

# Assessment of Temperature-Dependent Variation in Power and Voltage Output of Photovoltaic System in Abuja, Nigeria

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**ABSTRACT:** This study investigates the effect of temperature on the power and voltage output of photovoltaic (PV) systems deployed in Abuja, Nigeria. Meteorological data, specifically temperature and solar irradiance, were obtained from the Nigerian Meteorological Agency (NiMet), Abuja headquarters. The data were recorded at five-minute intervals over a two-year period (2021–2022) to capture temporal variations and to establish correlations between temperature fluctuations and PV system performance. Descriptive statistical tools were employed to analyze the relationship between local temperature, power, and voltage, thereby determining the extent of correlation between temperature and PV output. The results showed that power output ranged from  $-752.74$  W to  $313.83$  W, with a mean value of  $-219.46$  W, while voltage ranged from  $12.09$  V to  $14.42$  V, with a mean of  $13.26$  V. The average monthly temperature in Abuja during the study period varied between  $25.72^{\circ}\text{C}$  and  $33.01^{\circ}\text{C}$ , with a mean of  $29.37^{\circ}\text{C}$ . Graphical analyses of power output and voltage against temperature revealed a consistent inverse relationship across all months. The study concludes that both power output and voltage are strongly and inversely affected by temperature, thereby challenging the assumption that operating solar panels above  $25^{\circ}\text{C}$  enhances solar energy performance.

**KEYWORDS:** Photovoltaic, Meteorological Data, Temperature, Voltage

## I. INTRODUCTION

Photovoltaic (PV) technology converts solar radiation into electricity. While first-generation cells were silicon-based, advancements like thin-film and amorphous silicon cells have been developed to improve sunlight absorption and efficiency (Mugdha et al., 2021). The global capacity of PV systems is immense, reaching 505 GW by 2018 after an addition of 100 GW that year (Renewables 2019 Global Status Report, 2019). Globally, approximately 85% of energy demand is met by fossil fuels. Rapid population growth, urbanization, and economic expansion are projected to increase this demand by 50% by 2050 (Sokan, 2015), a figure corroborated by Chowdhury et al. (2020), who forecast a 48% rise by 2040. In 2020, the global energy consumption breakdown was 83% fossil fuels, 12.6% renewables (hydro, wind, solar), and 6.3% nuclear power. Achieving fossil fuel independence by 2050 would require a six to eight-fold increase in renewable energy production if demand remains at or rises 50% above 2020 levels. However, if global demand only increases by 25%, this goal becomes far more attainable (Holechek et al., 2022). In Nigeria, rising temperatures remain a major challenge for PV performance (Ogunjo et al., 2020), which is also subject to periodic fluctuations. Abuja is one of the fastest growing cities capitals in Africa and becoming a business hub hosting almost all of the company's headquarters that makes it a decision-making city and the city's rising population growing with the internet of things, hence the need for constant and steady supply of power using renewable energy source. Thus far, the average daily sunshine of Abuja is about 6 to 11 hours per day though varying between months, there is the urgent need for solar energy harvest. Therefore, this study aims to assess the power and voltage output of photovoltaic systems in relation to local temperature variations in the Federal Capital Territory, Abuja, Nigeria.

## II. RELATED WORKS

Energy is a fundamental driver of development and human progress in developing nations (Abdullah et al., 2015). Its consumption is deeply interconnected with environmental quality and the availability of other critical resources like water and food (Lior, 2011). This is particularly relevant in nations like Nigeria, which faces a significant energy deficit. Despite a population of over 200 million, Nigeria's installed electricity generation capacity is only 12,552 MW. In stark contrast, South Africa, with a population of approximately 60 million, generates about 58,000 MW (Umar et al., 2021). The World Bank identifies Nigeria as having the world's largest absolute energy access deficit, with 45% of its population around 90 million people lacking a connection to the national grid. A further disparity exists between urban areas, where 84% have access, and rural areas, where access plummets to 26%. While Nigeria's infrastructure has the theoretical capacity to transmit over 15,000 MW, outdated systems limit actual transmission to less than 5,000 MW from the roughly 13,000 MW generated. This amount is grossly insufficient for its vast population (Ayobami and Godwin, 2024). The sustained adoption of renewable energy is crucial for reducing dependence on fossil fuels (Igbokwe et al., 2022). Its environmental benefits continue to drive its popularity, positioning it as an indispensable power source for the future (Ndukwu et al., 2022). Adequate investment and effective deployment of solar energy, for instance, could help mitigate the issues tied to fossil fuel combustion (Kazem et al., 2015). This aligns directly with United Nations Sustainable Development Goal (SDG) 7, which advocates for affordable and clean energy by 2030 through the promotion of renewables (Ezealigo et al., 2021).

