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ANALYSIS OF PERCENTAGE OF POWER LOSS FOR PHOTOVOLTAIC MODULE UNDER TEMPERATURE CONDITION IN KADUNA STATE, NIGERIA

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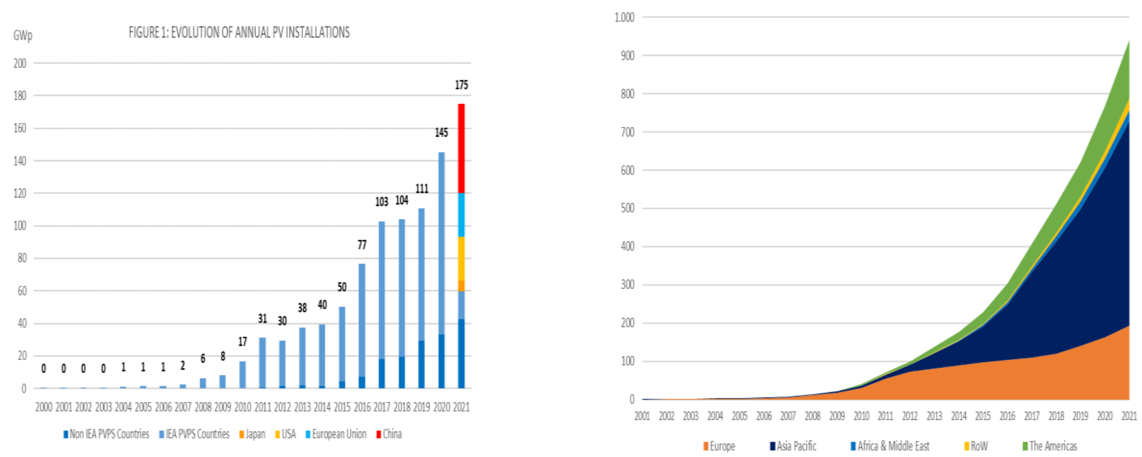
ABSTRACT

For optimal design and system planning, it is essential to assess the actual operating status of solar to determine the detrimental impact of power losses. The paper analyzes the power loss caused by photovoltaic (PV) modules under the temperature conditions of Kaduna State, Nigeria. The study conducted an outdoor experiment between 7:00 AM and 6:00 PM, with a 30-minute interval to evaluate the performance of the installed modules in real time. The power output parameters and temperature of a monocrystalline and polycrystalline 120Watt PV panel were measured for three months, covering three seasons: August, January, and April. The experiment used two MASTECH MY64 digital multimeters and a temperature sensor (thermostat). The study found that the PV panel should reach its peak point between 11:00 AM and 2:30 PM, due to the angle of incident rays from the sun, high solar irradiance, and temperature. However, it was also observed that the heat generated by the PV panel in that region as a result of the panel's prolonged exposure to the sun negatively affected the output voltage and power generated. The results also showed that as the temperature increased, the current output increased but the voltage and power output decreased. The findings observed that every 1°C rise in temperature resulted in an average decrease of 0.51 watts (0.43%) for monocrystalline and 0.9 watts (0.78%) for polycrystalline during the solar peak. The study concluded that determining the actual working state of PV modules is crucial for an optimal design solution and improved system efficiency.

Keywords: Mono-crystalline PV module, polycrystalline PV module, power loss, solar photovoltaic energy, temperature sensor

INTRODUCTION

Environmental and energy problems are widespread in today's society as the world population increases with day-to-day demand and use of fossil fuels (Lu Shen *et al.*, 2020). Therefore, to combat climate change and reduce greenhouse gas emissions (GHG) from the energy sector, several initiatives such as the integration of renewable energy sources (RES) i.e., solar PV and wind turbine (WT), hydro, solar energy, geothermal, wind, and biomass, etc., has proven to be the best alternative energy solutions in recent times. Thus, the adoption of RES technologies and their utilization in various forms has shown unprecedented achievement in meeting the insufficient energy demand crisis that affects the global economy (Chidubem *et al.*, 2021). Hybrid Solar photovoltaic (PV) power generation is the most utilize and the technology is progressing steadily with enhanced unique features, and fast practical implementation (Bahaidara *et al.*, 2015). According to the IEA report, 2022, solar PV has become the most affordable alternative energy generation, which is anticipated to spur investment in the years to come. However, in view of meeting the Net Zero Emissions mandate by 2050 scenario, the yearly generation increase must average 25% from 2022 to 2030. The global installed PV capacity passes 1.18 TW by the end of 2022 (IEA PVPS report, 2023) which increased by more than 25% last year thanks to post-COVID as depicted in Figure 1: (a) and (b) respectively.



