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TEMPERATURE SENSITIVITY OF SOLAR PHOTOVOLTAIC SYSTEMS IN MAKURDI, NIGERIA

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Cite this article as: *Uzer, J.M., Zhimwang, J.T., Nyam, G.G., Abuku, S.K., Uzer, F., Ayua, K.J. and Nakala, J. (2026). Temperature sensitivity of solar photovoltaic systems in Makurdi, Nigeria. Journal of Interdisciplinary Postgraduate Research, 2(1), 65–82.*

Abstract

Solar energy constitutes a pivotal renewable energy source, particularly in regions that receive high levels of direct sunlight such as Makurdi, Nigeria. The efficiency of solar photovoltaic (PV) systems is, however, constrained by a number of environmental parameters, among which ambient temperature ranks as one of the most influential. The inherent properties of semiconductor materials cause PV module efficiency to decline as operating temperature rises above the standard test condition (STC) of 25 °C. This phenomenon is of particular concern in tropical locations where elevated temperatures prevail throughout much of the year. The present study investigates the temperature sensitivity of a polycrystalline silicon PV system installed at the Solar Hybrid Power Plant of Joseph Sarwuan Tarka University, Makurdi. Monthly mean temperature, output power, and percentage deviation from STC were recorded and analysed over a period spanning July 2021 to June 2023. A temperature coefficient of maximum power (P_{max}) of −0.41%/°C was used for the assessment. The results reveal a consistent inverse relationship between temperature and PV power output across all three observation years. Months in which mean temperatures exceeded 28 °C generally exhibited negative power outputs, whereas months with temperatures closer to or below the STC value recorded substantially higher power yields. March 2022 recorded the highest temperature of 30.92 °C with the most severe output deficit of −471.76 kWh, while December 2021 recorded the lowest temperature of 24.29 °C and the highest output of 425.36 kWh. A linear regression analysis of aggregated data yielded a strong negative correlation between mean temperature and output power. These findings underscore the need for temperature mitigation strategies, including passive cooling, hybrid PV thermal (PVT) integration, and appropriate module orientation, to optimise photovoltaic energy harvesting in Makurdi and comparable tropical environments.

Keywords: *Solar photovoltaic; Temperature sensitivity; Power output; Standard test condition; Makurdi; Tropical climate; Polycrystalline silicon*

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1. Introduction

The global energy landscape is undergoing a transformative shift away from fossil fuel dependence towards renewable and sustainable sources of power generation. Fossil fuels continue to account for over 80% of the world's primary energy supply, and the environmental consequences of their continued combustion, including greenhouse gas emissions, air pollution, and accelerating climate change, are well documented (Alao *et al.*, 2022; Sokan■Adeaga and Ana, 2015). The urgency to diversify the energy mix has prompted extensive research into solar, wind, biomass, geothermal, and hydropower technologies (Dajuma *et al.*, 2016). Among these alternatives, solar photovoltaic (PV) energy stands out as one of the most promising because of its virtually limitless potential, declining capital costs, and adaptability to a wide range of geographical contexts (Mustafa *et al.*, 2020).

Nigeria occupies a strategic position within the global solar energy map. Situated between latitudes 4°N and 14°N, the country receives abundant solar irradiation throughout the year, with average daily values ranging from approximately 4.0 kWh/m^2 in the coastal south to 7.0 kWh/m^2 in the arid north (Orisaleye *et al.*, 2018; Ohiero and Ogbeche, 2018). Despite this resource endowment, the penetration of solar PV technology in Nigeria remains relatively modest, hampered by infrastructure deficits, policy inconsistencies, and incomplete technical understanding of system behaviour under local environmental conditions (Abdallah *et al.*, 2015). The significance of a reliable energy supply for economic development, food security, and improved quality of life cannot be overstated, and the transition to renewables offers a viable pathway towards these objectives (Lior, 2012).

