During the night, when solar power is unavailable, the plant is kept alive 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 the 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.

4. Methodology

The criteria employed to study the technical feasibility and environmental sustainability of the Ngonye and Bangweulu solar PV power plants involve three methods. These are collecting and analyzing data from the Global Solar Atlas (GSA), actual data from the two solar PV power plants, and simulation data from PVsyst software.

The GSA method is cardinal as it facilitates the much-needed information regarding solar power potential and solar resources globally. It is a World Bank Group-assisted project which was formulated by Solargis, who were contracted by the World Bank [14]. GSA is an internet-based tool application that gives data on solar resources and solar power potential. Therefore, the solar resource and solar power potential can be used to estimate the amount of PV power output (PVOUT in kWh/kW_p) that any size of a solar power plant can generate. The data provides the solar PV power plant developer with the actual performance of the plant. It gives a thorough insight into the expected plant yield with minimal deviations due to random and systematic errors.

PVsyst software is equipped with important tools that are user-friendly. Meteonorm 7.1 is the known data source in PVsyst [15]. To estimate the performance of the solar PV power plant, the software computes information from the three data sources (meteonorm database, ground based weather stations and satellite derived data) in terms of the location of the solar PV power plant under scrutiny.

4.1. Ngonye and Bangweulu Solar PV Power Plants Actual Data

The actual data for the Ngonye and Bangweulu solar PV power plants were obtained by plant site visitation. For Bangweulu, the monitoring period extended from July 2019 to December 2020, aligning with the Ngonye dataset in both temporal coverage and data quality. Both datasets underwent identical processing steps and quality checks to ensure comparability, including filtering of missing or erroneous records and validation of SCADA logging integrity. Private communication (meetings) with plant personnel, control room operation involvement, and field patrol of the plant facilitated comprehensive data collection from the two solar PV power plants. Comprehensive data for the Ngonye and Bangweulu solar PV power plants were recorded in Table 1 and Table 2 respectively.

Table 1. Measurement of in-plane global irradiance and PV module temperatures 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 2. Measurements of in-plane global irradiance, daily, monthly and annual energy outputs for Bangweulu solar PV power plant.

Average In-plane Global Irradiance (kWh/m^2)	Daily Average Energy Output (MWh)	Monthly Average Energy Output (MWh)	Annual Energy Output (MWh)
5.40	258.50	7755.00	94417.13

The pyranometers installed at both Ngonye and Bangweulu solar PV power plants are ISO 9060 Secondary Standard (Class A) instruments, factory calibrated prior to plant commissioning and subsequently recalibrated every after two years to maintain measurement integrity. These sensors provide an accuracy of ±2% for global horizontal irradiance (GHI) and plane-of-array irradiance (POA) measurements. Data acquisition is performed through a supervisory control and data acquisition (SCADA) system with a sampling interval of one minute, aggregated into hourly and daily values for analysis. The consistent calibration and high accuracy of these instruments ensure reliable irradiance data, comparable in quality between the two sites and compliant with IEC 61724-1 photovoltaic performance monitoring standards.

4.2. GSA Estimated Yearly Energy Output

The estimated annual energy outputs for Ngonye and Bangweulu solar PV power plants were calculated with the aid of the GSA data provided by the World Bank. The PVOUT for Lusaka, where the Ngonye and Bangweulu solar PV power plants are located, was obtained from GSA. The annual PVOUT for LSMFEZ (Ngonye and Bangweulu solar PV power plants) was found to be 1749 kWh/kW_p. The GSA computed values were compared to the actual values obtained from respective solar PV power plants, and the results are recorded in **Table 3**.

$$\text{Estimated output} = \text{PVout from GSA}\left(\text{kWh}/\text{kW}_\text{p}\right) \times \text{Plant capacity}\left(\text{kW}_\text{p}\right) \quad (9)$$

4.3. Simulation of Data

PVsyst software was used for the simulation of the performance of the Ngonye and Bangweulu solar PV power plants. The data fed into the software includes grid type, fixed or tracking system of solar panels, orientation of solar panels, type of solar panels (Polycrystalline for Ngonye and Cadmium Telluride for Bangweulu), number of solar panels, inverter rating, and type depending on the rating (size) of the plant. Results were imported, recorded, and compared to actual values as tabulated in **Table 3**.

Table 3. Annual energy generation by method at Ngonye and Bangweulu PV plants.

