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Assessment of the performance of Photovoltaic system in high altitude region of Jos, Nigeria

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Abstract: This study examined two years of temperature, humidity, and irradiance data collected at intervals of fiv minutes for the city of Jos, Nigeria to determine the relationship between temperatures Photovoltaic system voltage, and power output. Descriptive statistical tools were used to investigate the relationship between temperature, power output, and voltage. There is a wider range of responses to temperature change in the output power. The findings showed that the power output values range from 227.82 kWh to 950.10 kWh, and Voltage values range from 14.41 V to 16.12 V. Additionally, the average monthly temperature ranged from 20.42 ℃ to 25.76 ℃. The result shows a positive correlation between temperature below standard test condition (STC = 25 ^{o}C), and high output power, while a high temperature above STC negatively affects the output power. Notably, Jos has a higher power output and voltage while maintaining the lowest average temperature compared to other locations within the region. The study concludes that power output and voltage are strongly and inversely related to temperature, refuting the notion that operating solar panels above STC would improve performance.

1. Introduction

Energy is significant to the development and human accomplishment of any country, especially developing nations (Abdullah et al., 2015). There is a correlation between energy resources and consumption and environmental quality and other vital resources like food and water (Lior, 2011). Nigeria, with a population of over 200 million had an installed electricity generating capacity of 12,552 MW while SSouth Africa with a population of 60 million has a capacity of 58,000 MW (Umar et al., 2021). According to a recent World Bank analysis, Nigeria has the world's highest absolute energy access deficit, with 45 percent of the population (90 million) unable to connect to the grid. Access to electricity varies greatly between urban (84%) and rural areas (26%). Nigeria should be able to transmit over 15,000 megawatts (MW) of energy, however due to inadequate and aging infrastructure, it transmits less than 5000 MW of the approximately 13,000 MW of electricity generated to its over 200 million residents (Adedinni and Jimoh, 2024).

On average, 85% of the global energy demands are satisfied through energies from fossil fuels, and these demands are projected to increase by 50% by 2050; this is because of an increase in population, urbanization, and economic growth (Sokan-Adeaga and Ana, 2015). Chowdhury et al. (2020) estimated that by 2040 the energy demand would steadily increase by 48%.

In 2020, fossil fuels, renewable (hydro, wind, and solar), and nuclear sources accounted for 83%, 12.6%, and 6.3% of global energy consumption, respectively. To attain zero

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dependence on fossil fuels by 2050, energy from renewable sources production must increase by up to six or eight times, assuming that the energy need remains stable or grows by 50% compared to 2020. Minimizing 2050 global energy demand to a 25% increase over 2020 increases the chances of reaching its independence from fossil fuels (Holechek et al., 2022).

According to Igbokwe et al., 2022, continuous use of renewable energy sources could help in the shift away from fossil fuels. The anticipation is that energy from renewable sources will continue to play an important role as an essential form of energy in the future. Energy generated from renewable sources is becoming increasingly popular due to the environmental advantages it offers (Ndukwu et al., 2023). Adequate investment and proper utilization and implementation of solar energy as a source of electricity and thermal energy will help do away with issues caused by the burning of fossil fuels (Kazem et al., 2015).

Renewable and sustainable energy is important to realizing the UN SDG number 7 (affordable and clean energy) by 2030 (Ezealigo et al., 2021).

The solar energy system is one of the most abundant energy sources on earth. It is a renewable source of energy that is free from pollution, noiseless, and easy to maintain. Nigerian a sub-Sahara nation has in excess solar energy potentials, the daily solar irradiance in the Northern part of the country is 7.0 kWh/m^2 and 4.0 kWh/m^2 for the southern region of the country. This suggests that the north has higher solar irradiance compared to the South (Ohiero and Ogbeche 2018).

Solar irradiance is the energy per unit area received from the sun as electromagnetic radiation within the wavelength of the measuring instrument, usually in kilowatt-hours per square meter (kWh/m^2) (Kwok, 2023).

Solar energy, a type of renewable energy, is naturally available and abundant throughout the world, and it can be used directly for basic needs (Ndukwu et al., 2021). Nigeria is one of the emerging economies that have a plentiful stock of available renewable energy resources with much potential (Orisaleye et al., 2018). Mas'ud et al. (2015), in their work, confirmed that there are high potential for solar radiation and wind speed in Nigeria and Cameroon. His work also reviewed the abundance of energy resources that can stimulate economic growth and make available adequate capacity to meet present and future energy needs.

