Diurnal Variation of Solar Radiation, Ambient Temperature, Panel Temperature and Relative Humidity across some selected locations in Nigeria.

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ABSTRACT

This study presents a comprehensive analysis of the diurnal variation of solar radiation, ambient temperature, panel temperature, and relative humidity across selected locations in Nigeria. The objective is to examine how these environmental parameters influence photovoltaic (PV) module performance from both an experimental and solid-state physics perspective. Photovoltaic energy conversion is fundamentally governed by semiconductor processes within a p–n junction, where incident photons with energy $h\nu \geq E_g$ generate electron–hole pairs. The efficiency of charge carrier separation and transport is strongly influenced by temperature-dependent parameters such as carrier mobility, intrinsic carrier concentration, and recombination rates. Consequently, environmental variables introduce dynamic operating conditions that directly affect PV output. The results obtained from the locations exhibit a consistent diurnal pattern, with solar radiation increasing from near-zero values in the early morning to peak values ranging between approximately 900–1400 W/m² around midday (12:00–14:00 hrs), followed by a gradual decline toward evening. Correspondingly, both ambient and panel temperatures increase with solar irradiance, with panel temperatures consistently exceeding ambient temperatures by several degrees due to heat accumulation and limited convective cooling. Peak panel temperatures were observed in the range above 40°C, depending on location and module type. Relative humidity showed an inverse relationship with solar radiation and temperature, decreasing during peak irradiance periods and increasing during early morning and late evening hours. This behavior is attributed to atmospheric thermodynamics, where increased temperature reduces relative humidity through enhanced evaporation and air expansion. From a solid-state standpoint, the elevated panel temperatures observed across all locations contribute to a reduction in PV efficiency through increased carrier recombination and reduced open-circuit voltage. Comparative analysis of the different locations reveals notable spatial variations in peak irradiance and thermal behavior, reflecting the influence of local climatic conditions such as cloud cover, humidity levels, and atmospheric clarity. Inland and high-radiation locations exhibited sharper irradiance peaks and higher panel temperatures, while more humid regions showed moderated irradiance profiles and relatively lower thermal gradients. The findings highlight the critical interplay between environmental conditions and semiconductor physics in determining PV performance. The results emphasize that while high solar irradiance enhances photocurrent generation, excessive thermal loading reduces efficiency, thereby necessitating careful consideration of location-specific conditions in PV system design and deployment. This study provides valuable empirical data for optimizing photovoltaic systems in tropical environments and contributes to a deeper understanding of how diurnal environmental variations influence solid-state device performance in real-world applications.

Keywords: Photovoltaic (PV) modules; Diurnal variation; Solar radiation; Ambient temperature; Panel temperature; Relative humidity.

INTRODUCTION

The increasing global demand for sustainable and environmentally friendly energy sources has intensified research into renewable energy technologies, particularly solar energy (Gayen *et al.*, 2024). Among these technologies, photovoltaic (PV) systems have emerged as one of the most promising solutions for electricity generation due to their reliability, scalability, and minimal environmental impact. In developing countries such as Nigeria, where access to stable electricity remains a challenge, solar energy offers a viable alternative to conventional fossil-fuel-based power generation (Okojokwu-du *et al.,* 2025)

Photovoltaic systems operate based on principles rooted in solid-state physics, specifically the behavior of charge carriers in semiconductor materials (Tsakalakos, L. 2010). A typical solar cell is constructed from semiconductor materials such as silicon, which is engineered to form a p–n junction. This junction is created by doping the semiconductor with impurities to produce regions rich in electrons (n-type) and holes (p-type) (Smith *et al.*, 2018) The interaction between these regions establishes an internal electric field that is fundamental to the operation of the PV device.

When sunlight strikes the surface of a solar cell, photons with sufficient energy excite electrons from the valence band to the conduction band, creating electron–hole pairs. This process is governed by the photoelectric effect, which is a key concept in solid-state physics (Fahrenbruch, A., & Bube, R. 2012). The internal electric field at the p–n junction separates these charge carriers, directing electrons toward the n-side and holes toward the p-side, thereby generating an electric current when an external circuit is connected (Davies, R. L., & Gentry, F. E. 2005).

The efficiency of this conversion process depends on several solid-state parameters, including the band gap energy of the semiconductor, carrier mobility, recombination rates, and material quality. Silicon, with a band gap of approximately 1.1 eV, is widely used because it offers an optimal balance between absorption of solar radiation and electrical performance. However, real PV modules are subject to various losses such as recombination losses, resistive losses, and thermal effects, all of which reduce their efficiency below the theoretical maximum (Shen, L., Li, Z., & Ma, T. 2020).

In practical applications, the electrical behavior of a PV cell is described by the diode equation, which reflects its semiconductor nature. The current–voltage (I–V) characteristics of a solar cell reveal important operating points such as the short-circuit current (Isc), open-circuit voltage (Voc), and the maximum power point (MPP) (Morales-Acevedo, A. 2023). These parameters are critical in determining the performance of PV systems under real environmental conditions.

Several studies in the past have investigated PV performance at specific locations. (Okonkwo & Nwokoye 2014) examined PV systems in Awka and reported lower-than-expected outputs due to temperature and dust effects.

Yakubu *et al.,* (2022) investigated the performance of a bifacial solar PV system in Nigeria under various climatic regions according to them bifacial PV modules are known to be location-dependent. The In-Plane solar radiation received by tilted monofacial and bifacial PV modules was calculated and compared using an analytical model. In all climatic regions, the bifacial PV system receives more in-plane solar irradiance. The systems were simulated on PVsyst to determine the energy yield, and their results show that under natural ground (vegetation and sand) of the various regions and optimization of the tilt angle, the bifacial PV system yielded more energy than the monofacial system. The bifacial gain varies depending on location, and system parameters must be optimized to improve the bifacial energy gain.

