Behavioral Pattern of Photovoltaics Enhanced with Automatic Cooling Mechanism

ABSTRACT

The increase in PV panel temperature with increasing level of solar power and solar flux is a major disadvantage when using Photovoltaics for electricity generation. Nigeria is a country that is blessed with enormous amount of sunlight throughout the year which should make it a good environment for the generation of electricity via photovoltaic technology. The daytime temperature of Nigeria is a major barrier towards the effective generation of electricity via photovoltaic technology. To remedy this issue of temperature, a cooling mechanism has to be considered in the process of any PV system design. An automatic cooling mechanism and an intelligent photovoltaic maximum power point tracker were deployed in the study. Experimental measurements were carried out in real outdoor conditions. The results of the study reveal an average increase of 6.42%, 7.77%, 18.34%, and 18.15% for voltage, current, power and efficiency respectively for the PV module under thermal regulation. This study demonstrates that cooling mechanism should be incorporated in the process of designing photovoltaic systems for optimum energy yield.

Keywords: Threshold temperature, Cooling mechanism, Maximum power point, Photovoltaic module, Efficiency.

1. INTRODUCTION

As the world population continue to increase coupled with increasing sophistication of human, the demand for power is ever increasing. Over the past century human has greatly relied on the burning of fossil fuel for power generation [1], which is seen to be unsustainable because of the predicted depletion of fossil fuel in the near future [2]. The impending depletion of fossil fuel reserves has brought about technological advancement in the renewable sector [3]. Almost 80% of the world's energy consumption is generated through the burning of fossil fuel whose harmful by-product has brought about the issues of environmental pollution and global warming [4-6]. Utilizing renewable energy technologies for power generation is a viable solution towards the environmental and global challenges we face today due to the less impact it has on environmental degradation [7-8].

As years goes by, humans are becoming increasingly aware of the need to manage the earth in a sustainable way. Out of almost the seven billion peoples that shares the earth, about one billion of them are currently living a high energy consumption lifestyle which is not sustainable [9]. The sun baths the earth with enormous amount of energy even as it is seen as a run-of-the-mill star, and it is more than capable of taking care of human energy need [10]. Aside from it been sustainable and reliable, solar energy is the most favorable energy resource among the renewable energy resources discovered by human [11].

The conversion of sunlight for electric power generation expresses the acceptance of solar energy [12]. This energy can be converted directly with the aid of photovoltaics, where energetic photons from the sun are absorbed by semiconductor materials to produce electricity through a process known as photovoltaic effect.

Due to the advantages of photovoltaic systems over other systems for power generation, its demand is growing in the renewable energy market and is expected to play a key role in the future for energy sustenance [13]. The initial capital cost of PV systems coupled with factors that hinders its efficiency stands as a hindrance to the pervasive use of this technology. Panel temperature, solar power, solar flux and the band gap of the semiconductor are among the key factors determining the performance of photovoltaics. In the process of converting solar energy into electrical, only 15-20% of the incident solar radiation is converted while the remainder is converted to heat which inevitably hinders the photovoltaic efficiency [14]. Cooling of PV modules would provide a viable solution to the problems associated with heat if it could be implemented effectively at a cost-friendly rate.

Various researchers have studied how temperature hinders the performance of photovoltaics and even attempt to solve the problem. [15] investigated how high temperature hinders the efficiency of polycrystalline photovoltaic systems and came to a conclusion reporting that; photovoltaic systems will remain efficient coupled with a high-performance ratio if the temperature of the system is controlled in a way that the maximum operating cell temperature is not exceeded. While [16] utilized internet of things (IoT) facility to carry out active cooling on polycrystalline photovoltaic system. Their results show that the power output was significantly enhanced by the cooling process coupled with the battery state of charge (SOC) been expanded. [17] researched on the thermal and electrical performance of photovoltaic modules while integrating cooling systems made of DC fans into the setup. They reported that high operating temperature of a photovoltaic panel triggers significant decrease in the output power. Also [18] carried out enhancement techniques to improve the performance of solar panels via water cooling. they discovered that solar panels generate its highest output power when cooling begins when the temperature of the panels extents to the maximum allowable temperature (MAT). A numerical and experimental investigation on air cooling for photovoltaic panels via aluminum heat sinks was conducted by [19]. From their results it was revealed that the heat sink raised the open circuit voltage of the photovoltaic panel by 10%. [20] assessed the impact of water cooling on the efficiency of PV modules and reported that continuous cooling of PV modules during operation leads to an increase in the output power by 20%. Also, [21] Investigated the effect of evaporative cooling on PV modules and found that an increase in efficiency between 10 and 14% was achievable. [22] also investigated the effects of evaporative cooling on the efficiency of PV modules by using a layer of synthetic clay at the back of the module while at the front of the module thin film of water was made to evaporate. Their results reveal a maximum increase in output voltage and power by 19.4% and 19.1% respectively. [23] investigated the performance response of photovoltaic modules using water spray cooling techniques. Analysis of their result reveals that it is possible to achieve a maximal total increase of 7.7% and 5.9% for power output and efficiency respectively. While [24] reported that the amount of electrical power generated using photovoltaic modules depends on the temperature of the cells; the higher the cell temperature, the higher the lost in power output. [25] revealed that to obtain better performance efficiency from photovoltaics they should be operated in an environment with considerable wind speed to enable adequate cooling of the PV modules. While [26] employed multi-concept cooling techniques to enhance the output power and efficiency of PV modules. Analysis of their results shows an increase above 3% in the module efficiency, making the module more productive. [27] conducted a research on photovoltaics by using DC fans to perform cooling through induced air flow. The analysis of their results revealed better performance efficiency from the photovoltaics as the number of DC fans increased. [28] diurnally analysed polycrystalline solar photovoltaic systems enhanced with an automatic cooling mechanism. From their thorough analysis, the photovoltaic system under thermal regulation performed better in its output operating parameters (Voltage, current and power) and showed higher efficiency above the other photovoltaic systems without a cooling mechanism. [29] conducted an experimental investigation on building integrated photovoltaic by using a thermal roof collector combined with a liquid desiccant to enhance indirect evaporative cooling. Their result shows that the power energy performance of photovoltaic modules can be improved by 10.7% due to the achieved collector cooling as the cold water flow forms a passive cooling effect to remove waste heat from the photovoltaic modules.

