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Performances Analysis of On-Grid-Tied Large-Scale Solar PV Plant in Mali: A Case Study in Kita

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Abstract

The installation of on-grid-electricity-generation photovoltaic (PV) system is currently undergoing substantial growth and extension as an alternate source of energy that contributes to Malian buildings. This study presents an evaluation of a grid-connected of a 50 MW photovoltaic (PV) system installed in Kita, Mali region. The data was recorded year from 1st January to 31 December 2022 based on real time observation. The system is made up of 187,000 modules polycrystalline of 270 Wp. The assessed parameters of the PV installation include energy output, solar radiation, ambient temperature, yields, efficiencies, dust, performance ratio (PR), capacity factor and relationships between dust, yields; between dust and efficiencies. The results show that the final yield (Y_f) ranged from 3.56 to 5.04 kWh/kWp, the performance ratio (PR) ranged from 70.99% to 75.60% and the annual capacity factor was found to be 18.07%. The study further suggests that, at the observed levels, dust accumulation does no significantly impact on PV system efficiency. The results will proffer solutions to start-up companies and individuals to install PV plants to meet the energy demands of the country.

Keywords

Grid-Connected, Dust, Performance Ratio, Capacity Factor, Photovoltaic System

1. Introduction

Energy is essential in our modern society, propelling socioeconomic growth and technological advancement. It provides power to critical sectors such as housing, agriculture, transportation, industries, and services. However, despite the abundant renewable resources, the challenge is to provide energy in a sustainable way so that future generations can access and tap the resources they require. The continued reliance on fossil fuels has resulted in a slew of issues, including greenhouse gas emissions, resource depletion, rising energy costs, and environmental consequences for climate change. As a result, many countries are shifting their focus to low-carbon and renewable energy sources, paving the way for a more sustainable and resilient future [1]. Mali, with its abundant solar resources, is gradually embracing the global energy transition and has accounted for less than 1% of the country's newly installed solar energy sources totaling about 720 MW, while fuel thermal power stations produced approximately 72% of energy in 2018 [2]. Mali's solar potential is notable, with irradiation levels ranging between 5 - 7 kWh/m^2/day, significantly higher than the global average of 4 - 5 kWh/m^2/day. Depending on the season, the country receives 7 - 10 hours of sunlight each day. Furthermore, public and non-governmental organisation (NGOs) grants have reduced the cost of PV systems, encouraging widespread adoption [2].

Mali has recently entered a new phase in the development of solar energy systems. Frequent power outages since 2022 have prompted the government to broaden its renewable energy initiatives. Several grid-connected PV projects are currently under construction, totaling approximately 400 MW. Among these initiatives include the Kita photovoltaic solar power plant, a 50 MWP grid-connected photovoltaic system in southwestern Mali. This study focus on assessing the system's performance, providing valuable insights into the effectiveness of Mali's grid-connected PV systems, and guiding the country's future renewable energy development.

PV system performance is influenced by a variety of factors, including ambient temperature, relative humidity, and solar radiation. Furthermore, performance can vary depending on the type of PV technology used, the system's location, and the tilt angle of the modules, all of which affect energy production in real-world conditions [3] [4].

The Performance Ratio (PR) is a key metric for evaluating PV system performance. It is calculated by dividing the energy yield (Y_F) by the reference yield (Y_R) [5] [6]. The PR measures how efficiently a system converts available sunlight into usable electricity in relation to its installed capacity. Y_F represents the energy produced by the modules, while Y_R reflects the total solar irradiation received. Although Standard Test Conditions (STC) are commonly used in performance evaluations, they may not accurately reflect real-world operations [7].

This study investigates the 50 MWp Kita PV system's performance in 2022, assessing its response to changing climatic conditions. Due to administration and logistical constraints, the analysis is restricted to a one-year dataset. Despite this limitation, the dataset captures seasonal variations in system performance, providing valuable insights into efficiency fluctuations caused by weather conditions, solar irradiance, and temperature effects. While a single-year dataset provides useful observations, we recognize that multi-year data would enable trend evaluation, degradation studies, and long-term performance forecasting, providing a more complete understanding of the system's reliability and efficiency over time. It assesses key metrics such as efficiency (PV array η_{PV}, Inverter η_{inv} and system η_{sys} efficiencies), yields (PV array Y_A, reference Y_R and final Y_F), energy losses (Array capture L_C, system L_S), and the Performance Ratio (PR). Environmental factors, such as temperature, wind speed, and solar irradiance, have a significant impact on these parameters [8].

Dust accumulation is a major environmental issue in Mali's semi-arid-like Kita region. Dust on PV modules reduces the amount of sunlight reaching the solar cells, resulting in lower power output [9]. Regular panel cleaning is critical for mitigating this issue and ensuring optimal system performance [10].

Furthermore, the Kita region, which is especially vulnerable to the effects of climate change, has prioritised renewable energy and energy efficiency in its economic development strategies. Since 2020, these initiatives have been part of a larger strategy to address environmental and economic challenges, which was reflected Mali's growing commitment to sustainability.

2. Materials and Methods

2.1. Description of the Power Plant

The focus of this study is on grid-connected solar power systems in Mali's Kita region, which are part of the country's national renewable energy program. The 50 MWp solar plant (**Figure 1**), located in Mali's southwestern region, is intended to capitalise on the area's distinct climate. The solar panels, which are mounted on south-facing supports tilted at 15˚, feed the electricity they generate directly into the national grid, which powers homes, businesses, and communities throughout the area.

Since Kita, is located in the Northern Hemisphere, the PV panels are positioned southward in accordance with standard solar energy optimisation principles. This orientation ensures that the panels receive consistent solar exposure all year, increasing energy capture and efficiency. By aligning with the sun's natural path, the system operates more efficiently within local climatic conditions, making better use of the available solar resource. Studies conducted in West Africa support the efficacy of this approach. According to research conducted in Douala, Cameroon, tilting solar panels 10˚ to 20˚ southward results in the highest energy output [11]. Similarly, studies in Nigeria found that panels generate the most electricity when tilted 20˚ south [12]. In Mali, tests on various PV module inclinations revealed that a tilt angle slightly above the site's latitude-approximately 15˚ produces the highest efficiency [13].

The Kita Solar Power Plant is more than just a facility; it is a shining example of innovation and sustainability. It is designed to generate clean, renewable energy and is assisting Mali in transitioning to a more environmentally friendly environment. The plant, which spans 100 hectares (1,000,000 square meters), houses 187,000 polycrystalline solar panels, each of which can generate 270 watts of power. They generate a whopping 50 megawatts (MW) of electricity combined. To ensure that this energy is usable, the plant employs 834 Akuo Energy Solar GEM inverters, each with a capacity of 60 kVA (60 kW), which convert the solar panels' direct current (DC) into the alternating current (AC) that powers daily life. The plant, located at latitude 13.03˚ and longitude −9.52˚, is perfectly positioned to absorb Mali's abundant sunshine, allowing it to operate at full capacity and provide a consistent, reliable flow of energy. The plant produces 50 MW of clean power, assisting Mali in reducing its reliance on fossil fuels, lowering greenhouse gas emissions, and providing electricity to more people, whether in cities or remote villages. Its cutting-edge technology and decentralised inverter system set a high standard for how large-scale solar projects can be efficient and adaptable.

However, the Kita Solar Power Plant has an impact on more than just the environment. It also creates jobs, both during construction and now in day-to-day operations, which helps to boost the local economy. This project is a powerful reminder of solar energy's ability to transform lives in Sub-Saharan Africa, setting a precedent for future renewable energy efforts. The Kita Solar Power Plant is not only generating electricity; it is also paving the way for Mali's brighter, more sustainable future. It represents progress, demonstrating what is possible when innovation meets a commitment to a cleaner world.