	Solar PV power plant	Annual energy generated (MWh/year)
GSA	Ngonye	59466.00
	Bangweulu	94971.00
Actual	Ngonye	56095.00
	Bangweulu	94417.00
PVsyst	Ngonye	61280.00
	Bangweulu	95092.00

5. Results

5.1. Analysis of Results

Figure 2 shows the variation of in-plane irradiance for one year from October 2019 to September 2020.

Figure 3 shows the 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 shows the variation of energy output for different months of the year for the *Ngonye* PV power plant. Comparing **Figures 1-3**, the highest irradiance of

6.60 kWh/m^2 and module temperature of 41.61˚C were recorded in October, whilst the highest energy output of 5646.34 MWh was recorded in May. Despite irradiance being high in October, the highest energy output was recorded in May. This is attributed to the fact that higher module temperatures result in lower voltage output, which 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.

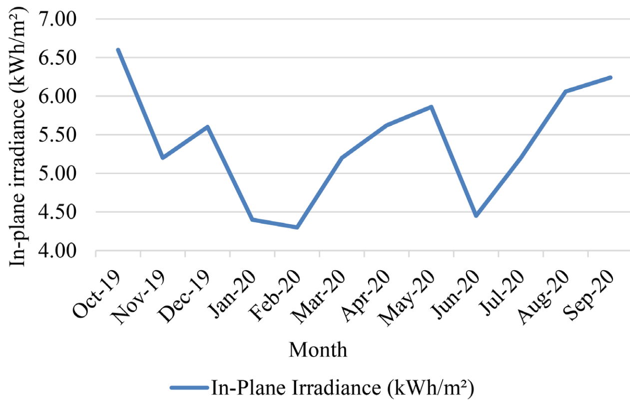

Figure 2. Ngonye PV system variation of in-plane irradiance for different months of the year for twelve months.

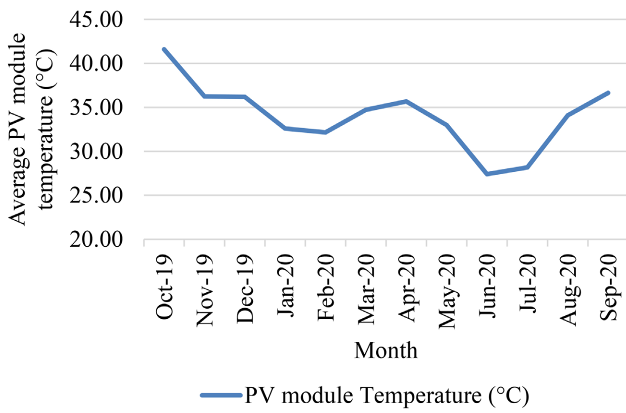

Figure 3. Ngonye PV system variation of module temperature for different months of the year for twelve months.

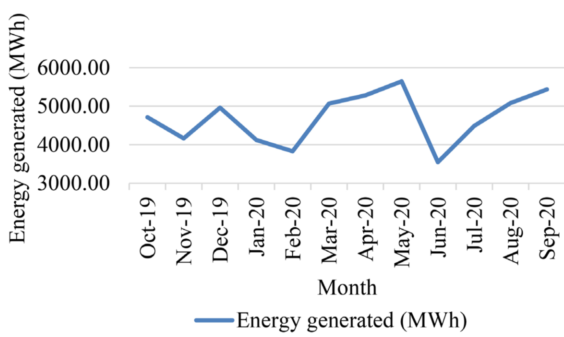

Figure 4. Ngonye PV system variation of energy output for different months of the year for twelve months.

Table 4 summarizes the PR of the Ngonyesolar 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 the breakdown of power conversion units.

Table 4. 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	206127.180	0.165	6958.647	4713.490	67.730
Nov-19	30	156.000	206127.180	0.165	5305.714	4163.960	78.481
Dec-19	31	173.600	206127.180	0.165	5904.307	4960.960	84.023
Jan-20	31	136.400	206127.180	0.165	4639.098	4123.350	88.882
Feb-20	29	124.700	206127.180	0.165	4241.170	3830.810	90.324
Mar-20	31	161.200	206127.180	0.165	5482.571	5066.360	92.408
Apr-20	30	168.600	206127.180	0.165	5734.252	5279.570	92.071
May-20	31	181.660	206127.180	0.165	6178.435	5646.340	91.388
Jun-20	30	133.500	206127.180	0.165	4540.466	3549.120	78.166
Jul-20	31	161.200	206127.180	0.165	5482.571	4487.220	81.845
Aug-20	31	187.860	206127.180	0.165	6389.303	5082.390	79.545
Sep-20	30	187.200	206127.180	0.165	6366.856	5435.900	85.378
Mean PR							84.187

Table 5 gives the PR of the 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.