Umar *et al.,* (2021) analyzed the effect of climatic variation on PV systems' performance and economic viability in four climatic zones of Nigeria (warm desert, warm semi-arid, tropical savanna, and monsoon climate). Performance ratio was found to be high in monsoon and tropical savanna climate due to the influence of cool-moist air from the ocean, low temperature, and increased cloud cover in the region. Meanwhile, the least performance ratio was noticed in the warm desert and warm semi-arid climate due to the dusty wind from the Sahara Desert, relatively high temperature, and low precipitation in the region. In order to assess the cost-effectiveness and profitability of the solar project in Nigeria, the Levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and payback period (PP) were employed. The average LCOE across the climatic zones is 0.21 \$/kWh, which is lower compared to the 0.25 \$/kWh grid tariff. The average NPV and IRR are found to be \$31,164 and 22%, respectively, making the project economically feasible. However, the payback period was found to be ranging from 3.7 to 5.2 years. Finally, the analysis has proven that solar PV technology is economically viable and profitable in Nigeria.

Aqachmar *et al*., (2020) investigated the performance of the high concentration photovoltaic power plants from an energy, economic, and environmental point of view in six different climatic zones in Morocco and compared its feasibility with that of photovoltaic power plants. They showed that installing the high concentration photovoltaic power plants in the Errachidia region is more cost effective. The minimum and maximum Levelized cost of energies for the photovoltaic module are 5.3c$/kWh and 19.72c$/kWh, respectively. Generally, high concentration photovoltaic power plants have a higher capacity factor than photovoltaic, while the Levelized cost of energy of photovoltaic systems is more cost-effective.

MATERIALS AND METHODS

The following materials were used for the study;

Commercial PV Modules (80watt)

Two 80W mono and polycrystalline commercial sunshine PV modules were used for the research. The primary function of a solar panel is to convert sunlight (solar irradiance) into direct current (DC) electricity using the photovoltaic effect. This enables us to measure voltage, current, calculate the output power given by;

$$P = V \times I$$

where; P, V, I are power, voltage and current respectively and determine how real sunlight conditions affect power output.

PV modules operate based on semiconductor physics, particularly the p–n junction formed in silicon materials. When photons from solar radiation strike the semiconductor, they transfer energy to electrons, exciting them from the valence band to the conduction band, thereby creating electron–hole pairs (Singh *et al.,* 2020).

The internal electric field at the p–n junction separates these charge carriers, generating a direct current (DC). This phenomenon is known as the photovoltaic effect as stated above.

According to (Pindado, S., & Cubas, J. 2017) the electrical behavior of a solar cell is described by the diode equation as seen in equation 3 above:

$$I = I_{ph} - I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$

Where:

I_{ph}: Photogenerated current

I_0: Reverse saturation current

q: Electron charge

V: Voltage

n: Ideality factor

T: Temperature

A solar panel in an outdoor experiment helps examine how environmental factors influence performance, including: Solar radiation (W/m²), Temperature, Cloud cover, Rainfall (important for your research dataset), Humidity, Dust or dirt accumulation, Shading patterns.

The solar panels also help us to calculate the module efficiency given by;

$$\eta = \frac{\text{Pout}}{G\,.\,A} \text{ X } 100\%$$

Where;

P_{out} = Output power (W)

G = Solar irradiance (W/m²)

A = Panel area (m²),

Maximum power, fill factor and performance ratio respectively.

This helps us to understand how PV modules behave under natural, dynamic weather conditions.

Module Type: Sunshine solar (mono and polycrystalline)

- Maximum power = 80W
- Output tolerance = ±5%
- Maximum current (Imp) = 4.58A
- Maximum voltage (Vmp) = 17.5V
- Short circuit current (Isc) = 4.85A
- Short circuit voltage (Voc) = 21.55V
- Surface area of panel = $0.61m^2$

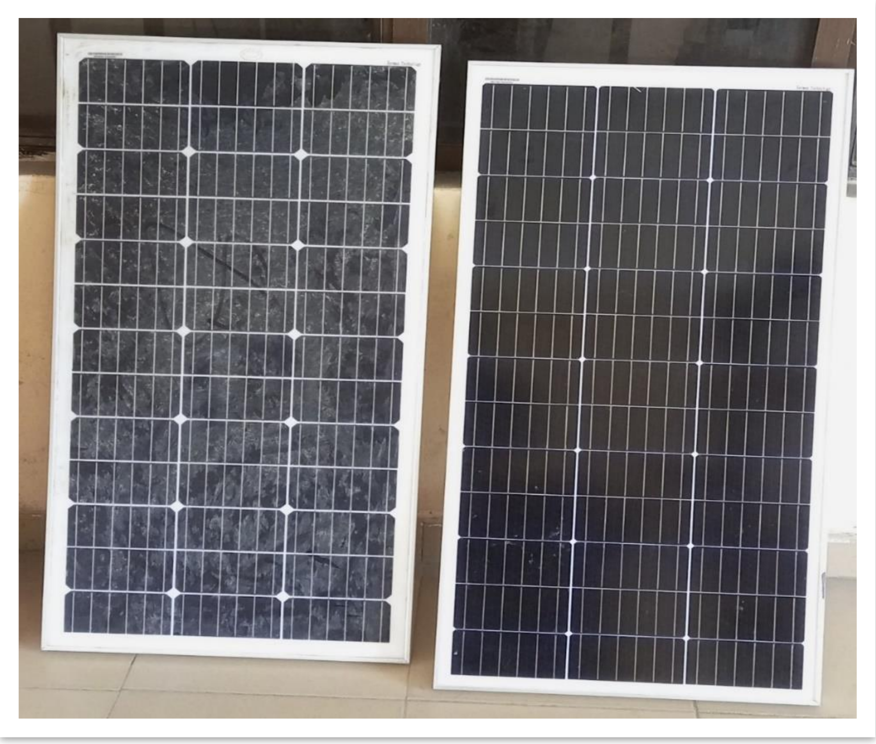


Figure 1. Monocrystalline PV Module

Thermo-hygrometer

A thermo-hygrometer is a critical environmental measuring instrument. Its main function is to measure ambient temperature and relative humidity, both of which strongly influence PV module performance, data interpretation, and result accuracy. This device converts physical environmental changes into electrical signals.

A thermo-hygrometer measures the ambient air temperature (°C) around the PV module. Since temperature directly affects PV electrical parameters, especially voltage given by the relation;

$$\frac{DV}{DT} < 0$$

As temperature increases:

- Open-circuit voltage V_{oc} decreases
- Maximum power voltage V_{mpp} decreases
- Overall output power reduces

The hygrometer component in the device measures relative humidity (%) of the air.