Global PV installations have expanded at an extraordinary pace, surpassing 505 GW of cumulative capacity by 2018 alone, with China accounting for a leading share of 176 GW (Renewables, 2019; Mustafa *et al.*, 2020). As manufacturing costs continue to decline and module efficiencies improve, PV technology is increasingly recognised as a credible vehicle for meeting long term energy demand while reducing the environmental footprint of power generation (Said Amar *et al.*, 2021). Nevertheless, the field performance of PV systems is shaped by a complex interplay of environmental variables, among which solar irradiance and ambient temperature are the most influential (Arjyadhare *et al.*, 2013; Bhattacharya *et al.*, 2014).

The effect of temperature on PV module performance is grounded in the physics of semiconductor junctions. As the operating temperature of a silicon solar cell rises above its standard test condition (STC) of 25 °C, the open circuit voltage decreases at a rate that outpaces the modest increase in short circuit current, resulting in a net reduction in maximum power output (Dubey *et al.*, 2013). This relationship is captured quantitatively by the temperature coefficient of maximum power (P_{max}), which for typical polycrystalline silicon modules lies in the range of –0.35% to –0.50% per degree Celsius (Skoplaki and Palyvos, 2009). For every degree above 25 °C, therefore, the module output declines by roughly 0.4% of its rated capacity. In tropical regions where mean ambient temperatures routinely exceed 28–32 °C, the cumulative annual energy loss can be substantial (Bouzid and Machich, 2010; Hamrouni *et al.*, 2008).

Makurdi, the administrative headquarters of Benue State, lies in the middle belt of Nigeria at approximately 7.73°N and 8.52°E. The city possesses a tropical wet and dry climate characterised by Guinea savanna vegetation, a pronounced hot dry season, and mean monthly temperatures that range from 26 °C to 31.2 °C (Iloeje, 2001). These conditions make Makurdi an instructive case study for evaluating the thermal sensitivity of PV systems under real world tropical conditions. Despite the increasing deployment of solar energy installations across the Benue Valley, systematic assessments of the temperature related power losses of these systems remain scarce. The present study addresses this gap by examining the monthly output power of a polycrystalline silicon PV array at the Solar Hybrid Power Plant of Joseph Sarwuan Tarka University Makurdi in relation to measured ambient temperatures from July 2021 to June 2023, and by quantifying the deviations from STC performance across the observation period.

2. Materials and Methods

2.1 Study Area

The study was conducted at the Solar Hybrid Power Plant located within the premises of Joseph Sarwuan Tarka University, Makurdi, Benue State, Nigeria. Makurdi is situated between latitudes 7.3°N and longitudes 8.3°E, with a land area of approximately 16 km^2. The city experiences a tropical wet and dry climate and is characterised by Guinea savanna vegetation. Mean annual temperatures hover around 28 °C, with monthly averages ranging from 26 °C during the cool season to 31.2 °C during the peak of the hot season. Relative humidity varies seasonally, peaking at approximately 92% during the rainy months and dropping considerably during the dry season. The dry season extends from November to March, during which time temperatures tend to be highest and cloud cover lowest, creating conditions of intense solar irradiance that simultaneously promote and constrain PV power output (Iloeje, 2001; Udo, 2000).

2.2 System Description

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The photovoltaic installation under study comprises 12,140 polycrystalline silicon modules, each rated at 330 W (±2.5%) under standard test conditions (irradiance of 1000 W/m^2, air mass 1.5, and cell temperature of 25 °C). Each module consists of 72 cells with an area of 1 m × 2 m and a rated module efficiency of 17.0%. The maximum power voltage (V_{mp}) and maximum power current (I_{mp}) are 37.4 V and 8.83 A, respectively, while the open circuit voltage (V_{OC}) is 45.8 V and the short circuit current (I_{sc}) is 9.28 A. The temperature coefficient of P_{max} is –0.41%/°C, and the temperature coefficient of V_{OC} is –0.32%/°C. The operational temperature range of the modules extends from –40 °C to +85 °C.

Table 1. Summary of PV module design and sizing parameters.