Solar energy stands out as one of the most abundant renewable resources. It is sustainable, pollution-free, silent, relatively inexpensive, and easy to maintain. Nigeria possesses enormous solar potential, with average daily solar irradiance of 7.0 kWh/m<sup>2</sup> in the north and 4.0 kWh/m<sup>2</sup> in the south, indicating a higher potential in the northern region (Ohiero and Ogbeche, 2018). Solar radiation—the energy per unit area received from the sun—is measured in kilowatt-hours per square meter (kWh/m<sup>2</sup>) (Steven Kwok, 2023). As an emerging economy, Nigeria has significant untapped potential in this and other renewable resources (Orisaleye et al., 2018), a fact echoed by Mas'ud et al. (2015), who confirmed high solar and wind potential in Nigeria and Cameroon. PV systems are rated under Standard Test Conditions (STC: 25°C, 1.0 kW/m<sup>2</sup> irradiance). However, real-world performance often deviates due to atmospheric conditions. A key factor is the temperature coefficient, which dictates how much a panel's efficiency decreases as its temperature rises (P. K. Dash & N. C. Gupta, 2015). Research shows PV efficiency is highly sensitive to heat. For example, in hot climates like Niamey, temperatures above 33°C cause a significant performance decline (Dajuma et al., 2016). Conversely, cooler temperate regions and higher altitudes generally offer better generation potential (Panjwani and Narejo, 2014). This is supported by findings that PV systems at higher altitudes yield greater efficiency due to lower temperatures (Aglietti & Tatnall, 2008; Sri Rama Phanindra Chitturi et al., 2018). One experiment demonstrated a 42% efficiency increase at 1,764 meters above sea level compared to 612 meters (Sri Rama Phanindra Chitturi et al., 2018). Even minor elevation gains can optimize output, with observed power increases of 7–12% at 27.4 meters above sea level (Panjwani & Narejo, 2014).

## III. METHODOLOGY

### A. Study Location and Data Collection

Meteorological data for this study, including temperature, humidity, and solar irradiance, were sourced from the headquarters of the Nigerian Meteorological Agency (NiMet) in Abuja. The city features a tropical wet and dry climate and is situated at an average elevation of approximately 455.89 meters above sea level (Nigerian Meteorological Agency [NiMet], n.d.). Its geographic coordinates are 9.07°N latitude and 7.60°E longitude, encompassing an area of 1,769 square kilometers. The topography immediately surrounding the city (within a 3.2 km radius) is characterized by relatively modest elevation changes. The maximum elevation shift in this area is 143 meters, with an average altitude of 494.7 meters above sea level (NiMet, n.d.). In terms of land cover, the city is predominantly composed of artificial surfaces (77%) and cropland (22%). On a broader scale, the landscapes within 16.1 km and 80.5 km of the city center are largely a mix of cropland and shrubs, accounting for 37% and 43% of the area, respectively. Abuja experiences annual temperatures that typically fluctuate between a low of 16.6°C and a high of 33.9°C (NiMet, n.d.). The hottest period lasts roughly 2.5 months, during which average daily high

temperatures exceed 32.2°C. A cooler season spans approximately 3.5 months, where average highs remain below 28.3°C. December is the coldest month, with average lows of 16.1°C and highs of 30.6°C. The city's clearest weather begins around November 7th and lasts for about 3.6 months, with January standing out as the clearest month. In contrast, a cloudier period starts around February 24th and persists for about 8.4 months, reaching its peak in May. The wet season extends for 6.2 months and carries a greater than 42% probability of precipitation on any given day. This is counterbalanced by a 5.8-month dry season; December has the fewest number of rainy days. August is the wettest month, while December is the driest. Daylight hours in Abuja remain relatively consistent year-round, averaging about 12 hours with only minor variation. Conversely, humidity levels shift significantly with the seasons. A muggy and often uncomfortable period lasts for about nine months, from late February to late November. During this time, conditions are humid or oppressive for at least 27% of the time. August is the most humid month, with nearly all 31 days classified as muggy or worse (NiMet, n.d.).