Why humidity matters

High humidity:

- Increases light scattering
- Reduces effective irradiance
- Enhances cloud formation
- Promotes moisture ingress and soiling

This indirectly reduces PV current:

Figure 2. Picture of a Thermo-hygrometer

Digital Solar Power Meter

A digital solar power meter (often called a *solar irradiance meter*) plays a central role in an outdoor photovoltaic (PV) experiment. It measures the amount of solar radiation falling on the PV module. It is a fundamental parameter that determines how much electrical power the module can generate. Its unit is in W/m². It shows the power of sunlight striking 1 square meter of the panel surface. Why this is essential;

- PV current is directly proportional to irradiance i.e. $I \propto G$.
- PV power output is strongly irradiance-dependent i.e. $P = V \times I$

Without accurate irradiance measurement, PV performance cannot be correctly analysed or compared.

Figure 3. Picture of Digital Solar Power Meter

Digital MPPT solar panel meter

A solar panel MPPT meter (sometimes called a *solar watt meter*, *solar analyzer*, or *PV meter*) is an instrument used in an outdoor PV experiment to monitor and measure the electrical output of a solar panel under real environmental conditions. It is different from a solar irradiance meter because it measures electrical performance, not sunlight intensity.

The primary function of an MPPT solar panel meter is to ensure that the PV module operates at the point where it delivers maximum power. It is based on power electronics and semiconductor switching devices such as MOSFETs.

It uses algorithms (e.g., Perturb and Observe, Incremental Conductance) to track the point where:

$$P = V \times I$$

The maximum power point occurs at:

$P_{max} = V_{mpp} \times I_{mpp}$

Figure 4. Digital MPPT solar panel meter

Anemometer

An anemometer is a vital environmental instrument in an outdoor photovoltaic (PV) experiment because wind speed has a direct impact on the temperature, efficiency, and overall power output of solar modules.

An anemometer measures wind speed (m/s or km/h) at the PV installation site. It converts wind motion into electrical signals through rotational speed or wave propagation changes.

Wind speed affects panel temperature, module cooling rate, efficiency and output power. Hence wind is an important environmental variable because PV modules operate better when kept cool.

Wind helps dissipate heat from the solar panel surface, reducing the cell temperature.

Figure 5. Picture of Anemometer

The integration of these instruments allows for a comprehensive evaluation of PV performance by capturing:

- Electrical parameters → PV module, MPPT meter
- Solar input → Solar power meter
- Environmental conditions → Thermo-hygrometer, anemometer

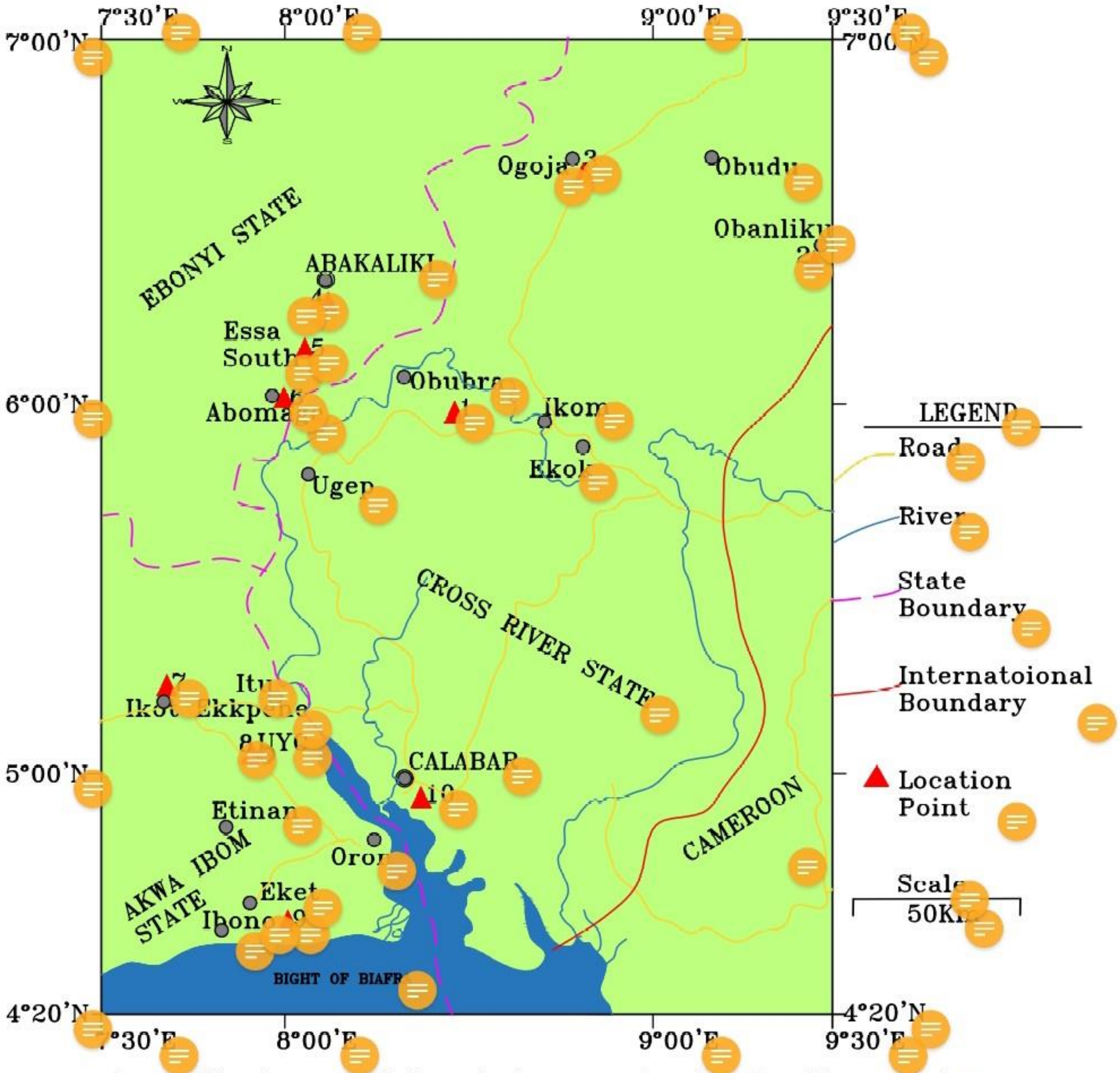
This multi-parameter approach ensures accurate assessment of how solid-state device behavior (PV cells) responds to environmental variations across different locations.