(a)

(b)

Figure 1 (a) and (b): Global PV Installation chat (Source: IEA PV PVPS report, 2022)

However, to meet the electricity demand challenges of many developing countries like Africa, high their dependency on fossil fuel has raised global concern over the concentration of atmospheric increase of carbon dioxide from environmental safety of energy production techniques, due to the massive greenhouse gas emissions from their energy generation sources (Nguyen & Pearce, 2010; Choi *et al.,* 2011). The demand for energy from power utilities has risen as a result of community growth and the fact that many areas in Nigeria lack connection to the national electrical grid. As a result, small-scale solar energy systems are now being used more often as an economical means to supply power to both domestic and commercial activities in these remote regions likewise in certain rural-urban towns that are yet not connected to the grid (Lu Shen *et al.,* 2020; Umar, 1999). In 2021, just 59.5% of Nigerians had access to electricity, according to a World Bank index of electrification, and 0% of energy output came from renewable sources other than hydroelectricity (kWh) (IEA study, 2014). Due to a scarcity of available energy, it is now necessary to use various energy sources, like the sun's abundant energy, to augment the country's typical hydropower, gas, and fossil fuel output. There are several estimates of Nigeria's monthly, seasonal, yearly, or local solar radiation (Ojosu 1988, Fadare 2009, Ezekwe & Ezeilo 1981, Chineke 2008, Chineke & Okoro 2010). The effectiveness and generated power of photovoltaic cells have been shown to vary with temperature and sun irradiation level (Carr & Pryor, 2001; Shaari et al., 2005). In 2005, the German Solar Energy Society. The biggest potential for solar PV power plants in Nigeria resides in the north of the nation by utilizing the availability of the sun and other sources of energy supply. Solar energy technology has become one of the most necessary alternative sources of energy due to the sun's abundance. Many research works had been reported in the literature on performance assessment of the solar PV module under different climatic conditions using various technological design strategies and configurations to mitigate the impact of temperature on energy yield as well as to reduce power loss using different real-time practical scenarios. This includes the optimal deployment of a hybrid PV system with a battery energy storage system (BESS) to balance their intermittent generation and improve system efficiency. In addition, in view of climate change, several innovative research are still ongoing aiming to enhance the performance of the solar PV module's electrical and thermal characteristics causing voltage instability and high power loss under higher temperature conditions. Bahaidarah et al. (2015) numerically modeled and analyzed the performance characteristics of a photovoltaic (PV) module, and the results obtained were empirically validated for the usual meteorological conditions in Dhahran, Saudi Arabia. Lu Shen et al, (2020) study analyzes the power loss and quantifies the energy distribution in PV modules using loss mechanisms in based on material characteristics (optical coefficient and cell bandgap), operation mechanisms (carriers' generation, transportation, and recombination mechanisms) and environmental factors (temperature and solar irradiance). Ike (2013) studied to determine the impact of environmental temperature on the performance of a standalone photovoltaic solar system in Awka, Nigeria. The work revealed that an indirect proportionality exists between the ambient temperature of a locality and the output power produced by the PV system. The PV module efficiency improvements have been the subject of contentious debates in the last decades by researchers. Studies have shown that losses that occur due to geographical differences in temperature most especially in Sahara Africa during the entire power generation process reduce conversion efficiency (Chidubem *et al.,* 2021), making it extremely difficult to categorize and quantify the energy distribution. The typical temperature in Kaduna State, for instance, is frequently higher than the photovoltaic panel's ideal operating temperature at STC, this might result in a considerable drop in PV power production. The results of this study would be useful to those who want to build and anticipate the performance of photovoltaic systems in the Chukun Local Government Area of Kaduna State, Nigeria. This includes solar system manufacturers, installers, and government agencies for construction and housing.

Mechanism of Photovoltaic P-N junctions

The mechanism of action of the photovoltaic p-n junction consists of a light beam in connection with the p-n junction of the photovoltaic cell. The n-type silicon knocks out an electron, creating a free electron and a hole. Both the free electron and the hole have enough energy to escape from the depletion region. Heat is generated by the recombination of newly generated charge carriers that are largely recombined. These charge carriers can be electron-hole pairs in solid semiconductor materials or electron-ion pairs in liquid electrolytes (Nabuisi & Dhaouadi, 2012). The generation of the photoelectric effect is due to the dissociation of these pairs before recombination. This is done in the presence of an internal electric field due to the space row. The movement of electrons in this electric field is transferred from the p-type semiconductor to the n-type semiconductor, and the holes are transferred from the n-type semiconductor to the p-type, causing the electron-hole pairs to separate, as shown in Figure 2. The minority carriers that are separated on one side of the connector become majority carriers of an unlimited lifetime on the other side, so they generate current (Isc) and voltage (Vsc) of the solar cell (Green, 1981, Chidubem et al., 2021). The resistance of the circuit multiplied by the square of the amperage is mechanical energy converted into electrical energy. The temperature of the cell is increased by the residual energy of the photon and is released into the atmosphere (Vongkoon & Liutanakul, 2012). The cell's current-voltage characteristics are a graph of the PV array output current versus voltage at a given temperature and radiation.