Figure 1. Mapping kita solar power plant (Google Earth 2024).

2.2. Performances Analysis of the Solar Photovoltaic Plant

The performance of solar PV power plant grid-connected has been analyzed using the technical indices based on the available data collected on the power plant, such as the performance indicators developed by the International Energy Agency (IEA) within the Photovoltaic Power Systems Program, which were established initially by the IEC standard 61,724 [14]-[16]. In this study, the evaluation takes into account several parameters, including energy output, various yields (reference yield, array yield, and final yield), energy losses in the array and system, and system efficiencies. In addition, the analysis takes into account important performance such as the performance ratio and capacity factor to evaluate the photovoltaic system's overall effectiveness and reliability [1] [3] [17]-[21]. The definitions of the main indices examined in this study for the performance analysis of the aforementioned solar PV plants are presented in detail in the following section.

2.2.1. Energy Output

The total energy refers to the amount of alternating current (AC) power produced by the system over a given time period. This energy can be calculated on an hourly, daily, or monthly basis, depending on the time period being studied [22] [23]. The corresponding energy values for these periods can be calculated as follows:

$$E_{AC,h} = \sum_{t=1}^{60} E_{AC,t} \tag{1}$$

$$E_{AC,d} = \sum_{h=1}^{24} E_{AC,h} \tag{2}$$

$$E_{AC,m} = \sum_{d=1}^{N} E_{AC,d} \tag{3}$$

$E_{AC,t}$ is the AC energy output at a specific time t (measured in minutes), $E_{AC,h}$ is the AC energy output over an hour, $E_{AC,d}$ is the total AC energy output for a day, and $E_{AC,m}$ is the total AC energy output for a month. The variable N represents the number of days in the specified month.

2.2.2. System Yields

System yields are divided into three types: array yield, final yield, and reference yield. These yields provide insight into the PV array's actual performance in relation to its rated capacity. The array yield (Y_A) is the direct current (DC) energy output from the PV array over a specific time period, normalised by the PV system's rated power. Essentially, it indicates how long (in kWh/kWp) the PV array would need to operate at its nominal power to produce the observed energy output. This parameter aids in determining how effectively the array performs in real-world scenarios [1] [19]. The calculation is as follows:

$$Y_A = \frac{E_{DC}}{P_{PV,rated}} \left(\text{kWh/kW}_\text{P}\right) \tag{4}$$

Here, EDC refers to the PV array's DC energy output (measured in kWh). The final yield (Y_F) is the total AC energy produced by the PV system over a specified period, divided by the system's rated output power. This metric indicates how many hours per day the PV system would need to operate at full power to produce the observed amount of energy [22] [23]. It provides a clear measure of the system's overall performance. It is calculated as follows:

$$Y_F = \frac{E_{AC}}{P_{PV,rated}} \left(\text{kWh/kW}_\text{P}\right) \tag{5}$$

where E_{DC} is the AC energy output (kWh).

The reference yield Y_R represents the total in-plane insolation or global horizontal insolation divided by the reference irradiance under standard test conditions, which is set at 1 kW/m^2. This yield serves as a theoretical measure of the energy available at a specific location over a given time period, providing a benchmark for understanding the potential solar energy that can be harnessed.

It plays a critical role in assessing system efficiency, particularly when used in Performance Ratio (PR) calculations. The actual energy output can be compared to the available solar resource to determine how efficiently the system is operating. It also allows for fair comparison of different PV installations, regardless of size or geographic location, by standardizing performance metrics. It is useful not only for efficiency analysis, but also for diagnostic purposes. Significantly deviations from expected values may indicate shading, dirt accumulation, or equipment malfunctions, necessitating maintenance or adjustments. It is calculated as follows:

$$Y_R = \frac{H_T}{H_R} \left(\text{kWh/kW}_\text{P}\right) \tag{6}$$

where H_T is the in-plane solar radiation and H_R is the reference irradiance.

Array and system energy losses

Array capture losses (L_C) are the losses that occur during the operation of the PV array, reflecting the inability to fully utilise the available solar irradiance [16] [24]. These losses are calculated as the difference between the reference yield (Y_R) and the array yield (Y_A). This metric assists in identifying inefficiencies within the array and is expressed as follows:

$$L_C = Y_R - Y_A \left(\text{kWh/kW}_\text{P}\right) \tag{7}$$

The term "system losses" (L_S) refers to the energy lost when the inverter converts DC power from the PV array into AC power. These losses result from the inefficiencies of the inverter and other system components involved in the conversion process. System losses can be calculated as follows:

$$L_S = Y_A - Y_F \left(\text{kWh/kW}_\text{P}\right) \tag{8}$$

2.2.3. System Efficiencies

A photovoltaic (PV) system's efficiency is usually divided into three categories: PV array efficiency, system efficiency, and inverter efficiency. Depending on the available data and desired level of detail, these efficiencies can be measured at various time intervals, such as instantaneous, hourly, daily, monthly, or annual. PV array efficiency (η_{PV}) is based on the array's DC power output, indicating how efficiently solar panels convert sunlight into electricity.

System efficiency is calculated using the AC power output, which takes into account the overall performance of the system, including energy losses during conversion.

The PV array efficiency (η_{PV}) measures the average energy conversion efficiency of a PV array. It is calculated as the daily DC energy output divided by the total daily in-plane solar irradiation received by the PV array multiplied by its total surface area [24]. This efficiency is used to assess how well the solar panels perform in real-world conditions. The formula for PV module efficiency is given as follows:

$$\eta_{PV} = \frac{E_{DC} * 100}{H_t * A} (\%) \tag{9}$$

Where A: array area (m^2). Overall system efficiency reflects the performance of the entire photovoltaic system, including all energy generation and conversion components [16]. The system efficiency is calculated as follows:

$$\eta_{SYS} = \frac{E_{AC} * 100}{H_t * A} (\%) \tag{10}$$

The inverter efficiency is given as:

$$\eta_{inv} = \frac{E_{AC} * 100}{E_{DC}} (\%) \tag{11}$$

2.2.4. Performance Ratio

The performance ratio (PR) is an important metric that depicts the overall impact of energy losses on a PV system's expected power output. It compares the system's efficiency in real-world conditions to its theoretical maximum performance. The PR value indicates how closely the system performs to its ideal efficiency, allowing for a fair comparison of different PV systems, regardless of location, tilt angle, orientation, or nominal rated power capacity [25] [26]. Under standard test conditions, the PV system's efficiency is compared to the nominal efficiency of the photovoltaic generator to determine performance. [15] [17] define the performance ratio as the ratio of the final energy yield (Y_F) to the reference yield (Y_R), which provides insight into the system's actual output relative to the available solar energy.

$$PR = \frac{Y_F * 100}{Y_R} (\%) \tag{12}$$

2.2.5. Capacity Factor

The capacity factor is an important metric for determining an electricity-generating system's energy output over time [19] [27]. It is calculated as the ratio of the actual AC energy produced by the PV system over a given time period-typically one year-to the maximum possible energy the system could have generated if it had been operating at full capacity throughout. This metric provides insight into the PV system's overall performance and efficiency, allowing you to assess how well it converts available solar energy into electricity throughout the year. A PV system's annual capacity factor can be calculated using the equation below:

$$CF = \frac{E_{AC}}{P_{PV,rated} * 8760} \tag{13}$$

2.3. Dust

Satellite-based data from NASA's Giovanni platform (MERRA-2 dataset) provided hourly Dust Surface Mass Concentration (DUSMASS) readings (kg/m^3), for the year 2022, with a spatial resolution of 0.5 × 0.625˚. These values were converted into daily and monthly averages, ensuring consistency with the PV system's performance records and allowing for the assessment of variations over time.