Parameter	Value
Module type	Polycrystalline Si
Module efficiency (η)	17.0%
Area	1 m × 2 m
Maximum power (Pmax)	330 W ± 2.5%
Max. power voltage (Vmp)	37.4 V
Max. power current (Imp)	8.83 A
Open circuit voltage (VOC)	45.8 V
Short circuit current (Isc)	9.28 A ± 4%
Total modules at site	12,140
Temp. coeff. of Pmax	–0.41%/°C
Temp. coeff. of VOC	–0.32%/°C
Operational temp.	–40 to +85 °C

2.3 Instrumentation and Data Collection

Environmental and electrical data were collected from daily measurements at the Solar Hybrid Power Plant. A pyranometer was used to measure incident solar radiation, while a calibrated thermometer recorded ambient air temperature. Atmospheric pressure, wind speed, and humidity were monitored using a barometer, anemometer, and hygrometer, respectively. The PV output power was recorded through the charge controller and monitoring system of the installation. Data were aggregated on a monthly basis to obtain mean temperature and cumulative output power for each month of the study period, which spanned July 2021 to June 2023.

2.4 Analytical Model

The influence of temperature on PV output power was assessed using the standard linear derating model. This model expresses the power at any operating temperature as a function of the rated power at the standard test condition, the temperature coefficient of P_{max}, and the deviation of the operating temperature from the STC reference (Dubey *et al.*, 2013; Skoplaki and Palyvos, 2009):

$$P_t = P_{st} \times [1 + \alpha(T_c - T_s)] \quad (1)$$

where P_t is the power output at operating temperature T_c (°C), P_{st} is the rated power at the standard test temperature T_s (25 °C), and α is the temperature coefficient of maximum power (–0.41%/°C for the modules in this study). The percentage deviation of the monthly mean temperature from STC was calculated as:

$$\text{Percentage deviation (\%)} = [(T_{mean} - 25) / 25] \times 100 \quad (2)$$

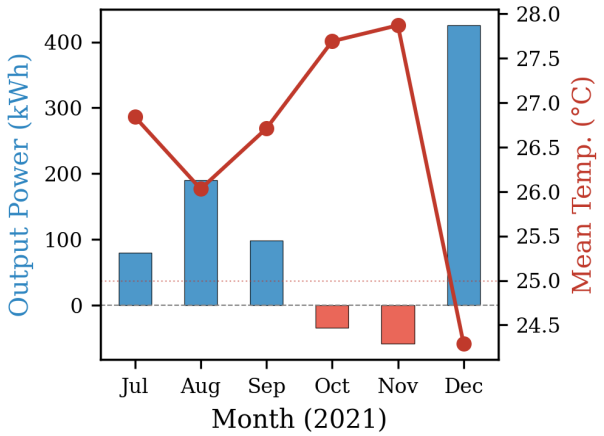
3. Results and Discussion

3.1 Temperature and Power Output: 2021

The monthly mean temperatures and corresponding PV power outputs for the period July to December 2021 are presented in Table 2. During this six month window, mean temperatures ranged from 24.29 °C in December to 27.87 °C in November. The percentage deviation from STC varied accordingly, from –2.84% in December to +11.48% in November. The data reveal a clear pattern: months in which the mean temperature substantially exceeded the STC reference produced reduced or negative power outputs, while the coolest month (December) yielded the highest output of 425.36 kWh.

Table 2. Monthly mean temperature, output power, and STC deviation for Makurdi, 2021.

Month	Mean Temp. (°C)	Output (kWh)	STC Dev. (%)
July	26.84	80.18	+7.36
August	26.03	189.85	+4.12
September	26.71	98.02	+6.84
October	27.69	–34.43	+10.76
November	27.87	–58.13	+11.48
December	24.29	425.36	–2.84



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Figure 1: *Monthly mean temperature and PV output power for Makurdi, July to December 2021. The dashed line indicates the STC reference temperature of 25 °C.*

Figure 1 illustrates the inverse relationship between temperature and output power in 2021. The temperature dropped by approximately 3.0% from July to August, yet output power increased markedly to 189.85 kWh, demonstrating the beneficial effect of even a small temperature reduction. By contrast, October and November experienced temperature increases of 3.17% and 3.84% above the July baseline, respectively, and the system returned negative power outputs during both months. The most striking observation relates to December, when the mean temperature fell below the STC threshold to 24.29 °C (–2.84% deviation), and the PV system delivered its highest recorded output of 425.36 kWh. This single observation encapsulates the central finding of this study: PV performance in Makurdi is profoundly sensitive to temperature, and even modest reductions below the STC value translate into substantial power gains (Dubey *et al.*, 2013; Bhattacharya *et al.*, 2014).