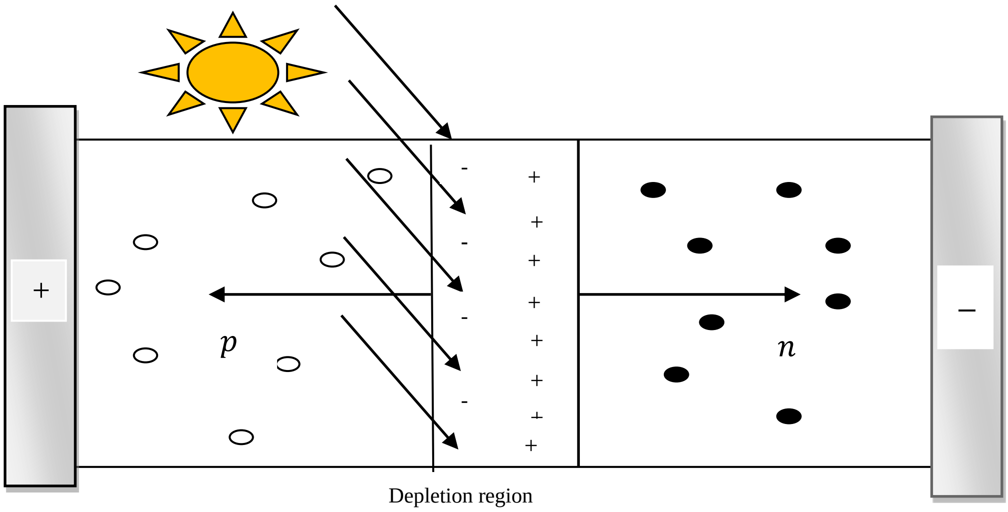


Figure: 2: Basic P-N Junction of Photovoltaic Cell and Charge Transport Phenomena

Photovoltaic Module Standard Test Conditions

Standard test conditions (STCs) for a PV module's performance include a cell temperature of 25°C, a 1.5 air mass's standard spectral distribution (AM), and an incidence normal irradiance of 1000W/m2 (Mustapha et al., 2013). A typical I-V characteristics curve for a PV module is shown in Figure 1.2 (Abdul et al., 2014). According to Saloux et al. (2011), the power (P) is the result of the component's current (I) and voltage (V). Also, based on Chow (2003), the basic equation that describes the relationships between the variables as a consequence of how temperature affects a PV cell's electrical efficiency is as follows:

$$P_m = I_{mp} V_{mp} = (FF)\, I_{Is} V_{oc} \qquad (1)$$

Where Isc represents the short circuit current, Voc is the open circuit voltage, FF is the fill factor, Vmp is the maximum supply voltage and Imp is the maximum current at the maximum power point of the I-V curve of the module. Figure 3, shows a typical I-V characteristic curve of a PV module.

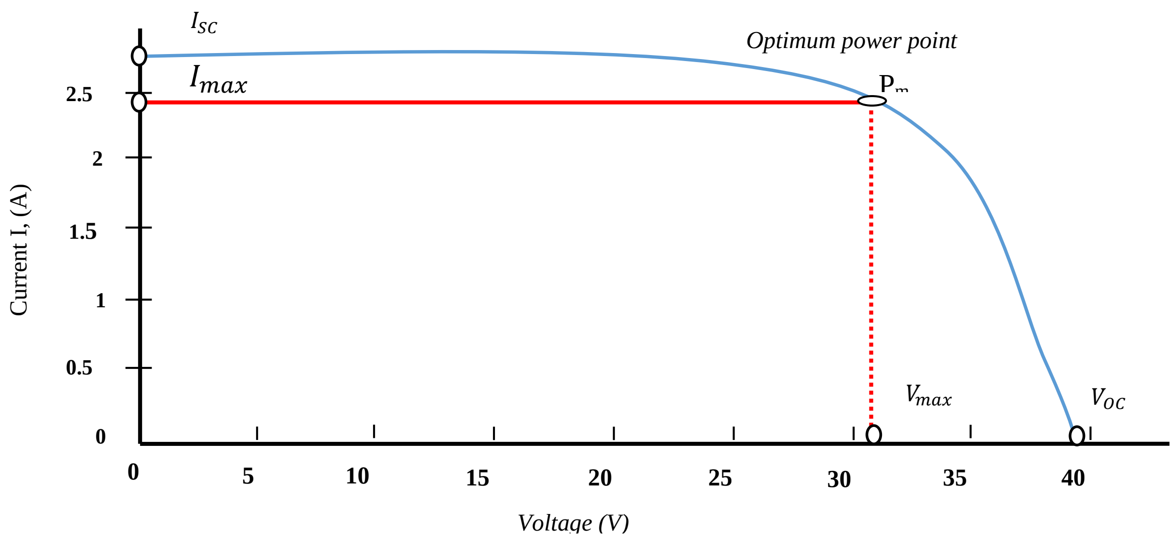


Figure 3: Typical I-V Characteristic Curve of a PV Module (Abdul et al, 2014)

MATERIALS AND METHODS

In this study, an outdoor experiment was used to measure the PV panel performance. To compare their performance, a 120 Wp monocrystalline and polycrystalline PV panel is placed side by side on a simple vertical surface (Portrait) facing south. The facilities of Rana World Tech Engineering Limited, Narayi, Kaduna, located at latitude 10.4549° N and 7.4057° longitude E and South Kaduna, Nigeria were used to evaluate the PV properties. A map of the experimental study area and solar potential is shown in Figure 4.