3. Results and Discussion

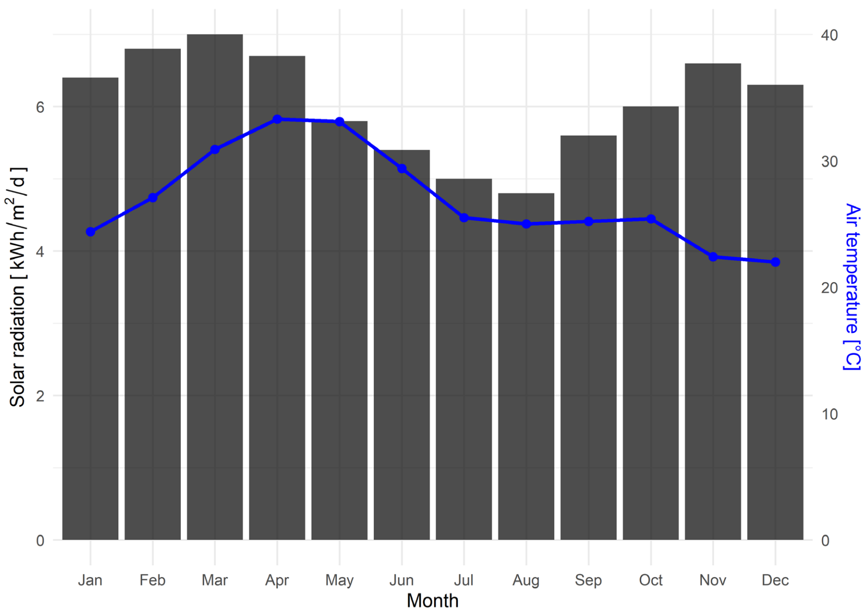

Figure 2. Solar radiation in ($kWh/m^2/day$) and ambient temperature (˚C).

Solar radiation (**Figure 2**) shows a distinct seasonal pattern, reaching its peak at approximately 6.86 $kWh/m^2/day$ in March and April, the driest months of the year. From January to May, solar radiation remains consistently high, ranging between 5.75 and 6.86 $kWh/m^2/day$, creating favorable conditions for solar energy generation. In contrast, solar radiation declines significantly during the rainy season, from June to September, with the lowest values observed in August at approximately 4.79 $kWh/m^2/day$. It begins to recover after September, reaching around 6.48 $kWh/m^2/day$ by November and December. The air temperature follows a similar seasonal trend, temperatures rise steadily from January (approximately 24˚C) to peak at around 33˚C in April, coinciding with high solar radiation. During the rainy season, temperatures drop to their lowest, stabilizing at around 25˚C from July to September. After the rains, temperatures decrease slightly, reaching 24˚C in the post-rainy months of November to December. The ambient temperature varied from 22˚C to 33˚C. Over the course of a year, the temperature typically varies from 24˚C to 33˚C, being the annual average of 27 ˚C. Rarely its ambient temperature is below 22˚C or above 32˚C.

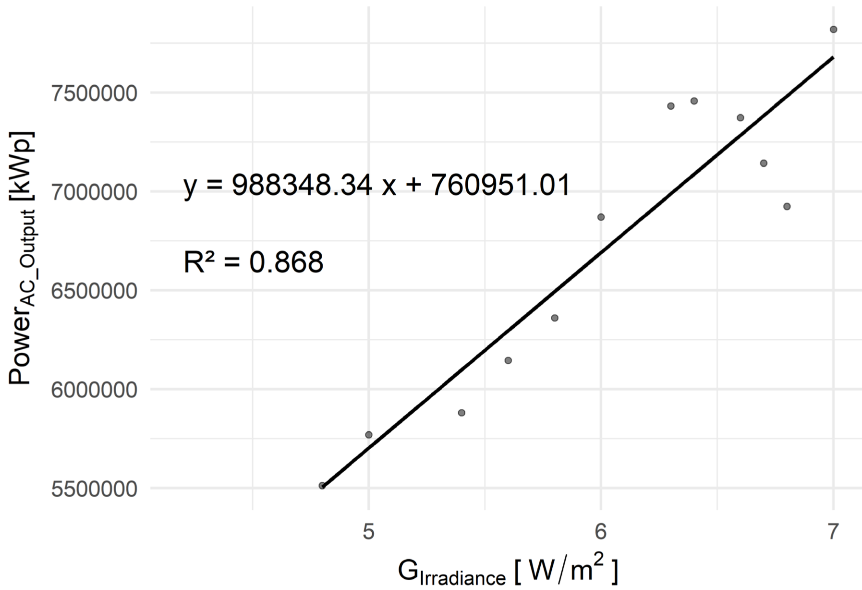

Figure 3. correlation between solar irradiance ($G_{Irradiance}$) and AC power output (P_{AC_Output}).

Figure 3 shows the correlation between solar irradiance ($G_{Irradiance}$) and AC power output (P_{AC_Output}) in a photovoltaic (PV) system. The data points are actual observations of system performance, and the trendline shows a clear linear relationship between the two variables. The equation and R^2 value provide additional information about the correlation's strength and nature.

The equation of the correlation line, $P_{AC\_Output} = 988348.34 \times G_{Irradiance} + 760951.01$, shows that the system's power output increases proportionally with solar irradiance. The slope indicates that for every 1 W/m^2 increase in solar irradiance, the AC output power rises by approximately 988,348.34 kWp. The intercept of 760,951.01 kWp suggests that even in low-light conditions, some level of power generation is recorded, possibly due to operational constants rather than actual power generation, or environmental factors.

The R^2 value of 0.868 suggests that changes in solar irradiance account for 86.8% of the variability in power output. This high value confirms a strong positive correlation between the two variables, implying that the system's performance is closely related to solar irradiance with little external influence. This relationship is further supported by the observed data ranges. Solar irradiance ranges from 5 to 7 W/m^2, resulting in AC power outputs of 5,500,000 to 7,500,000 kWp. This linear trend (**Figure 3**) shows that as irradiance increases, the system effectively converts the extra solar energy into higher power outputs, which is consistent with the expected behaviour of a well-designed PV system. At a low power output of 5,500,000 kWp, adding 1 W/m^2 of irradiance increases power output by approximately 17.97%. While at a power output of 7,500,000 kWp, the percentage increase per 1 W/m^2 of irradiance is approximately 13.18%. [1] equation yields a value that is approximately 5% lower than the current one. This difference is within the experimental uncertainty. The significance of this equation is that it allows for the evaluation of a PV system's energy output based solely on incident in-plane solar radiation. [26] also presented one of these equations, with a value of approximately 15%, which falls between the minimum and maximum values of this study.