Table 5. Computation of plant performance ratios for Bangweulu solar PV power plant.

<table>
<tr><th>Module rating (W)</th><th>GHI (kWh/m²)</th><th>Effective surface area (m²)</th><th>Module Efficiency</th><th>Annual nominal Energy (MWh)</th><th>Total annual nominal energy (MWh)</th><th>Total annual actual energy (MWh)</th><th>PR (%)</th></tr>
<tr><td>120.000</td><td>2092.000</td><td>288000.000</td><td>0.167</td><td>100616.832</td><td rowspan="2">113776.550</td><td rowspan="2">94417.125</td><td rowspan="2">82.980</td></tr>
<tr><td>117.500</td><td>2092.000</td><td>38592.000</td><td>0.163</td><td>13159.718</td></tr>
</table>

Table 6 summarizes the performance of Ngonye and Bangweulu solar PV power plants. Their CFs are within an acceptable range as per research findings. The acceptable range of values for CF for good performance of a solar PV system is 12% - 24%.

Table 6. Analysis of specific yield (S_y) and capacity factor (CUF) for Ngonye and Bangweulu solar PV power plants.

Solar PV power plant	Ngonye	Bangweulu
Installed capacity (MW_P)	34.00	54.30
Net annual energy generation (MWh)	56095.17	94417.12
S_y (kWh/kW_P)	1649.86	1738.80
CUF (%)	18.83	19.85

Table 7 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 and 4.76 hours for Ngonye and Bangweulu solar PV systems, respectively.

Table 7. Determination of final PV system yield for two 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

Table 8 gives the average number of sunshine hours in a year for the solar PV systems. The reference yield for both plants was found to be 5.39 hours for Ngonye and Bangweulu solar PV systems, respectively. This translates into the number of sunshine hours for the two solar PV power plants.

Table 8. Determination of reference yield for the two mini-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

Table 9 gives PRs of the solar PV power system for Y_f and Y_r. This is an alternative way of determining the PR of the solar PV power system. It is a theoretically reliable method of determining the PR of a PV solar power plant.

Table 9. Determination of PR with respect to Y_r and Y_f.

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

Figure 5 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 interpretation of this is that, 5.684 kWh/m²/day is assumed to be received with the assumption that there are no losses.

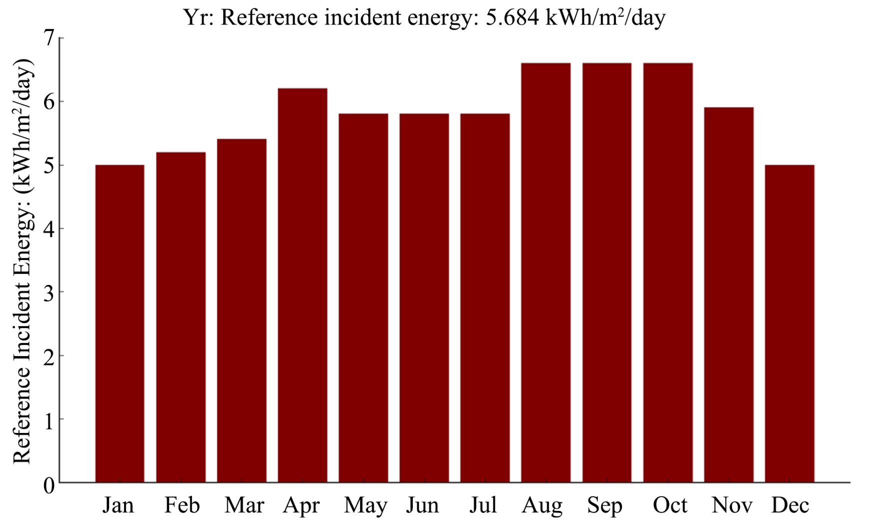

Figure 5. Reference incident radiation in the collector plane using PVsyst software for the Bangweulu solar PV power plant.