Solar photovoltaic technology converts incident solar radiation into electrical energy. Solar cells made with silicon are the first generation of solar cells. It was discovered that more improvement is required for the massive absorption of incoming sunlight and increased efficiency of solar cells. To meet these specifications, thin film technology and amorphous silicon solar cells were developed (Dambhare et al., 2021).

Photovoltaic (PV) systems have the potential to power the entire world's electricity production. One hundred gigawatts (GW) were added in 2018, bringing the total capacity of installed photovoltaic systems to 505 GW globally (REN21, 2024).

The rating of PV modules is on ideal condition, standard test condition (STC) i.e. at the temperature of 25 ^{o}C, irradiance of 1.0 kWh/m^{2,} and solar spectrum of air mass 1.5G. The real output of the PV modules varies from its rated output due to changes in atmospheric conditions from the STC. Temperature coefficient which varies with the type of technology used for the solar modules determines the decrease in the output due to temperature (Dash and Gupta, 2015).

Dajuma et al. (2016) in their research findings state that the efficiency of a PV system is sensitive to temperature change, particularly climate conditions in Niamey (warmer than Abidjan) where temperature exceeding 33 ^{o}C cause a drastic drop in PV efficiency. Cold climate locations are likely to have better power generation potentials from PV systems, since at low temperatures the efficiency increases. At high altitudes, PV systems generate more energy compared to sea-level installations (Panjwani and Narejo, 2014).

Latest studies indicate that at high altitudes, PV systems produce better solar power and are more efficient than at sea level, (Aglietti, et al., 2008). There is a general trend of temperature decrease with height, so it is on mountains. There is a possibility of a temperature inversion effect on such regions, though there is a consideration that the effect on solar power will be less since the effects are common in the winter season (low general temperature) and nighttime (Chitturi et al., 2018). Results of two experimental setups of systems installed at a height of 612 meters and 1764 meters on the mountain illustrate an increase in efficiency of 42% for the system installed at a higher altitude of 1764 meters above the ground (Chitturi et al., 2018).

Experiment shows a power increase of 7-12% when the solar panel was installed at an altitude 27.432 m above the ground level, which is known as the likely and easy way to utilize fewer resources to get maximum power output (Panjwani and Narejo, 2014). Seasonal fluctuations were found to affect the monthly mean production of solar power systems in the four locations studied. It is therefore found that rising temperatures are a major issue limiting PV generation in Nigeria. (Ogunjo et al., 2021). Therefore, this study is aimed at Evaluating the power and voltage output of photovoltaic systems, the relationship between temperature and Photovoltaic output power and voltage; and relating the output power and voltage of Photovoltaic systems to local temperature in the city of Jos, Nigeria.

2. Materials and methods

2.1 Study Location

The city of Jos is located in the North Central region of Nigeria. The Jos temperature is more temperate than that of the remainder of Nigeria because it elevated 1,217 m (3,993 ft) above sea level, with Coordinates of 9.55°N and 8.25°E.

The lowest nighttime temperatures are 7°C from mid-November to late January, with an average monthly temperature of 21–25°C. Artificial surfaces and cropland make up 15% of the area, followed by cropland and shrubs for 16.1 km (16%), and cropland and shrubs for 80.5 km (21%). The 2.5-month hot season, which runs from February 11 to April 27, has daily highs that average more than 31°C. April has the highest average temperature, reaching 32°C on a high and 19°C on a low. The 2.9-month cool season, which runs from July 7 to October 4, has daily highs that are typically lower than 26.1°C. December is the coldest month, with an average low temperature of 12.2°C and a peak of 28.9°C. From April 22 to October 8, the wetter season lasts for 5.5 months, during which time there is a greater than 39% chance of rain on any given day. The month of December has the fewest rainy days during the 6.5-month dry season. The 7.2-month rainy season has the most precipitation in August. The 4.7-month dry spell has the least amount of precipitation in December. Jos's day lasts the same amount of time every year 42 minutes for every 12 hours. With 11 hours, and 33 minutes of daylight, December 22 is the shortest day of the year, and June 21 has the longest, with 12 hours, and 42 minutes. Jos's perceived humidity varies dramatically with the seasons; the muggier season lasts 6.7 months from April 4 to October 27, and at least 15% of the time is comfortable, muggy, oppressive, or miserable. February is the brightest month during the 2.5-month brighter period, and July is the darkest month during the 2.0-month darker period (Daniel et al., 2016).

