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Diurnal analysis of enhanced solar photovoltaic systems using automatic cooling mechanism

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Abstract

Africa and Nigeria in particular are blessed with abundance of sunshine throughout the year. Unfortunately, the region is associated with high temperature values which is a major factor militating against the efficiency of photovoltaic systems in use today. Since for each degree rise in temperature, about 0.50% efficiency is lost, then this implies that once a photovoltaic panel enters the Nigeria atmosphere about 5%-10% of its maximum power is lost. To tackle this problem, a cooling mechanism has to be incorporated into photovoltaic system design for adequate cooling and temperature monitoring. A smart automatic cooling mechanism and a smart photovoltaic MPPT tester were deployed in the study. In situ measurements were obtained in outdoor real-time conditions. The results reveal better performances for voltage, current, power and efficiency for the photovoltaic module whose temperatures was regulated not to exceed the threshold temperature of 35⁰C. This study shows and suggest that lowering the panel temperature of photovoltaics through the application of cooling mechanism should be considered in the design of photovoltaic systems.

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

1. Introduction

The problems brought by climate change, energy security and possible depletion of fossil fuel reserves have triggered the improvement of renewable energy technologies [1], [2]. Presently, approximately 80% of the total energy which is consumed in the world is obtained from fossil fuels which is among the major contributors to global climate change (ozone layer depletion and global warming) [3], [4]. The application of renewable energy technologies, such as solar energy, has become valuable due to its less negative impact on the environment, coupled with the unlimited availability of the resources [5]. Apart from been sustainable and reliable, solar energy stands as the most favorable renewable energy resources due to its clean, noiseless and pollution free nature [6], [7]. The harvesting of solar energy through the use of photovoltaic systems for the generation of power is seen as one of the potential game changers in the renewable energy sector [8].

Photovoltaic is the technology that produces direct current (DC) electricity from semiconductors when exposed to light (natural or artificial). As long as light reaches a photovoltaic cell, DC electricity will be generated. Unlike batteries, photovoltaic cells do not need to be recharged, and some of them have been in continuous outdoor operation on earth or in space for more than 30 years [9].

Solar photovoltaic efficiency is largely influenced by the temperature it is exposed to, which depends on the ambient temperature and the level of sunlight (solar power and solar flux) [10], [11]. Manufacturers of solar photovoltaics design them to function in an ideal environment known as standard test conditions, where the module temperature is held constant at 25⁰C with an air mass of 1.5 around it while receiving irradiance at a constant level of 1000W/m². But in

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real outdoor environment these weather parameters are continually changing, hence photovoltaic modules do not operate under the ideal environment they were designed for [12], [13]. Even in an ideal environment, the efficiency of photovoltaic modules drops by about 0.40%-0.50% for each degree rise in temperature [14].

Photovoltaic modules will inevitably generate less power and efficiency when forced to operate under higher temperatures compared to when they operate in a relatively cooler environment. Incidentally, Solar photovoltaic systems often produce higher electricity on a day with hazy sun and cool wind than when the sun is blazing and the temperature is high. On exposure to the sun, their temperature increases due to the absorption of infrared and other wavelengths of lights that adversely affect their efficiency [15]. Also, due to their dark nature photovoltaics can easily heat up quite considerably [16]. In a hot climate, such as the one in Nigeria [17], [18], [19], a solar panel can easily heat up to temperatures above 60°C.

Ogbulezie et al. [20] investigated the impact high temperature and irradiance has on the efficiency of polycrystalline photovoltaic systems and reported that, as long as the temperature of the system does not exceed the maximum operating cell temperature, it exhibits high efficiency and hence, high-performance ratio. Amelia et al. [21] also investigated the temperature effect on the output performance of PV modules and concluded that PV module temperature influences its power production. While Syafiqah et al. [22] carried out a thermal and electrical study for photovoltaic modules incorporating cooling systems and reported that increase in the operating temperature of a photovoltaic panel triggers a decrease in the output power. Kamarudin et al. [23] conducted a research on active cooling photovoltaic with IoT (internet of things) facility and concluded that cooling of photovoltaics improves its power output. While Leow et al. [24] using ANSYS investigated the performance of photovoltaic modules based on different wind speeds and revealed that the performance of photovoltaics could be improved if they are operated in an environment with considerable wind speed. Khan et al. [25] evaluated the performance of photovoltaic systems by employing different cooling methods and realized that under the same solar radiation conditions, the output power of the system decreases as the operating temperature increases. While Moharram et al. [26] attempted to enhance the performance of photovoltaic panels by employing water cooling techniques and discovered that PV panel improves in output power when the cooling of the panels begins when the temperature of the PV panels reaches the maximum allowable temperature (MAT). Arifin et al. [27] carried out a numerical and experimental investigation of air cooling for photovoltaic panels using aluminum heat sinks. Their results revealed that the heat sink raised the open circuit voltage by 10%. While Govardhanan et al. [28] experimentally investigated a PV module with uniform water flow on its surface for adequate cooling. Their report shows that due to cooling, the output power and efficiency of the module was enhanced by 15% and 14% respectively.