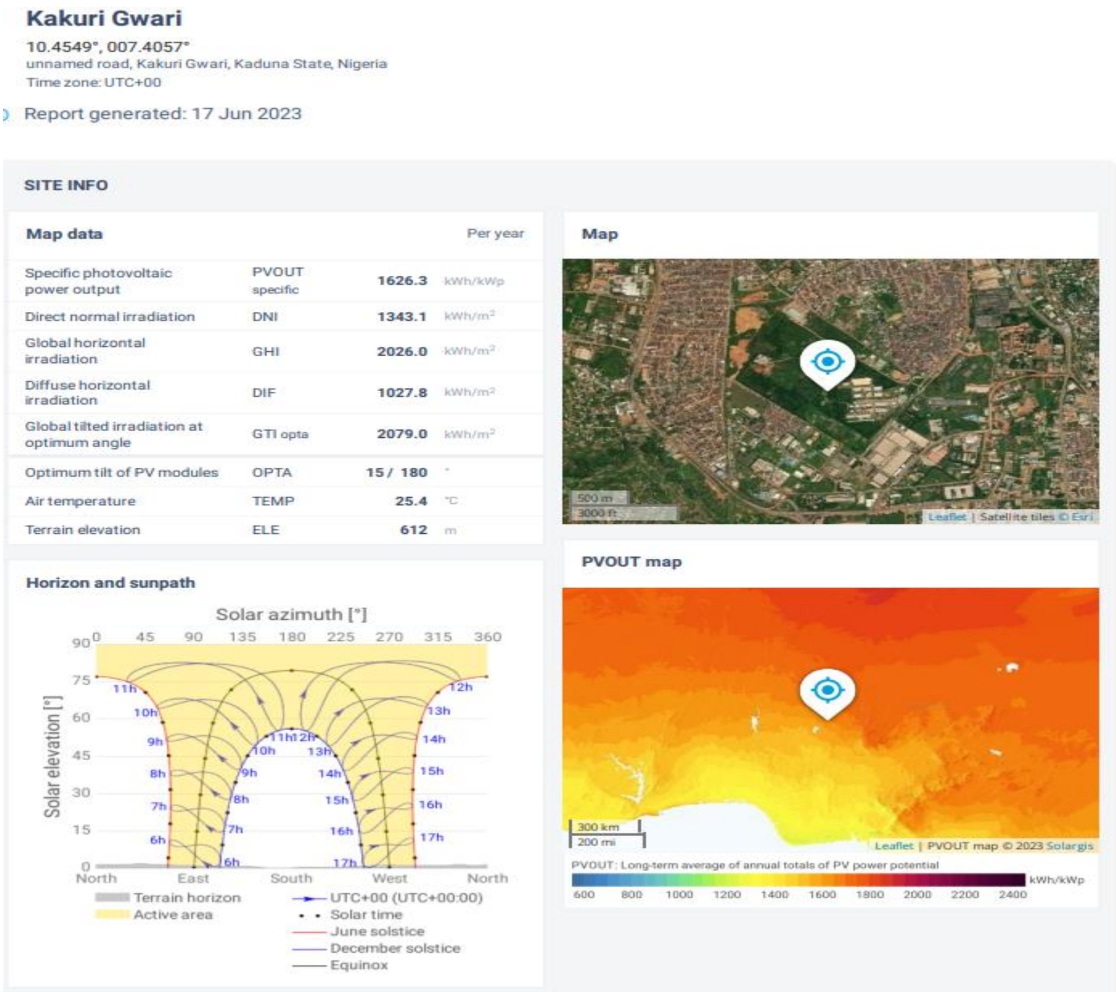


Figure 4: Geographical Map and Solar Energy Potential of the Study Site in Kaduna (Source: Global Solar Atlas)

In order to capture the three seasons of August, January, and April, all data were collected daily for three (3) months at intervals of 30 minutes between 7:00 AM and 6:00 PM. We used two MASTECH (MY64) Multi-meters; one was used to measure the PV panel's temperature, and the other was used to evaluate the surrounding environment and its electrical properties. An overview of the experimental setup is shown in Figure 5. To calculate the power generated by the PV panel, the following equation was employed (Chidubem et al., 2021):

$$P_{out} = I * V \qquad (2)$$

Where; P_{out} represents the output power of the photovoltaic module, I= Output Current (Isc), V= Output Voltage (Voc)