Figure 6 shows that of the 5.684 kWh/m²/day of radiation received, about 0.86 kWh/m²/day is not converted into electrical energy due to system losses by inverters and other plant components and array losses (losses from solar panels). Therefore, of the 5.684 kWh/m²/day, only about 4.82 kWh/m²/day is converted to useful energy.

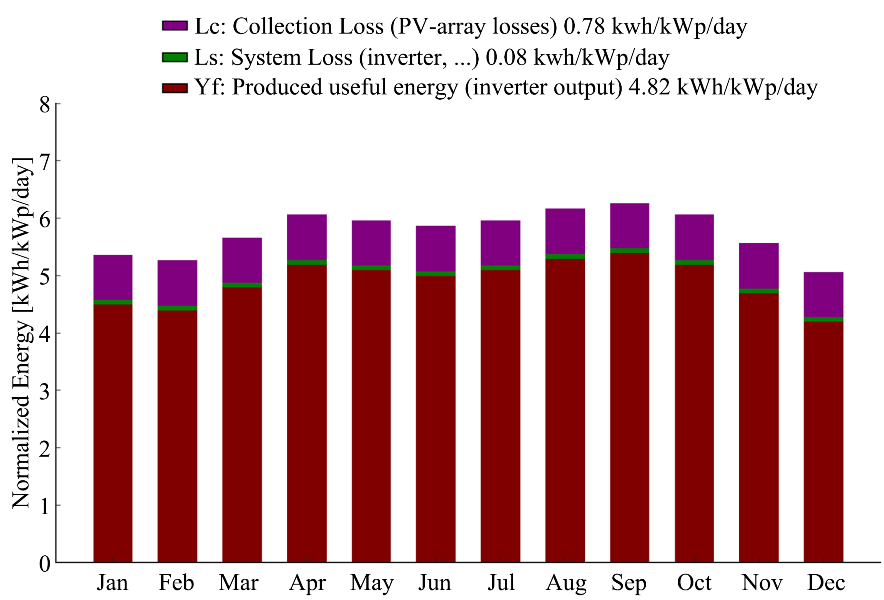

Figure 6. Normalised productions (per installed kWp) for Bangweulu solar PV power plant: Nominal power 54 MW_p.

Figure 7 indicates that 15.1% of the solar resource received by the Bangweulu solar PV power plant in the assessed period was not transformed into electrical energy owing to factors including conduction losses, inverter downtimes, module efficiency, losses due to lose contacts, and plant component defects.

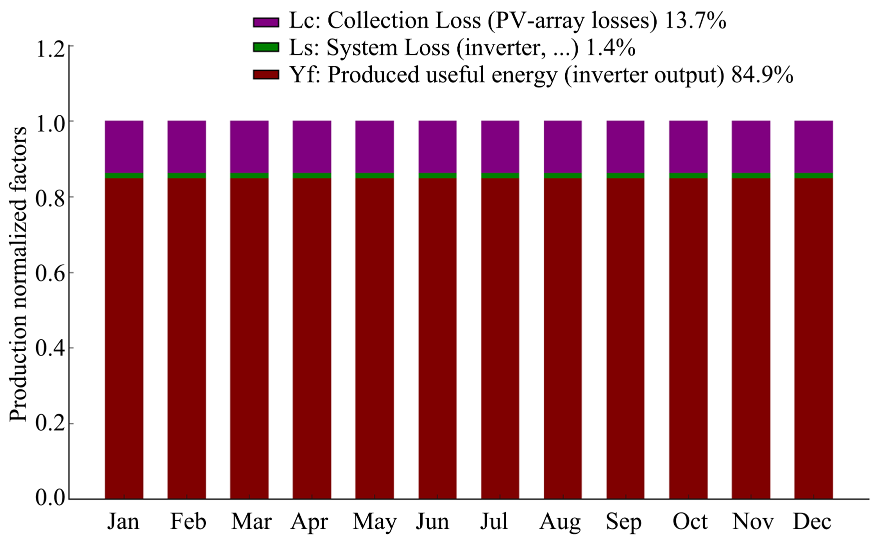

Figure 7. Normalised production and loss factors for Bangweulu solar PV power plant: Nominal power 54 MW_p.

Figure 8 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 interpretation of this is that, 6.096 kWh/m²/day is assumed to be received with the assumption that there are no losses.