Each instrument plays a critical role in linking solid-state physics with real-world environmental conditions. The PV module operates on semiconductor principles, while supporting instruments measure environmental variables that directly influence charge carrier dynamics, recombination rates, and overall system efficiency. Together, they provide a robust framework for evaluating and comparing PV performance across diverse climatic zones.

Study Area

The study was conducted across selected locations in Ebonyi State, Cross River State, and Akwa Ibom State, representing inland, midland, and coastal climatic zones. These locations include Abakaliki, Ezza South, Abomege, Ogoja, Obanliku, Obubra, Calabar, Uyo, Ikot Ekpene, Eket.

The geographical spread allows for the investigation of PV performance under varying environmental conditions such as solar irradiance, temperature, humidity, and wind speed.



An outlined map of the study area showing location points

Method

Field measurements were conducted across multiple representative locations spanning inland, midland, and coastal climatic zones. Key environmental parameters including solar radiation (W/m²), ambient temperature (°C), panel temperature (°C), and relative humidity (%) were recorded at regular intervals throughout the day (morning to evening) using calibrated instruments comprising a digital solar power meter, thermo-hygrometer, and contact/non-contact temperature sensors. PV module output parameters were simultaneously monitored using a digital MPPT solar meter. The collected data were analyzed to evaluate the diurnal trends and inter-parameter relationships. Comparative analysis across locations was performed to assess spatial variability in environmental conditions and PV response.

RESULTS AND DISCUSSION

The results reveal a consistent diurnal pattern, with solar radiation increasing from near-zero values in the early morning to peak values of approximately 900–1400 W/m² around midday (12:00–14:00 h), followed by a gradual decline. Ambient temperature exhibits a corresponding increase, while panel temperature consistently exceeds ambient temperature due to solar heating and internal energy dissipation within the semiconductor structure, reaching values between 40 °C and 70 °C. Relative humidity shows an inverse relationship with irradiance and temperature, decreasing during peak solar periods and increasing toward morning and evening.

From a solid-state perspective, elevated panel temperature leads to reduced PV efficiency through enhanced carrier recombination and a decrease in open-circuit voltage, expressed as:

$$V_{oc} \propto \ln\left(\frac{I_{ph}}{I_0}\right)$$

where the saturation current I_0increases exponentially with temperature. Additionally, the intrinsic carrier concentration follows:

$$n_i \propto T^{3/2} e^{-\frac{E_g}{2kT}}$$

leading to increased recombination losses at higher temperatures.

Comparative analysis indicates that inland locations with higher irradiance exhibit greater power potential but also higher thermal losses, whereas coastal and humid regions experience reduced effective irradiance due to atmospheric attenuation. These findings highlight the critical interplay between environmental conditions and semiconductor physics in determining PV performance.

The study provides empirical insights for optimizing photovoltaic systems in tropical climates and emphasizes the importance of location-specific environmental assessment for improving solar energy conversion efficiency in Nigeria. The results are presented graphically as;