3.2 Temperature and Power Output: 2022

The year 2022 provides the most complete data set, spanning all twelve months (Table 3). Mean temperatures ranged from 25.9 °C in January to 30.92 °C in March, which represents the hottest month recorded across the entire study period. The corresponding STC deviations ranged from +3.6% in January to +23.68% in March. The output power exhibited a pronounced seasonal cycle: positive values during the relatively cooler months (January, June through September, and December) and negative values during the hottest months (March through May and November).

Table 3. Monthly mean temperature, output power, and STC deviation for Makurdi, 2022.

Month	Temp. (°C)	Output (kWh)	STC Dev. (%)
January	25.90	207.01	+3.60
February	27.33	14.50	+9.32
March	30.92	–471.76	+23.68
April	29.21	–240.92	+16.84
May	28.02	–78.61	+12.08
June	27.24	26.65	+8.96
July	26.60	113.34	+6.40
August	26.03	190.37	+4.12
September	26.30	153.43	+5.20
October	27.02	55.73	+8.08
November	28.06	–84.64	+12.24
December	27.15	38.45	+8.60

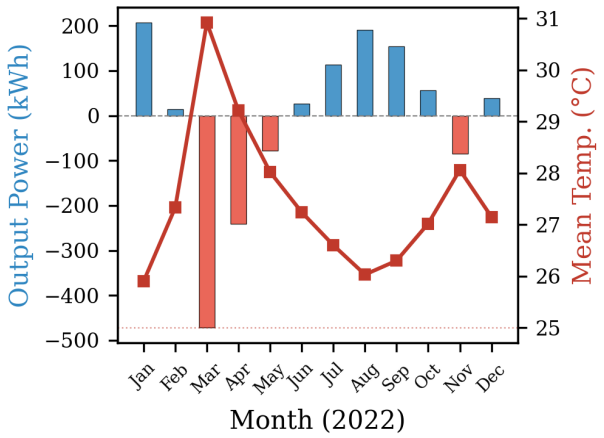


Figure 2: *Monthly mean temperature and PV output power for Makurdi, January to December 2022. Blue bars indicate positive output; red bars indicate deficit.*

The transition from January (25.9 °C, 207.01 kWh) to February (27.33 °C, 14.5 kWh) is instructive: a temperature increase of merely 1.43 °C was accompanied by a precipitous decline in output power of over 90%. This steep response highlights the sensitivity of the system at operating points near the threshold where positive output transitions to deficit. The most dramatic loss occurred in March, when the temperature reached 30.92 °C (23.68% above STC) and the system deficit reached –471.76 kWh. Similar patterns of severe output depression at high temperatures have been reported in studies conducted in Algeria, Tunisia, and West Africa (Bouzid and Machich, 2010; Hamrouni *et al.*, 2008; Dajuma *et al.*, 2016).

From April through July, a gradual cooling trend drove a steady recovery in power output. The STC deviation declined from 16.84% in April to 6.40% in July, and the output recovered from –240.92 kWh to +113.34 kWh over the same interval. August recorded the highest positive output for 2022 at 190.37 kWh, coinciding with the lowest temperature of 26.03 °C. The onset of the late dry season in November brought renewed warming (28.06 °C) and a return to negative output (–84.64 kWh), before a marginal improvement in December (27.15 °C, 38.45 kWh). These seasonal oscillations underscore the dominant role of temperature in modulating PV performance in Makurdi (Skoplaki and Palyvos, 2009).

3.3 Temperature and Power Output: 2023

The first half of 2023 (Table 4) provides further evidence of temperature driven output suppression. The period from February through May was characterised by exceptionally high temperatures, with mean values consistently exceeding 29.5 °C. February recorded the highest temperature across the entire study (30.95 °C, STC deviation of +23.8%) and the largest single month deficit (–475.71 kWh). Power output remained

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severely negative from February to May, recovering to a positive value of 55.16 kWh only in June, when the mean temperature dropped to 27.03 °C.

