

Temperature – Induced Variations in the Electrical Performance of Three Polycrystalline Photovoltaic Modules under Afaka Climatic Conditions, Kaduna, Nigeria

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ABSTRACT

The performance of photovoltaic (PV) modules is strongly influenced by environmental conditions, particularly temperature. This study investigated the effect of temperature on the electrical performance of three commercially available 80 W polycrystalline photovoltaic modules installed under the climatic conditions of Afaka, Kaduna, Nigeria. Measurements were conducted over a 151 – day period during the dry season using hourly observations of ambient temperature, Module Temperature, relative humidity, open – circuit voltage (Voc), and short – circuit current (Isc). Daily global radiation data were obtained from the Nigerian Meteorological Agency (NiMet). Results showed that ambient temperature varied between approximately 24 °C and 40 °C, while Module Temperature frequently exceeded ambient temperature and reached values above 45 °C during periods of intense solar radiation. Relative humidity decreased substantially during the hottest periods, creating conditions that intensified thermal loading of the modules. Short – circuit current exhibited a positive response to increasing solar radiation, whereas open - circuit voltage decreased as Module Temperature increased. Correlation analysis revealed a strong positive relationship between Module Temperature and ambient temperature ($R^2 = 0.8583$) and a strong inverse relationship between ambient temperature and relative humidity ($R^2 = 0.8772$). These environmental interactions contributed significantly to variations in module electrical behaviour throughout the monitoring period.

Keywords:

Photovoltaic Modules,
Module Temperature,
Open – Circuit Voltage,
Short – Circuit Current,
Solar Radiation,
Northern Nigeria.

Among the modules investigated, Sample A produced the highest short – circuit current, while Sample C consistently exhibited the highest open – circuit voltage. The findings demonstrate that temperature is a major factor affecting photovoltaic module electrical performance under northern Nigerian climatic conditions and highlight the importance of thermal considerations in photovoltaic system design and module selection for hot environments.

INTRODUCTION

Photovoltaic (PV) technology has become one of the fastest growing renewable energy technologies worldwide because of its ability to provide clean, sustainable, and environmentally friendly electricity generation. Growing concerns regarding climate change, increasing energy demand, and the depletion of conventional fossil fuel resources have accelerated global investment in solar energy technologies. In developing countries, photovoltaic systems have emerged as a practical solution for improving energy accessibility, particularly in regions where electricity supply remains inadequate or unreliable. Nigeria is endowed with abundant solar energy resources due to its location within the tropical solar belt, where high levels of solar radiation

are received throughout the year (Ohunakin et al., 2014). This significant solar potential makes photovoltaic technology an attractive option for enhancing energy security and supporting sustainable development.

The electrical characteristics of photovoltaic modules are usually specified under Standard Test Conditions (STC), which assume an irradiance of 1000 W m^{-2} , a module temperature of 25 °C, and an air mass of 1.5. Under actual operating conditions, however, photovoltaic modules are subjected to continuous variations in environmental factors such as solar radiation, ambient temperature, relative humidity, wind speed, cloud cover, and dust accumulation. These factors influence module operating conditions and may result in substantial deviations from manufacturer rated performance. Consequently,

assessment of photovoltaic behaviour under real environmental conditions is necessary for reliable system design, performance prediction, and energy-yield estimation (Skoplaki & Palyvos, 2009; Armstrong & Hurley, 2010).

Among the environmental variables affecting photovoltaic operation, temperature has been identified as one of the most influential. Photovoltaic cells convert only a portion of incident solar radiation into electrical energy, while the remaining energy is dissipated as heat. As a result, photovoltaic modules often operate at temperatures considerably higher than the surrounding air, particularly under conditions of intense solar radiation and limited convective cooling. The operating temperature of a photovoltaic module therefore plays a critical role in determining electrical performance (Faiman, 2008).

The influence of temperature on silicon photovoltaic devices is well established in semiconductor physics. Increasing module temperature alters semiconductor band-gap energy and increases the reverse saturation current of the p – n junction. Consequently, open – circuit voltage (V_{oc}) generally decreases as temperature increases, whereas short – circuit current (I_{sc}) exhibits a comparatively weaker response. The combined effect of these temperature-induced changes can result in deterioration of module electrical performance under hot operating conditions (Green, 1982; Radziemska, 2003). Understanding these thermal effects is particularly important in regions characterised by high ambient temperatures, where photovoltaic modules frequently operate under substantial thermal stress.

Previous studies have demonstrated the importance of temperature in determining photovoltaic performance. Dubey et al. (2013) reported that elevated operating temperatures adversely affect photovoltaic electrical performance and highlighted the importance of considering environmental conditions when evaluating module behaviour. Similarly, research on photovoltaic module operation under outdoor conditions has consistently shown that temperature influences voltage output more strongly than current generation (Radziemska, 2003; Skoplaki & Palyvos, 2009). These findings emphasise the need for site-specific investigations under local climatic conditions.

In addition to temperature, relative humidity may influence photovoltaic operation through its effect on atmospheric cooling processes. Low humidity conditions are often associated with elevated temperatures and increased solar radiation, reducing the effectiveness of natural cooling and allowing modules to attain higher operating temperatures. Consequently, interactions among ambient temperature, module temperature, relative humidity, and solar radiation play an important role in determining photovoltaic operating behaviour. Investigation of these environmental relationships is

therefore necessary for understanding photovoltaic performance under actual field conditions.

Northern Nigeria provides a suitable environment for studying the influence of environmental conditions on photovoltaic operation. During the dry season, ambient temperatures frequently exceed 35 °C, while relative humidity may decrease to very low levels. The combination of intense solar radiation, prolonged sunshine duration, and Harmattan conditions create a thermally demanding environment for photovoltaic systems. Despite increasing deployment of solar energy technologies within Nigeria, relatively few long term field studies have examined how these conditions influence the electrical performance of commercially available photovoltaic modules. Such information is essential for optimising system design and improving the reliability of photovoltaic installations within the region.

Another important consideration is the variation in performance among photovoltaic modules from different manufacturers. Differences in cell quality, manufacturing standards, encapsulation materials, and module construction can produce variations in electrical characteristics and thermal response. Consequently, photovoltaic modules with similar nominal ratings may exhibit different behaviour when exposed to identical environmental conditions. Comparative evaluation of different modules under the same climatic conditions therefore provides valuable information for module selection and deployment in hot environments.

This study investigates the influence of temperature and associated environmental variables on the electrical performance of three commercially available 80 W polycrystalline photovoltaic modules installed at Afaka, Kaduna State, Nigeria. Measurements of ambient temperature, module temperature, relative humidity, open – circuit voltage, and short – circuit current were obtained over a 151 – day monitoring period, while solar radiation data were acquired from the Nigerian Meteorological Agency (NiMet), Abuja. The study aims to evaluate temporal variations in environmental conditions, assess their influence on module electrical characteristics, compare the performance of the three modules under identical operating conditions, and establish relationships among temperature, humidity, solar radiation, and photovoltaic electrical behaviour. The findings contribute to the understanding of photovoltaic performance in hot tropical environments and provide useful information for module selection, system design, and performance optimisation in northern Nigeria and similar climatic regions.

Experimental Details

The field experiment was conducted at the Department of Physics, Nigerian Defence Academy (NDA), Afaka Campus, Kaduna State, Nigeria, located at approximately 11.13° N latitude and 7.67° E longitude. The study area

lies within the Northern Guinea Savannah ecological zone and experiences a tropical continental climate characterised by distinct wet and dry seasons. The dry season, which extends from approximately November to March, is marked by high solar irradiance, elevated ambient temperatures, low relative humidity and Harmattan dust transport from the Sahara Desert. These environmental conditions provide a suitable natural setting for investigating the influence of temperature on photovoltaic module performance under prolonged thermal stress.

Data collection was carried out over a 151 – day period spanning the dry-season months. During the monitoring period, the study area experienced typical dry-season weather conditions characterised by clear skies, intense solar radiation, and substantial diurnal variations in temperature and humidity. Ambient temperatures frequently exceeded 35 °C during afternoon periods, while relative humidity declined considerably during periods of maximum heating. Such conditions are known to promote increased photovoltaic module operating temperatures and provide an opportunity to evaluate module behaviour under realistic field conditions.