A handful of studies exist on the regulation of PV panel temperature via cooling mechanism, but a huge percentage of the available information is only valid for a specific location. Generally, there is a lack of information on the behavioral pattern of photovoltaics enhanced with automatic cooling mechanism in Nigeria that can be used effectively in the design, maintenance and sizing of Photovoltaic modules.

A decrease in the performance of photovoltaics over a period of time is very undesirable due to the initial capital cost in setting up the system. It is of great value to be able to achieve a system that can effectively convert solar to electrical energy without the influence of its ambient temperature. Earlier studies have revealed that photovoltaics are most efficient with temperatures below their peak operating temperature, then the solution is to design and create a system that is capable of operating at a stable temperature without been influenced by that of its ambience. Hence the introduction of automatic cooling mechanism may boost the performance of the power output by monitoring and ensuring that the PV modules function below its peak operating cell temperature. The polycrystalline PV technology is mostly used for small business and residential purposes coupled with the fact that it is one of the dominant PV technologies flooding the Nigerian market. Hence the need to develop a method to reap as much energy from it as possible. Investigation on the behavioral pattern of photovoltaics enhanced with automatic cooling mechanism is yet to be investigated in the Nigeria's prospect.

The study aims to experimentally investigate the performance of polycrystalline PV modules enhanced with automatic cooling mechanism using water as the coolant. The objectives of the study include investigating the behavioral pattern of the photovoltaic system with thermal regulation, and achieving a photovoltaic system that is capable of operating at temperature below 35^0C regardless of how high the ambient temperature is. The difference between this study and others that use water as the coolant is that our system is setup or programmed in a way that the panel temperature is not allowed to rise beyond the threshold temperature of 35^0C, while other studies permits the panel temperature to rise beyond the threshold temperature to a certain level before the cooling mechanism drops the panel temperature back to the threshold temperature. The objectives of the study were achieved via the application of a digital temperature sensor coupled with relays that is linked to the cooling mechanism. The cooling mechanism activates and shutdown automatically once the panel temperature goes above and below the preset temperature respectively. This study provides vital information that will aid users and engineers in designing, maintaining and manipulating PV system in harvesting more energy from PV modules.

2. MATERIALS AND METHODS

The study used two identical polycrystalline photovoltaic modules of the model AF-130W manufactured by Africell solar with a rated maximum power of 130W. The electrical characteristics of the module are shown in table 1. A digital solar power meter (model SM206) and a digital solar flux meter (model MS6612) was employed for the effective tracking and measurement of the solar power and solar flux respectively at the surface of the PV modules. A digital high precision photovoltaic panel maximum power point tracker (MPPT) of the model WS400A was used to track and determine the maximum power generated by the photovoltaic module. A submersible DC solar water pump of the model AD20P-1230A, hose, and water sprinkler were also employed. While an intelligent automatic digital temperature sensor of the model W1209 coupled to a relay was also utilized for the study. A digital infrared gun thermometer, solar battery (Gel battery: 12V, 100A), and a digital charge controller were also employed.