Due to the high cost of Photovoltaic systems, it is always desirable to achieve a system that is capable of effectively converting solar energy to electrical energy with minimal loses irrespective of the ambient temperature. But the temperature of Nigeria and Africa as a whole stand as a hindrance to the effectiveness of photovoltaic systems. Since photovoltaic systems are most efficient with temperatures below their optimal operating cell temperature, then the problem is to design and create a photovoltaic system that is capable of operating at a steady temperature irrespective of its ambient temperature. Thus the introduction of automatic cooling mechanism may enhance the performance of the power output by regulating and ensuring that the photovoltaic modules are operated below its optimal operating cell temperature. The polycrystalline technology is one of the technologies flooding and easily found in the Nigerian market. This technology is mostly used for household and residential purposes. Hence the need to devised a means to harvest maximum energy from it. Investigation on the performance of polycrystalline photovoltaic systems with automatic cooling mechanism is not yet investigated especially in the Nigeria's prospects.

This study is aimed at experimentally investigating the effect of automatic cooling mechanism on the performance efficiency of photovoltaic systems. In achieving its objectives, a smart digital temperature sensor coupled with relays that is linked to the cooling mechanism was employed. The cooling mechanism turns on and shutdown automatically once the preset temperature is reached. This study provides information which may enable users in manipulating photovoltaic systems in harvesting more energy from it, and also enhance the prospects of the product in the tropics where temperature surges are common.

2. Material and methods

This section presents the materials used in the study, how the experimental setup was done, the procedures taken in the course of measurement including how the data was processed.

2.1. Materials Used in This Study

Two identical polycrystalline photovoltaic module of the model AF-130W manufactured by Africell solar with rated maximum power of 130W was used in the study: electrical characteristics of the module is shown in table 1. A digital high precision photovoltaic smart panel maximum power point tracker (MPPT) tester of the model WS400A was used to track and determine the maximum power generated by the photovoltaic module. A submersible DC solar water pump, hose and water sprinkler were also employed. While a smart automatic digital temperature sensor (model W1209) coupled to a relay were also utilized for the study. A digital infrared thermometer, solar battery (Gel battery: 12V, 100A) and a digital charge controller 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	1480 mm*670 mm*35 mm