The investigation focused on the relationship between environmental variables and the electrical characteristics of photovoltaic modules. Attention was given to ambient temperature (AT), module temperature (CT), relative humidity (RH), solar radiation, open – circuit voltage (Voc) and short – circuit current (Isc). Environmental and electrical measurements were obtained between 08:00 h and 17:00 h each day to capture the full range of operating conditions from morning warming through peak afternoon heating and subsequent cooling.

Solar radiation data used in the analysis were obtained from the Nigerian Meteorological Agency (NiMet), Abuja. These data provided daily global solar radiation values for the study period and were used to examine the influence of solar energy availability on module performance. The use of NiMet radiation records ensured consistency in the solar resource dataset and avoided uncertainties associated with short-term local irradiance measurements.

The climatic characteristics of Afaka make the study location representative of several regions across northern Nigeria and other tropical and semi-arid environments where photovoltaic systems are increasingly deployed. High solar irradiance combined with elevated ambient temperatures and low atmospheric moisture content creates operating conditions that are substantially different from Standard Test Conditions (STC). Consequently, modules installed in such environments frequently operate at temperatures significantly above 25 °C, resulting in changes in electrical behaviour that are not reflected in manufacturer specifications.

The primary objective of the experimental programme was therefore to quantify the influence of naturally

occurring environmental conditions on the electrical performance of polycrystalline photovoltaic modules under field conditions. By conducting the study under real operating conditions rather than laboratory-controlled environments, the resulting data provide a realistic assessment of module behaviour within the climatic conditions commonly encountered in northern Nigeria.

MATERIALS AND METHODS

Photovoltaic Modules and Experimental Setup

The study was conducted using three commercially available 80 W polycrystalline photovoltaic (PV) modules, designated as Sample A, Sample B, and Sample C. Each module represented a different manufacturer and was evaluated under identical environmental conditions to investigate temperature-induced variations in electrical performance.

The modules were installed outdoors at the experimental site described in Section 2 and mounted on the same support structure with identical tilt angles and orientation. This arrangement ensured that all modules received comparable solar exposure throughout the monitoring period. The modules were operated simultaneously under the same atmospheric conditions, thereby minimising the influence of environmental variability on the comparative assessment. Differences observed in the electrical characteristics of the modules were therefore attributed primarily to module specific properties such as material quality, manufacturing characteristics and thermal response.

Measurement of Environmental and Electrical Parameters

Measurements were conducted over a period of 151 days during the dry season. Data were collected hourly between 08:00 h and 17:00 h to capture the diurnal variations in environmental conditions and PV module performance.

The environmental variables monitored included ambient temperature (AT), relative humidity (RH), and module temperature. Ambient temperature and relative humidity were measured using a calibrated digital thermo-hygrometer with manufacturer reported accuracies of ± 0.5 °C and $\pm 3\%$ RH, respectively. Module temperature was monitored using temperature sensors attached to the rear surface of each PV module. Since direct measurement of cell junction temperature was not feasible under field conditions, the recorded backsheet temperature was used as an approximation of module operating temperature.

The electrical parameters measured were open – circuit voltage (Voc) and short – circuit current (Isc). Open – circuit voltage was measured using a calibrated digital multimeter with a stated accuracy of $\pm 0.5\%$ of reading, while short – circuit current was measured using a digital DC clamp meter with an accuracy of approximately $\pm 2\%$

of reading. Prior to deployment, all instruments were inspected and tested to ensure operational consistency throughout the monitoring programme.

Daily global solar radiation data were obtained from the Nigerian Meteorological Agency (NiMet), Abuja. These data were used to characterise solar energy availability during the study period and to examine its relationship with module temperature and electrical performance.

Data Acquisition and Statistical Analysis

Hourly measurements of AT, RH, module temperature, Voc, and Isc were recorded throughout the study period. Daily average values were calculated from the hourly observations, while weekly averages were subsequently derived to examine longer-term trends and seasonal variations.

The data were organised and analysed using Microsoft Excel. Descriptive statistical methods were employed to determine temporal variations, mean values and observed ranges of the measured parameters. Linear regression analysis was used to evaluate relationships between environmental variables and module electrical characteristics. The coefficient of determination (R^2) was employed to assess the strength of the observed relationships.

For consistency, correlation analyses were performed using averaged datasets rather than individual hourly observations. Consequently, the resulting regression relationships describe average environmental and electrical behaviour over the observation period rather than instantaneous responses.

Measurement Uncertainty and Data Quality Assessment

All field-based measurements are subject to uncertainty arising from instrument accuracy, environmental variability, sensor positioning and observational procedures. The uncertainties associated with ambient temperature ($\pm 0.5^\circ\text{C}$), relative humidity ($\pm 3\%$ RH), voltage ($\pm 0.5\%$ of reading) and current ($\pm 2\%$ of reading) were based on the specifications provided by the instrument manufacturers.

An additional source of uncertainty is associated with module temperature determination. Temperature sensors were attached to the rear surfaces of the PV modules and therefore measured backsheet temperatures rather than actual solar-cell junction temperatures. Previous studies have shown that, under outdoor operating conditions, Module Temperature may exceed backsheet temperature by approximately $1 - 5^\circ\text{C}$ depending on irradiance level, wind speed, and module construction (Faiman, 2008; Armstrong & Hurley, 2010). Accordingly, the reported module temperatures should be regarded as estimates of operating temperature rather than direct measurements of junction temperature.

Other environmental factors such as wind speed, transient cloud cover, atmospheric dust concentration and seasonal aerosol loading were not monitored directly. These factors may have influenced module heating and electrical behaviour and therefore constitute additional sources of uncertainty in the observed relationships.

Despite these limitations, the consistency of the measurement protocol, the length of the monitoring period and the large number of observations obtained provide confidence that the dataset adequately represents PV module behaviour under the climatic conditions of Afaka.

Study Limitations

A principal limitation of this study is that only one module from each manufacturer was available for testing ($n = 1$ per brand). Consequently, the observed differences among Samples A, B, and C may reflect a combination of manufacturer-specific characteristics and normal unit-to-unit variation within each product line. Since replicate modules were not available, it was not possible to quantify within-brand variability or perform statistical comparisons among identical units.

Therefore, comparisons among the three modules should be interpreted as indicative evaluations of field performance rather than definitive rankings of manufacturer quality. Future studies should include multiple modules from each manufacturer to permit a more rigorous assessment of manufacturing variability and module – to – module consistency.

Conversion of Global Radiation to Equivalent Irradiance

Daily global solar radiation values provided by the Nigerian Meteorological Agency (NiMet) were reported in $\text{MJ m}^{-2} \text{day}^{-1}$. To facilitate comparison with conventional photovoltaic performance metrics and standard PV literature, the radiation values were converted to equivalent average irradiance values expressed in W m^{-2} .

The conversion was performed using:

$$G = \frac{H \times 10^6}{86400}$$

Where:

- i. G = average irradiance (W m^{-2})
- ii. H = daily global solar radiation ($\text{MJ m}^{-2} \text{day}^{-1}$)
- iii. 86,400 = number of seconds in one day

This conversion provided a standardised basis for interpreting the relationship between solar energy availability, module temperature and electrical performance, while facilitating comparison with values reported under Standard Test Conditions and in previous photovoltaic studies.

RESULTS AND DISCUSSION

Environmental Conditions during the Monitoring Period

The electrical performance of photovoltaic modules is influenced by environmental factors such as ambient temperature, module temperature, relative humidity and solar radiation. During the 151 – day monitoring period, substantial variations were observed in these parameters, reflecting the characteristic dry season conditions of northern Nigeria. The environmental conditions recorded during the study established the operating environment under which the three polycrystalline photovoltaic modules were evaluated and provide important context for interpreting their electrical behaviour.

Ambient Temperature

The variation of daily average ambient temperature during the monitoring period is presented in Figure 4.1.

Ambient temperature ranged from approximately 24.0 °C to 40.0 °C, with a mean value of 32.15 °C. Higher temperatures were generally recorded during the early and late stages of the monitoring period, whereas comparatively lower values occurred during intervals influenced by Harmattan conditions and increased atmospheric moisture.