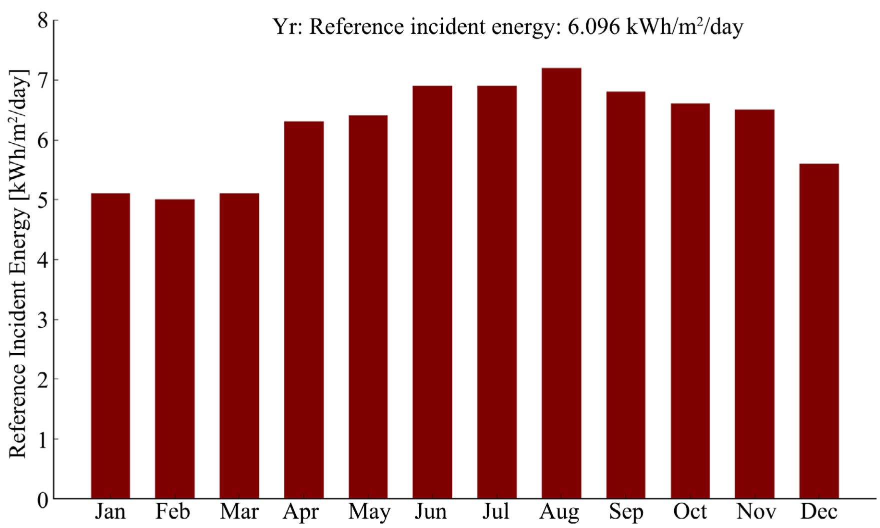

Figure 8. Reference incident radiation in the collector plane using PVsyst software.

Figure 9 shows that of the 6092 kWh/m²/day of radiation received, about 1.16 kWh/m²/day is not converted into electrical energy due to system losses by inverters and other plant components and array losses (losses from solar panels). Therefore, out of the 6092 kWh/m²/day, only about 4.94 kWh/m²/day is converted to useful energy.

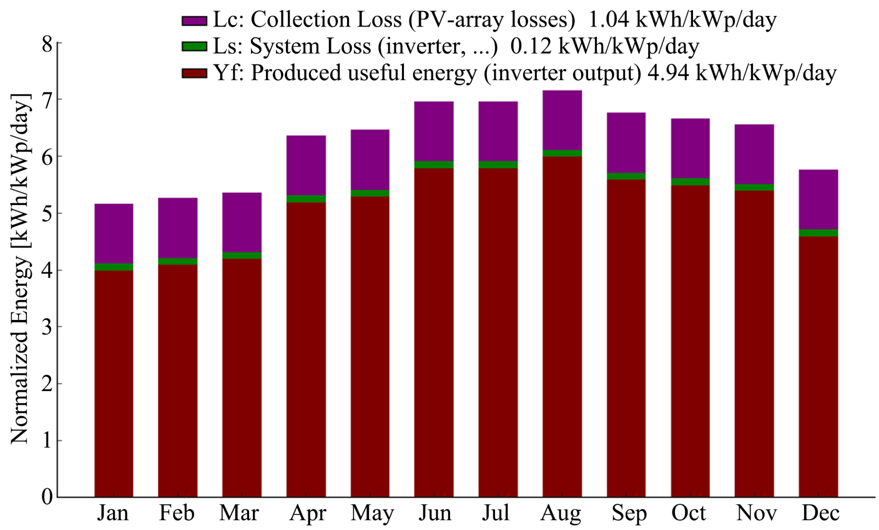

Figure 9. Normalised productions (per installed kWp) for Ngonye solar PV power plant: Nominal power 34 MW_p.

Figure 10 indicates that 19% of the solar resource received by the Ngonye solar PV power plant in the assessed period was not transformed into electrical energy owing to factors including inverter downtimes, module efficiency, losses due to lose contacts, and plant component defects.