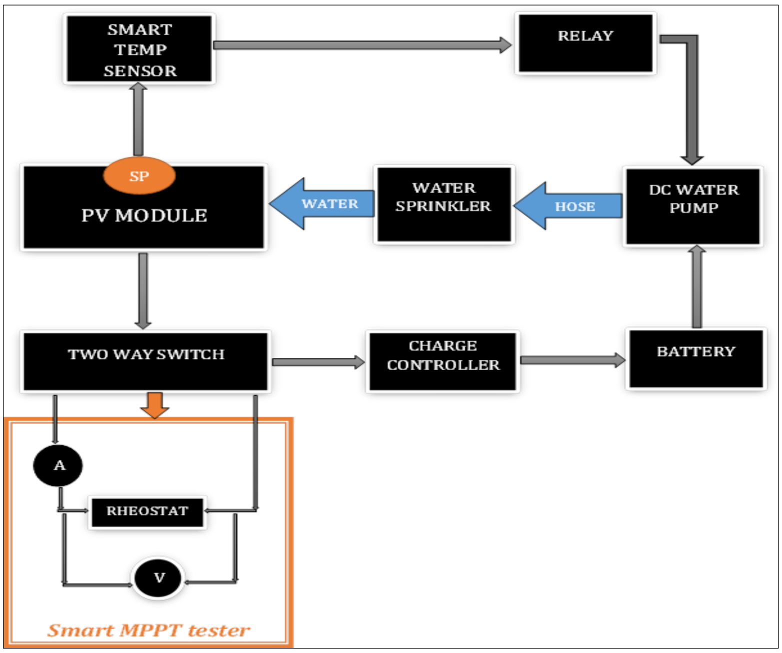

Figure 1 PV module experimental setup

2.2. Experimental Setup

The experiment was carried out in an outdoor environment in Calabar at a location close to the Calabar river (latitude $4^0 57'38.6161''$ N and Longitude $8^0 18'58.482''$). The two photovoltaic modules were installed at an angle of 5^0 facing the north on a platform of 1m above sea level. One module served as the control while the other was installed with the cooling mechanism. Connecting cables were connected from the output of the photovoltaic module to the input of the photovoltaic smart panel MPPT tester from which the maximum power points where tracked and determined as can be seen from figure 1. Also from the output of the photovoltaic module, connecting cables were linked to the charge controller which the battery was connected to for its smooth charging. While the smart automatic digital temperature sensor was installed at the surface of panel and its output linked to a relay from which the submersible DC solar water pump was powered.

2.3. Measurement procedure

Data was acquired from the photovoltaic module 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.

Data processing and measurements: the experiment was conducted in real outdoor condition. With the aid of the digital infrared thermometer the panel temperatures 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 smart panel MPPT tester. The open circuit voltage (V_{oc}) and the voltage at maximum power V_{mp} of the PV module is greatly influenced by several parameters including design and maintenance of the module and temperature (T), and may be determined by (1) as shown by [29], while the normalized power output efficiency was computed by (2) as shown by [30].

$$V_{oc} = \frac{KT}{Q} ln \frac{I_{sc}}{I_o} \quad (1)$$

$$\eta_P = \frac{P_{mea}}{P_{max}} \times 100 \quad (2)$$

3. Results and discussion

This section presents data acquired by in situ measurement and analysis. It reveals the impact of the cooling mechanism on the photovoltaic module. 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.

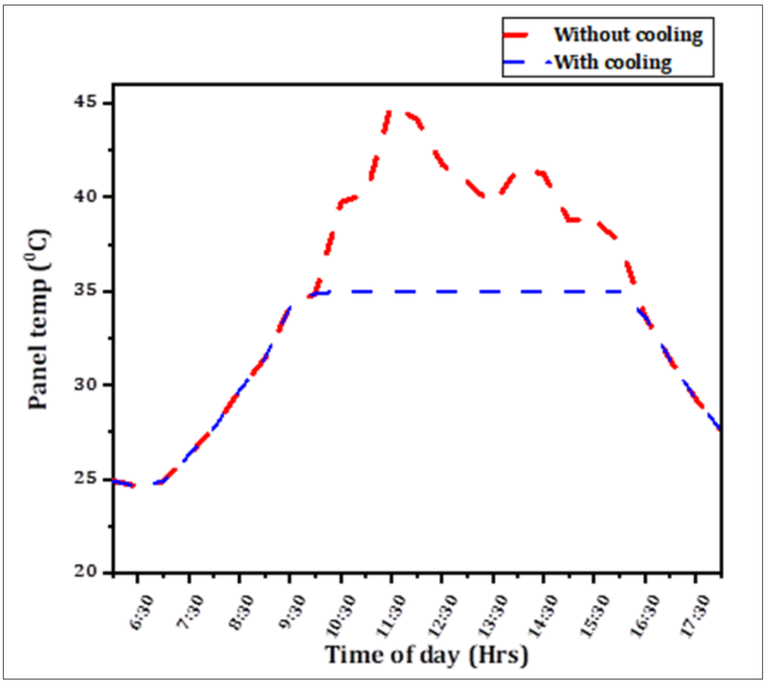

Figure 2 Panel temperature at different time of day

Figure 2 shows the temperature of both modules throughout the day. From the figure it is seen that the panel temperature rises between 6:00am to 11:30am before decreasing gradually. Furthermore, the figure also shows the automatic cooling mechanism been triggered once the panel temperature exceeds 35^{0}C which occurs at 10:30am.