The consistently high ambient temperatures observed throughout the study indicate that the photovoltaic modules operated under thermal conditions substantially different from Standard Test Conditions (25 °C). Elevated ambient temperatures reduce the effectiveness of natural cooling and contribute to increased module operating temperatures, thereby influencing photovoltaic electrical performance.

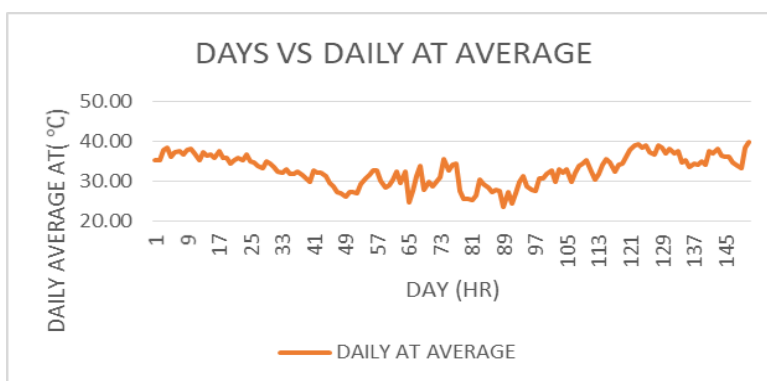


Figure 1: Variation of Daily Average Ambient Temperature with Time

Relative Humidity

Figure 4.2 presents the variation of daily average relative humidity during the study period. Relative humidity ranged from 10.0% to 44.0%, with a mean value of 13.68%. Extended periods of low humidity were observed during the peak dry season, while relatively higher values occurred during short transitional weather periods.

An inverse relationship between ambient temperature and relative humidity was evident throughout the monitoring period. Periods characterised by high temperatures generally coincided with lower humidity values. The predominance of low humidity conditions is typical of the dry season climate of northern Nigeria and contributes to enhanced solar transmission and increased module heating.

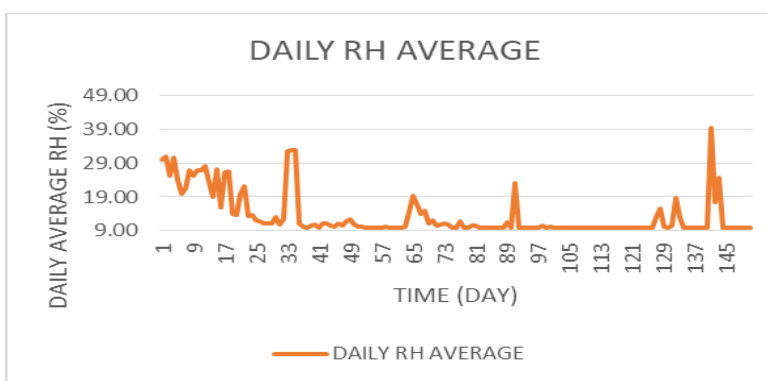


Figure 2: Variation of Daily Average Relative Humidity with Time

Module Temperature

The variation of daily average module temperature is shown in Figure 4.3. Module temperatures ranged from approximately 27.0 °C to 47.0 °C, with a mean value of 38.40 °C. Throughout the monitoring period, module temperature consistently exceeded ambient temperature, reflecting the absorption of solar radiation by the photovoltaic modules.

Higher module temperatures were generally observed during periods characterised by strong solar radiation and low relative humidity. These conditions increased thermal loading and reduced cooling effectiveness. Because module temperature directly affects semiconductor behaviour, the observed temperature variations are expected to influence module electrical characteristics, particularly open - circuit voltage.

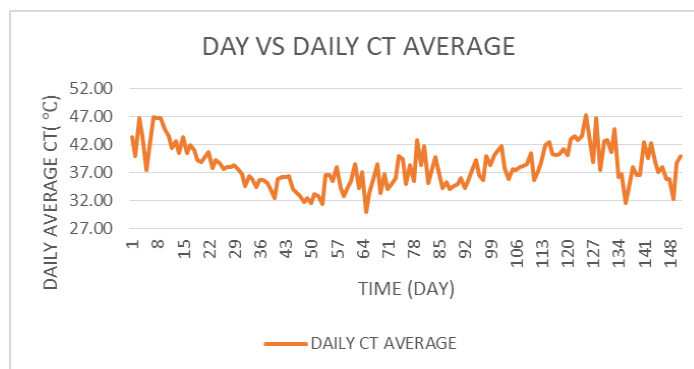


Figure 3: Variation of Daily Average Module Temperature with Time

Global Solar Radiation

Daily global solar radiation obtained from the Nigerian Meteorological Agency (NiMet) is presented in Figure 4.4. Radiation values ranged from 18.1 to 28.4 MJ m⁻² day⁻¹, with an average value of 24.17 MJ m⁻² day⁻¹. These values indicate a consistently strong solar resource throughout the monitoring period.

Higher radiation levels were generally associated with clear sky conditions during the peak dry season, while occasional reductions were linked to dust events, cloud cover, and short-term increases in atmospheric moisture. The consistently high radiation levels contributed directly to module heating and provided the energy input required for photovoltaic electricity generation.

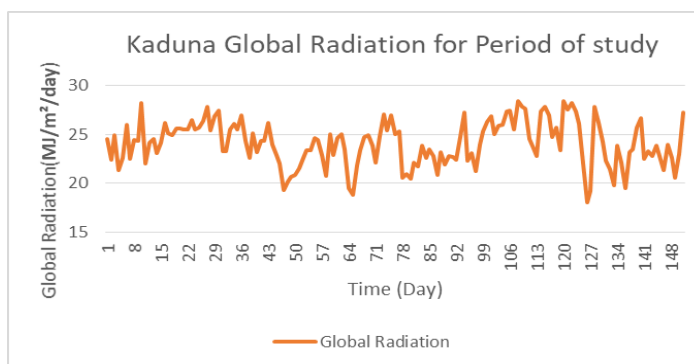


Figure 4: Daily Global Radiation Distribution

Table 1: Environmental Statistics during the Monitoring Period

Parameter	Mean	Minimum	Maximum
Ambient Temperature (°C)	32.15	24.0	40.0
Relative Humidity (%)	13.68	10.0	44.0
Module Temperature (°C)	38.40	27.0	47.0
Global Radiation (MJ m ⁻² day ⁻¹)	24.17	18.1	28.4

Source: Computed from weekly mean environmental data and NiMet global radiation records.

Table 4.1 summarises the environmental conditions experienced by the photovoltaic modules during the monitoring period. Mean ambient temperature, relative

humidity, module temperature and global radiation were 32.15 °C, 13.68%, 38.40 °C, and 24.17 MJ m⁻² day⁻¹, respectively. The results indicate that the modules

operated under persistently high temperatures, low relative humidity and strong solar radiation, conditions characteristic of the dry season in northern Nigeria.

The difference between mean ambient temperature and mean module temperature demonstrates the additional thermal loading experienced by the modules due to solar energy absorption. Furthermore, the combination of low relative humidity and high solar radiation created conditions conducive to elevated module temperatures throughout much of the study period. These environmental conditions provide the basis for the analysis of photovoltaic electrical performance presented in the subsequent sections.

Electrical Performance of the Photovoltaic Modules

The electrical performance of the three polycrystalline photovoltaic modules was evaluated using short – circuit current (I_{sc}) and open – circuit voltage (V_{oc}). These parameters are widely used to characterise photovoltaic module behaviour under field conditions because they respond differently to environmental variables. Short – circuit current is primarily influenced by incident solar radiation, whereas open – circuit voltage exhibits greater sensitivity to temperature variations (King et al., 1997; Dubey et al., 2013). Consequently, evaluation of these parameters provides insight into the response of photovoltaic modules to the environmental conditions described in Section 4.1.

Short – Circuit Current Behaviour

The variation of daily average short – circuit current for Samples A, B, and C is presented in Figures 4.5 - 4.7. All

three modules exhibited substantial temporal variability throughout the monitoring period, reflecting changes in solar radiation availability and atmospheric conditions.