Table 4. Monthly mean temperature, output power, and STC deviation for Makurdi, January to June 2023.

Month	Temp. (°C)	Output (kWh)	STC Dev. (%)
January	26.77	90.21	+7.08
February	30.95	–475.71	+23.80
March	30.63	–432.00	+22.52
April	30.52	–417.44	+21.84
May	29.55	–286.88	+18.20
June	27.03	55.16	+8.12

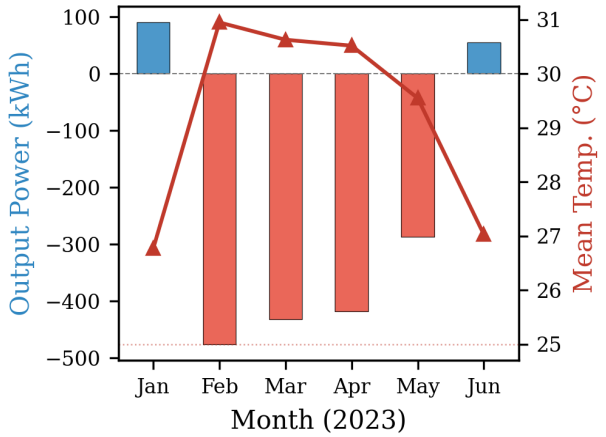


Figure 3: *Monthly mean temperature and PV output power for Makurdi, January to June 2023.*

The January to February transition in 2023 was the most abrupt of any consecutive month pair in the data set. The temperature surged by 15.63% relative to January, and output power collapsed from +90.21 kWh to –475.71 kWh. This result confirms that the period spanning late February to May constitutes the most thermally adverse window for PV operation in Makurdi, a finding that aligns with the known climatology of the region (Iloeje, 2001). The gradual recovery from March (–432.00 kWh) through May (–286.88 kWh) to June (+55.16 kWh) mirrors the onset of the rainy season, which introduces cloud cover and cooler temperatures that progressively relieve the thermal stress on the PV modules (Udo, 2000).

3.4 Comparative Analysis Across Years

Figure 4 presents the percentage deviation from STC for overlapping months across 2021, 2022, and 2023. The comparison reveals a consistent pattern: the late dry season months (February through April) exhibit the highest thermal deviations, while the rainy season months (July through September) offer the most favourable thermal conditions for PV operation. The 2023 dry season was notably hotter than the corresponding period in 2022, with STC deviations reaching 23.8% in February 2023 compared to 9.32% in February 2022 (Mustafa *et al.*, 2020).

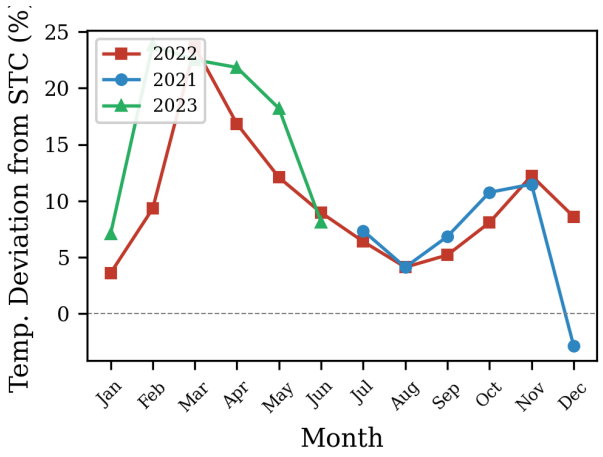


Figure 4: *Comparison of monthly percentage deviation from STC across 2021, 2022, and 2023.*

3.5 Correlation Analysis

To quantify the overall relationship between ambient temperature and PV output, the aggregated data from all three years were subjected to a scatter plot analysis with linear regression fitting. Figure 5 presents the resulting scatter plot. The linear fit yields a strong negative slope of approximately –100 kWh/°C, confirming that output power declines steeply as operating temperature increases above the STC reference. The scatter is widest at intermediate temperatures (26–28 °C), reflecting the influence of secondary variables such as irradiance variability, cloud cover, and system losses (Bhattacharya *et al.*, 2014; Dajuma *et al.*, 2016).