## B. Materials

The used materials along with their functions are itemized below:

- (a). 72-cell poly crystalline panel, at the Module Efficiency  $\eta$  (%) of 17.0, with an area of 1m×2m, maximum power of 330w ± 2.5%, maximum power voltage 37.4v, Maximum power current (Imp) A 8.83A, Open circuit voltage (Voc) V 45.8 V, Short circuit current (Isc) A 9.28A ± 4%, Maximum system Voltage 1000 V.
- (b). Pyrometer for measuring solar radiation
- (c). Thermometer for measuring air temperature
- (d). Barometer for measuring atmospheric pressure
- (e). Anemometer for measuring wind speed
- (f). Hygrometer for measuring humidity
- (g). Charge control
- (h). Cables/wires
- (i). Panel metal stand
- (j). Laptop

## C. Data Analysis and Model Used

The temperature dependence of a material is described with a temperature coefficient. The general equation for estimating the voltage of a given PV system at a given temperature is:

$$V_{estimated} = T_{coefficient} \times (T_{STC} - T + V_{Ocrated}) \tag{1}$$

Where  $V_{OC}$  is open circuit voltage given as 24V,  $T_{STC}$  is temperature at standard test condition (25°C, 1000 W/m<sup>2</sup> solar irradiance and 1.5 G air mass)  $T$  is the temperature of the location measured in °C. Every solar panel has a temperature coefficient. This indicates how much the panel's efficiency decreases for every degree above its standard testing condition. Equation (1) is used for the calculation of estimated voltage of the system in this research work. Temperature effect on the PV efficiency (output power) can be estimated using the equation below:

$$P_t = P_{st} \times [1 + \alpha (T_c - T_s)] \tag{2}$$

Where:

$P_t$  = power at temperature  $T_c$

$P_{st}$  = power at standard testing condition (usually 25°C)

$\alpha$  = Temperature coefficient of the panels

$T_c$  = operating temperature of the panels in °C

$T_s$  = standard testing temperature (usually 25°C)

## IV. RESULTS AND DISCUSSION

An analysis of temperature's impact on photovoltaic (PV) output power in Abuja was conducted for January 2021 and 2022. The results indicate a complex relationship, where the system's power output responds to temperature changes in diverse ways. For instance, in January 2021, a clear inverse correlation was observed on days 9 through

13 and on day 31, where higher ambient temperatures corresponded with a measurable decrease in power output. A similar pattern was recorded in January 2022 on days 12 and 26 through 31, when peak temperatures had an adverse effect on the system's performance. This phenomenon is attributed to the negative temperature coefficient of power inherent in solar panels, meaning their electrical output decreases as their operational temperature rises.

The impact of temperature variation was even more pronounced during February of both years. Data shows that higher temperatures consistently correlated with reduced power generation across all measured days in February 2021 and 2022. The consistent trend of declining power output suggests that as temperatures increase, the panels' efficiency drops significantly. Under extreme heat, solar panels can operate outside their optimal temperature range, leading to reduced efficiency and potentially causing them to consume energy rather than generate it, which would explain the negative power values. This pattern of heat-induced efficiency loss is a critical factor affecting PV performance throughout the year in Abuja's climate.