TABLE 1: PV module technical characteristics

Electrical Specification	**Value**
Maximum Power	130W
Current at Maximum Power	7.18A
Voltage at Maximum Power	18.10V
Short Circuit Current	7.91A
Open-circuit Voltage	21.72V
Number of cells	36
Module dimension	1480mm*670mm*35mm

2.1. Experimental Setup

The experiment was carried out in an outdoor environment in Calabar close to the Calabar river (latitude $4^0 57^{'}38.6161$" N and Longitude $8^0$18'58.482"). The two PV modules were installed at an angle of 5^0 facing the north on a platform of 1m above sea level. One module was used as the reference module, while the other was installed with the cooling mechanism. Connecting cables were connected from the output of the PV module to the input of the intelligent PV panel MPP tracker from which the maximum power points were tracked and determined as described in figure 1. Also, from the output of the PV module, connecting cables were linked to the charge controller to which the battery was connected for smooth charging. The automatic digital temperature sensor was installed at the panel's surface, and its output was linked to a relay from which the submersible DC solar water pump was powered. Figure 1 shows the experimental setup for the panel installed with automatic cooling mechanism, while figure 2 shows the setup for the solar panel without temperature control.

The data was acquired from the PV modules at an interval of 30 minutes from 6 am to 6 pm for a period of 4months. During data acquisition, measurements were taken from both modules simultaneously.

The experiment was conducted in real outdoor conditions. With the aid of the digital infrared gun thermometer, the panel temperatures were measured and recorded. While with the aid of the solar power meter and solar flux meter the solar power and solar flux respectively at the surface of the PV modules were measured and recorded. The instantaneous voltage (V_{mp}) and current (I_{mp}) at maximum power under a particular real-time condition were measured and recorded. The open-circuit voltage V_{oc}, V_{mp}, $I_{mp,}$ and P_{max} were measured directly with the aid of the intelligent panel MPP tracker. The current at maximum power I_{mp}, the voltage at maximum power V_{mp} and the open circuit voltage V_{oc} of the PV module are greatly influenced by several parameters, including design, maintenance of the module, and temperature (T), and may be determined by (1) and (2) respectively as shown by [30].

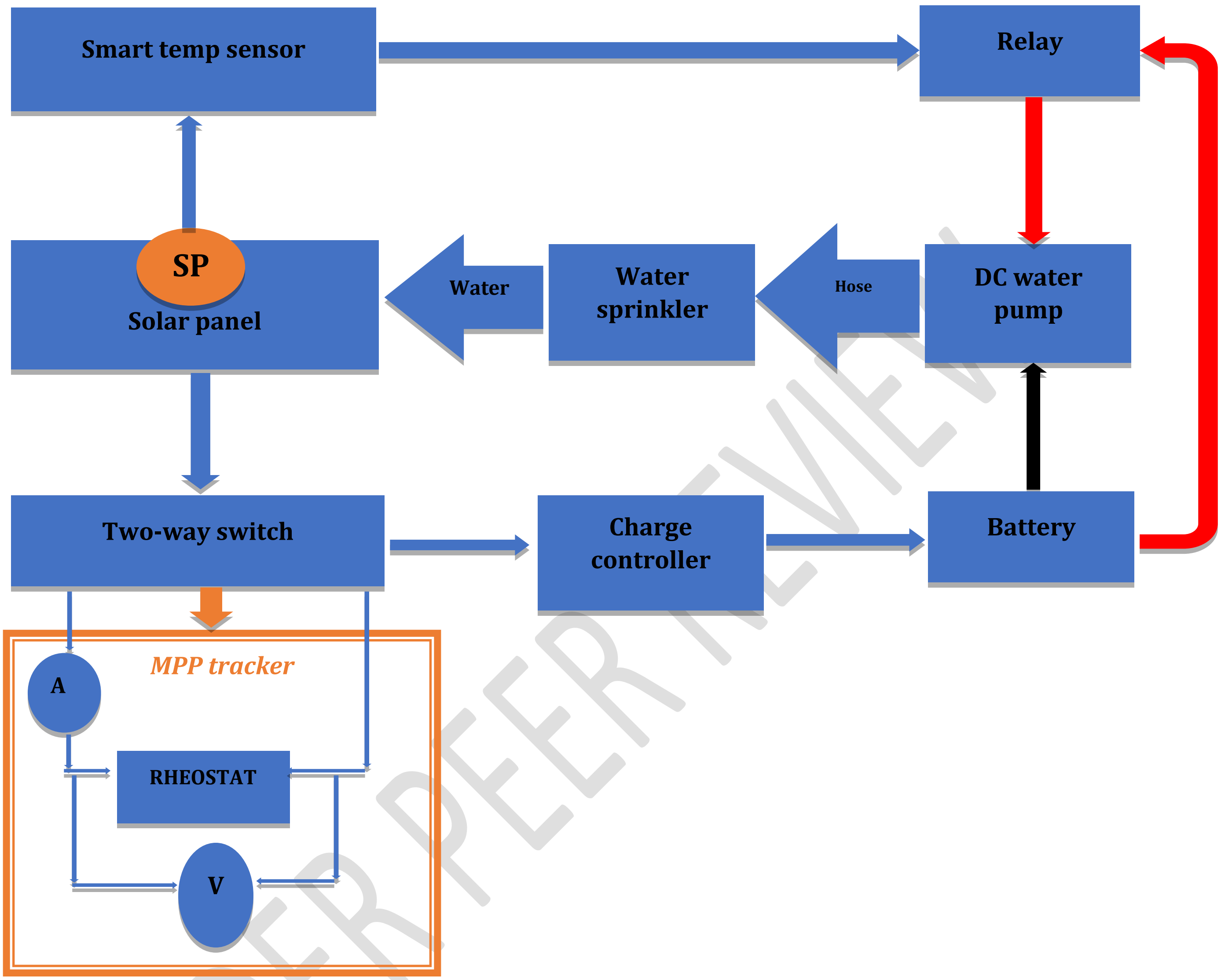


Figure 1: The experimental setup for the panel installed with automatic cooling mechanism.