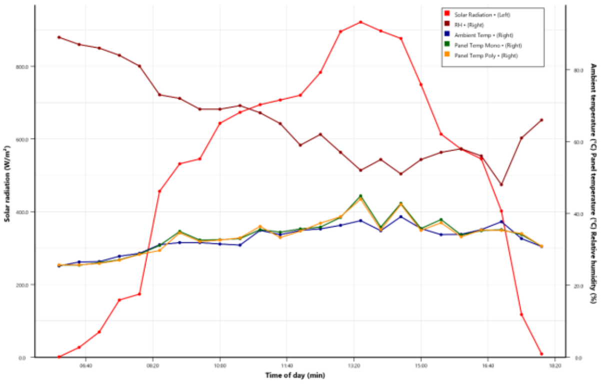


Figure 6a: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Abakaliki

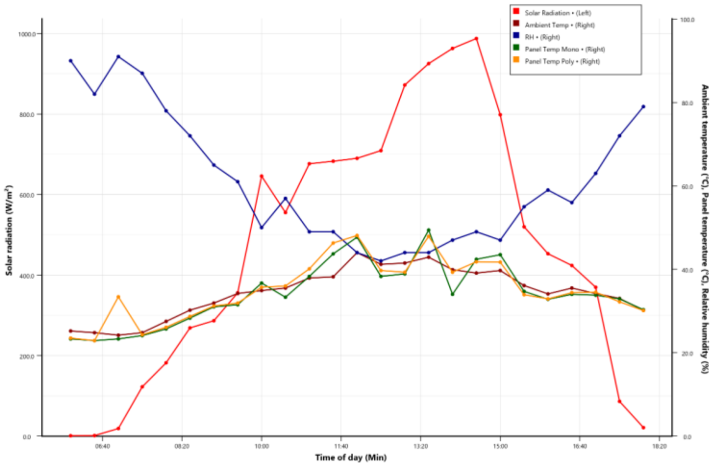


Figure 6b: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Abomege

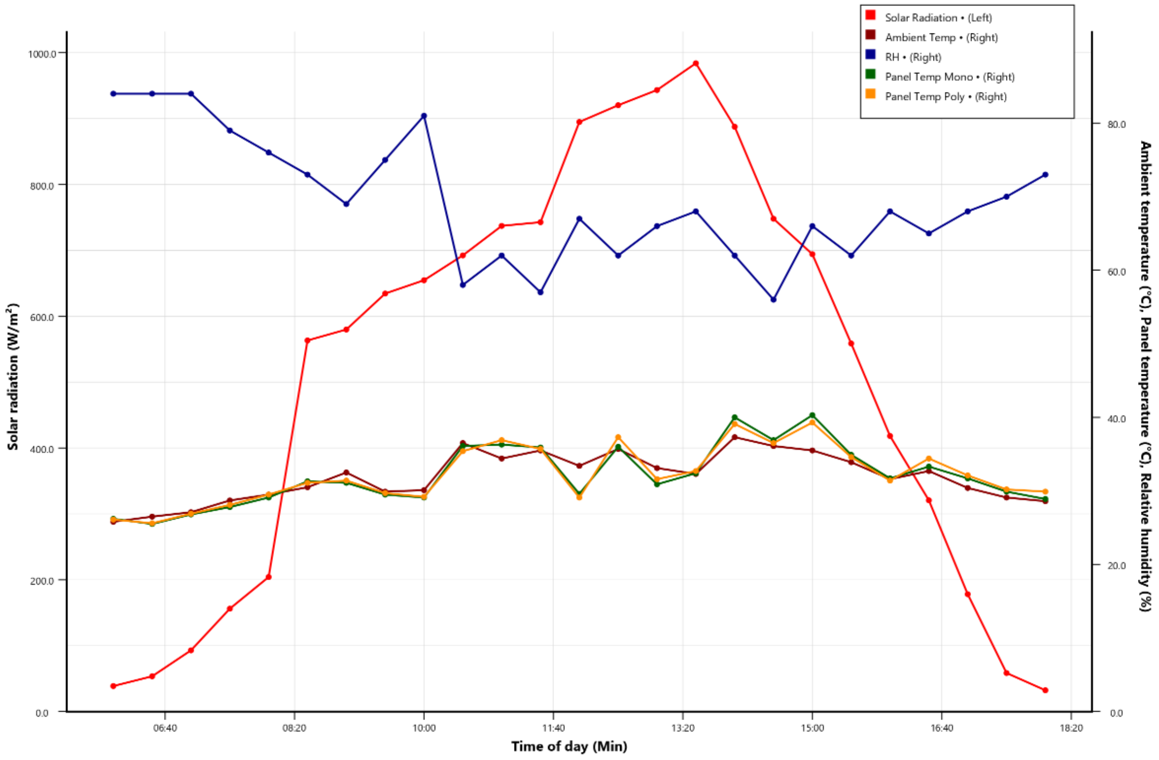


Figure 6c: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Calabar

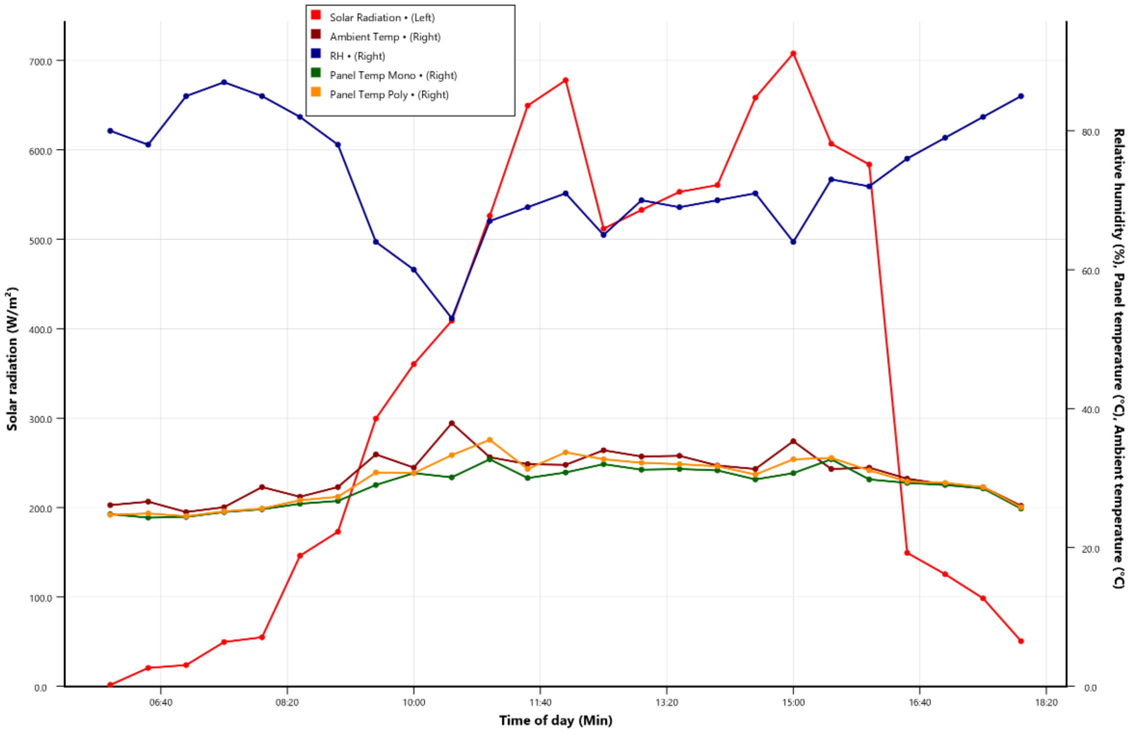


Figure 6d: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Eket

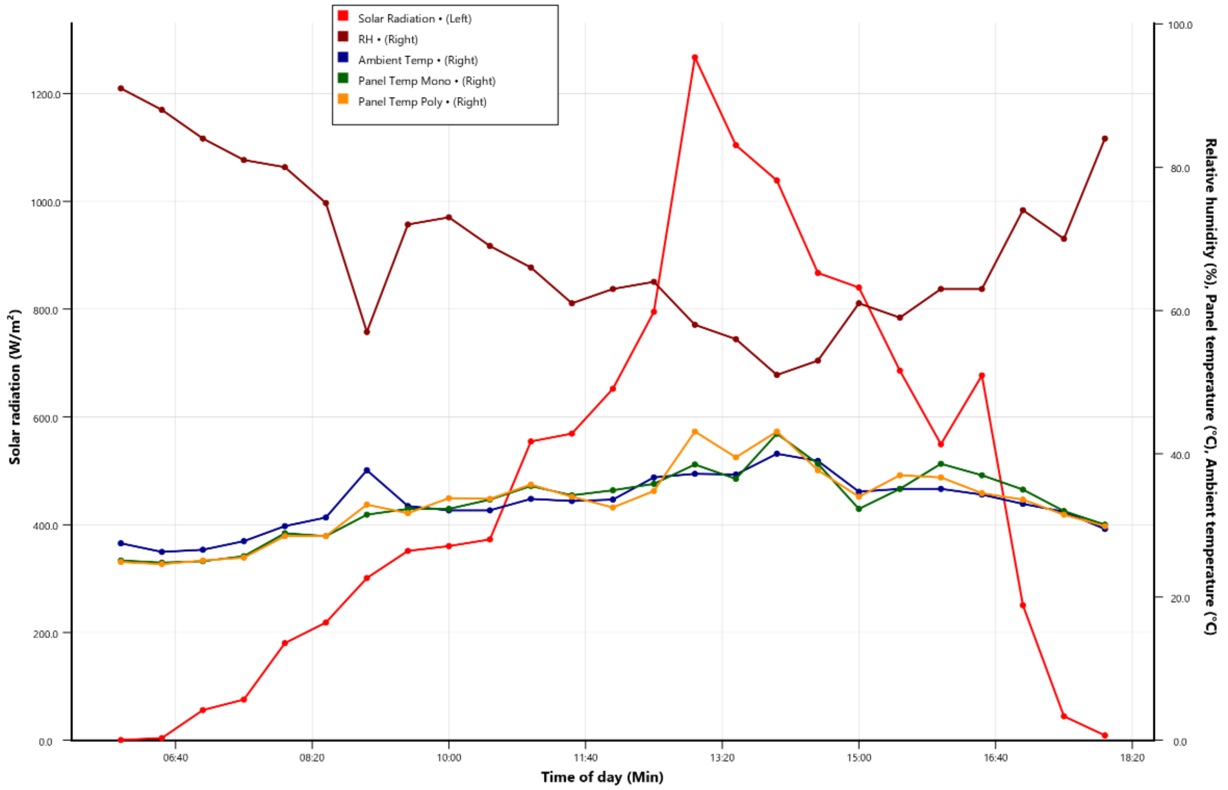


Figure 6e: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Ezza south

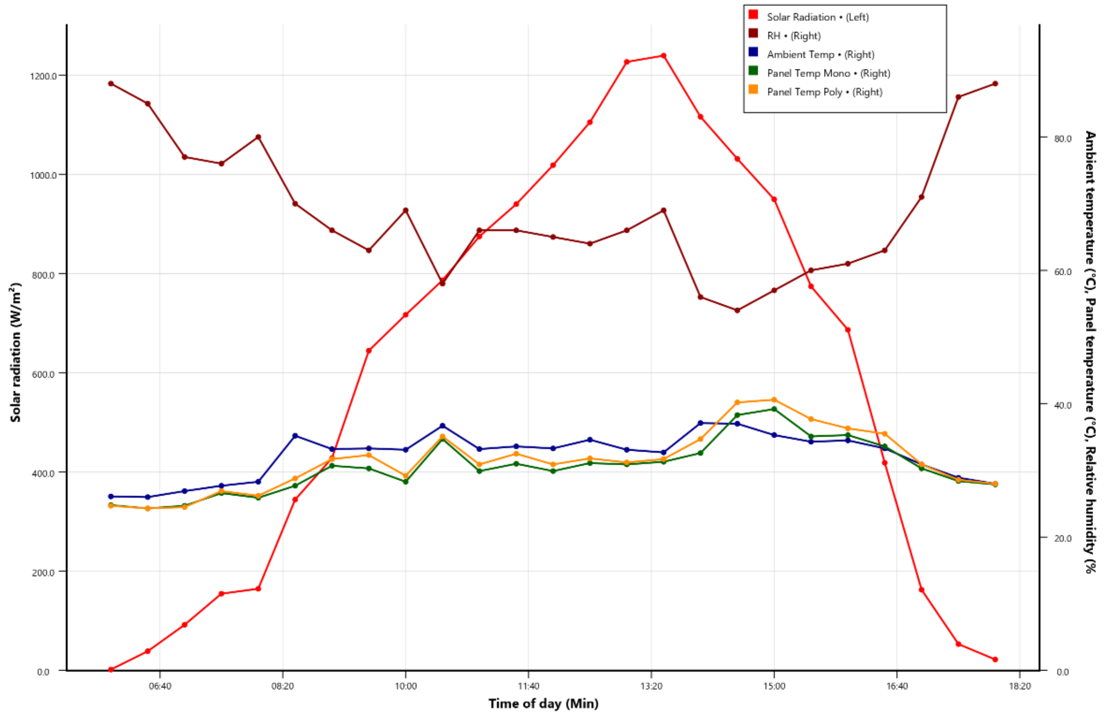


Figure 6f: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Ikot Ekpene

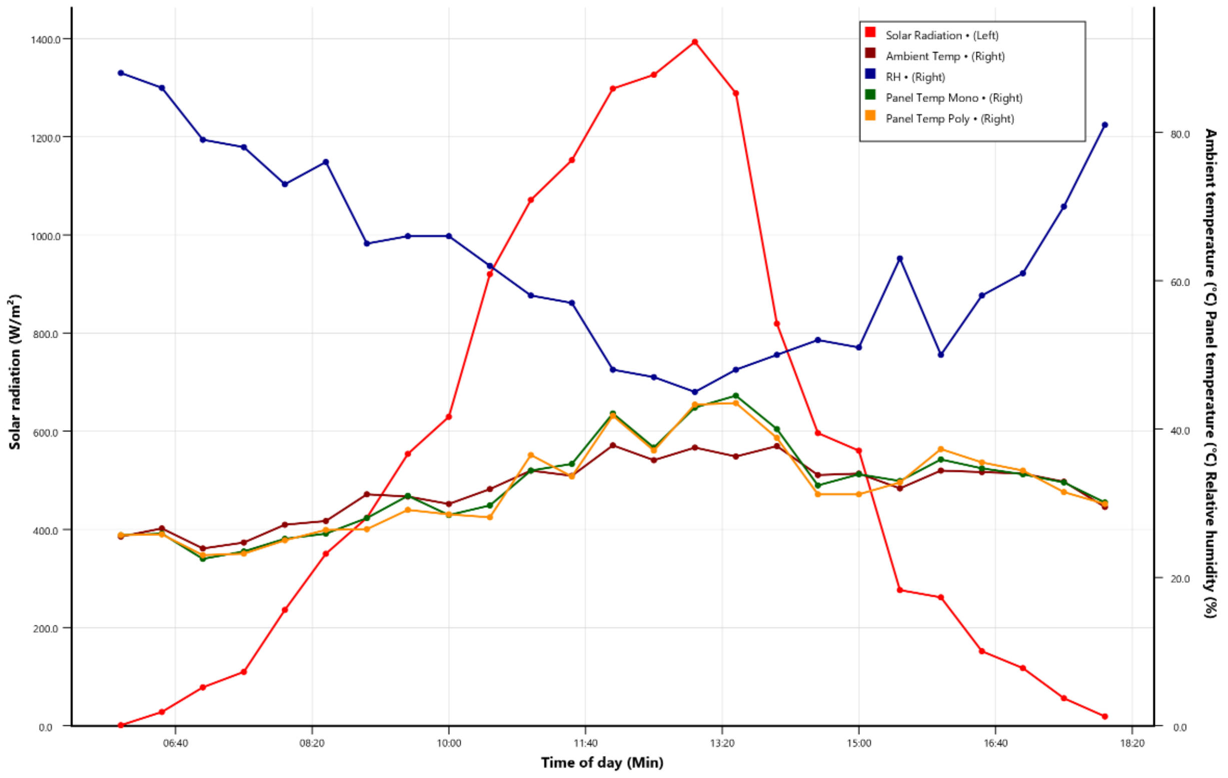


Figure 6g: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Obanlikwu

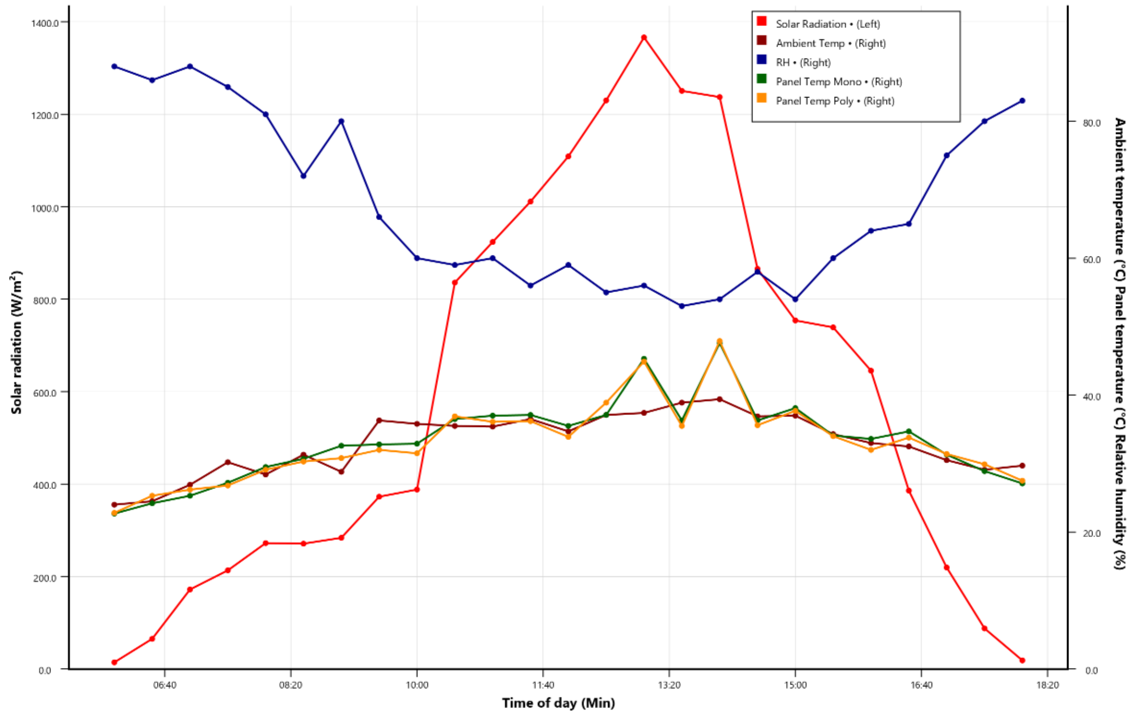


Figure 6h: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Obubra

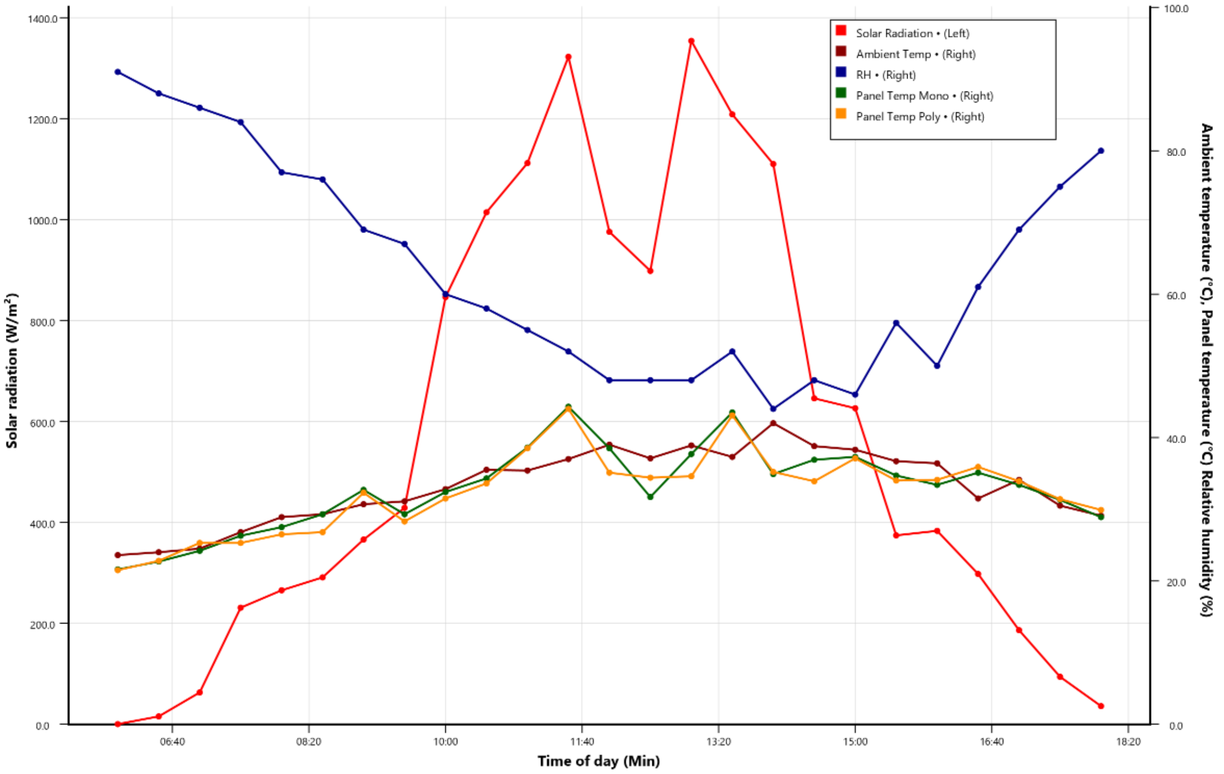


Figure 6i: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Ogoja

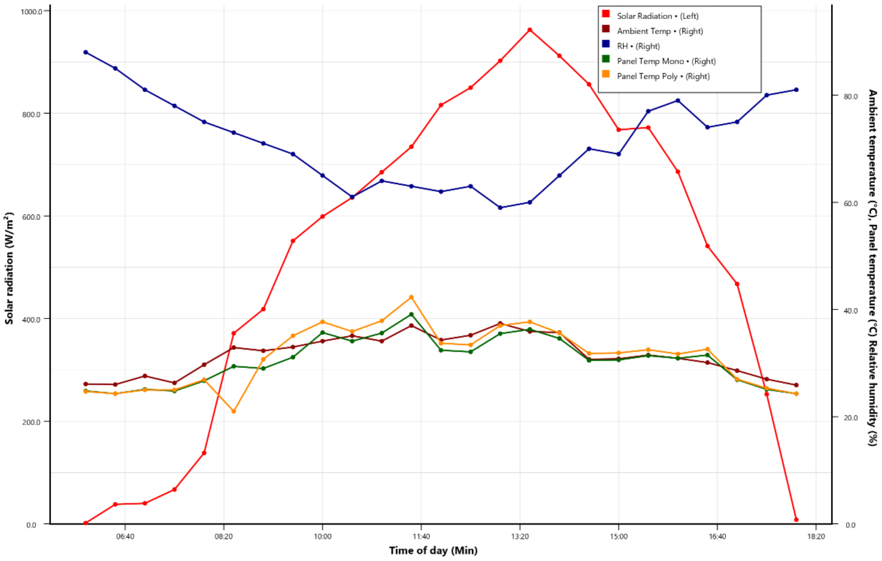


Figure 6j: Graph of Solar radiation (W/m^2), Ambient temperature (°C), Panel temperature (°C), Relative humidity (%) against Time of day (Min)

Location: Uyo

Figures 6a to 6j shows a consistent diurnal pattern of solar radiation, ambient temperature, panel temperatures (mono and poly), and relative humidity (RH), with notable spatial variations. All sites exhibit a typical diurnal