Among the tested modules, Sample A generally recorded higher short – circuit current values than Samples B and C during much of the monitoring period. Short – circuit current values ranged approximately between 1.03 and 5.30 A for Sample A, 0.90 and 3.80 A for Sample B, and 0.80 and 3.30 A for Sample C. The calculated mean I_{sc} values were 1.87 A, 1.63 A, and 1.61 A for Samples A, B, and C, respectively.

The three modules displayed similar temporal patterns, with higher current generation generally occurring during periods of increased solar radiation and lower current output during periods of reduced solar energy availability. This behaviour is consistent with photovoltaic theory, which indicates that short – circuit current is primarily governed by the flux of incident solar radiation reaching the photovoltaic surface. Increased irradiance enhances electron-hole pair generation within the semiconductor material, leading to higher current production (King et al., 1997; Dubey et al., 2013).

Although differences were observed among the tested modules, the present study does not permit definitive conclusions regarding manufacturer performance because only one module from each manufacturer was evaluated. Consequently, the observed differences should be interpreted as characteristics of the tested modules rather than statistically validated differences among manufacturers.

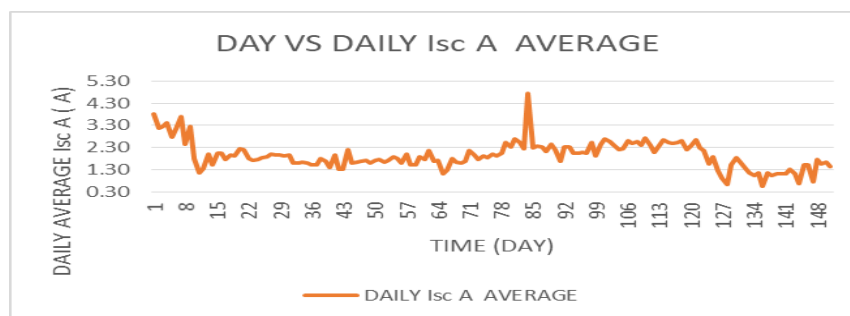


Figure 5: Variation of Daily Average Short – Circuit Current for Sample A

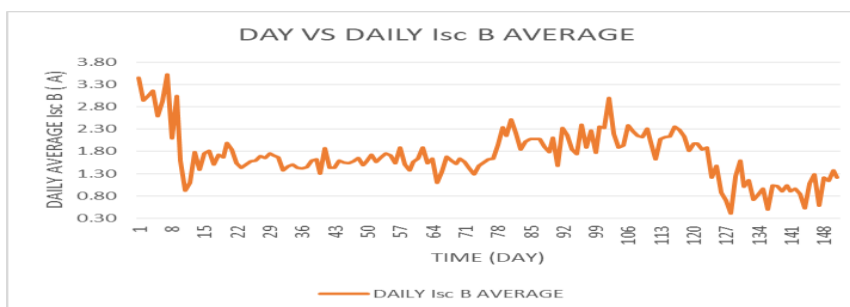


Figure 6: Variation of Daily Average Short – Circuit Current for Sample B

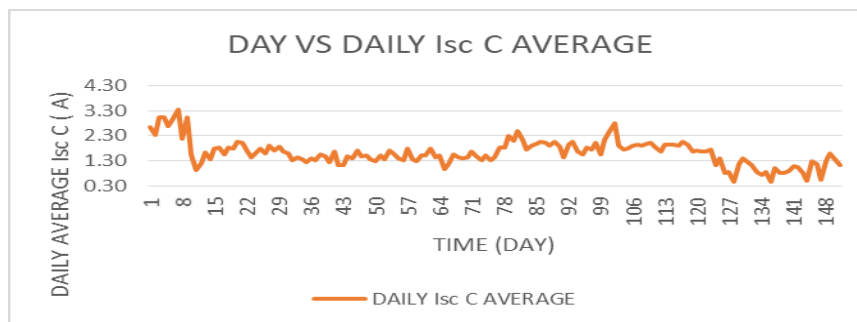


Figure 7: Variation of Daily Average Short – Circuit Current for Sample C

Open – Circuit Voltage Behaviour

The variation of daily average open – circuit voltage for the three modules is presented in Figures 4.8 – 4.10. In contrast to short – circuit current, voltage output exhibited a stronger response to variations in module operating temperature.

Sample C generally exhibited higher open - circuit voltage values than Samples A and B throughout much of the observation period. The maximum recorded Voc values were approximately 23.3 V, 22.3 V, and 27.1 V for Samples A, B, and C, respectively, while the corresponding mean values were 19.61 V, 19.42 V, and 21.47 V.

Variations in voltage output were characterised by reductions during periods of elevated module temperature and partial recovery during comparatively cooler conditions. This behaviour is consistent with established semiconductor theory, which indicates that increasing

Module Temperature increases reverse saturation current and reduces the open – circuit voltage of crystalline silicon photovoltaic devices (Radziemska, 2003; Skoplaki & Palyvos, 2009).

Periods associated with elevated module temperatures generally corresponded to lower Voc values, suggesting that thermal loading influenced voltage behaviour during the monitoring period. Compared with Isc, the voltage response exhibited greater sensitivity to environmental temperature variations, consistent with previous photovoltaic studies (Dubey et al., 2013).

While Sample C displayed higher voltage values over much of the monitoring period, caution is required in interpreting these differences because the study design did not include replicate modules from each manufacturer. Therefore, the observed behaviour should be regarded as representative of the tested units rather than conclusive evidence of manufacturer level performance differences.

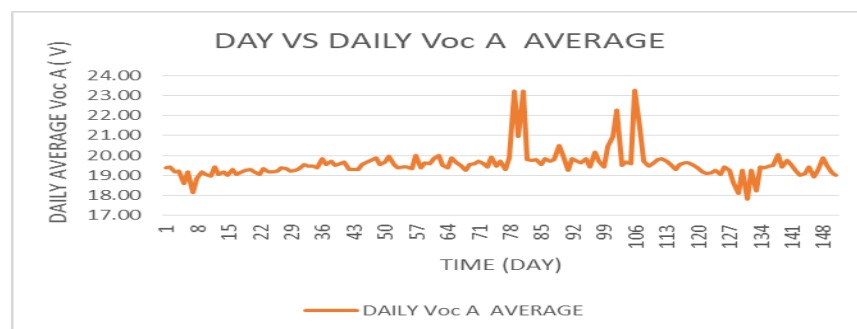


Figure 8: Variation of Daily Average Open - circuit voltage for Sample A

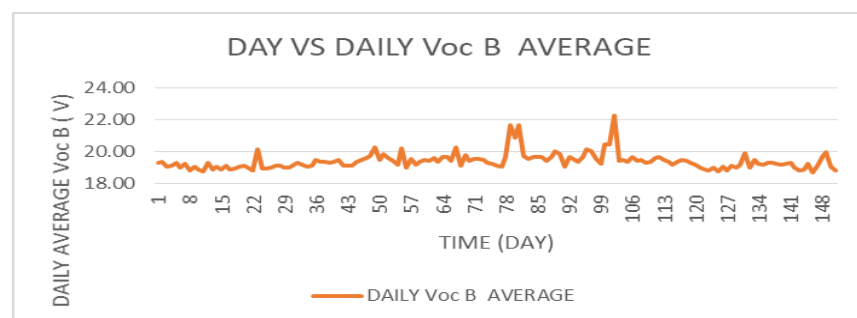


Figure 9: Variation of Daily Average Open - circuit voltage for Sample B

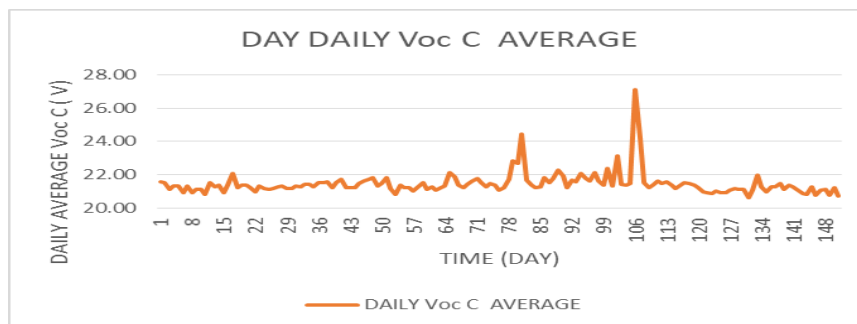


Figure 10: Variation of Daily Average Open - circuit voltage for Sample C

Table 2: Electrical Performance Summary

Parameter	Sample A	Sample B	Sample C
Mean Voc (V)	19.61	19.42	21.47
Maximum Voc (V)	23.3	22.3	27.1
Mean Isc (A)	1.87	1.63	1.61
Maximum Isc (A)	5.3	3.8	3.3

Source: Computed from the weekly mean dataset.