Load current:

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

Open circuit voltage:

$$V_{oc} = \frac{K_B T}{q} ln\left(\frac{I_{ph}}{I_0} + 1\right) \quad (2)$$

Where I_{ph} is the photogenerated current, I_0 is the diode reverse saturated current, q is the electron charge, K_B is the Boltzmann constant, T is the absolute temperature, and V is the voltage at the terminals of the module.

According to [31] (2) can be approximated and reduced to (3)

Open circuit voltage approximated:

$$V_{oc} = \frac{K_B T}{q} ln\left(\frac{I_{ph}}{I_0}\right) \quad (3)$$

According to [32], the photogenerated current I_{ph} is equal to the short circuit current I_{sc} and is closely related to the photon flux incident on the PV modules and given as (4)

Short circuit current:

$$I_{SC} = bH \tag{4}$$

Where H is the incident solar flux and b is a constant that depends on the junction properties of the semiconductor.

The normalized power output efficiency was computed by (5) as shown by [33].

Normalized power output efficiency:

$$\eta_P = \frac{P_{mea}}{P_{max}} \times 100 \tag{5}$$

Where P_{mea} is the measured power at maximum power points, while P_{max} is the maximum power of the PV module (as specified by the manufacturer) at STC.
From the individual output electrical parameters (X), the performance gains X_{gain} of the PV module with thermal regulation can be calculated using (6) as shown by [34].

Gain in output electrical characteristics

$$X_{gain} = \frac{X_{with\ cooling} - X_{without\ cooling}}{X_{without\ cooling}} \times 100\% \tag{6}$$

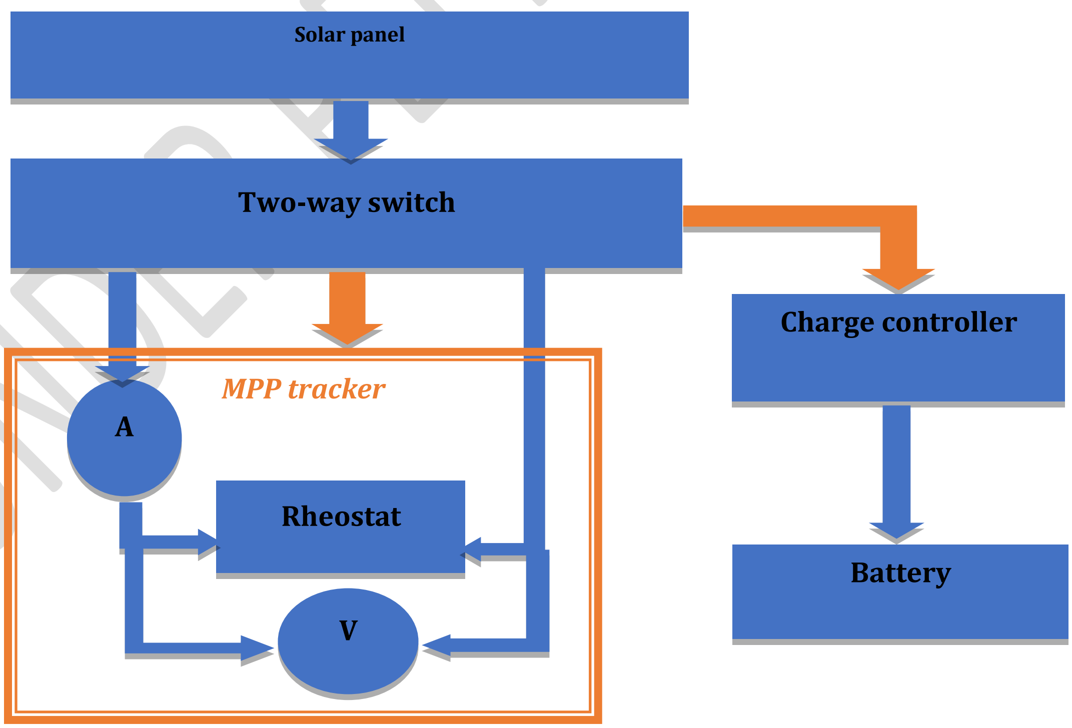


Figure 2: The experimental setup for solar panel without temperature control

3. RESULTS AND DISCUSSION

This section presents data acquired by in situ measurement and the analysis; it is divided into three parts. The first part discusses the impact of the cooling mechanism on the panel temperature with increasing level of sunlight. In the second part, analysis of the result is given concerning the influence of the cooling mechanism on the electrical parameters with varying solar power reaching the modules. while the third part discusses the result concerning the influence of the cooling mechanism over the electrical parameters with varying solar flux reaching the modules. The cooling mechanism is program to maintain the panel temperature at 35^{0}C. It should be noted that the voltage, current, and power used in the analysis of the results are the maximum voltage, current, and power respectively that the modules can generate under a particular temperature and environmental condition. It should be noted that "(+) C" indicates the photovoltaic system with the automatic cooling mechanism, while "(-) C" indicates the photovoltaic system without the automatic cooling mechanism.