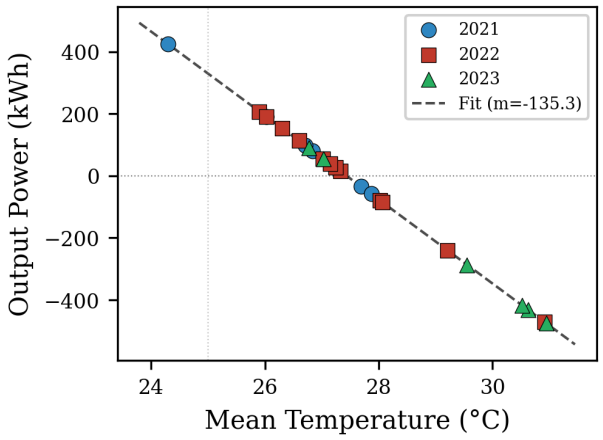


Figure 5: *Scatter plot of mean monthly temperature versus PV output power (2021–2023) with linear regression fit.*

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The regression analysis provides quantitative support for the temperature sensitivity reported in the tabulated data. At a temperature of approximately 27 °C, the fitted model predicts a near zero output, consistent with the observed transition from positive to negative power outputs. Below 25 °C, the model predicts substantial positive outputs, in agreement with the December 2021 observation. Above 30 °C, the predicted deficits are severe, consistent with the March 2022 and February 2023 data points (Said Amar *et al.*, 2021; Arjyadhare *et al.*, 2013).

3.6 Power Loss Characteristics

Figure 6 presents the theoretical power loss curve for the polycrystalline modules used in this study, based on the manufacturer specified temperature coefficient of −0.41%/°C. For each degree of temperature above the STC, the rated power of 330 W is reduced by 1.353 W. At a temperature excess of 5 °C (corresponding to an operating temperature of 30 °C), the percentage power loss reaches 2.05%, equivalent to approximately 6.77 W per module. For the full installation of 12,140 modules, this translates to a collective power deficit in excess of 82 kW at any given instant (Skoplaki and Palyvos, 2009).

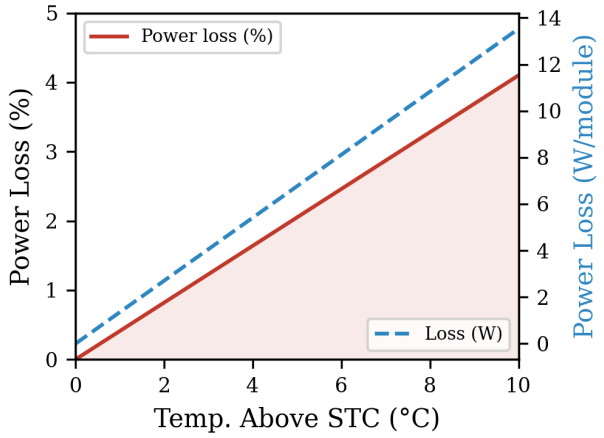


Figure 6: *Theoretical percentage and absolute power loss per module as a function of temperature above STC.*

3.7 Efficiency Variation: 2022

Figure 7 illustrates the estimated monthly module efficiency for 2022, computed by applying the temperature coefficient to the nominal STC efficiency of 17.0%. During the coolest months (January and August), module efficiency approaches or marginally exceeds 16.9%, whereas the hottest month (March) sees efficiency fall to approximately 15.96%. This range of nearly one full percentage point, when applied across a facility with over 12,000 modules operating continuously, results in cumulative energy losses that are both operationally and financially significant (Dubey *et al.*, 2013).

