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PERFORMANCE OPTIMIZATION OF SOLAR PV MODULE USING PHASE CHANGE MATERIAL

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ABSTRACT

Controlling the surface temperature of a typical solar photovoltaic module is key in achieving higher efficiency. Apt cooling can improve the electrical performance and bring down the rate of the PV module's degradation. An integrated passive cooling technique is presented in this paper. A 0.5cm thick phase change material (paraffin wax) was incorporated in a commercially available photovoltaic PV module. Concurrently, the fabricated (cooled) and the reference (without cooling) PV modules were subjected to the same operational conditions for 5 consecutive days. The electrical parameters of the duo were recorded at a regular interval of time. The average power generated by each are; 8.12W and 9.58W for the reference and fabricated PV modules respectively. This yielded an average power gain of 18% for fabricated module over reference one. Similarly, the average surface temperature of the reference module is 50°C and that of the fabricated module was 46.5°C against 38.4°C of atmospheric temperature. With paraffin wax being inexpensive and available, a more efficient solar photovoltaic module can be achieved through this technique.

Keywords: Solar PV module, Cooling, Phase Change Material, Optimization.

INTRODUCTION

A solar module is a processed semiconductor device that directly converts light energy from sunlight into electrical energy (voltage) through the process of photovoltaic. The first solar cell was built around 1883 by Charles Fritts, who used junctions formed by coating selenium with an extremely thin layer of gold. However, cell efficiencies remained around 1% until 1950s when U. S. researchers were essentially given a blank check to develop a means of generating electricity onboard space vehicles. Bell Laboratories quickly achieved 11% efficiency and in 1958, the Vanguard Satellite employed the first practical photovoltaic generator producing a modest one watt (Dharmendra, *et al.*, 2016). Figure 1 shows schematic of the working principle of a typical Solar Photovoltaic Cell (SPVC). It functions in such a way that there is continues recombination of charges (electron-hole pairs) within the cell. These electron-hole pairs are generated provided that the photon striking the SPVC surface has energy greater than the material's band gap. Any energy below, or above, the band gap is converted to heat and is the source of heating within the module.

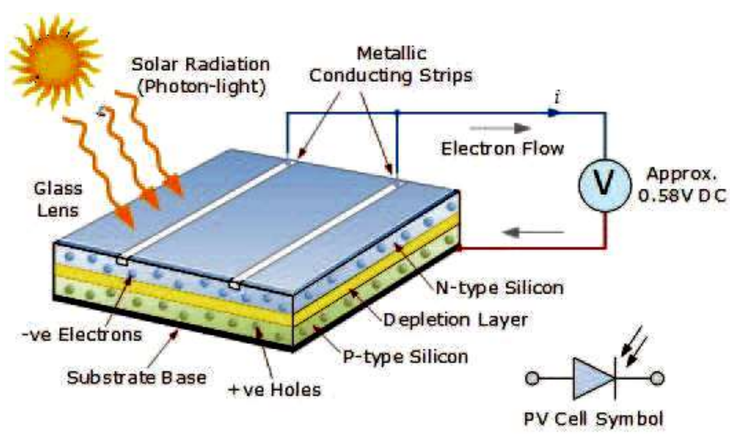


Figure 1: A Diagram of a Solar Photovoltaic Cell Showing the Electron-Hole Pairs (Source: Cox, et al., (2020)).

Heating leads to two main issues in photovoltaic (PV): decreased efficiency and increased degradation, thus shortening the life of the PV module (Cox *et al.*, 2020). During normal operation, surface temperature of solar PV module can rise to about 50-60°C depending on location and weather conditions. As PV modules heat up, 0.4-0.5% decrease in power per 1°C rise in temperature occurs within the silicon cells, depending on the manufacturing technology employed (Honsberg and Bowden, 2020). This leads to decrease in electricity productions most especially during hotter climates when electricity demands are high. The immediate negative impacts of solar PV modules overheating have been researched and well documented. An economically optimized cooling technique for both PV modules' industries and end users is yet to be investigated.

Many literatures aimed to investigate a suitable and cost-effective cooling method for PV modules using PCM. However, some of the outcomes show a very good improvement in terms of electrical performance but too costly to be implemented while others were not good enough industrial consideration. According to Seto *et all.* (2021), after assessing the past studies on cooling through PCMs, they deduced; "The successful use of PCM from latent heat storage systems is highly dependent on the thermal reliability and stability of the PCMs used. In conclusion, the overall energy utilization ratio of cooled PV modules using a PCM system can be increased through a thermal regulation strategy, further research of this system is still needed to achieve maximum results in PV efficiency." To this reason, this paper therefore focuses on providing a singular solution to this overheating problem through the incorporation of paraffin wax beneath a piloted solar PV module. This is due to its thermal characteristics such latent heat of fusion (0-36^{o}C solid and 37-46^{o}C Transition range), abundancy, cost-efficiency and its harmlessness for both human and environment.