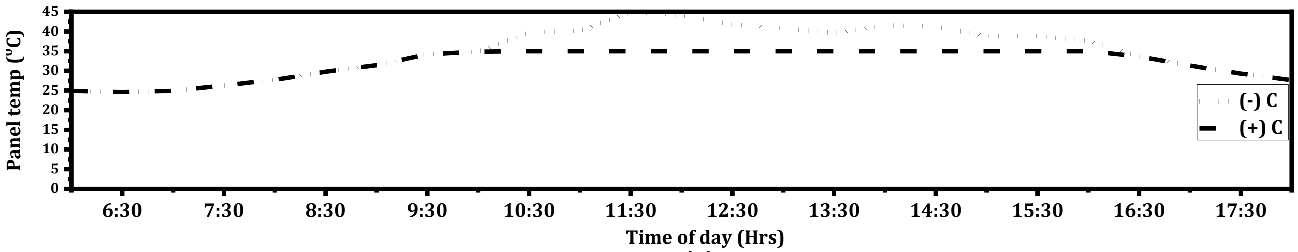
Table 2: Uncertainty analysis of solar panel data obtained from in-situ measurement

	Panel Temp (^{0}C)		**Voltage (V)**		**Current (A)**		**Power (W)**		**Efficiency (%)**	
Statistic	**(+) C**	**(-) C**	**(+) C**	**(-) C**	**(+) C**	**(-) C**	**(+) C**	**(-) C**	**(+) C**	**(-) C**
Minimum	24.61	24.61	1.56	1.56	0.00	0.00	0.00	0.00	0%	0%
Maximum	35.00	44.94	17.20	15.29	4.82	4.38	82.30	66.51	63.33%	51.16%
Mean	32.02	34.80	15.08	14.17	2.08	1.93	34.58	29.22	26.56%	22.48%
Median	34.89	34.89	15.24	15.11	2.33	2.24	35.58	33.62	27.37%	25.86%
Variance	15.10	43.03	10.86	8.02	2.18	1.76	662.14	409.60	3.91%	2.42%
Standard Deviation	3.89	6.56	3.30	2.83	1.48	1.32	25.73	20.24	19.80%	15.57%
Standard Error	0.78	1.31	0.66	0.57	0.30	0.26	5.15	4.05	3.96%	3.11%

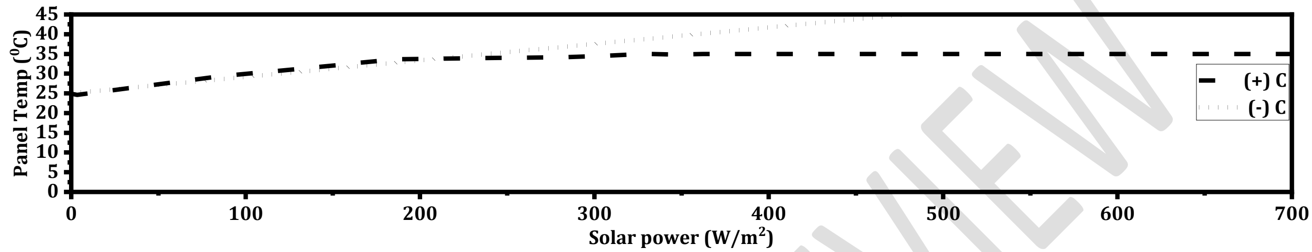
3.1. Influence of cooling mechanism on panel temperature with increasing level of sunlight

Figure 3 shows the panel temperature of the photovoltaic modules throughout daytime as solar power and solar flux increases. The figure reveals a gradual increase in panel temperature as we proceed into the day with rising solar power and solar flux. Once the panel temperature exceeds 35^{0}C, the cooling mechanism was activated to maintain the panel temperature at 35^{0}C for the module with thermal regulation.