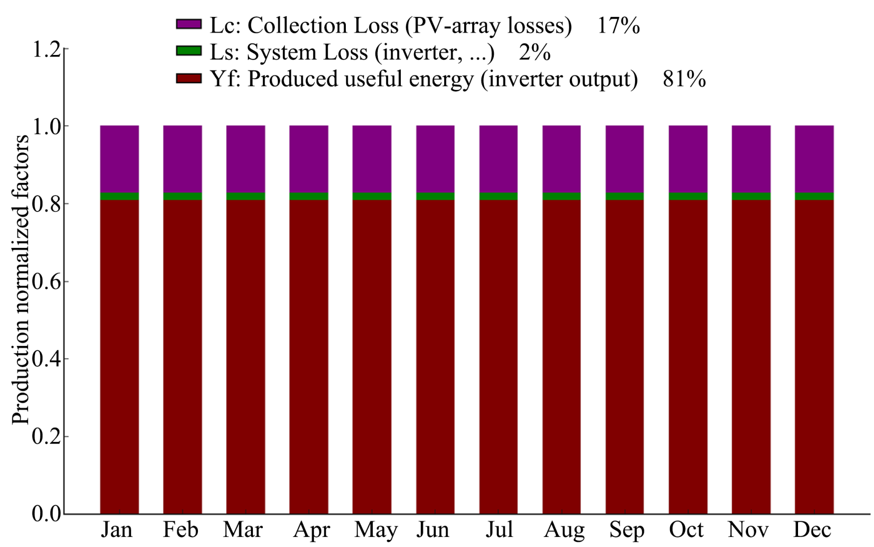

Figure 10. Normalised production and loss factors for Ngonye PV solar power plant: Nominal power 34 MW_p.

Table 10 shows comparisons of actual energy generated per year, performance ratio, final yield, and reference yield for the Ngonye and Bangweulu solar PV power plants, GSA, actual values, and simulated values (PVsyst). The deviations are minimal, and this is due to systematic and random errors attributed to plant operations.

Table 10. Comparisons of annual energy yield, PR, Y_f, and Y_r for Ngonye and Bangweulu solar PV power plants.

	Solar PV power plant	Actual energy generated (MWh/year)	PR (%)	Y_f (Hours)	Y_r (Hours)
GSA	Ngonye	59466.00	-	-	-
	Bangweulu	94971.00	-	-	-
Actual	Ngonye	56095.00	84.00	4.52	5.36
	Bangweulu	94417.00	83.00	4.76	5.36
PVsyst	Ngonye	61280.00	81.00	4.94	6.10
	Bangweulu	95092.00	85.00	4.82	5.68

Table 11 shows comparisons of the amount of carbon dioxide (CO_2) equivalent to greenhouse gases that are emitted to the atmosphere for producing a total of 150 GWh of energy from the Ngonye and Bangweulu solar PV power plants. This is based on the fact that the production of 1 kWh of energy is accompanied by the emission of 1 kg of carbon dioxide, which is equivalent to the same amount of greenhouse gases. This shows that solar PV technology is environmentally friendly.

Table 11. Comparison of carbon emissions from solar PV power generation to that of coal.

Power Technology	Total annual energy output (GWh)	CO_2 eq GHGs emission (Kg)
Solar projects	150	Negligible
Coal projects	150	1.5×10^9

Error and Uncertainity Analysis

To assess the robustness of the performance indicators derived from plant data, a quantitative error analysis was undertaken. The main sources of measurement uncertainty include pyranometer calibration error (±2%), temperature sensor error (±0.5%), inverter metering accuracy (±1%), and SCADA data acquisition error (±0.5%). Operational variability, such as minor outages and environmental soiling effects not captured in real time, introduces an additional uncertainty estimated at ±2%.

These uncertainties were combined using the root-sum-square propagation method:

$$U_{total} = \sqrt{U_{pyr}^2 + U_{temp}^2 + U_{inv}^2 + U_{data}^2 + U_{op}^2} \quad (10)$$

where;

Pyranometer uncertainty (U_{pyr}) = ±2.0%

Temperature sensor uncertainty (U_{temp}) = ±0.5%

Inverter metering uncertainty (U_{inv}) = ±1.0%

Data acquisition uncertainty (U_{data}) = ±0.5%

Operational variability (U_{op}) = ±2.0%

Resulting in a total uncertainty of ±3.1% for the irradiance and energy yield measurements. This translates to an overall ±3.5% uncertainty in performance ratio (PR) and capacity utilisation factor (CUF) calculations. For derived ratio indicators, PR and CUF, the uncertainty propagates slightly higher (±3.5%) due to combined numerator and denominator error interactions, which is consistent with error propagation principles outlined in IEC 61724-1 for PV performance assessment. The observed deviations between simulated and actual yields (≤5%) therefore fall within the combined measurement uncertainty, indicating that systematic and random errors have no material impact on the study's conclusions.

5.2. Discussion of Results

The Ngonye and Bangweulu solar PV plants show strong technical performance and operational efficiency, confirming solar energy's viability in Zambia. This analysis examines irradiance, energy output, system efficiency, and environmental impact over a year. Both plants receive similar solar input, averaging 5.39 kWh/m^2/day, but energy output varies with temperature. Despite October having the highest irradiance and module temperature (41.6˚C), May had the highest output at Ngonye (5646.34 MWh), illustrating the negative impact of heat on PV efficiency.