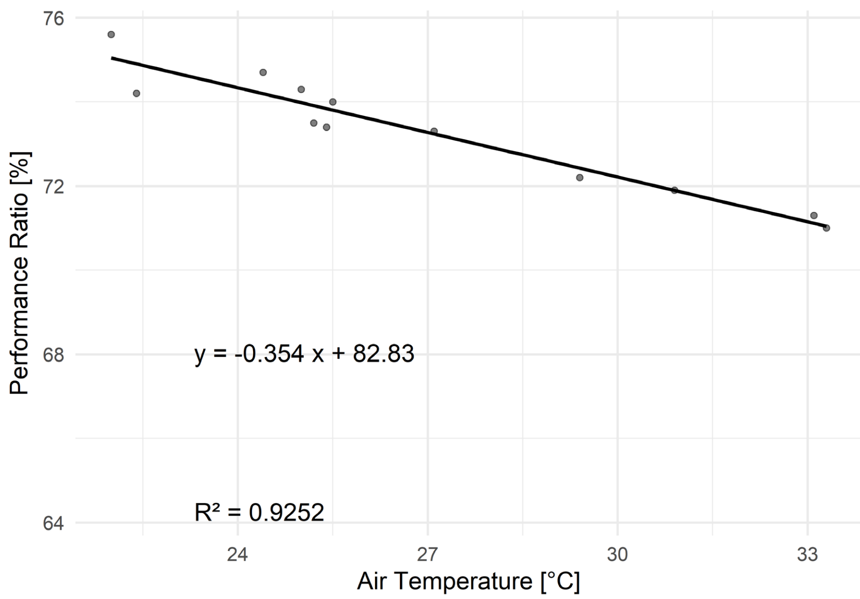

Figure 4. relationship between the solar system's performance ratio and air temperature.

Figure 4 clearly illustrates a negative linear relationship between the solar system's performance ratio and air temperature. The performance ratio decreases as the air temperature rises. The regression equation $y = -0.354x + 82.83$ quantifies the relationship between performance ratio (y) and air temperature. The slope of −0.354 indicates that for every 1˚C increase in air temperature, the performance ratio drops by approximately 0.354%. The R^2 value of 0.9252 indicates that changes in air temperature explain 92.52% of the variation in the performance ratio, implying a strong and reliable correlation. The performance ratio ranges between 70.99% and 75.60%, with higher ratios observed at lower temperatures and lower ratios at higher temperatures. As a result, rising temperatures reduce the effectiveness of energy conversion. Our study found temperature variation ranging from 24˚C to 33˚C, with the PR gradually decreasing. Research from West African countries, like Burkina Faso [28], indicates that the performance ratio undergoes a nearly negative linear regression with temperature. The correlation coefficient, R^2, of 34%, 54% and 65% is calculated in 2019, 2020 and 2021, respectively. These results show that the performance ratio becomes more sensitive to the temperature effect over time in agreement with our study.

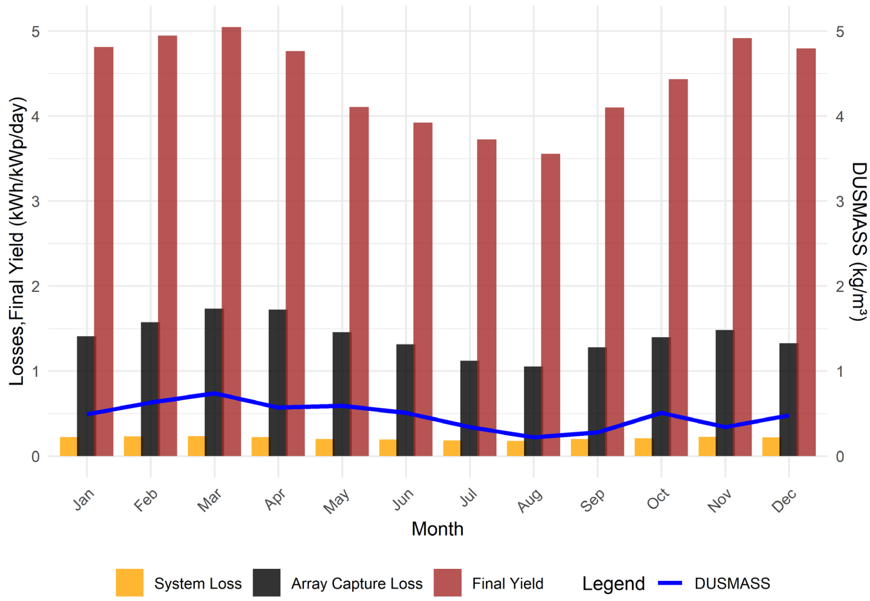

Figure 5. Installation final yield and corresponding capture, system losses and dust per month.

Figure 5 shows the impact of dust levels (DUSMASS) on Array Capture Loss, System Loss, and Final Yield throughout the year, highlighting their interrelationship and seasonal variations. Dust accumulation (DUSMASS), represented by the blue line, shows significant seasonal variation, while the energy losses and yields, represented by bars, reflect the performance of the photovoltaic (PV) system in response to these changes.

The DUSMASS peaks during the dry months, with the highest dust concentration observed in March around 7.4×10^{-6} kg/m³ and a sligh increase from January to May 6×10^{-6} kg/m³. During the rainy season, from June to September, dust levels decrease significantly, reaching their lowest value of about 3×10^{-6} kg/m³ from July to August. This seasonal fluctuation in dust accumulation has a direct impact on the performance of the PV system, particularly the array capture losses and final yield.

The Array Capture Losses reflects energy losses within the PV array due to factors such as soiling from dust. These losses are highest in months with elevated dust levels, particularly in March and April, where the array capture loss reaches around 1.73 kWh/kWp/day and 1.72 kWh/kWp/day, respectively. Conversely, during the rainy season, when dust levels are at their lowest, array capture losses decrease significantly, ranging from 1.12 to 1.05 kWh/kWp/day in July and August. This strong correlation between dust accumulation and array capture losses highlights the importance of maintaining clean panels to optimize performance during high-dust months.

The System Losses, representing losses during the DC-to-AC conversion process, remains relatively constant throughout the year, ranging between 0.18 and 0.23 kWh/kWp/day. Unlike array capture losses, system losses are largely unaffected by environmental factors like dust, suggesting consistent performance of the inverter and other system components irrespective of seasonal changes.

The Final Yield, which measures the system's AC energy output, demonstrates an inverse relationship with dust levels. During March, when dust levels are at their highest, the final yield peaks around 5.0 kWh/kWp/day. In contrast, during the rainy season, particularly in July and August, when dust levels are lowest, the final yield decreases at approximately 3.63 kWh/kWp/day. This similar trend underscores the significant impact of dust on the system's energy output, as higher dust levels reduce the amount of solar energy available for conversion. in Hungary the annual daily final yields were 3.02 kWh/kWp/day, 2.18 kWh/kWp/day, 2.30 kWh/kWp/day, for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si), respectively [29].

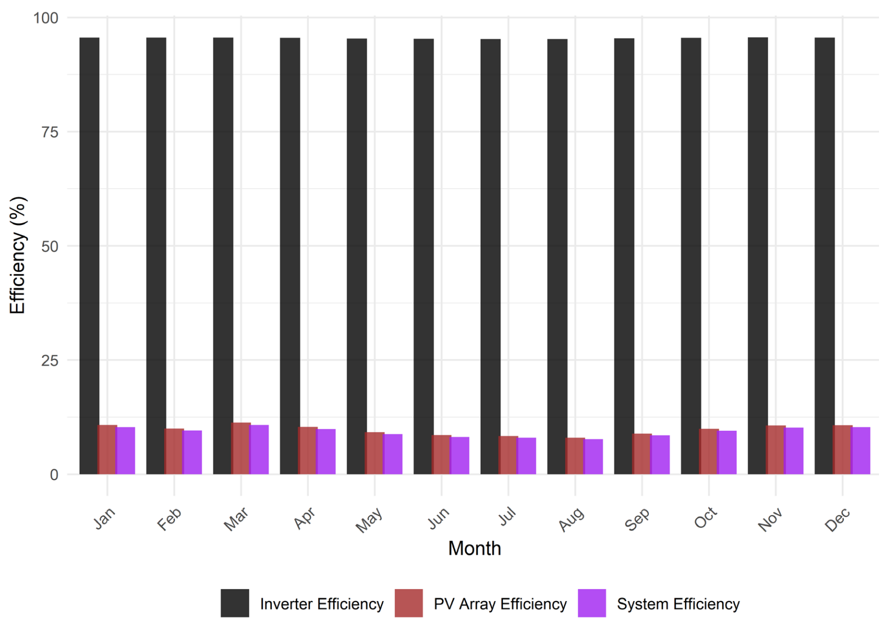

Figure 6. The variation of the monthly average daily efficiencies.