Cooling Techniques

A number of researchers have worked on cooling solar PV module with different approaches. These approaches include; passive and active cooling techniques. Chong and Kelvin (2021); Zainal *et al.* (2020) conducted a comprehensive computational fluid dynamics (CFD) simulation for solar PV module with and without aluminum heat sinks installed. The results showed a reduction of up to 10°C in the average temperature of the module with a heat sink installed. A physical experiment was further conducted with an installed heat sink. It was observed that, installed heat sink reduces the panel temperature, increases the open circuit voltage (V_{OC}) and maximum panel power (P_{MPP}) by10°C, 10% and 18.67%, respectively. Huda *et. al.* (2020), carried out an investigation on the effort to control the overheating of solar PV module and improve its efficiency through the application of ZnO Nanoparticles as a luminescent down-shifting material for Si solar module. It was observed that, when the ZnO Nanoparticles is placed on the front surface of a module, it's temperature reduces by 4.5°C and the corresponding output voltage increased to about 1.2V. Anmar (2020) studied the power management of a solar PV module using a programmed micro-controller which operates sprinklers and wipers to clean the SPVC of dust for the period of 2 minutes.

The system was provided with a sensor which signals to the micro-controller when temperature rises above 25^{o}C. The micro-controller operates a fan to cool the module. When temperature rises to higher degrees and the fan fails to cool it to the desired degree, the micro-controller sends a signal to the sprinklers to start work. The statistics revealed that; this method has significantly improved the productive capacity of the

module to about 34.55%. Mawoli et al., (2019) investigated the effectiveness of the developed solar PV module's surface-to-rear temperature-controlled solenoid valves for PV module cooling application. The cooling fluid is regulated by energizing normally closed (NC) solenoid valve with control parameters as modules rear and surface temperatures. ATmega32 microcontroller was utilized as central processing unit with two (2) LM35 as input sensors and solenoid valve as an output device. The module's mean surface temperatures of 49.31^0C and 54.92^0C were recorded for temperature-controlled PV cooling applications and a standard solar photovoltaic/thermal (PV/T) system. The maximum recorded surface temperatures for temperature-controlled PV cooling and a standard PV/T systems were 54.0^0C and 57.6^0C respectively. The maximum absorber temperature recorded for temperature-controlled PV cooling and standard PV/T were 48.30^0C and 41.63^0C respectively. The solar cells temperature is reduced by5.38% through solenoid valve temperature controlled solar module cooling application.
Jaemin *et al.* (2019) tested the performance of three identical solar PV modules, two prototyped under cooling by fins and metal mesh respectively, while the other served as a reference module. The results demonstrated that; solar PV module can be cooled by attaching fins or metal mesh. The average temperature of the cell dropped by 1.49°C and 3.18°C for the metal mesh and fins respectively. Furthermore, a simulation (computational fluids dynamic) was performed under the assumption; both the metal mesh and fins were completely in contact with the bottom of the module and there was no thermal contact resistance. Accordingly, the results indicated that; under a similar heat transfer area, the cooling performance of fins was superior to that of the metal mesh. Benny and Tobias (2018) studied cooling module with a phase-change-material (PCM) separated into 12 bags and then placed in a 3x4 shaped pattern fastened to an aluminum plate which was placed on the back of an SPVC. It was tested first through a pilot test method, then tested outdoor on panels with insulation on its back to simulate 'building integrated photovoltaic BIPV-panels. The PCM was able to cool down however, PCM technologies needs to be more optimized in terms of materials use, nature and the pattern of applying it. Thus, it wasn't economically viable. Base on the method of Kande *et al.* (2016) where they conducted an experiment aimed at cooling solar PV module via different vegetation and water tray.
Their study made use of a polycrystalline silicon cell. The plants selected for the experimentation has good evapotranspiration. The numerical value of increase in instantaneous efficiency obtained was 3 to 4%, 1.8 to 2.2%, 1.2 to 2% and 0.2 to 0.5% for water tray, peppermint, tulsi and aloe vera respectively. Zeyad *et all.* (2016) studied the application of a model consisting a solar PV module attached to an inclined duct. The dimensions of the duct were 3x67x140cm. On the lower side of the duct, water flows on a piece of cloth. Air was blown inside the duct via a fan relative to the direction of water flow (concurrent configuration). The lower part of the duct is adiabatic. The PV module is subjected to uniform solar radiation intensity. As the air flows over the wetted surface inside the duct, water evaporates and cools the air which in turn, absorbs the heat from the SPVC. As the heat is transferred to the air, the temperature of the PV panel decreases (about 6^oC) and electricity production enhances. Joson and Sajith (2017) also conducted a similar research. This research aimed at finding a cooling technique which is cost-effective and applicable for both small and large PV arrays. Since the rise in operational temperature of a solar PV cell is an

unavoidable natural phenomenon so long as it is functioning. Base on the recent conclusion made by Seto *et all*. (2021), which call for further investigations on systems of cooling using PCMs. To this reason, it is anticipated that, if an optimized cooling system is incorporated to each module from the design stage, it will significantly manage the thermal fluctuation of the entire system during operation and change the whole narration of energy lost in that regards. Thus, this research is keen to towards achieving that with a little amount of financial and resource input.