solar cycle, where solar radiation starts near zero in the early morning, increases steadily to a peak around midday (12:00–14:00), and declines toward evening. Correspondingly, ambient and panel temperatures increase with solar radiation, reaching their maximum slightly after peak radiation due to thermal lag. In all cases, panel temperatures (mono and poly) are higher than ambient temperature, with very small differences between mono and poly modules, indicating similar thermal behavior.

An inverse relationship between solar radiation and relative humidity is also evident across all locations. RH is highest in the early morning, decreases toward midday as temperature and radiation increase, and rises again in the evening.

Highest radiation levels are observed in Obubra (6h), Ogoja (6i), Ikot Ekpene (6f), and Obanlikwu (6g), with peaks exceeding 1200–1400 W/m². Moderate radiation occurs in Ezza South (6e), Abomege (6b) and Abakaliki (6a) while Lowest radiation is seen in Eket (6d), Calabar (6c), and Uyo (6j) respectively where peaks are significantly reduced.

In terms of stability, Obanlikwu (6g) and Ogoja (6i) show smoother curves, indicating stable atmospheric conditions. Obubra (6h) and Ikot Ekpene (6f) exhibit noticeable fluctuations, suggesting intermittent cloud cover. Also, Coastal locations (Calabar, Eket, Uyo) show flattened and suppressed radiation profiles, likely due to persistent cloudiness and moisture.