Table 4.2 summarises the principal electrical characteristics of the three photovoltaic modules during the monitoring period. Sample A recorded the highest mean short-circuit current, whereas Sample C exhibited the highest mean open - circuit voltage. The observed differences indicate variations in the electrical behaviour of the tested modules under identical environmental conditions. However, because only one module from each manufacturer was evaluated ($n = 1$ per brand), these differences should be interpreted as characteristics of the individual modules tested rather than definitive evidence of manufacturer level performance differences. The results nevertheless provide a useful basis for examining the influence of environmental conditions on the electrical behaviour of polycrystalline photovoltaic modules under the climatic conditions of northern Nigeria.

Influence of Temperature on Electrical Performance

The hourly and weekly observations indicate that environmental conditions influenced the electrical behaviour of the photovoltaic modules throughout the monitoring period. As shown in Figures 4.11 and 4.12, increases in global radiation and ambient temperature (AT) were accompanied by increases in module temperature (CT), while relative humidity (RH) generally decreased during the hottest periods of the day. Module temperature remained consistently higher than ambient temperature, reflecting the absorption of solar energy by the modules and the limited cooling effect associated with the dry-season conditions.

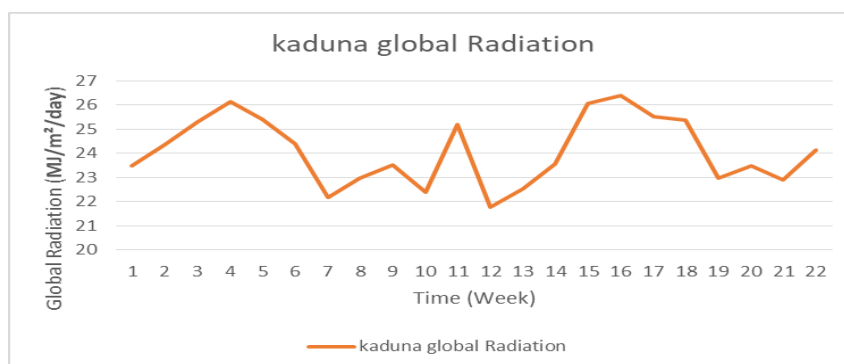


Figure 11: Weekly Global Radiation Trends

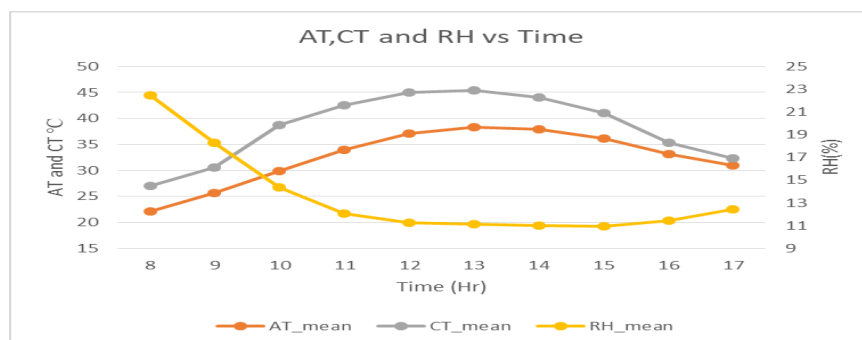


Figure 12: Hourly Variation of Ambient Temperature, Module Temperature, and Relative Humidity

The observed diurnal pattern demonstrates that module temperatures increased progressively from morning to midday, reaching peak values during periods of maximum solar exposure. At the same time, relative humidity declined as atmospheric heating intensified. These conditions created an environment conducive to increased thermal loading of the photovoltaic modules.

The influence of these environmental conditions on short – circuit current (I_{sc}) is presented in Figure 4.13. For all three modules, I_{sc} increased from morning hours to

midday before declining toward evening. This pattern broadly followed the availability of solar radiation and suggests that current generation was more closely associated with irradiance levels than with temperature. Similar behaviour has been reported for crystalline silicon photovoltaic modules, where I_{sc} is primarily influenced by incident solar radiation and exhibits relatively limited sensitivity to temperature (King et al., 1997; Dubey et al., 2013).

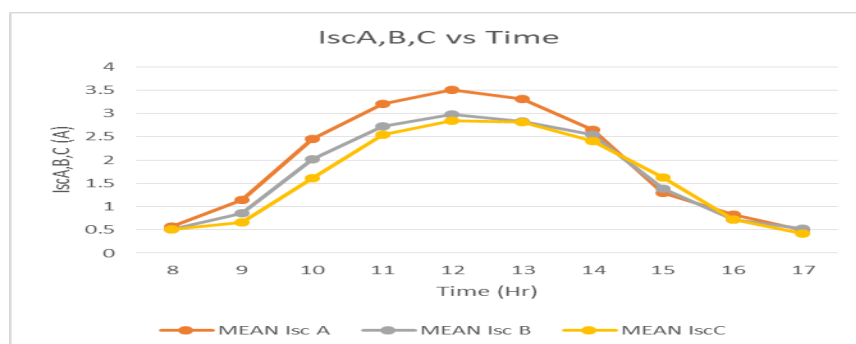


Figure 13: Hourly Variation of Short – Circuit Current for Samples A, B, and C

In contrast, open – circuit voltage (V_{oc}) exhibited an opposite response to temperature variations. As shown in Figure 4.14, voltage values generally declined during periods of elevated module temperature and recovered as temperatures decreased. This behaviour is consistent with

the established temperature dependence of crystalline silicon photovoltaic devices, where increasing temperature reduces open – circuit voltage due to changes in semiconductor properties (Radziemska, 2003; Skoplaki & Palyvos, 2009).

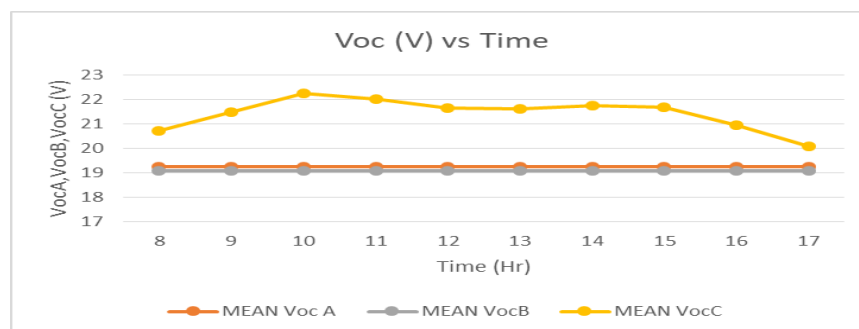


Figure 14: Hourly Variation of Open - circuit voltage for Samples A, B, and C

The weekly trends further support these observations. Figures 4.15 and 4.16 show that periods characterised by higher average module temperatures were generally associated with lower average voltage values. Although

the relationship was not perfectly uniform throughout the study period, the overall pattern suggests that temperature had a greater influence on voltage output than on current generation.