Annually, Ngonye generated 56,095 MWh and Bangweulu 94,417 MWh, consistent with their capacities of 34 MWp and 54.3 MWp. PVsyst projections (61,280 MWh and 95,092 MWh) closely matched actual outputs, validating the model. Average performance ratios were 84.18% (Ngonye) and 82.98% (Bangweulu), exceeding the 75% global benchmark. October's PR drop at Ngonye (67.73%) was due to a power conversion failure. PR calculations using different methods remained consistent, confirming reliability.

Capacity factors were 18.83% (Ngonye) and 19.85% (Bangweulu), within the typical 12% - 24% range. Specific yields were strong at 1649.86 kWh/kWp and 1738.80 kWh/kWp, respectively. System losses were moderate, with 15.1% for Bangweulu and 19% for Ngonye, mainly from inverter inefficiencies and minor outages. Regular maintenance and quality components can reduce these losses.

Environmentally, solar PV offers major benefits. Replacing 150 GWh of coal power with solar avoids about 1.5 billion kg of CO_2 emissions, supporting Zambia's sustainability goals. The plants' high efficiency, strong yields, and alignment with models confirm solar PV as a clean, reliable energy source. With grid capacity for 816 MWp and only 88.3 MWp installed as of December 2022, Zambia has significant potential for solar expansion.

6. Conclusions

As of December 2022, Zambia had 88.3 MWp of installed solar PV capacity out of a total of 2981 MWp. However, the national grid has the capacity to support up to 816 MWp of solar energy, highlighting significant untapped potential. Given Zambia's abundant solar resources and consistent irradiance levels, solar energy is both technically feasible and environmentally sustainable. Its expansion is essential for diversifying the energy mix, enhancing energy security, and addressing climate change through mitigation and adaptation.

The success of the Ngonye and Bangweulu solar PV plants demonstrates the viability of large-scale solar in Zambia. Their strong performance, closely matching or exceeding modeled projections (e.g., from PVsyst), confirms the technical reliability and economic attractiveness of such projects. These outcomes are supported by favorable climatic conditions, investor interest, and a policy environment increasingly supportive of renewable energy.

Zambia's overreliance on hydropower has become vulnerable due to declining water levels and recurring droughts. This has led to persistent load shedding and energy shortages, especially during dry seasons. Meanwhile, growing electricity demand from urbanization, industrial development, and rural electrification underscores the urgency for new, scalable energy sources. Solar PV, which requires minimal water and can be deployed relatively quickly, offers a timely and sustainable solution.

With proven plant success, available grid capacity, and rising energy needs, scaling up solar PV is not only viable but crucial. Prioritizing its integration to the grid's full capacity will support energy reliability, economic growth, and climate resilience.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

AC	Alternating Current
CdTe	Cadmium Telluride
CO_2 eq	Carbon Dioxide Equivalent
CU	Conversion Unit
CUF	Capacity Utilization Factor
DC	Direct Current
EIA	Energy Information Administration
ERB	Energy Regulation Board
FAO	Food and Agriculture Organization
GHGs	Greenhouse Gases
GHI	Global Horizontal Irradiance
GIS	Gas Insulated Substation
GSA	Global Solar Atlas
HT	High Tension
IFC	International Finance Corporation
IPPs	Independent Power Producers
LSMFEZ	Lusaka South Multi-Facility Economic Zone
LT	Low Tension
MCR	Main Control Room
MW	Megawatt
MWp	Megawatt-peak (PV rated capacity)
PPC	Power Plant Controller
PQM	Power Quality Monitor
PR	Performance Ratio
PV	Photovoltaic
PVC	Polyvinyl Chloride
PVOUT	Photovoltaic Energy Output
PVsyst	Photovoltaic System Simulation Software
QPPI	Quick Power Parallel Integration
RES	Renewable Energy Sources
RMU	Ring Main Unit
SCADA	Supervisory Control and Data Acquisition
SF_6	Sulfur Hexafluoride
SO	System Operator (ZESCO)

STC	Standard Test Conditions
Sy	Specific Yield
WBG	World Bank Group
Y_f	Final Yield
Y_r	Reference Yield
ZESCO	Zambia Electricity Supply Corporation Limited