2.2 Description of the PV system

72-cell polycrystalline panel, at the Module Efficiency ŋ (%) of 17.0, with an area of 1m×2m, maximum power of 330w ± 2.5%, maximum power voltage 37.4 v, 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, Pyrometer for measuring solar radiation, Thermometer for measuring air temperature. Barometer for measuring atmospheric pressure, Anemometer for measuring wind speed. Hygrometer for measuring humidity, Charge control, Cables/wires, and Panel metal stand.

2.3 Data collection

Meteorological data such as Temperature, Humidity, and Irradiance were obtained from the Nigerian Meteorological Agency (NiMet).

2.4 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:

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

Where V_{OC} is open circuit voltage given as 24V, T_{STC} is the temperature at standard test conditions (25 ^{o}C, 1000 W/m^2 solar irradiance, and 1.5 G air mass) T is the temperature of the location measured in ^{0}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. A typical temperature coefficient range of -0.38%/°C to -0.45%/°C, an average temperature coefficient of -0.41%/°C for polycrystalline silicon PV modules, a temperature coefficient of power for the polycrystalline PV module was −0.41 W/˚C. This means that for each degree rise of the module temperature above 25˚C, the module loses approximately 0.41 W of power. Equation (1) is used for the calculation of the estimated voltage of the system in this research work.

The temperature effect on the PV efficiency (output power) can be estimated using the

equation below: -

$$P_t = P_{st} \times (1 - \alpha(T_c - T_s)) \quad (2)$$

Where:

Pt = power at temperature Tc

Pst = power at standard testing conditions (usually 25 °C)

α = Temperature coefficient of the panels

Tc = operating temperature of the panels in °C

Ts = standard testing temperature (usually 25 °C)

3. RESULTS AND DISCUSSION

3.1. Average values for the Years 2021 and 2022

The study looked at the effect of temperature on the PV system's power output in 2021 (Table 1 and Fig. 1). A wide range of responses to temperature changes were at the output power. The result shows a positive correlation between temperatures below STC (25 °C) and high output power. Based on analysis of the data collected, January had an average temperature below 22.29 °C producing an impressive output power of 723.29 kWh. There was an increase in temperature in February compared to January, 24.10 °C affecting the output power of 451.38 kWh, a 37.57% percentage difference from the previous month. The temperature rise continued in March as temperature increased by 7.63% i.e. 26.09 °C causing a decrease in the output power by 59.7% bringing the power down to 181.95 kWh. April temperature dropped slightly 3.64%,

Table 1. Monthly average values Jos (2021).

MONTH	MEAN TEMP. (°C)	OUTPUT VOLTAGE (V)	OUTPUT POWER (kWh)
Jan	22.09	15.58	723.28
Feb	24.10	14.94	451.38
Mar	26.09	14.3	181.95
Apr	25.14	14.6	310.29
May	24.01	14.97	463.42
Jun	22.75	15.37	634.37
Jul	21.46	15.78	808.00
Aug	21.38	15.81	818.91
Sep	22.06	15.59	726.66
Oct	22.95	15.30	606.28
Nov	21.91	15.64	746.99
Dec	20.21	16.18	977.95

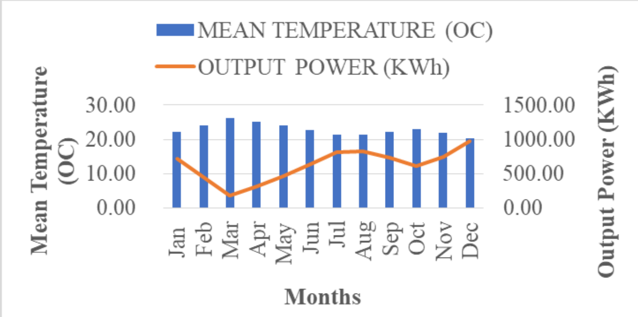

Fig. 1. Mean Temperature (°C) against Output Power (kWh) of Jos in 2021.