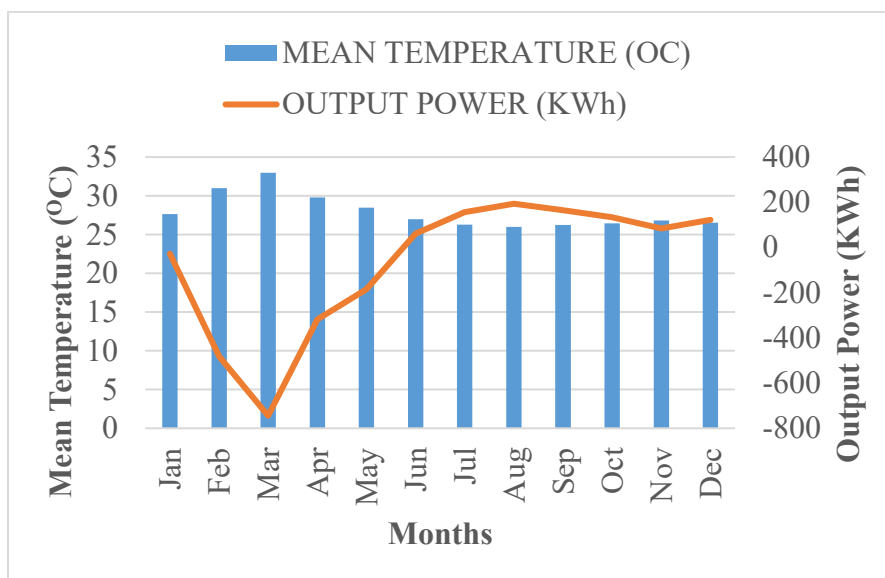


Figure 1: Abuja 2021 Mean Temperature (OC) against Output Power (KWh)

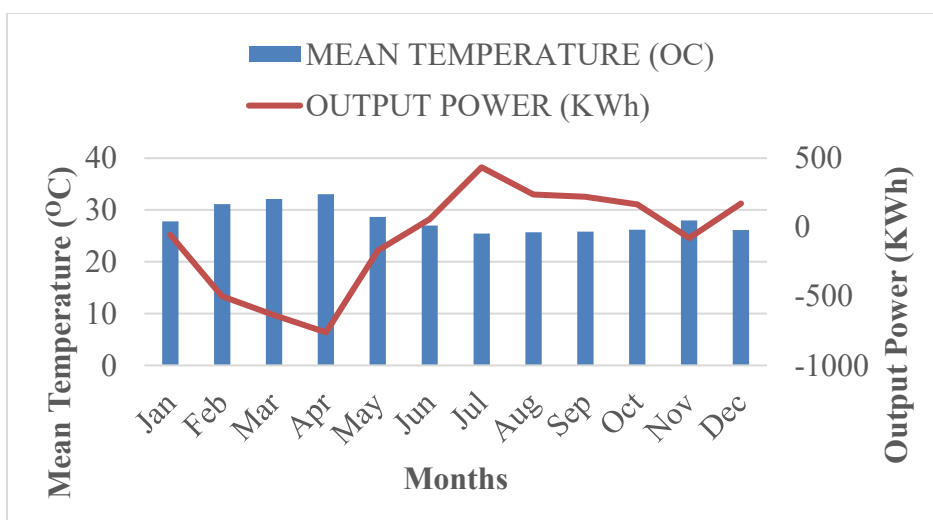


Figure 2: Abuja 2022 Mean Temperature (OC) against Output Power (KWh)

Figures 3 and 4 illustrate the relationship between ambient temperature and the output voltage of a photovoltaic (PV) system in Abuja for the years 2021 and 2022. The data shows a clear seasonal temperature trend. The year begins with a gradual warming period, as temperatures rise from 27.64°C in January to a peak of 32.96°C in March. While April remains quite warm at 29.78°C, a cooling trend begins, with temperatures declining slightly in May (28.47°C) and more noticeably in June (26.98°C). This decrease continues into July (26.27°C) and August (26.00°C), after which the temperature stabilizes with a minor increase in September (26.22°C). Overall, the annual temperature fluctuates within a moderate range, characterized by a warming phase from January to March, followed by a cooling period from April onward. Critically, the results demonstrate the adverse effect of heat on PV system performance. This is most evident in the data from March 2021, where the highest recorded temperature directly correlated with a significant drop in the system's output voltage. This inverse relationship confirms that increased heat reduces the efficiency and voltage output of the solar panels.