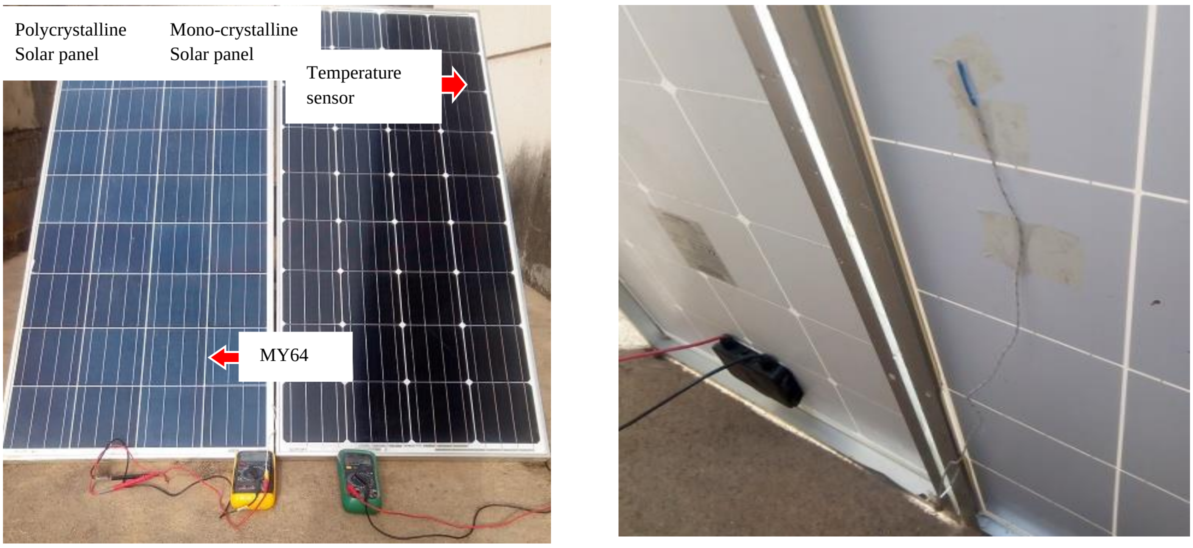


Figure 5: Photographic View for Outdoor Experiment

Table 2: Specification sheet for a 120Wp Monocrystalline and Polycrystalline Solar PV Module

MATERIAL DATA STC DATA QUALITY FOR SUNSHINE SOLAR PANEL		
Cell Type	**Monocrystalline**	**Polycrystalline**
Dimension	1956x992x40mm	1958x998x38mm
Weight	23kg	24.6kg
Cell size	156x156mm	156x156mm
Glass thickness	4mm	4mm
ELECTRICAL DATA AT STC		
Maximum Power (Pmax)	120 W	120W
The voltage at Max Power (Vmpp)	17.65V	17.3V
Maximum Power Current (Ipm)	6.8A	6.9A
Open Circuit Voltage (Voc)	21.9V	22.6V
Short Circuit Current (Isc)	7.6A	7.6A
Max Power Tolerance (positive)	+3%	+3%
Min Power Tolerance (negative)	-3%	-3%

RESULTS AND DISCUSSIONS

Normally, as the solar irradiance continues to intensify over time as shown in Figure 6, the ambient temperature increases and thereby increasing the temperature of the PV panel. The heat generated by the panel was due to prolonged exposure of the PV panel to the sun.

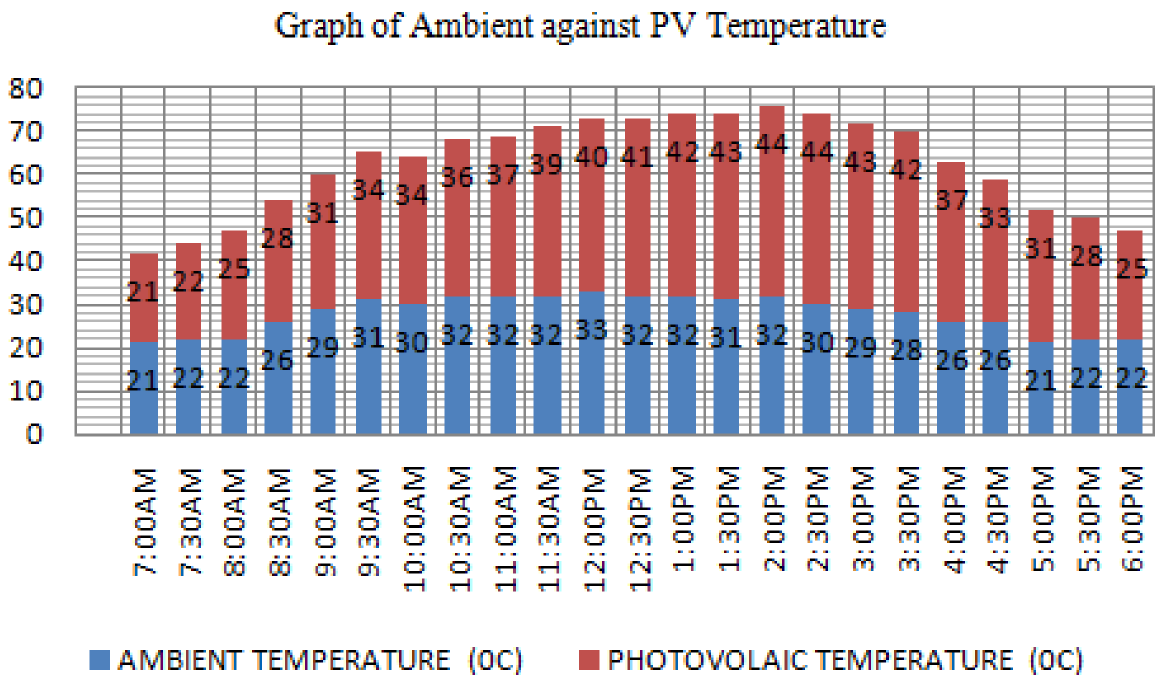


Figure 6: Graph of Ambient Temperature against Solar PV Temperature Measurement

Table 1a and 1b shows the performance characteristics of the two PV modules used during the outdoor experiment at different temperature and solar irradiance intensity. The electrical parameters of each module were measured. The average temperature at twilight was 22^{0}C, but as time went by, the sun's surface and the irradiance of the sun started increasing. The maximum ambient temperature was recorded between 11:00 AM and 3:00 PM at an average of 32^{0}C. The PV panel recorded a maximum average temperature of 44^{0}C while the minimum average temperature recorded was 22^{0}C at the lowest solar irradiance.