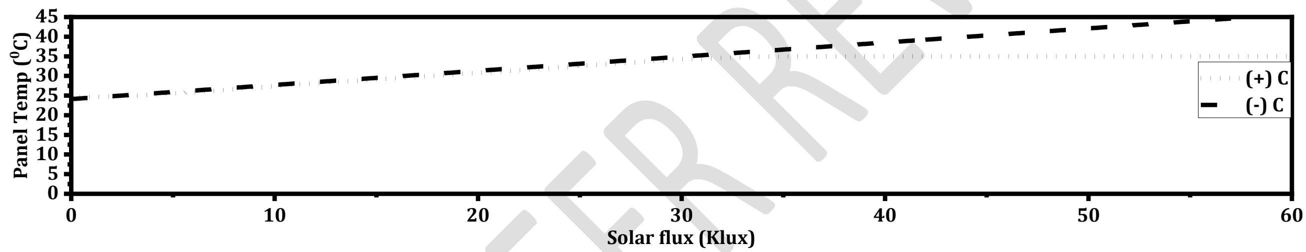
Figure 3a displays the temperature of the PV modules throughout the daytime. The figure depicts the panel temperature rising between 6:00 am to 11:30 am before decreasing gradually. In addition, the figure also portrays the automatic cooling mechanism being triggered at 10:30 am once the module temperature exceeds 35^{0}C. while figure 3b shows the module temperature with an increasing level of solar power. The figure reveals a steady increase in module temperature as the solar power reaching it increases. However, the cooling mechanism was triggered at about 360 W/m^2 of solar power when the threshold temperature was exceeded. For the other module without thermal regulation, a constant and linear increase in panel temperature was observed as solar power increases. Figure 3c represent the temperature of both modules with rising level of solar flux. A linear increase in module temperature was experienced as the solar flux reaching the modules increases. For the module with thermal regulation, the cooling mechanism was triggered at about 35 Klux of solar flux when the threshold temperature was exceeded.



(a)



(b)



(c)

Figure 3: panel temperature at different time of day with increasing level of solar power and solar flux

3.2. Influence of solar power on the electrical parameters of thermal regulated and unregulated PV modules

Figure 4 depicts the impact of the cooling mechanism on the output electrical parameters of the PV modules with respect to solar power. The figure depicts the PV module with thermal regulation generating higher electricity.

Figure 4a portrays the influence of the cooling mechanism on the voltage output of both modules with respect to solar power. The figure reveals both modules giving out the same amount of voltage as the solar power reaching them rises to about 360 W/m^2. Once the cooling mechanism was activated, the module whose temperature was regulated produced a higher level of voltage with an average increase of 6.42% as displayed in table 2. The result shown in figure 4a agrees with earlier research by Tjahjana, et al. [19], which reported that removing excess heat from PV modules can raise the open-circuit voltage by at least 10%. Figure 4b depicts the influence of the cooling mechanism on the current generated by both modules with respect to solar power. The figure illustrates the module generating the same amount of current initially. However, once the threshold temperature is exceeded, the module with regulated temperature generates a significantly higher amount of current with an average increase of 7.77% which is evident from table 2, and also agrees with earlier research by Tjahjana, et al. [19]. Figure 4c reveals the modules' power output with increasing solar power with and without thermal regulation. The figure demonstrates the module with thermal regulation generating a higher amount of power with an average increase of 18.34%, which conforms with earlier studies by Wojciech, et al. [20], which reported that continuous cooling of PV modules during operation increases the output power by 20%. The lower output power generated by the module without thermal regulation is because charge carriers are liberated at a lower potential, due to the shrinking of the of the intrinsic semiconductor band gap as temperature rises. Figure 4d depicts the modules efficiency with and without thermal regulation with respect to solar power. The figure describes the module with thermal regulation being more efficient above the other module under the same level of solar power. Furthermore, an average increase of 18.15% in efficiency was observed from the module with thermal regulation, which conforms to research by Ogbulezie, et al. [15], which concluded that photovoltaic systems would remain efficient coupled with a high-performance ratio if the temperature of the system is controlled in a way that the maximum operating cell temperature is not exceeded.