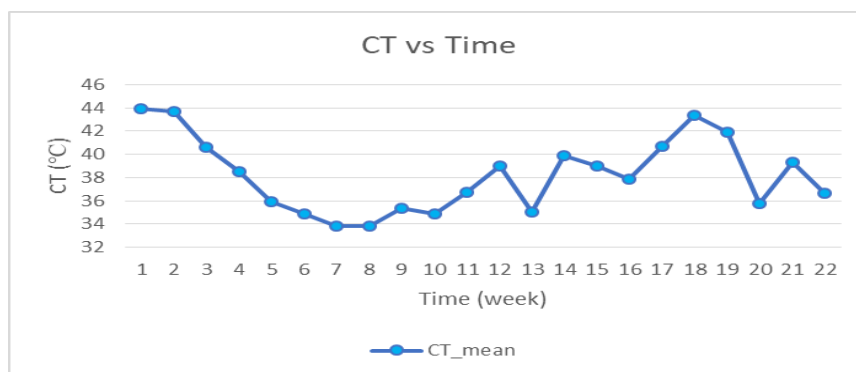


Figure 15: Weekly Variation of Module Temperature

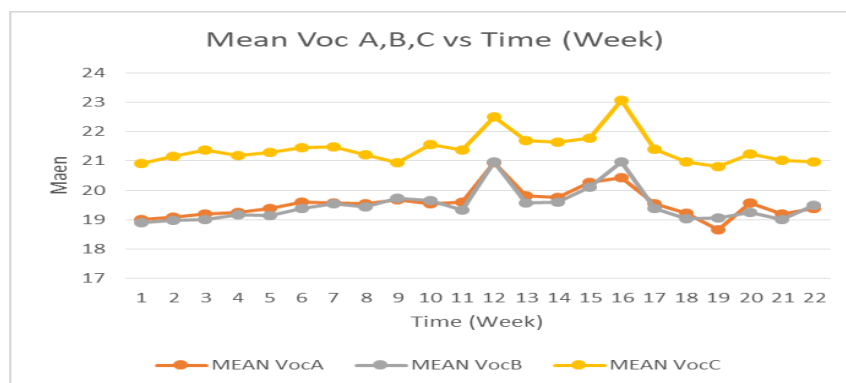


Figure 16: Weekly Variation of Open – Circuit Voltage for Samples A, B, and C

Overall, the results indicate that module temperature was an important factor affecting the electrical performance of the photovoltaic modules. While I_{sc} generally followed variations in solar radiation, V_{oc} exhibited greater sensitivity to temperature fluctuations. These findings are consistent with previous studies of polycrystalline silicon photovoltaic modules operating under hot climatic conditions (Dubey et al., 2013; Skoplaki & Palyvos, 2009). However, because only one module from each manufacturer was evaluated, the observed responses should be interpreted as characteristics of the tested modules rather than definitive indicators of manufacturer specific performance.

Correlation Analysis

Linear regression analysis was performed to evaluate the relationships between environmental variables and photovoltaic electrical parameters. The resulting regression equations and coefficients of determination (R^2) are presented in Figures 4.17 – 4.23.

Relationship between Global Radiation and Open - Circuit Voltage

Figure 4.17 shows the relationship between global radiation and open - circuit voltage (V_{oc}). The regression equations obtained for Samples A, B, and C were:

$$V_{ocA} = -0.0099R + 20.21$$

$$V_{ocB} = -0.0131R + 20.03$$

$$V_{ocC} = 0.0441R + 20.80$$

Where R is global radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

The corresponding coefficients of determination were $R^2 = 0.0008$, $R^2 = 0.0011$, and $R^2 = 0.0139$ for Samples A, B, and C, respectively. These very low values indicate that global radiation explained little of the observed variability in V_{oc} . The results therefore suggest that voltage output was influenced more strongly by other environmental factors, particularly module temperature, than by radiation alone (Radziemska, 2003; Skoplaki & Palyvos, 2009).

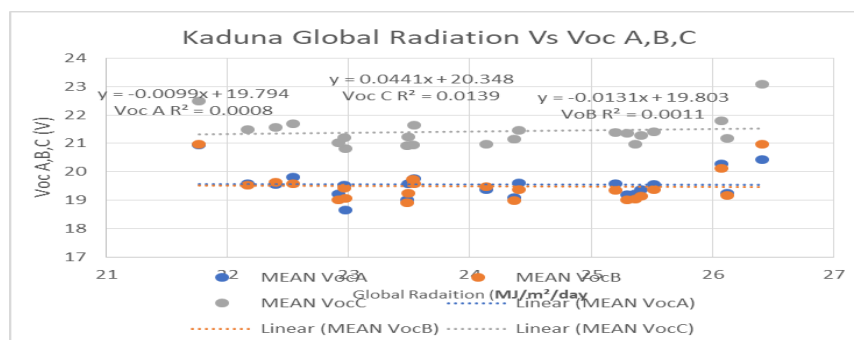


Figure 17: Relationship between Global Radiation and Open – Circuit Voltage

Relationship between Global Radiation and Short – Circuit Current

The relationship between global radiation and short – circuit current (I_{sc}) is presented in Figure 4.18. The regression equations obtained were:

$$I_{scA} = 0.0593R + 0.39$$

$$I_{scB} = 0.0453R + 0.43$$

$$I_{scC} = 0.0688R + 0.12$$

The positive slopes indicate that higher radiation levels were generally associated with increased current output. However, the coefficients of determination were low ($R^2 = 0.016 - 0.035$), indicating that radiation alone accounted for only a small proportion of the observed variability in I_{sc} . Consequently, while the regression slopes suggest an influence of irradiance on current generation, the weak correlations indicate that additional environmental and operational factors contributed substantially to the observed variation.

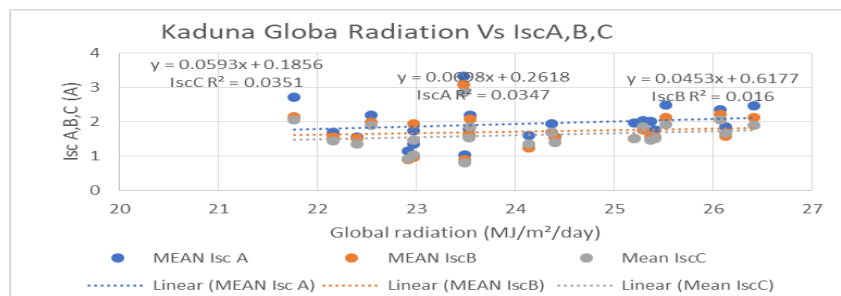


Figure 18: Relationship between Global Radiation and Short – Circuit Current

Relationship between Global Radiation and Temperature

Figures 4.19 and 4.20 present the relationships between global radiation and ambient temperature (AT) and module temperature (CT), respectively.

For ambient temperature:

$$AT = 0.816R + 12.835$$

$$R^2 = 0.088$$

For module temperature:

$$CT = 0.6115R + 23.472$$

$$R^2 = 0.0719$$

The positive slopes indicate that both AT and CT generally increased with increasing radiation. However, the low coefficients of determination show that radiation explained less than 10% of the observed temperature variability. These weak relationships suggest that additional factors, including relative humidity, wind conditions, and atmospheric dust loading, influenced temperature variations during the monitoring period.

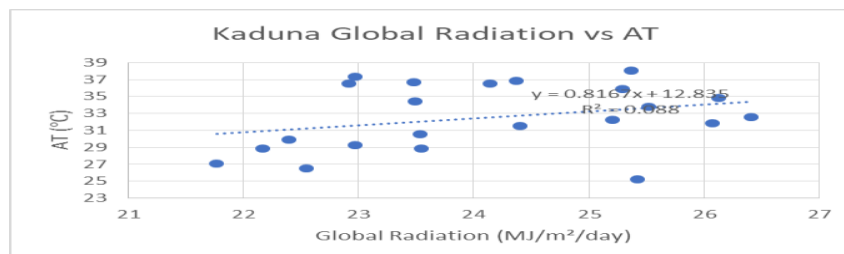


Figure 19: Relationship between Global Radiation and Ambient Temperature.