Table 1a: Average Measured Experimental Value for 120Wp Monocrystalline Module

Time	Ambient Temp. (^{0}C)	PV Temp. (^{0}C)	Voc (V)	Isc (A)	Power (Watts)	Time	Ambient Temp. (^{0}C)	PV Temp. (^{0}C)	Voc (V)	Isc (A)	Power (Watts)
7:00AM	21	21	14.16	0.52	7.3632	1:00PM	32	42	18.48	5.02	92.77
7:30AM	22	22	15.89	0.89	14.14	1:30PM	31	43	18.08	5.11	92.39
8:00AM	22	25	18.76	1.45	27.20	2:00PM	32	44	17.68	5.19	91.76
8:30AM	26	28	20.36	1.72	35.02	2:30PM	30	44	17.67	5.2	91.88
9:00AM	29	31	20.78	2.98	61.92	3:00PM	29	43	18.07	3.46	62.52

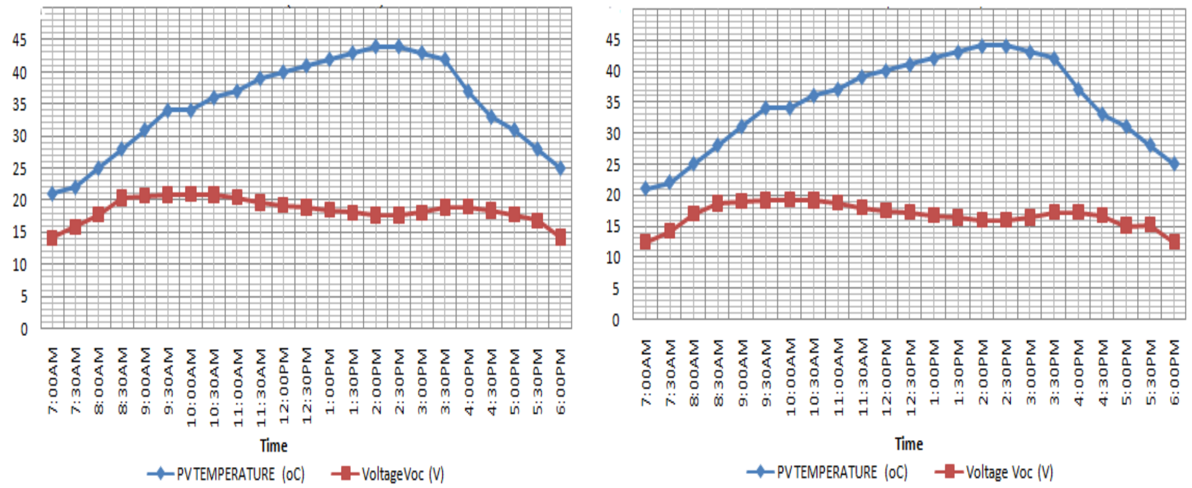
9:30AM	31	34	20.86	3.28	68.42	3:30PM	28	42	18.89	2.5	47.23
10:00AM	30	34	20.96	4.3	90.13	4:00PM	26	37	18.97	2.05	38.89
10:30AM	32	36	20.88	4.48	93.54	4:30PM	26	33	18.45	1.69	31.18
11:00AM	32	37	20.48	4.66	95.44	5:00PM	21	31	16.79	1.51	25.35
11:30AM	32	39	19.68	4.75	93.48	5:30PM	22	28	16.9	1.45	24.51
12:00PM	33	40	19.44	4.79	93.12	6:00PM	22	25	14.22	1.24	17.63
12:30PM	32	41	18.96	4.9	92.904						

Table 1b: Average Measured Experimental Value for 120Wp Polycrystalline Module

Time	Ambient Temp. (^{0}C)	PV Temp. (^{0}C)	Voc (V)	Isc (A)	Power (Watts)	Time	Ambient Temp. (^{0}C)	PV Temp. (^{0}C)	Voc (V)	Isc (A)	Power (Watts)
7:00AM	21	21	14.18	0.51	7.2318	1:00PM	32	42	18.5	4.91	90.84
7:30AM	22	22	15.91	0.88	14.00	1:30PM	31	43	17.98	5.02	90.26
8:00AM	22	25	18.78	1.44	27.043	2:00PM	32	44	17.76	5.08	90.22
8:30AM	26	28	20.38	1.71	34.85	2:30PM	30	44	17.69	5.1	90.21
9:00AM	29	31	20.8	2.97	61.78	3:00PM	29	43	18.45	3.45	63.65
9:30AM	31	34	20.88	3.27	68.28	3:30PM	28	42	18.91	2.49	47.09
10:00AM	30	34	20.98	4.29	90.00	4:00PM	26	37	18.99	2.04	38.74
10:30AM	32	36	20.9	4.47	93.42	4:30PM	26	33	18.47	1.68	31.03
11:00AM	32	37	20.5	4.65	95.33	5:00PM	21	31	16.81	1.5	25.22
11:30AM	32	39	19.7	4.74	93.38	5:30PM	22	28	16.92	1.44	24.36
12:00PM	33	40	19.3	4.81	92.83	6:00PM	22	25	14.24	1.23	17.52
12:30PM	32	41	18.9	4.85	91.67						