Figure 6 presents the monthly average efficiencies of the array, system and inverter throughout the recording period, highlighting their variations over time. The monthly average values are 9.7%, 9.3% and 95.4%, respectively. The highest values of efficiencies in the array, system and inverter were 11.29% (in March), 10.79% (in March) and 95.61% (in November), respectively. In the months from May to September, seasonal changes, such as solar irradiance levels, temperature, and environmental factors like soiling or shading of the panels, can all contribute to these variations of the system caused reduction in the efficiencies of array and system, and possibly in the inverter efficiency. The aforementioned factors contributed to the reduction in yields during the mentioned months, resulting in grid and system yields of 7.98% and 7.60%, respectively. During these months, the inverter efficiency averaged 95.20%, the lowest value. According to [30], the efficiency of mc-Si inverters varies from 87.50% in October to 92.62% in February for mc-Si1, and from 86.43% in October to 92.08% in February for mc-Si2. Meanwhile, CIS-based inverters exhibit slightly lower performance, with efficiency levels ranging from 79.22% in October to 90.93% in June for CIS1 and 79.68% in October to 91.22% in June for CIS2.

Inverter performance in solar power systems is extremely stable, primarily to optimized power electronics, advanced control systems, and efficient thermal management. The average inverter efficiency in this study was 95.447%, indicating that it could consistently convert DC power to AC with minimal losses. Inverters, unlike other system components, operate in a controlled environment, making them less susceptible to external fluctuations. Their ability to synchronise with the grid and adapt to voltage and frequency changes adds to their stability.

PV modules system is made up of several essential components that work together to convert sunlight into usable electricity [31]. Solar panels, which capture solar energy and generate direct current (DC) electricity, from the system's core. An inverter converts this power into alternating current (AC), which is suitable for household use or integration into the electrical grid. In off-grid systems, a change controller manages the battery charging process, ensuring that energy is effectively stored for periods when sunlight is unavailable. Furthermore, mounting structures provide stability and proper orientation for the panels, maximising solar exposure, while wiring and safety devices ensure efficient and secure power distribution throughout the system. Similarly, charge-discharge cycling depth of discharge, and exposure to extreme temperature all contribute to the loss of efficiency in battery storage systems over time [32].

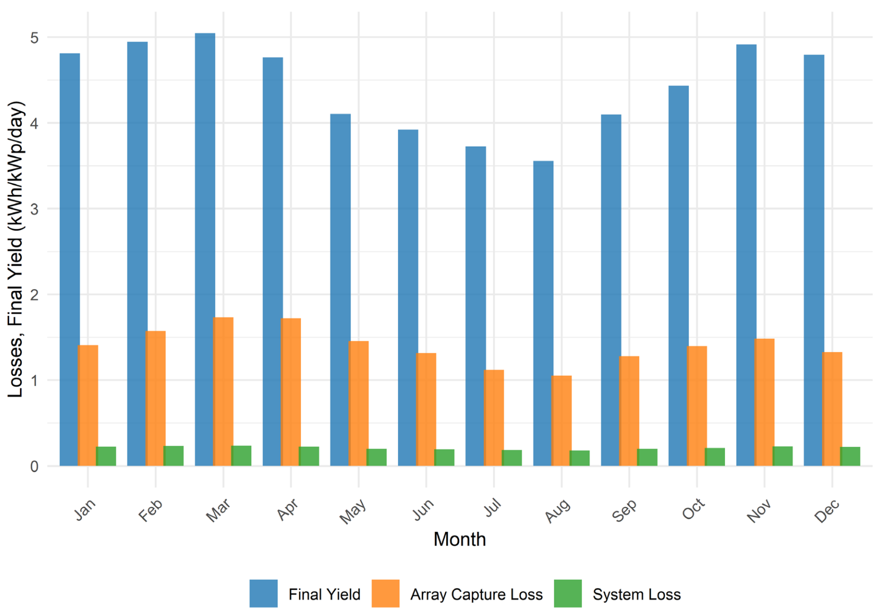

Figure 7. Monthly average daily array capture and system losses relative to reference yield.

Figure 7 illustrates the monthly variations in Final Yield, Array Capture Loss, and System Loss (kWh/kWp/day) for a photovoltaic (PV) system. These components collectively provide insights into the system's energy output and the inefficiencies present at different stages of operation.

The Final Yield (blue bars), which represents the AC energy output normalized by the system's rated capacity, is consistently the highest value across all months. The system performs at its best in March and April, where the Final Yield exceeds 4.8 kWh/kWp/day, reflecting ideal solar irradiance and favorable operating conditions. During the rainy months of July and August, the Final Yield decreases to approximately 3.5 kWh/kWp/day, likely due to reduced sunlight and weather-related inefficiencies. Towards the end of the year, the Final Yield recovers, reaching values around 4.8 kWh/kWp/day in November and December, demonstrating strong performance in the drier post-monsoon period.

The Array Capture Losses (orange bars), which measures losses within the PV array, shows notable variation across the year. The highest array capture losses occur in March, at approximately 1.73 kWh/kWp/day, which accounts for 24.72% of the Reference Yield for that month. This could be due to factors such as soiling, shading, or suboptimal environmental conditions. In contrast, the lowest array capture loss is observed in August, at just 1.05 kWh/kWp/day, equivalent to 21.96% of the Reference Yield. This indicates that the PV array operates most efficiently in August, with minimal energy losses. For instance, Capture losses in a PV system installed in Rajkot, India were 22.27% and 3.79% of the reference yields, respectively [18]. In Singapore, the numbers were 22.66% and 17.06%, respectively [24]. One of the factors contributing to the increase in array losses in November was the influence of shadowing from a concrete post near the PV system.

The System Losses (green bars), which represents losses during the conversion of DC to AC power by the inverter, remains consistently low throughout the year. These losses range from 0.18 kWh/kWp/day to 0.23 kWh/kWp/day, indicating excellent inverter performance. The lowest system loss is seen in August, at around 0.18 kWh/kWp/day, while the highest occurs in March, at approximately 0.23 kWh/kWp/day. These numbers correspond to 3.74% and 3.35% of the respective reference yields. The small variation in system losses highlights the reliability and consistency of the inverter technology used in the PV system. Corresponding values of 3.34% and 3.74% were found in PV systems in Mauritania [19], 18.57% and 10.34% in Lesotho [20], 5.55% and 5.06% in Singapore [24].

Figure 8 illustrates the average monthly Performance Ratio (PR) of a photovoltaic (PV) system over one year, expressed as a percentage. The performance ratio is a critical metric that measures how effectively a PV system converts available solar energy into usable electricity, accounting for all losses. A higher PR indicates better system efficiency and minimal energy losses. Throughout the year, the PR remains consistent, ranging between 70.99% and 75.60%, which is indicative of a well-maintained and efficient PV system. In January, the PR is approximately 74.67%, reflecting optimal system performance during the cooler winter months when lower temperatures help improve the efficiency of solar panels. From April to June, the PR slightly dips to around 71.49%, likely due to the impact of higher temperatures on PV module efficiency, which can reduce energy output. During the months of July to September, the performance ratio shows a slight improvement, peaking at around 74.29% in August. This could be attributed to stable weather conditions, better solar irradiance, and effective system operation during this period. From October to December, the PR stabilizes again at approximately 74.40%, demonstrating consistent efficiency as the system operates under favorable cooler temperatures during the post-monsoon or early winter months. in Malaysia [24] the system's average monthly PV performance ratio is 77.28%.