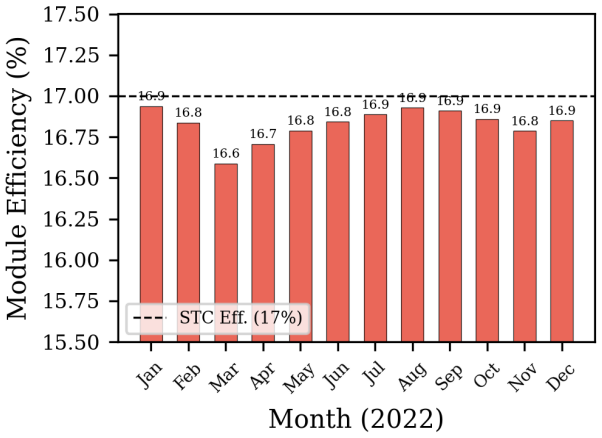


Figure 7: *Estimated monthly module efficiency for the Makurdi PV installation, 2022. Dashed line indicates STC efficiency of 17%.*

3.8 Implications and Mitigation Strategies

The findings of this study carry several practical implications for PV system design, installation, and operation in Makurdi and comparable tropical environments. First, the data confirm that the hottest months of the dry season (February through April) represent a critical window during which PV output is severely compromised. Designers and operators should factor in these seasonal losses when estimating annual energy yields and financial returns. Second, the sharp temperature sensitivity observed here motivates the exploration of mitigation strategies aimed at reducing module operating temperatures (Skoplaki and Palyvos, 2009).

Passive cooling approaches, such as improved mounting structures that permit natural convection beneath the modules, reflective rear surface coatings, and phase change material (PCM) integration, have been shown to reduce cell temperatures by 5–12 °C under tropical conditions (Hasanuzzaman *et al.*, 2016). Hybrid PV thermal (PVT) systems, which extract waste heat from the rear of the module and utilise it for water or space heating, offer a dual benefit: reduced cell temperature and increased total system efficiency (Chow, 2010). Given the hot climate of Makurdi, the conversion of the existing PV array into a PVT configuration warrants serious consideration as a route to recovering a portion of the thermal losses documented in this study.

Third, the interannual variability in dry season temperatures observed between 2022 and 2023 underscores the value of long term climate monitoring and adaptive energy management systems. Real time temperature sensing coupled with predictive algorithms could enable operators to adjust load scheduling and storage strategies in response to forecasted thermal conditions, thereby minimising the mismatch between supply and demand during the most adverse months (Mustafa *et al.*, 2020;

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Renewables, 2019).

4. Conclusion

This study has demonstrated a significant and consistent negative relationship between ambient temperature and the output power of a polycrystalline silicon photovoltaic system in Makurdi, Nigeria, over a 24 month observation period from July 2021 to June 2023. Months in which the mean temperature exceeded approximately 28 °C (corresponding to a deviation of 12% or more above the STC of 25 °C) consistently returned negative power outputs, indicating that the system operated below its expected baseline under those conditions. The lowest temperatures and highest power outputs occurred during December 2021 (24.29 °C, 425.36 kWh), while the most severe thermal penalties were recorded in March 2022 (30.92 °C, –471.76 kWh) and February 2023 (30.95 °C, –475.71 kWh).

Linear regression analysis of the aggregated data confirmed a strong negative correlation between temperature and power output. The application of the temperature coefficient of –0.41%/°C to the rated module parameters showed that a temperature excess of 5 °C reduces the individual module output by approximately 6.77 W, translating to a system wide deficit exceeding 82 kW across the 12,140 module installation. These results carry important implications for the design, financial modelling, and operational management of PV systems in the tropics. Temperature mitigation strategies, including passive cooling techniques, PVT hybrid configurations, and adaptive load management, should be incorporated into future PV deployments in Makurdi and similar low latitude regions to maximise energy harvest and system reliability. Future work should extend the observation period and incorporate detailed irradiance, humidity, and wind speed data to enable multivariate modelling of PV system performance.

Acknowledgments

The authors gratefully acknowledge the management of the Solar Hybrid Power Plant at Joseph Sarwuan Tarka University Makurdi for granting access to the installation and facilitating the collection of operational data. The support of the Department of Physics, Federal University Lokoja, and the Department of Physics, University of Abuja, is also recognised.

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