Temperature Vs Voltage Characteristics

In the experiment, it was found that between 9:00 AM and 11:30 AM, the maximum voltage was recorded. However, between 11:00 AM and 3:00 PM, when solar radiation is at its strongest and the PV panels are heating up, it was found that the voltage of the two crystalline modules started to experience a slight decrease in voltage. According to Tables 1 and 2, it was found that the PV module's temperature was higher than the surrounding air's temperature. According to the experiment, both mono-crystalline and polycrystalline PV modules experience a drop in voltage when the temperature of the cell increases. The influence of temperature on the voltage of both mono-crystalline and polycrystalline modules was depicted graphically in Figures 7(a) and (b).



(a) Mono-Crystalline Panel (b) Polycrystalline Panel

Figure 7: Influence of Temperature on the Open-circuit Voltage (Voc) of a PV Module

Temperature Vs Current Characteristics

The general typical current behavior throughout the experiment is shown in Figures 8(a) and (b). It is found that as the intensity of the sun and the temperature of the solar panels increase, the output current of the solar panels also increases. This current increase was seen between 11:30 AM and 15:00 PM when solar radiation is at its maximum. In contrast, at a PV temperature of 22^{0}C, only 0.52A was produced. At 2:00 PM, the average temperature measured was 37^{o}C and the maximum output current is 5.1A. According to Tables 1 and 2, the number of hours of maximum solar radiation and high temperature corresponds to the time when the average maximum open-circuit current is measured. It is found that the output current of PV is low at low radiation and at the lowest PV temperature. As a result, solar radiation directly affects how much current the PV panel can produce. The relationship between temperature and current in monocrystalline and polycrystalline modules is depicted graphically in Figure 8.

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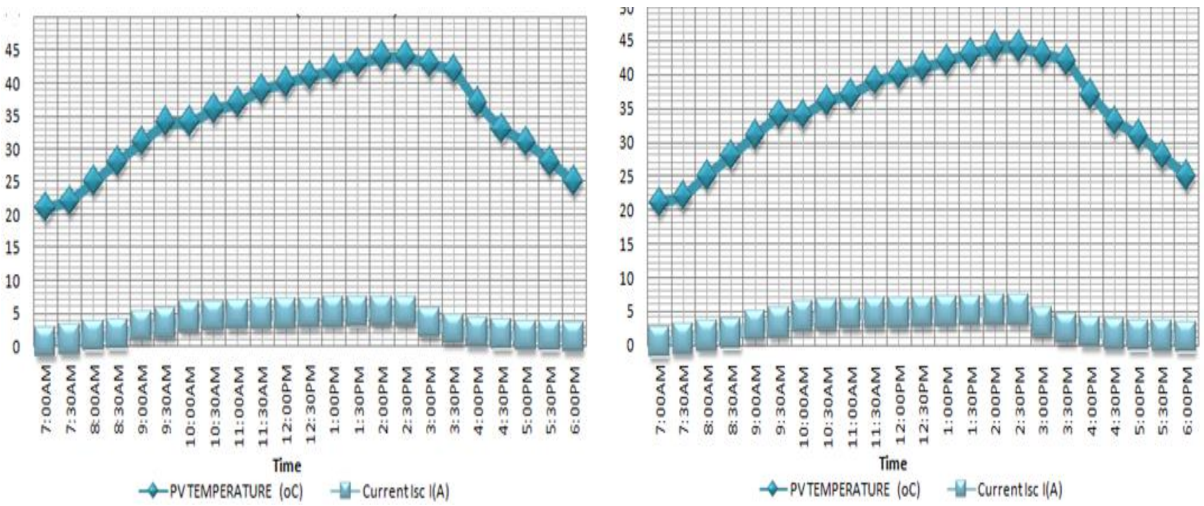
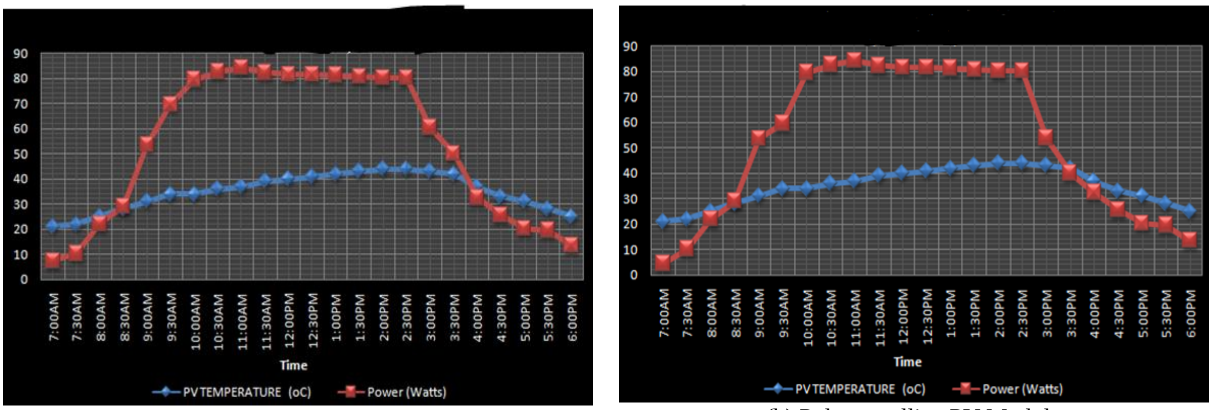