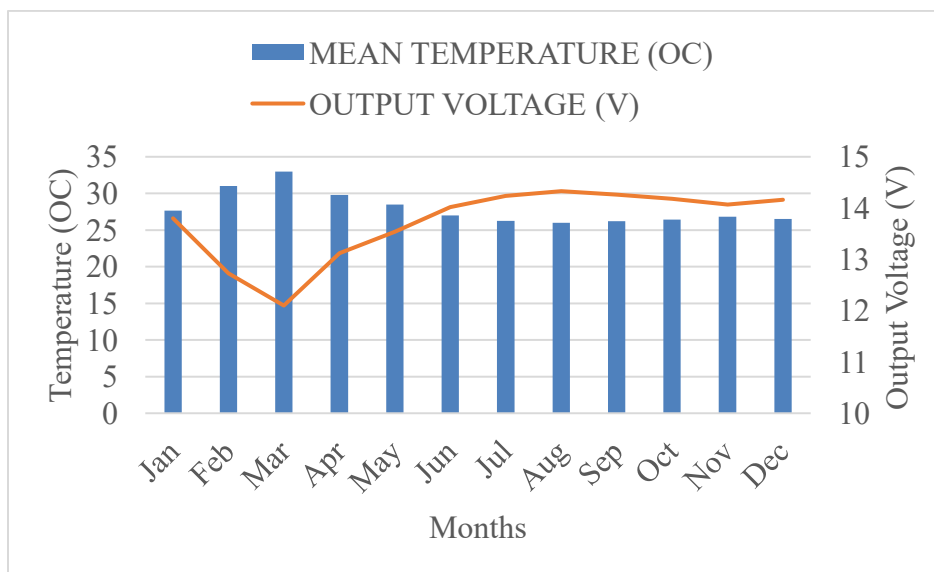


Figure 3: Abuja 2021 Mean Temperature (OC) against Output Voltage (V)

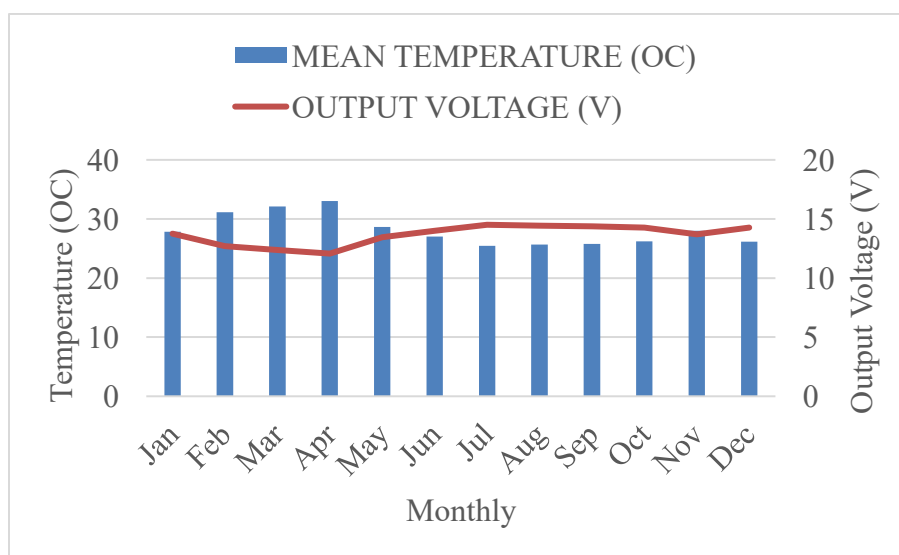


Figure 4: Abuja 2022 Mean Temperature (OC) against Output Voltage (V)

V. CONCLUSION

A study was conducted in Abuja to examine the influence of temperature on the performance of photovoltaic (PV) systems. Throughout the study period, temperature fluctuations were relatively moderate, showing a general trend of gradual increase from January to March (warmer months), followed by a decline between April and June (cooler months), with additional variations observed in the subsequent months. The study revealed that output power exhibited only slight changes with increasing temperature, whereas voltage showed a more pronounced decline as temperature rose. Overall, higher temperatures were associated with reduced output power, indicating an adverse effect on PV system performance. These variations are partly attributed to Abuja's relatively low altitude and the high ambient temperatures commonly experienced in such regions. The research also examined the spatial distribution of PV energy potential, accounting for the combined effects of both irradiance and temperature on system efficiency. Furthermore, it was noted that temperature alone does not fully explain the performance variations. Other contributing factors likely include the PV module design, the materials used in manufacturing, inherent efficiency characteristics, and broader environmental conditions.

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