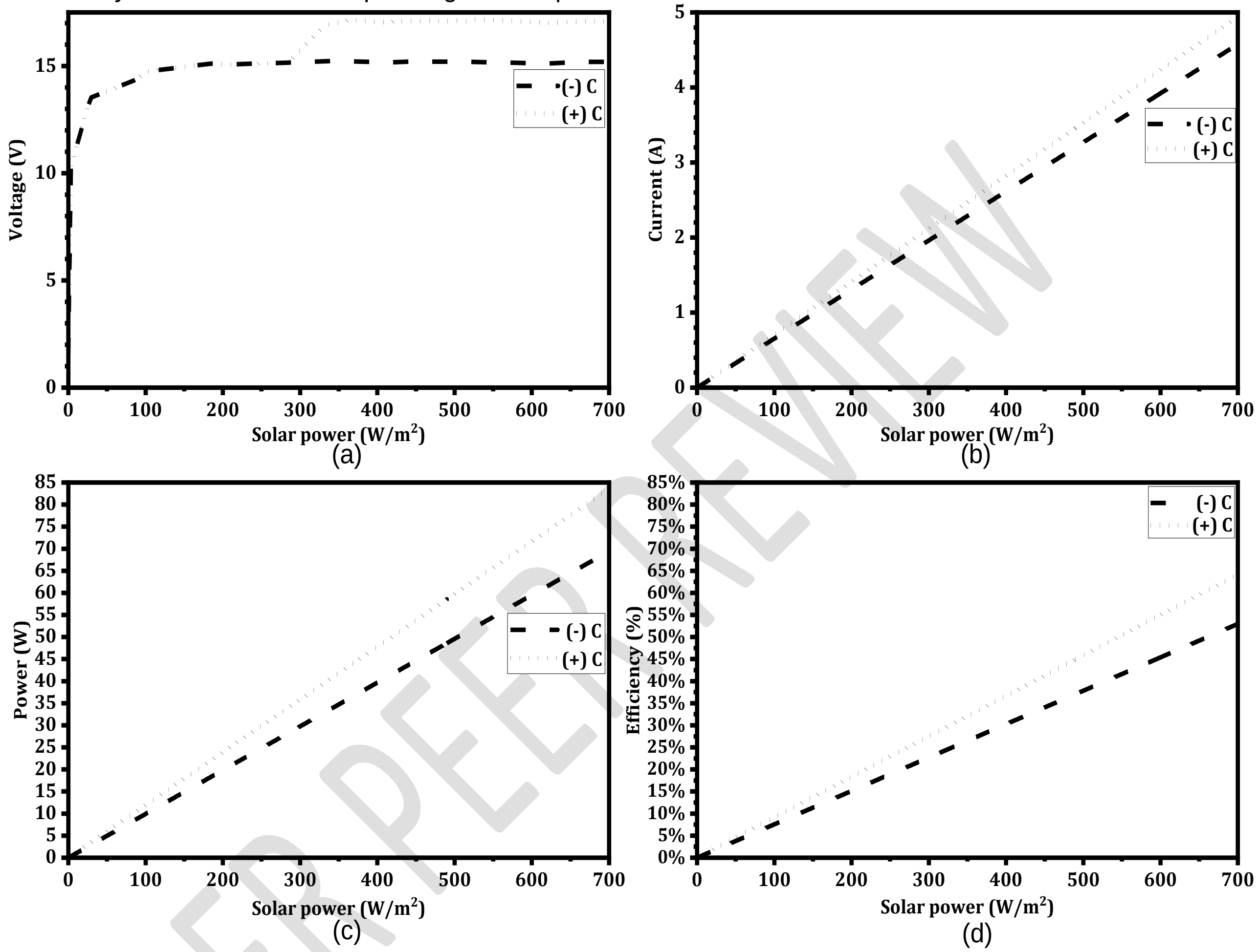


Figure 4: Influence of cooling mechanism on modules output electrical parameters with respect to solar power

3.3. Influence of solar flux on the electrical parameters of thermal regulated and unregulated PV modules

Figure 5 reveals how significant improvement on the output electrical parameters of the PV modules with respect to solar flux has been made by the cooling mechanism. The figure shows that PV systems are more effective when their temperature are regulated.

Figure 5a portrays how the cooling mechanism influences the voltage of both modules with the same level of solar flux. The figure reveals both modules giving out the same amount of voltage as the solar flux at their surfaces reaches 35 Klux. Once the cooling mechanism was activated, thermal regulation enabled a higher voltage to be generated with a significant increase of 6.42% on average, which agrees with work by Alami [22], whose results reveal a maximum increase in output voltage by 19.4%. Figure 5b depicts the influence of the cooling mechanism on the current generated by both modules under the same level of solar flux. Once the threshold temperature was exceeded, the module with regulated temperature showed higher current performance with an average increase of 7.77% as revealed in table 2, which still agrees with the work by Alami [22]. Figure 5c reveals the electrical power performance of both modules with the same amount of solar flux falling on them. The figure shows the module with thermal regulation having better electrical power performance with an average increase of 18.34% in electrical power generated, which corresponds with work by Alami [22], whose results reveal a maximum increase in electrical power output by 19.1%. Whereas Figure 5d depicts the efficiency of the modules under the same level of solar flux with and without thermal regulation. From the figure, it could be seen that the module with thermal regulation attained higher efficiency, which shows the adverse effect high temperature has on PV efficiency, which agrees with work research by Ogbulezie, et al. [15].