(a) Mono-Crystalline PV module (b) Polycrystalline PV Module

Figure 8(a) and (b): Influence of Temperature on the Short Circuit Current (I_{sc}) of a PV Module

Temperature Vs Power Output Characteristics

The voltage and current of the PV panels were measured in other to obtain the power produced by the PV modules. The power outputs of the PV module (i.e. solar panel) at every point in time were calculated by using Equation 2. Table 1 and 2 presents the average output power generated by the PV panel during the outdoor experiment. The output power which is supposed to significantly rise to its peak between 11:00 AM and 3:00 PM was observed to reduce gradually as the temperature of the PV panel continue to rise above the STC. The decrease was a result of the negative effect of high temperature on panel open circuit voltage. The major productions of solar energy were recorded between 8:00 AM and 11:00 PM. During peak hours of solar radiation, the maximum power (95.44W) was recorded at a PV temperature of 37 ^{0}C, whereas the minimum (91.88W) was recorded at 44^{0}C. Figure 9 presents a graphical representation of the Influence of temperature on the current on both mono-crystalline and polycrystalline modules.



(a) mono-crystalline PV Module (b) Polycrystalline PV Module

Figure 9: Influence of Temperature on the Power Output of PV modules.

Power Loss on PV Modules

The quantity of power produced by a PV module is a result of the sun`s illumination of light rays that land on the PV module's surface. The experiment revealed that the output power keeps rising as the irradiance rises and the sun's position shifts from dusk to about 11:00 AM. The variability of the weather, which tends to block the sun's light due to cloud movement, is one of the main obstacles that PV power generation must overcome. The power output of the PV panels changes during this process, either increasing (power gain) or decreasing (power loss). But when the PV temperature was high during peak hours, there is a temperature effect that reduces performance efficiency. The PV power loss occurs during these times because current marginally rises while voltage and power fall (see Tables 2a and 2b).

Table 2a: Power Loss at Peak Hour for Monocrystalline Module

TIME	LOCATION A MONO-CRYSTALLINE MODULE			
	V_{oc} (V)	I_{sc} (A)	Power (W)	Power Loss (%)
11:00am	20.48	4.66	95.44	20.47
11:30am	19.68	4.75	93.48	22.10
12:00pm	19.44	4.79	93.12	22.40

12:30pm	18.96	4.9	92.904	22.58
1:00pm	18.48	5.02	92.77	22.69
1:30pm	18.08	5.11	92.39	23.01
2:00pm	17.68	5.19	91.76	23.53
2:30pm	17.67	5.2	91.88	23.43
3:00pm	18.07	3.46	62.52	47.90
3:30pm	20.48	4.66	95.44	20.47

Table 2b: Power Loss at Peak Hour for Polycrystalline Module

TIME	LOCATION A POLYCRYSTALLINE MODULE			
	V_{oc} (V)	I_{sc} (A)	Power (W)	Power Loss (%)
11:00am	18.72	4.5	84.24	29.8
11:30am	17.92	4.59	82.25	31.46
12:00pm	17.52	4.66	81.64	31.96
12:30pm	17.12	4.77	81.66	31.95
1:00pm	16.72	4.86	81.26	32.28
1:30pm	16.32	4.95	80.78	32.68
2:00pm	15.92	5.02	79.92	33.40
2:30pm	15.41	5.04	77.67	35.28
3:00pm	16.31	4.3	70.13	41.55
3:30pm	18.72	4.5	84.24	29.8

CONCLUSION

An outside experiment was used to estimate the percentage of power loss experienced by the PV module under the temperature conditions in Kaduna state, Nigeria. From the experiment, it is evident that the output voltage, which is decreased by the rise in PV panel temperature, is the noticeable parameter that has a negative impact on temperature. Although the PV panel's current output is increasing, this decrease in output voltage prevents it from performing at its best. As a result, the photovoltaic panel's power production and efficiency likewise decline. The experiment's findings provide an explanation for the correlation between localized solar module power losses and ambient temperature. The power output was found to decrease during solar peak (between 11:00AM and 2:30PM), with an average value of 0.51Watts (0.43%) for mono-crystalline and 0.9Watts (0.78%) for polycrystalline, at every 1^{o}C rise in temperature. This experiment proves that the ambient temperature is a factor that must be taken into consideration when predicting and designing the behavior of mono-crystalline and polycrystalline solar panels in that location.

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