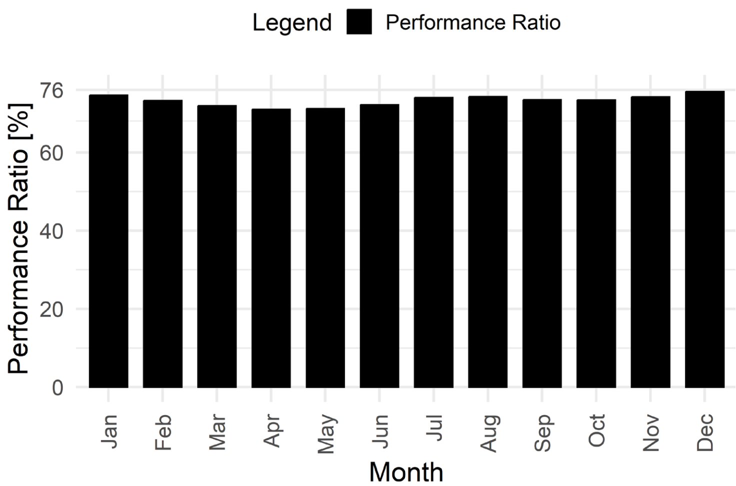

Figure 8. Average monthly performance ratio (PR).

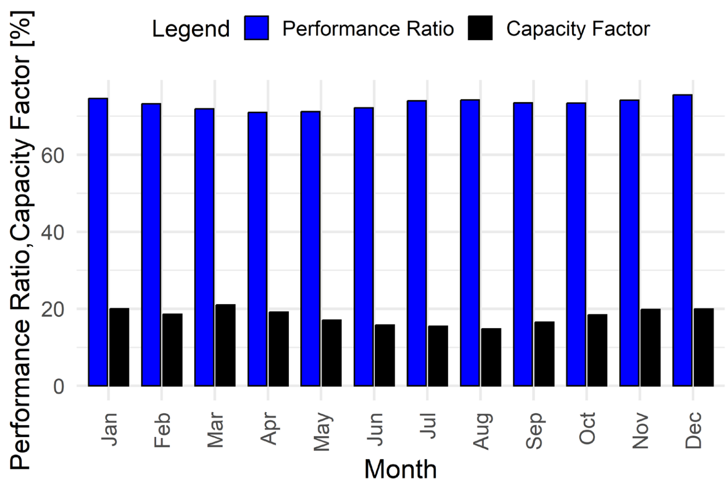

Figure 9. Monthly variation of Performance Ratio (PR) and Capacity Factor (CF).

Figure 9 presents the Performance Ratio (PR) and Capacity Factor (CF) of a photovoltaic (PV) system across the months of the year. These two metrics, while distinct, are interlinked, as the PR reflects the efficiency of the system in converting solar energy into electricity, and the CF represents how much of the system's maximum potential is utilized. Together, they provide a comprehensive picture of the system's performance.

The Performance Ratio (PR), shown by the blue bars, remains consistently high throughout the year, ranging between 70.99% and 75.59%. For example, in January, the PR is approximately 74.67%, indicating that the system is operating efficiently with minimal energy losses. A slight dip is observed during April and May, where the PR decreases to around 71.49%, likely due to higher ambient temperatures reducing panel efficiency. The PR peaks at 74.29% in August and stabilizes at around 74.40% towards the end of the year in November and December, reflecting the system's ability to maintain efficiency despite seasonal changes.

The Capacity Factor (CF), represented by the black bars, fluctuates more significantly than the PR, reflecting seasonal variations in solar energy availability. The CF ranges from approximately 14.82% to 21.02%, with the highest value observed in March, where it reaches about 21.02%. This corresponds to a period of high energy output due to optimal solar irradiance. During the rainy season, particularly in July and August, the CF drops to around 15.51% - 14.82%, reflecting reduced solar energy production due to increased cloud cover and lower irradiance levels. These seasonal trends in CF highlight the direct impact of environmental conditions on the system's energy output.

The relationship between PR and CF lies in their interplay: while the PR measures how efficiently the system converts available solar energy into electricity, the CF indicates how much of the system's potential capacity is utilized. For instance, in March, both parameters perform well-the PR is high 71.93%, and the CF peaks at 21.02%-demonstrating optimal system performance and favorable solar conditions. Conversely, during July and August, while the PR remains stable around 74.04% - 74.29%, the CF declines to 15.17%, showing that the system is still operating efficiently but is limited by reduced solar energy availability. The annual average performance ratio was 73.28% with the minimum value in April of 70.99% and the maximum value of 75.60% in December. The performance ratio of our system accused a seasonal decline from March to June due to dry season. The rainy season from July to September also a slight decline in the performance ratio. Some performance ratio of different systems in Africa, in Mauritania it varies from 63.6% to 73.6% [19], in Lesotho it varies from 35% to 79% [24], in Malbaza, Niger it varies between 60.82% to 78.27% in the dry season [33]. Therefore, to combine with the performance ratio, capacity factor is a very important parameter to evaluate a grid-connected photovoltaic system. The annual average capacity factor was 18.08%, with a minimum value of 14.82% in August and the maximum value of 21.02% in March. For instance in Mauritania capacity factor varies from 11.7% in winter to 20.5% [19]. The average is 17.2% ranging from 8.7% to 21% in Lesotho according to [24], while in Malaysia a system presented capacity factor of 10.47% [34], additional in Malaysia the system's average monthly PV capacity factor of 15.70% [35].

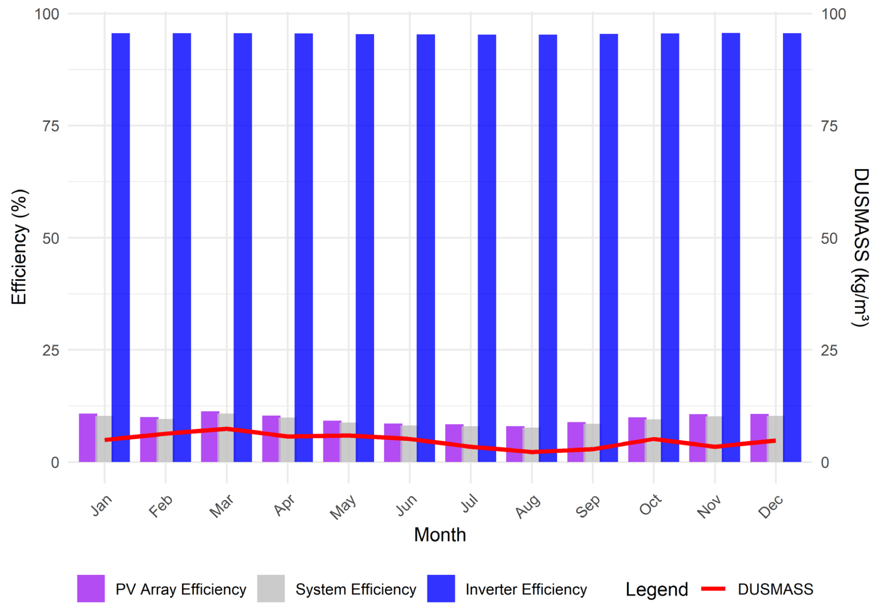

Figure 10. Installation final yield and corresponding capture and system losses per month.