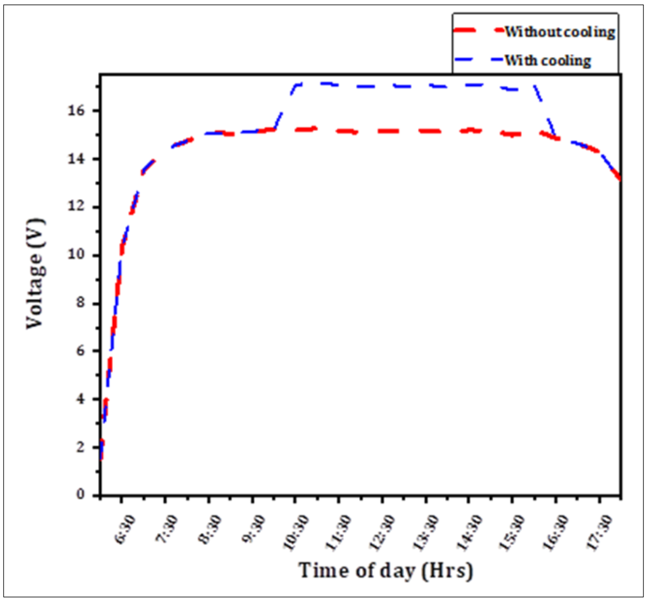

Figure 3 Influence of cooling mechanism on module voltage at different time of day

Figure 3 is the analysis of the voltages produced by both photovoltaic modules throughout the day. The figure reveals both modules generating the same amount of voltage between 6:00am to 10:00am. Between 10:30am to 4:00pm the module with the cooling mechanism generated higher voltage above that without the cooling mechanism which conforms with studies by Arifin et al. [27], which reported that removing excess heat from PV panels raises the open circuit voltage by 10%. From 4:30 pm when the module temperature is below 35^0C both modules generated the same voltages again.

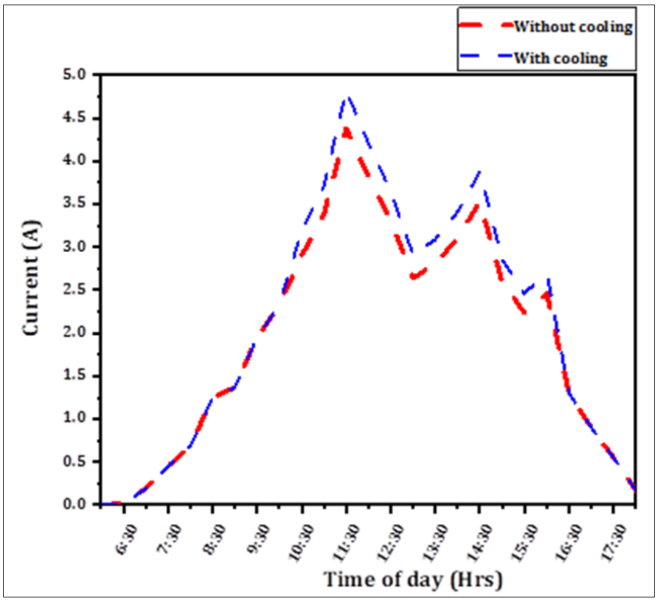

Figure 4 Influence of cooling mechanism on module current at different time of day

Figure 4 reveals the impact of the cooling mechanism on current produced by the modules. The figure depicts the module with the cooling mechanism producing higher levels of current between 10:00am and 4:00pm once the temperature threshold is exceeded. This result agrees with work by Khan et al. [25] which reveals that the output power of the system decreases as the operating temperature increases.

Figure 5 portrays the power generated by both modules throughout the day. From the figure it can be seen that the module with the cooling mechanism generated significantly higher amount of power. The higher amount of power generated by the module with the cooling mechanism is due to the fact that it generated higher voltage and current over the module without cooling as evident in figures 3 and 4 respectively. The higher level of power generated by the module with the cooling mechanism take place between 10:30am and 4:00pm when the temperature threshold is exceeded.