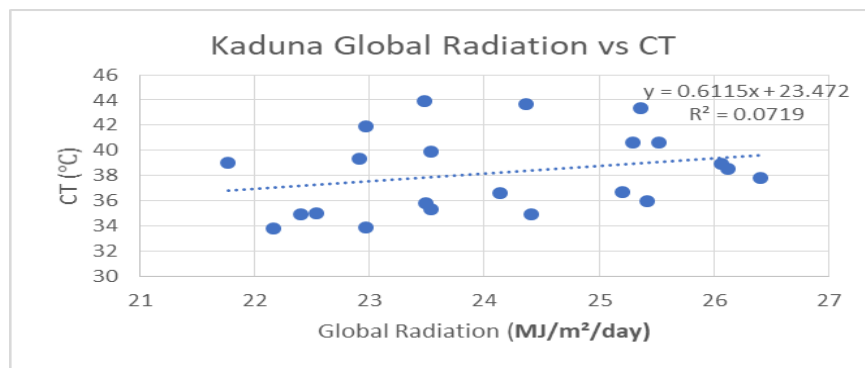


Figure 20: Relationship between Global Radiation and Module Temperature

Relationship between Module Temperature and Ambient Temperature

Figure 4.21 shows the relationship between module temperature and ambient temperature, described by:

$$CT = 1.12(AT) + 1.31$$

With

$$R^2 = 0.8583$$

The coefficient of determination indicates that approximately 85.8% of the observed variation in module temperature was associated with variation in ambient temperature. This strong relationship demonstrates the close thermal coupling between the photovoltaic modules and their surrounding environment.

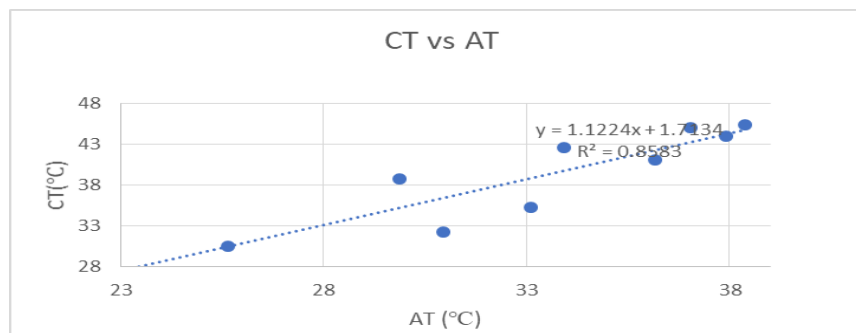


Figure 21: Relationship between Module Temperature and Ambient Temperature

Relationship between Module Temperature and Relative Humidity

The relationship between module temperature and relative humidity is shown in Figure 4.22:

$$CT = -1.37(RH) + 58.54$$

$$R^2 = 0.6549$$

The negative slope indicates that higher relative humidity was generally associated with lower module temperatures. The coefficient of determination suggests a moderately strong relationship, indicating that humidity contributed substantially to module-temperature variability, although other environmental factors also influenced module heating.

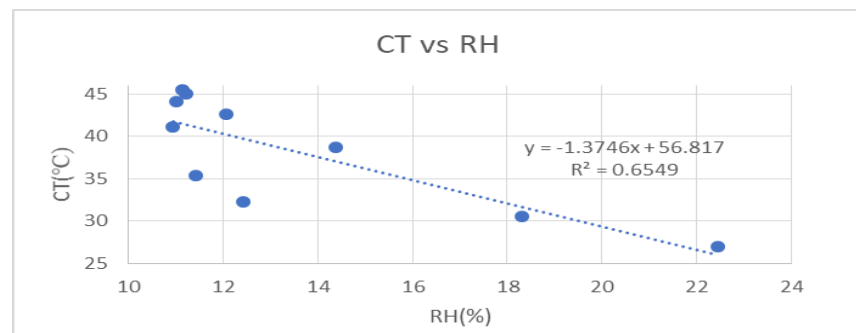


Figure 22: Relationship between Module Temperature and Relative Humidity

Relationship between Ambient Temperature and Relative Humidity

Figure 4.23 shows the relationship between ambient temperature and relative humidity:

$$AT = -1.31(RH) + 46.18$$

$$R^2 = 0.8772$$

The coefficient of determination indicates a strong inverse association between ambient temperature and relative humidity. This relationship is characteristic of the dry-season climatic conditions of the study area, where high temperatures generally coincide with low atmospheric moisture levels.

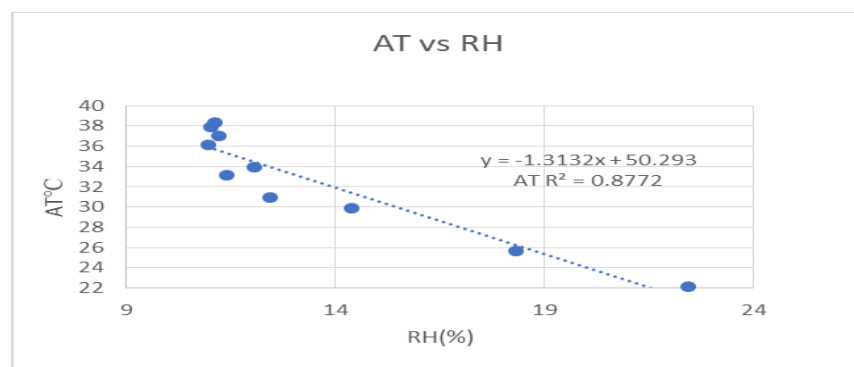


Figure 23: Relationship between Ambient Temperature and Relative Humidity

Overall, stronger relationships were observed among the environmental variables themselves than between global radiation and the electrical parameters. The CT-AT ($R^2 = 0.8583$) and AT-RH ($R^2 = 0.8772$) relationships exhibited the highest coefficients of determination, indicating strong associations among these climatic variables. In contrast, the weak relationships between global radiation and both V_{oc} and I_{sc} suggest that photovoltaic electrical behaviour under field conditions was influenced by multiple interacting environmental factors rather than by radiation alone. These findings are consistent with the complex nature of photovoltaic operation under outdoor climatic conditions.

Comparative Assessment of the Tested Modules

A comparative assessment of the three photovoltaic modules was undertaken using the principal electrical performance indicators obtained during the monitoring period. The comparison focused on short – circuit current output, open - circuit voltage output and observed thermal response under the prevailing environmental conditions. Because only one module from each manufacturer was evaluated ($n = 1$ per brand), the assessment interpreted as a comparison of the tested modules rather than a definitive ranking of manufacturer performance.

Table 3: Comparative Assessment of the Tested Modules

Performance Indicator	Sample A	Sample B	Sample C
Current Output	Highest	Moderate	Lower
Voltage Output	Moderate	Lower	Highest
Thermal Sensitivity	Moderate	Moderate	Higher
Relative Performance	Good	Fair	Good

The results indicate that Sample A generally recorded the highest short – circuit current values during the monitoring period, with a mean I_{sc} of 1.87 A, compared with 1.63 A and 1.61 A for Samples B and C, respectively. Sample C, however, exhibited the highest voltage output, with a mean V_{oc} of 21.47 V, compared with 19.61 V for Sample A and 19.42 V for Sample B. These differences suggest variations in the electrical characteristics of the tested modules under identical environmental conditions. The temperature analysis presented in Sections 4.3 and 4.4 further indicated that voltage output was more sensitive to thermal variations than current generation. Sample C generally maintained higher voltage values but also exhibited greater variability during periods of

elevated module temperature. Sample A maintained comparatively higher current output throughout much of the observation period, while Sample B generally recorded lower values for both I_{sc} and V_{oc} . However, because replicate modules were not available, these observations cannot be interpreted as statistically significant differences among manufacturers.

Within the limitations of the present dataset, Sample A exhibited the highest current output, whereas Sample C produced the highest voltage output. The results demonstrate that modules with similar nominal power ratings may respond differently when operated under the same environmental conditions. Nevertheless, additional studies involving multiple modules from each

manufacturer would be required to determine whether the observed differences are attributable to manufacturer-specific characteristics or normal unit-to-unit variability.