Figure 10 demonstrates the relationships between dust levels (DUSMASS) and the key performance metrics of a photovoltaic (PV) system, namely PV Array Efficiency, System Efficiency, and Inverter Efficiency, measured across the months of the year. These metrics provide critical insights into how dust accumulation affects the system's performance.

The dust levels (DUSMASS) (Figure 6), shown as a blue line, fluctuate significantly throughout the year, reflecting seasonal environmental conditions. Dust levels peak during the dry months, particularly in March, reaching approximately 7×10^{-6} kg/m^3, and decrease during the rainy season, with the lowest levels observed in July and August, around 3×10^{-6} kg/m^3. This pattern highlights how dry weather contributes to increased airborne dust, while rainfall during the wet season washes away dust particles, reducing their impact on the system.

The PV Array Efficiency, which measures the panels' ability to convert sunlight into DC electricity, shows a relationship with dust levels. During months of high dust accumulation, such as January to May and October, December, the efficiency increases to around 10.59% and 10.42%, and slight increases in November while dust decreases, reflecting the positive correlation of dust on panel performance. Conversely, during the rainy months, particularly in July and August, when dust levels are at their lowest, PV Array Efficiency is at its lowest around 8.17%, indicating better performance as the panels remain cleaner and can absorb more sunlight.

The System Efficiency, which accounts for the overall performance of the PV system, including array and inverter losses, follows a similar trend to the PV Array Efficiency. As show the (Figure 10) System Efficiency is high during the high-dust months, ranging between 10.12% and 9.97% in January to April and October, December and slight increases in November while dust decreases. During the rainy months, reaching around 7.78% in July and August. This pattern confirms that dust accumulation has a similar trend with system losses, particularly at the array level.

The Inverter Efficiency, in contrast, remains consistently high at nearly 95% throughout the year, indicating that the inverter technology is unaffected by dust levels or seasonal environmental changes. This stability demonstrates the reliability and robustness of the inverter in converting DC energy from the PV array into usable AC power, regardless of external conditions.

4. Conclusions

This study monitored and evaluated the performance of a 50 MW_P grid-connected PV system in Kita, throughout the year 2022. The analysis revealed an annual average daily final yield of 4.43 kWh/kWp/day, with a total energy output of 80687.832 MWh. System efficiency was influenced by Solar irradiance, with an average a capacity factor of 18.04% and performance ratio (PR) of 73.28%. Based on the PR performance index results (more than 70%), according to [36] the installation can be considered one of the best performing systems. The findings indicate that system losses are primarily affected by environmental conditions and conversion efficiencies at the installation site.

This study suggests that dust accumulation, at the levels observed, did not significantly impact PV system efficiency. However, further research is needed to examine higher dust concentration scenarios and their potential long-term effects on energy generation. Expanding this analysis to include multi-year datasets will enhance reliability assessments and predictive modeling, providing a more comprehensive understanding of solar PV performance trends in the region. Future efforts will focus on collaborating with energy agencies and institutions to ensure a more robust evaluation of inter-annual variability and the long-term sustainability of PV installations in West Africa.

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Conflicts of Interest

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

References

[1] Adaramola, M.S. and Vågnes, E.E.T. (2015) Preliminary Assessment of a Small-Scale Rooftop PV-Grid Tied in Norwegian Climatic Conditions. *Energy Conversion and Management*, **90**, 458-465. https://doi.org/10.1016/j.enconman.2014.11.028

[2] Sacko, B.d.D., Sanogo, S. and Ba, A. (2023) Data Related to Performance Evaluation

of an Installed On-Grid Photovoltaic System at Bamako. *Data in Brief*, **50**, Article 109514. https://doi.org/10.1016/j.dib.2023.109514

[3] Sundaram, S. and Babu, J.S.C. (2015) Performance Evaluation and Validation of 5mwp Grid Connected Solar Photovoltaic Plant in South India. *Energy Conversion and Management*, **100**, 429-439. https://doi.org/10.1016/j.enconman.2015.04.069

[4] Saber, E.M., Lee, S.E., Manthapuri, S., Yi, W. and Deb, C. (2014) PV (Photovoltaics) Performance Evaluation and Simulation-Based Energy Yield Prediction for Tropical Buildings. *Energy*, **71**, 588-595. https://doi.org/10.1016/j.energy.2014.04.115

[5] Jahn, U. (1997) Performance of 170 Grid Connected PV Plants in Northern Germany—Analysis of Yields and Optimization Potentials. *Solar Energy*, 59, 127-133.

[6] Leloux, J., Narvarte, L. and Trebosc, D. (2011) Performance Analysis of 10,000 Residential PV Systems in France and Belgium. 26*th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 5-9 September 2011, 3939-3946. https://userarea.eupvsec.org/proceedings/26th-EU-PVSEC/5AO.6.4/

[7] Micheli, D., Alessandrini, S., Radu, R. and Casula, I. (2014) Analysis of the Outdoor Performance and Efficiency of Two Grid Connected Photovoltaic Systems in Northern Italy. *Energy Conversion and Management*, **80**, 436-445. https://doi.org/10.1016/j.enconman.2014.01.053

[8] Dabou, R., Bouchafaa, F., Arab, A.H., Bouraiou, A., Draou, M.D., Neçaibia, A., *et al.* (2016) Monitoring and Performance Analysis of Grid Connected Photovoltaic under Different Climatic Conditions in South Algeria. *Energy Conversion and Management*, **130**, 200-206. https://doi.org/10.1016/j.enconman.2016.10.058

[9] Sayyah, A., Horenstein, M.N. and Mazumder, M.K. (2014) Energy Yield Loss Caused by Dust Deposition on Photovoltaic Panels. *Solar Energy*, **107**, 576-604. https://doi.org/10.1016/j.solener.2014.05.030

[10] Ndiaye, A., Charki, A., Kobi, A., Kébé, C.M.F., Ndiaye, P.A. and Sambou, V. (2013) Degradations of Silicon Photovoltaic Modules: A Literature Review. *Solar Energy*, **96**, 140-151. https://doi.org/10.1016/j.solener.2013.07.005

[11] Ekoe A Akata, A.M., Njomo, D., Agrawal, B., Mackpayen, A. and Ali, A.M. (2022) Tilt Angle and Orientation Assessment of Photovoltaic Thermal (PVT) System for Sub-Saharan Tropical Regions: Case Study Douala, Cameroon. *Sustainability*, **14**, Article 15591.

[12] Etukudor, C., Orovwode, H., Wara, S., Agbetuyi, F., Adozhe, A., Obieje, B.O., *et al.* (2018). Optimum Tilt and Azimuth Angles for Solar Photovoltaic Systems in South-West Nigeria. 2018 *IEEE PES/IAS PowerAfrica*, Cape Town, 28-29 June 2018, 348-353. https://doi.org/10.1109/powerafrica.2018.8521047

[13] Sidiki, D., Li, W. and Issa, M.A. (2018) Experimental Evaluation of the Effect of Inclination and Dust Deposition on Production Capacity of Photovoltaic Installations in West African Nations: Case Study in Mali. *Iranian Journal of Energy and Environment* (*IJEE*), **9**, 91-99.