Again, locations with higher radiation (Obubra, Ogoja, Ikot Ekpene) also record higher panel temperatures (≈45–55°C). Coastal areas (Calabar, Eket, Uyo) have lower panel and ambient temperatures, rarely exceeding ~40–45°C while (Abakaliki, Abomege, Ezza South) show moderate temperature levels. This confirms a strong positive correlation between solar radiation and temperature.

High RH levels are prominent in Calabar, Eket and Uyo throughout the day, even at peak radiation periods. Lower RH values are observed in inland/northern locations like Ogoja, Obanlikwu and Abomege.

This suggests that coastal regions experience persistent atmospheric moisture, which reduces solar radiation reaching the panels and lowers PV performance. Therefore Ogoja, Obanlikwu and Ezza South are seen as the best performed locations because of their high radiation values, relatively stable profiles and moderate humidity. While Eket, Calabar and Uyo are the least performed locations because of their high relative humidity values, lower radiation and reduced temperature response.

Conclusively, figure 6a-6j reveals that geographical location significantly affects PV performance. Inland and northern areas generally experience higher and more stable solar radiation with lower humidity, making them more suitable for solar energy generation. In contrast, coastal regions are characterized by high relative humidity and reduced solar intensity, which negatively impacts panel efficiency.

Additionally, the similar behavior of mono and poly panels across all locations suggests that environmental conditions have a greater influence on performance than panel type in this study

CONCLUSION

The study demonstrates that while high solar irradiance enhances photocurrent generation and power output, elevated panel temperatures significantly reduce PV efficiency due to temperature-dependent semiconductor losses. Inland locations with higher irradiance offer greater energy potential but require thermal management strategies, whereas coastal regions experience reduced performance due to humidity and atmospheric attenuation. These findings highlight the importance of location-specific optimization of PV systems and provide a solid-state-based framework for improving photovoltaic performance in tropical climates such as Nigeria.

Recommendation

It is recommended that PV installations in high-irradiance inland regions incorporate effective thermal management systems such as natural ventilation, heat sinks, or active cooling mechanisms to reduce panel temperature. In humid coastal regions, anti-corrosion coatings and regular maintenance should be employed to mitigate moisture-related degradation. Furthermore, location-specific environmental assessment should be prioritized in PV system design and deployment to optimize energy yield and long-term performance in tropical climates such as Nigeria.

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