(25.14 °C) but still a little above STC with a drastic increase in the output of 41.36% (310.29 kWh). The temperature in May decreased marginally by approximately 4.5% below STC (24.01 °C) increasing the output power by 33.0% (463.42 kWh). The temperature continues to drop in the subsequent months 5.2% (22.75 °C) in June output power 634.37 kWh, 5.67% (21.46 °C) in July 808.00 kWh power output, and 0.37% (21.38 °C) in August from the 24.01 °C of May having output power of 818.91 kWh. The temperature in September increased by 3.1% (22.06 °C), experiencing a marginal power drop (726.66 kWh) the increase continues in October by 3.9% (22.95 °C) with the output power dropping further to 606.28 kWh. There was a switch in the trend; the temperature then dropped 4.5% (21.91 °C) in November having the power output increase of 746.99KWh. December happens to experience the lowest temperature, 20.21 °C, which is a 7.76% temperature drop from the previous month, which produces the highest output power in 2021 from the system (977.95 kWh).

The study examined the effect of temperature on the PV system's power output in 2022. Based on the analysis of the data collected, it is observed that the year has a positive correlation between output power and temperature. As shown in Table 2 and Fig. 2, January experiences an average temperature of 14.84% below STC (21.29 °C) with a good output power of 830.91 kWh. February temperature increases marginally by 8.78% (23.34 °C) with a drop in the output power 553.92 kWh. Temperature increases further in March 1.61% above STC (25.41 °C) having a drastic effect on the output power (273.69 kWh). April temperature dropped from the previous month by 8.6% below STC (22.85 °C), an output power of 620.59 kWh. May has a 4.67% temperature increase (23.97 °C) higher than the previous month, power output 468.83 kWh. The temperature in June dropped

7.84% from the previous month (22.09 °C) with a corresponding increase in output power of 723.27 kWh. Further temperature drop was observed in July (21.23 °C) which is 15.08% below STC giving an output power of 839.90 kWh. August dropped a further 15.88% below STC (21.03 °C) with a power increase (867.05 kWh). Marginal temperature increases from the previous month September (21.21 °C) with a corresponding drop in power output of 842.11 kWh. Temperature continued to increase marginally in October (21.40 °C) that is 0.89% increase with the output power of 817.08 kWh. The unsteady temperature continued in November, a 3.64% temperature decrease was observed (20.62 °C) output power of 922.75 kWh, the month with the lowest temperature and highest output power. December average temperature was 20.68 °C a little increase from the previous month and a marginal drop in the power output 913.75 kWh. This is shown on the graph (i.e. in Fig. 2).

Table 2. Monthly average values of Jos in 2022.

MONTH	MEAN TEMP. (°C)	OUTPUT VOLTAGE (V)	OUTPUT POWER (kWh)
Jan	21.29	15.84	830.91
Feb	23.34	15.18	553.92
Mar	25.41	14.52	273.69
Apr	22.85	15.34	620.59
May	23.97	14.98	468.83
Jun	22.09	15.58	723.27
Jul	21.23	15.86	839.90
Aug	21.03	15.92	867.05
Sep	21.21	15.86	842.11
Oct	21.4	15.80	817.08
Nov	20.62	16.05	922.25
Dec	20.68	16.03	913.75

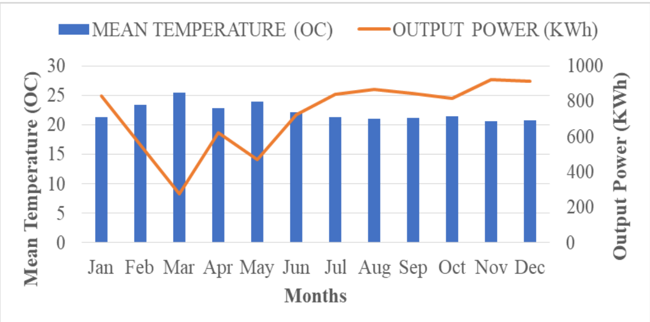

Fig. 2. Mean Temperature (°C) against Output Power (KWh) of Jos in 2022.

The analysis of temperature's impact on photovoltaic (PV) system output voltage in Jos, Nigeria, for 2021 reveals a significant relationship between temperature fluctuations and output variations in voltage. The highest temperature recorded in March (26.09 °C) marks the start of a warming trend, up from 22.09 °C in January. The changes in temperature affect the output voltages all year round. The month of April maintained a steady increase in temperature slightly above STC at 25.14 °C, while the temperature in May slightly dropped below STC at 24.01 °C, giving an output voltage of 14.97V. June having a more pronounced decrease in temperature 22.75 °C, that is 2.25 °C below STC with an output voltage of 15.37 volts. Analysis showed further temperature drops in the months of July and August, 21.46 °C and 21.38 °C having output voltages of 15.78V and 15.81V.A slight increase in September and October, temperatures rise slightly to 22.06 °C and 22.95 °C, respectively, but the output voltage remains stable at 15.30V and 15.59V. The downward trend of temperatures goes on in November (21.91 °C), with the lowest temperature and highest output voltage observed in December (20.21 °C and 16.18 V, respectively) shown on Fig. 3.