Comparison with Previous Studies

The results obtained in this study are generally consistent with previous investigations of crystalline silicon photovoltaic modules operating under hot climatic conditions. Earlier studies reported that increasing module temperature leads to reductions in open – circuit voltage, while short – circuit current is influenced more strongly by solar irradiance than temperature (Radziemska, 2003; Skoplaki & Palyvos, 2009; Dubey et al., 2013). Similar behaviour was observed in the present study, where module temperature exhibited strong associations with ambient temperature and relative

humidity, while the relationships between global radiation and the electrical parameters were comparatively weak. Previous research has also shown that photovoltaic modules commonly operate at temperatures significantly higher than ambient temperature under outdoor conditions, particularly in regions characterised by high solar irradiance and limited cooling (Faiman, 2008). The present study produced comparable results, with module temperatures consistently exceeding ambient temperatures throughout the monitoring period. Furthermore, the stronger sensitivity of open – circuit voltage to temperature observed in this study agrees with the findings of Skoplaki and Palyvos (2009), who reported that voltage output is more strongly affected by temperature variations than current generation in crystalline silicon photovoltaic modules.

Table 4: Comparison of Present Findings with Previous Studies

Study	Location	Key Findings	Comparison with Present Study
Radziemska (2003)	Poland	Increasing temperature reduced open - circuit voltage	Consistent with the observed inverse relationship between module temperature and Voc
Faiman (2008)	Israel	Module temperatures exceeded ambient temperature during outdoor operation	Consistent with module temperature remaining higher than ambient temperature throughout the monitoring period
Skoplaki and Palyvos (2009)	Review study	Voc is more temperature-sensitive than Isc	Consistent with the stronger thermal response of Voc observed in this study
Dubey et al. (2013)	India	Isc responds primarily to irradiance, while Voc decreases with increasing temperature	Consistent with the observed Isc and Voc behaviour
Present Study	Kaduna, Nigeria	Strong CT-AT ($R^2 = 0.8583$) and AT-RH ($R^2 = 0.8772$) relationships; Voc more temperature-sensitive than Isc	Supports previous findings under hot tropical conditions

The agreement between the present findings and previous studies suggests that the observed electrical behaviour is consistent with the established thermal characteristics of crystalline silicon photovoltaic modules. However, the combination of high ambient temperatures, low relative humidity, and prolonged dry season conditions in Afaka creates a particularly demanding operating environment that can intensify module heating and influence voltage behaviour. These findings highlight the importance of considering local climatic conditions when evaluating photovoltaic performance and designing systems for deployment in hot tropical environments.

Implications for PV Deployment in Hot Climates

The results of this study demonstrate that environmental conditions, particularly temperature and humidity, have important implications for photovoltaic deployment in hot tropical and semi-arid regions. The strong associations observed between ambient temperature, module temperature, and voltage behaviour indicate that thermal effects should be considered during photovoltaic system design and module selection.

Photovoltaic modules with low temperature coefficients are likely to perform more favourably under prolonged high-temperature conditions because they experience smaller voltage reductions as operating temperature

increases. Module specifications should therefore be evaluated not only on rated power output but also on thermal performance characteristics.

Adequate ventilation beneath photovoltaic modules is also important. Improved airflow enhances convective cooling and can reduce module operating temperatures during periods of intense solar radiation. Similarly, elevated mounting structures that provide sufficient clearance between the module and mounting surface can improve air circulation and reduce heat accumulation at the rear of the module.

Thermal management should therefore form an integral part of photovoltaic system design in hot climates. Appropriate mounting configurations, adequate module spacing, and site-specific installation practices can help reduce thermal loading and improve operational performance.

Overall, the findings indicate that consideration of temperature-related effects is essential for maximising photovoltaic performance in northern Nigeria and similar hot-climate environments. Incorporating thermal considerations into module selection and system design may contribute to improved energy yield, enhanced reliability, and more effective long-term deployment of photovoltaic technologies.

CONCLUSION

This study investigated the influence of environmental conditions on the electrical performance of three commercially available 80 W polycrystalline photovoltaic modules operating under the climatic conditions of Afaka, Kaduna State, Nigeria. Measurements of ambient temperature, module temperature, relative humidity, open - circuit voltage (V_{oc}) and short - circuit current (I_{sc}) were obtained over a 151 - day monitoring period, while global solar radiation data were obtained from the Nigerian Meteorological Agency (NiMet).

The results showed that the study area experienced high solar radiation, elevated temperatures, and low relative humidity characteristic of the dry season in northern Nigeria. Ambient temperature ranged from approximately 24 °C to 40 °C, while module temperature frequently exceeded ambient temperature and reached values of about 47 °C. Relative humidity varied between approximately 10% and 44%, with the lowest values occurring during periods of intense heating.

The electrical performance of the photovoltaic modules was influenced by these environmental conditions. Short - circuit current generally increased during periods of higher solar radiation, while open - circuit voltage exhibited greater sensitivity to temperature variations. Sample A recorded the highest mean short - circuit current (1.87 A), whereas Sample C exhibited the highest mean open - circuit voltage (21.47 V). These observations indicate differences in the electrical behaviour of the tested modules under identical environmental conditions. Correlation analysis showed strong relationships among the environmental variables. Module temperature exhibited a strong positive relationship with ambient temperature ($R^2 = 0.8583$), while ambient temperature showed a strong inverse relationship with relative humidity ($R^2 = 0.8772$). In contrast, the relationships between global radiation and the electrical parameters were relatively weak, suggesting that photovoltaic performance under field conditions is influenced by multiple interacting environmental factors rather than solar radiation alone.

Overall, the findings demonstrate that temperature is an important factor affecting the electrical behaviour of photovoltaic modules in hot tropical environments. The study further highlights the importance of considering local environmental conditions when evaluating photovoltaic module performance and selecting modules for deployment in northern Nigeria.

Based on the findings of this study, the following recommendations are proposed:

- i. Photovoltaic modules intended for deployment in hot tropical environments should be selected with consideration for their temperature coefficients, particularly where sustained high operating temperatures are expected.

- ii. Adequate ventilation should be incorporated into photovoltaic system design to enhance air circulation and reduce module operating temperatures.
- iii. Elevated mounting structures should be used where possible to improve convective cooling and minimise heat accumulation at the rear surface of photovoltaic modules.
- iv. Thermal management considerations, including appropriate module spacing and installation configurations, should be integrated into photovoltaic system design to reduce temperature-related performance losses.
- v. Future studies should include multiple modules from each manufacturer and monitor additional environmental variables over both wet and dry seasons to provide a more comprehensive assessment of photovoltaic performance under Nigerian climatic conditions.

REFERENCES

- Armstrong, S., & Hurley, W. G. (2010). A thermal model for photovoltaic panels under varying atmospheric conditions. *Applied Thermal Engineering*, 30(11–12), 1488–1495.
<https://doi.org/10.1016/j.applthermaleng.2010.03.012>
- Dubey, S., Sarvaiya, J. N., & Seshadri, B. (2013). Temperature dependent photovoltaic efficiency and its effect on PV production in the world: A review. *Energy Procedia*, 33, 311–321.
<https://doi.org/10.1016/j.egypro.2013.05.072>
- Faiman, D. (2008). Assessing the outdoor operating temperature of photovoltaic modules. *Progress in Photovoltaics: Research and Applications*, 16(4), 307–315. <https://doi.org/10.1002/pip.813>
- Green, M. A. (1982). *Solar cells: Operating principles, technology and system applications*. Prentice-Hall.
- King, D. L., Boyson, W. E., & Kratochvil, J. A. (1997). Photovoltaic array performance model. Sandia National Laboratories.
- Nigerian Meteorological Agency (NiMet). (2024). Daily global solar radiation data for Kaduna Station [Meteorological dataset]. Abuja, Nigeria: Nigerian Meteorological Agency.
- Ohunakin, O. S., Adaramola, M. S., Oyewola, O. M., & Fagbenle, R. O. (2014). Solar energy applications and development in Nigeria: Drivers and barriers. *Renewable and Sustainable Energy Reviews*, 32, 294–301.
<https://doi.org/10.1016/j.rser.2014.01.014>

Radziemska, E. (2003). The effect of temperature on the power drop in crystalline silicon solar cells. *Renewable Energy*, 28(1), 1–12. [https://doi.org/10.1016/S0960-1481\(02\)00015-0](https://doi.org/10.1016/S0960-1481(02)00015-0)

Skoplaki, E., & Palyvos, J. A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy*, 83(5), 614–624. <https://doi.org/10.1016/j.solener.2008.10.008>