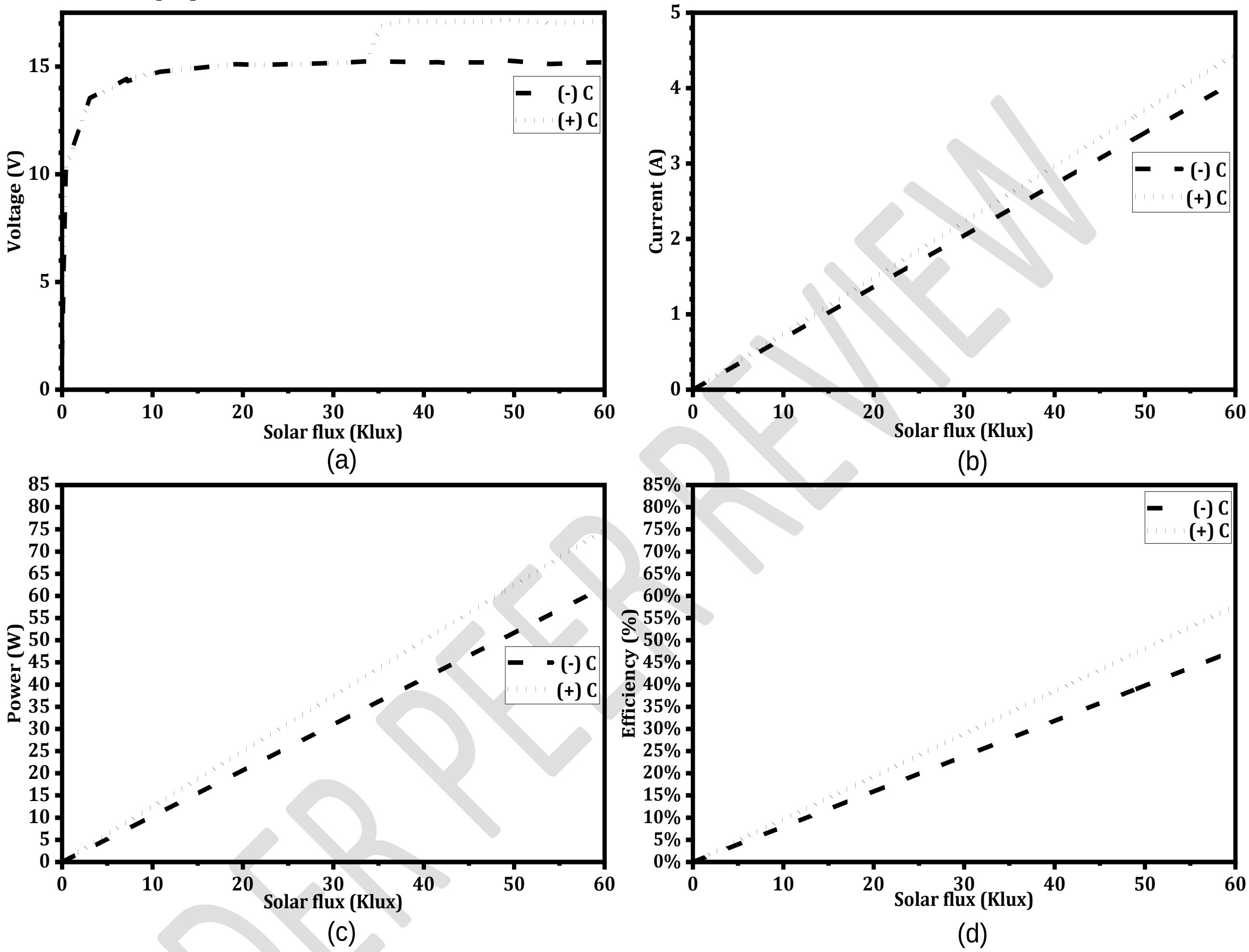


Figure 5: Influence of cooling mechanism on modules output electrical parameters with respect to solar flux

4. CONCLUSION

An experimental study of the behavioral pattern of photovoltaics enhanced with an automatic cooling mechanism was conducted in Calabar, Nigeria. An automatic cooling mechanism was utilized to prevent the PV module from exceeding the preset threshold temperature. In contrast, an intelligent high precision photovoltaic panel maximum power point tracker was used to track and determine the maximum power generated by the photovoltaic modules at a particular level of solar power and solar flux at each time of day. The outdoor experimental investigation of two polycrystalline photovoltaic modules was conducted. The impact of the cooling mechanism on the modules was determined by measuring the electrical operating parameters as well as tracking the maximum power and efficiency of the modules at a particular level of solar power and solar flux at each time of day. The study results revealed better voltage, current, power, and efficiency performance for the PV module under thermal regulation. The results further reveal an average increase of 6.42%, 7.77%, 18.34%, and 18.15% for voltage, current, power, and efficiency, respectively. The study also shows that the preset threshold temperature should be lowered to increase the PV module's performance. The major importance of the cooling mechanism in the PV system is to prevent the creation of electron-hole pair through thermal agitation as much as possible. As temperature increases, the gap between the valence and conduction band of a semiconductor diminishes along with the open circuit voltage. The creation of electron-hole pairs in the junction region of the solar cells through thermal agitation leads to the narrowing of the potential barrier which inevitably leads to a drop in voltage as well as efficiency. Moreover, thermal agitated electron-hole pairs can trigger unwanted sequence of recombination which can further increase the cell temperature, since electrons that undergo recombination give up their energy as heat. This research demonstrates that a cooling mechanism should be incorporated in designing photovoltaic systems, especially in developing countries like Nigeria.

ABBREVIATIONS

PV: Photovoltaic
V_{mp}: Voltage at maximum power
I_{mp}: Current at maximum power
MPPT: Maximum power point tracker
STC: Standard test condition
SP: Sensor probe

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