A similar trend to the previous year, 2022 experienced a steady increase in temperature in the warmer months of January to March. The analyzed data of January showed a temperature of 21.30 °C, February 23.34 °C, and March 25.41 °C, with the corresponding voltages of 15.84V, 15.18 V, and 14.52 V, respectively. This is followed by a decrease during the colder months, April 22.85 °C, May 23.97 °C, June 22.09 °C, and July 21.23 °C, with output voltages of 15.34V, 14.98 V, 15.58 V, and 15.86 V, respectively.

Further marginal variations were observed in the subsequent months; September 21.03 °C gave an output voltage of 15.86 V, October 21.40 °C had a corresponding

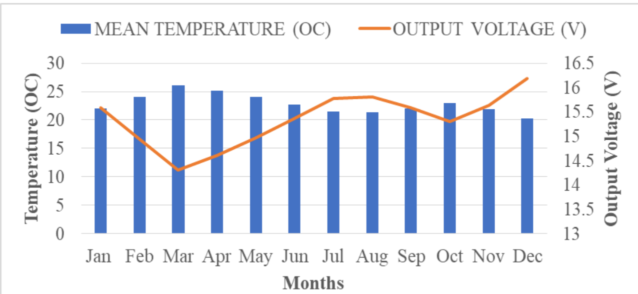

Fig. 3. Mean Temperature (°C) against Output Voltage (V) of Jos in 2021.

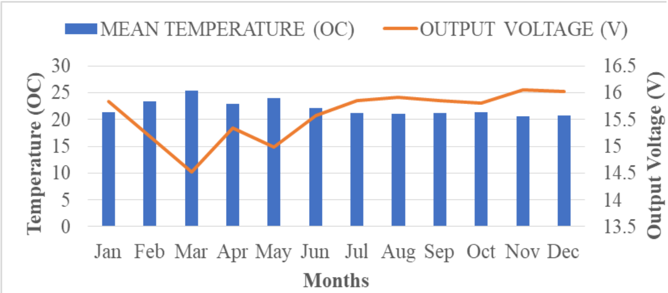

Fig. 4. Mean Temperature (°C) against Output Voltage (V) of Jos in 2022.

output voltage of 15.80V, November 20.62 °C had an output voltage of 16.05 V and December 20.68 °C had an output voltage of 16.03 V as shown on Fig. 4.

4. Conclusion

The two-years (2021 and 2022) study, which yielded the effect of temperature on the efficiency (output power) and voltages of a PV system's performance in the high-altitude region of Jos, Nigeria, was carried out in Jos using data obtained from Nimet, produced a significant result. The results revealed a positive correlation between temperature and PV system output, with its optimal performance at temperatures lower than the standard test condition (STC) of 25 °C.

This investigation found that, as the temperature dropped below STC, the output power increased. The peak output power was recorded as 977.95 kWh in December 2021, while 922.75 kWh in November 2022, with temperatures of 20.21 °C and 20.62 °C, respectively. The minimum power yield is 181.95 kWh in March 2021, and 273.69 kWh in March 2022, at temperatures of 26.09 °C and 25.41 °C, respectively.

Furthermore, output voltages follow a similar trend, with higher voltages measured at lower temperatures at their peak of 16.18 V in December 2021 and 16.03 V in November 2022, and higher temperatures of 26.09 °C output voltage of 14.3 V in March 2021 and 25.41 °C output voltage of 25.41 V in March 2022. These findings have far-reaching implications for the design, installations, and optimization of PV systems in Jos, Nigeria, and other regions, with a focus on the importance of temperature considerations in maximizing energy generation while also encouraging sustainability.

Nomenclature

Pt	power at temperature Tc
Pst	power at standard testing conditions (usually 25° C)
Tc	operating temperature of the panels in °C
Ts	standard testing temperature (usually 25 °C)
V_{OC}	open circuit voltage
T_{STC}	temperature at standard test condition

Greek symbols

α	Temperature coefficient of the panels

Subscripts

oc	open circuit
stc	standard test condition

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