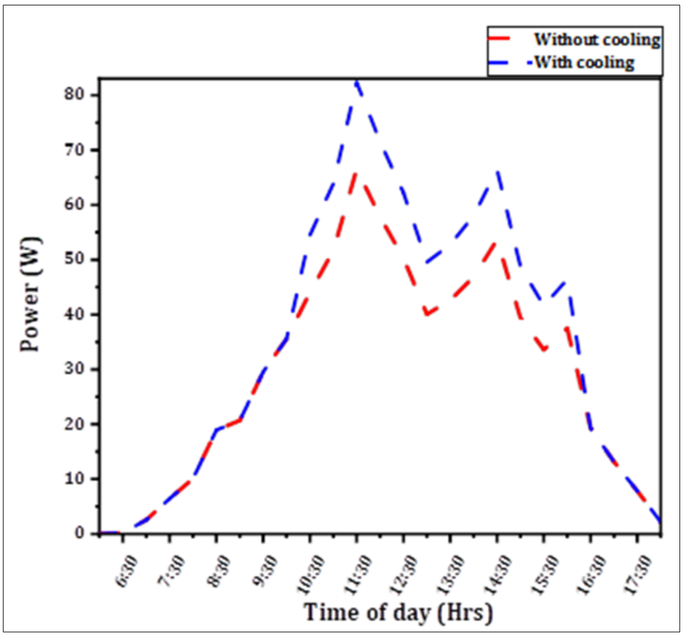

Figure 5 Influence of cooling mechanism on power generated by module at different time of day

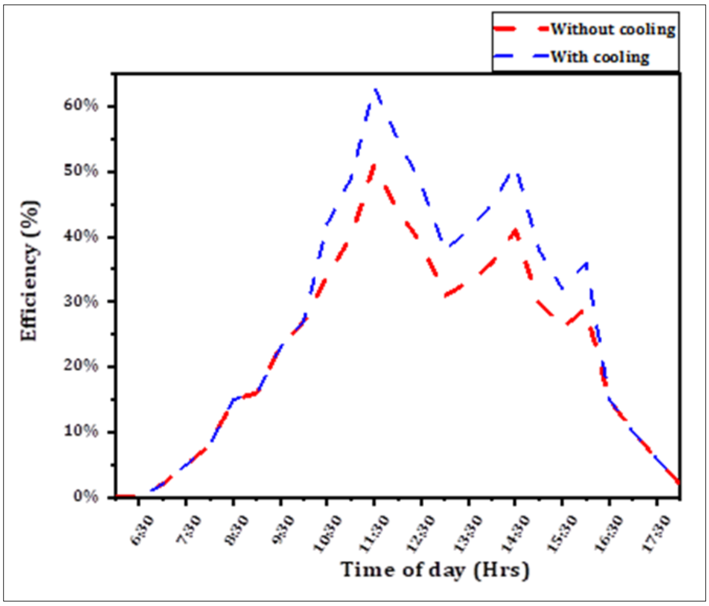

Figure 6 Influence of cooling mechanism on module efficiency at different time of day

Figure 6 is the analysis of the efficiency level reached by the modules. The figure clearly shows the module with the cooling mechanism reaching higher efficiency when the temperature threshold is exceeded; which occurs between 10:30am and 4:00pm as evident in figure 2. Moreover, it should be noted that the higher level of efficiency reached by the module with the cooling mechanism is due to the higher amount of power generated by the module as seen from figure 5. The result of figure 6 agrees with earlier research by Govardhanan et al. [28] which report that due to cooling, the output power and efficiency of the module was enhanced.

4. Conclusion

Africa and Nigeria in particular are blessed with abundance of sunshine throughout the year but the high temperatures associated with this region do not favor the effective harvest of solar energy through photovoltaic technologies. Since for each degree rise in temperature, about 0.50% efficiency is lost, it implies that panels used in the Nigerian atmosphere will generate 5%-10% less of its maximum power rating. The experimental study of the daily analysis of solar photovoltaic systems enhanced with automatic cooling mechanism has demonstrated marked improvement in energy yield. A smart automatic cooling mechanism was deployed to prevent the photovoltaic module from exceeding the preset threshold temperature, while a digital high precision photovoltaic smart panel maximum power point tracker was used to track and determine the maximum power generated by the photovoltaic modules at each time of day. The outdoor experimental investigation of two polycrystalline photovoltaic modules was conducted; 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 each time of day. After careful and thorough analysis, it was observed that the module with the cooling mechanism showed better performance in voltage, current, power and efficiency. This study proves that cooling mechanism should be incorporated into photovoltaic systems designs.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that no conflict of interest exist between them.

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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