[14] Sharma, R. and Goel, S. (2017) Performance Analysis of a 11.2kW$_p$ Roof Top Grid-Connected PV System in Eastern India. *Energy Reports*, **3**, 76-84. https://doi.org/10.1016/j.egyr.2017.05.001

[15] Saxena, A.K., Saxena, S. and Sudhakar, K. (2021) Energy, Economic and Environmental Performance Assessment of a Grid-Tied Rooftop System in Different Cities of India Based on 3E Analysis. *Clean Energy*, **5**, 288-301. https://doi.org/10.1093/ce/zkab008

[16] Kafui, A.D., Seres, I. and Farkas, I. (2019) Efficiency Comparison of Different Photo-

voltaic Modules. *Acta Technologica Agriculturae*, **22**, 5-11. https://doi.org/10.2478/ata-2019-0002

[17] Ozden, T., Akinoglu, B.G. and Turan, R. (2017) Long Term Outdoor Performances of Three Different On-Grid PV Arrays in Central Anatolia—An Extended Analysis. *Renewable Energy*, **101**, 182-195. https://doi.org/10.1016/j.renene.2016.08.045

[18] Dobaria, B., Pandya, M. and Aware, M. (2016) Analytical Assessment of 5.05 kW_p Grid Tied Photovoltaic Plant Performance on the System Level in a Composite Climate of Western India. *Energy*, **111**, 47-51. https://doi.org/10.1016/j.energy.2016.05.082

[19] Elhadj Sidi, C.E.B., Ndiaye, M.L., El Bah, M., Mbodji, A., Ndiaye, A. and Ndiaye, P.A. (2016) Performance Analysis of the First Large-Scale (15MW_p) Grid-Connected Photovoltaic Plant in Mauritania. *Energy Conversion and Management*, **119**, 411-421. https://doi.org/10.1016/j.enconman.2016.04.070

[20] Mpholo, M., Nchaba, T. and Monese, M. (2015) Yield and Performance Analysis of the First Grid-Connected Solar Farm at Moshoeshoe I International Airport, Lesotho. *Renewable Energy*, **81**, 845-852. https://doi.org/10.1016/j.renene.2015.04.001

[21] Kumar, K.A., Sundareswaran, K. and Venkateswaran, P.R. (2014) Performance Study on a Grid Connected 20 Kw P Solar Photovoltaic Installation in an Industry in Tiruchirappalli (India). *Energy for Sustainable Development*, **23**, 294-304. https://doi.org/10.1016/j.esd.2014.10.002

[22] Sharma, V. and Chandel, S.S. (2013) Performance Analysis of a 190kW_p Grid Interactive Solar Photovoltaic Power Plant in India. *Energy*, **55**, 476-485. https://doi.org/10.1016/j.energy.2013.03.075

[23] de Lima, L.C., de Araújo Ferreira, L. and de Lima Morais, F.H.B. (2017) Performance Analysis of a Grid Connected Photovoltaic System in Northeastern Brazil. *Energy for Sustainable Development*, **37**, 79-85. https://doi.org/10.1016/j.esd.2017.01.004

[24] Wittkopf, S., Valliappan, S., Liu, L., Ang, K.S. and Cheng, S.C.J. (2012) Analytical Performance Monitoring of a 142.5kW_p Grid-Connected Rooftop BIPV System in Singapore. *Renewable Energy*, **47**, 9-20. https://doi.org/10.1016/j.renene.2012.03.034

[25] Padmavathi, K. and Daniel, S.A. (2013) Performance Analysis of a 3MW_p Grid Connected Solar Photovoltaic Power Plant in India. *Energy for Sustainable Development*, **17**, 615-625. https://doi.org/10.1016/j.esd.2013.09.002

[26] Ayompe, L.M., Duffy, A., McCormack, S.J. and Conlon, M. (2011) Measured Performance of a 1.72kW Rooftop Grid Connected Photovoltaic System in Ireland. *Energy Conversion and Management*, **52**, 816-825. https://doi.org/10.1016/j.enconman.2010.08.007

[27] Shravanth Vasisht, M., Srinivasan, J. and Ramasesha, S.K. (2016) Performance of Solar Photovoltaic Installations: Effect of Seasonal Variations. *Solar Energy*, **131**, 39-46. https://doi.org/10.1016/j.solener.2016.02.013

[28] Kaboré, A., Ouoba, S., Haro, K., Ouedraogo, T.L., Bagré, B., Korsaga, B.A., *et al.* (2024) Assessing the Efficiency of the Zagtouli Solar Plant: A Large-Scale Grid-Connected PV System in Burkina Faso. *IRA-International Journal of Applied Sciences*, **18**, Article 67.

[29] Atsu, D., Seres, I. and Farkas, I. (2021) The State of Solar PV and Performance Analysis of Different PV Technologies Grid-Connected Installations in Hungary. *Renewable and Sustainable Energy Reviews*, **141**, Article 110808. https://doi.org/10.1016/j.rser.2021.110808

[30] Tahri, F., Tahri, A. and Oozeki, T. (2018) Performance Evaluation of Grid-Connected

Photovoltaic Systems Based on Two Photovoltaic Module Technologies under Tropical Climate Conditions. *Energy Conversion and Management*, **165**, 244-252. https://doi.org/10.1016/j.enconman.2018.03.065

[31] Kalogirou, S. (2014) Solar Energy Engineering: Processes and Systems. 2nd Edition, Academic Press Elsevier.

[32] Koller, M., Borsche, T., Ulbig, A. and Andersson, G. (2013). Defining a Degradation Cost Function for Optimal Control of a Battery Energy Storage System. 2013 *IEEE Grenoble Conference*, Grenoble, 16-20 June 2013, 1-6. https://doi.org/10.1109/ptc.2013.6652329

[33] Abdoulaye, B.M., Abdourahimoun, D., Harouna, S.d.N., Saidou, M. and Makinta, B. (2023) Performance Ratio and Loss Analysis for a Grid-Connected Solar Photovoltaic System: Case of the 7MW Plant in Malbaza, Niger. *Journal of Energy Research and Reviews*, **13**, 38-45. https://doi.org/10.9734/jenrr/2023/v13i1256

[34] Khatib, T., Sopian, K. and Kazem, H.A. (2013) Actual Performance and Characteristic of a Grid Connected Photovoltaic Power System in the Tropics: A Short Term Evaluation. *Energy Conversion and Management*, **71**, 115-119. https://doi.org/10.1016/j.enconman.2013.03.030

[35] Farhoodnea, M., Mohamed, A., Khatib, T. and Elmenreich, W. (2015) Performance Evaluation and Characterization of a 3-kWp Grid-Connected Photovoltaic System Based on Tropical Field Experimental Results: New Results and Comparative Study. *Renewable and Sustainable Energy Reviews*, **42**, 1047-1054. https://doi.org/10.1016/j.rser.2014.10.090

[36] Guingane, T.T., Korsaga, E., Tassembedo, S. and Ouedraogo, R. (2024) Determination of the Performance Scores of a Photovoltaic Power Plant Connected to the Grid: The Zagtouli Photovoltaic Power Plant in Burkina-Faso. *Advances in Materials Physics and Chemistry*, **14**, 264-272. https://doi.org/10.4236/ampc.2024.1411019

Nomenclature

Y_f final yield
Y_R reference yield
Y_F energy yield
η_{PV} PV array
η_{inv} Inverter efficiency
η_{sys} system efficiency
Y_A PV array yield
L_C Array capture Loss
L_S system Loss
$E_{AC,t}$ AC energy output at a specific time
$E_{AC,h}$ AC energy output over an hour
$E_{AC,d}$ total AC energy output for a day
$E_{AC,m}$ total AC energy output for a month
Abbreviations
PV photovoltaic
PR performance ratio
NGOs non-governmental organisation
STC Standard Test Conditions
IEA International Energy Agency
DC direct current
AC alternating current
direct current DC
CF capacity factor
DUSMASS Dust Surface Mass Concentration
mc-Si multi-crystalline (1 - 2)
CIS copper indium selenium (1 - 2)
ASE (pc-Si) annual sub-system efficiency polycrystalline silicon (pc-Si)
DS (1 - 2) amorphous silicon (a-Si) thin-film