MATERIALS AND METHODS

Two commercial mono facial solar photovoltaic modules (see Table 1 for specification) were used in the study. The first module served as the reference module (R-Module) while the other was doctored and prototyped to suit the design, here referred to as fabricated module (F-Module). Paraffin wax was heated to about 65-70°C until it changes phase (from solid to liquid). The liquid paraffin wax was then poured on the back surface of the solar module to gauge up to the level of the protrusion of the aluminum frame as depicted in Figure 2. The groove thickness of the aluminum frame is 1.0cm, thus placing a constrain of 1.0cm as the thickness of the deposited paraffin wax. To avoid crystal defects due to thermal fluctuation, the fabrication was carried out in a container full of water. Subsequently, the liquid paraffin wax was allowed to cool and solidify to stays on. Thereafter, the surface was covered with an aluminum sheet of about 0.4mm thick using an acrylic adhesive to further facilitate dissipation of heat.

Table 1: Module Specifications

Manufacturer	**Sunshine Solar**
Model number	AP-PM-10
Module active area	661.26cm^2
Maximum power (P_{max})	10W
Rated voltage at maximum power (V_{max})	17.5V
Rated current at maximum power (I_{max})	0.57A
Open circuit voltage (V_{oc})	22.05V
Short circuit current (I_{sc})	0.63A
Output tolerance	±5%
All ratings at STC 1000W/m^2, Air Mass (AM) 1.5 Spectrum, 25°C	

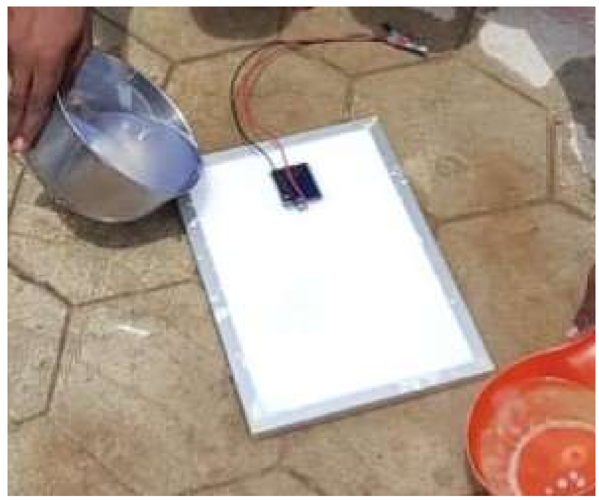


Figure 2: Fabrication process

The R- and F- Modules are then placed side by side during the measurement campaign. Log-tags (is a temperature monitoring logger approved by WHO to monitor temperatures for pharmaceuticals and cold-chain facilities from as low as -2°C to more than 100°C) were programmed to automatically and digitally capture ambient temperature at predefined regular time intervals (after 15 minutes), starting and stopping times every day. In order to minimize errors and irregularities due to unavoidable delay in measurements, the surface or working temperature of each module was randomly measured by two persons at different points on the individual modules at a time using infrared thermometer. The average of each session was taken. Both the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of each module were measured and recorded with the aid of digital multi-meters at the same time intervals, as shown schematically in figure 4 below. These readings were obtained for the period of 5 consecutive days (from 23rd to 27th of May 2021), starting from 11:00am to 3:00pm of each day, being it the period of peak sun shine hours (PSH), as published online by Solynta Energy (2018). The experimental set up and the atmospheric information of the location where the campaign took place are shown in Figure 4 and Table 2 respectively.

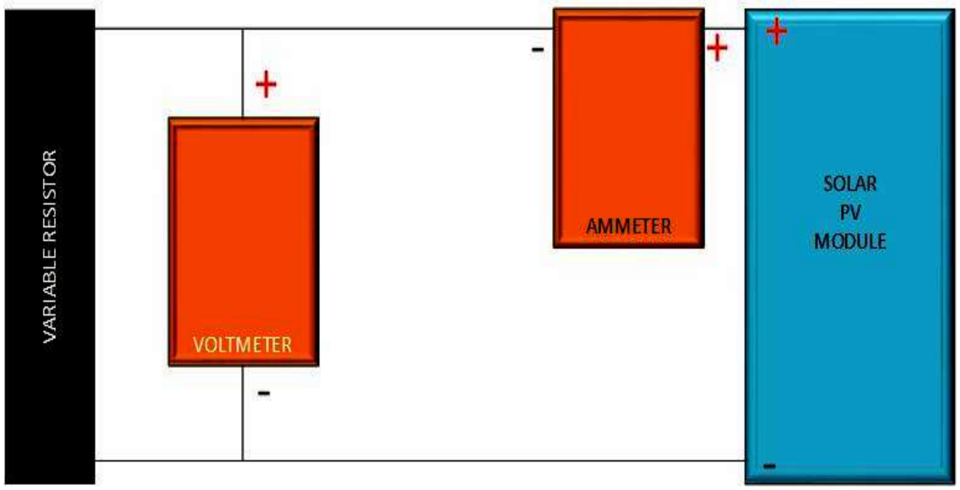


Figure 3: schematic experimental set up

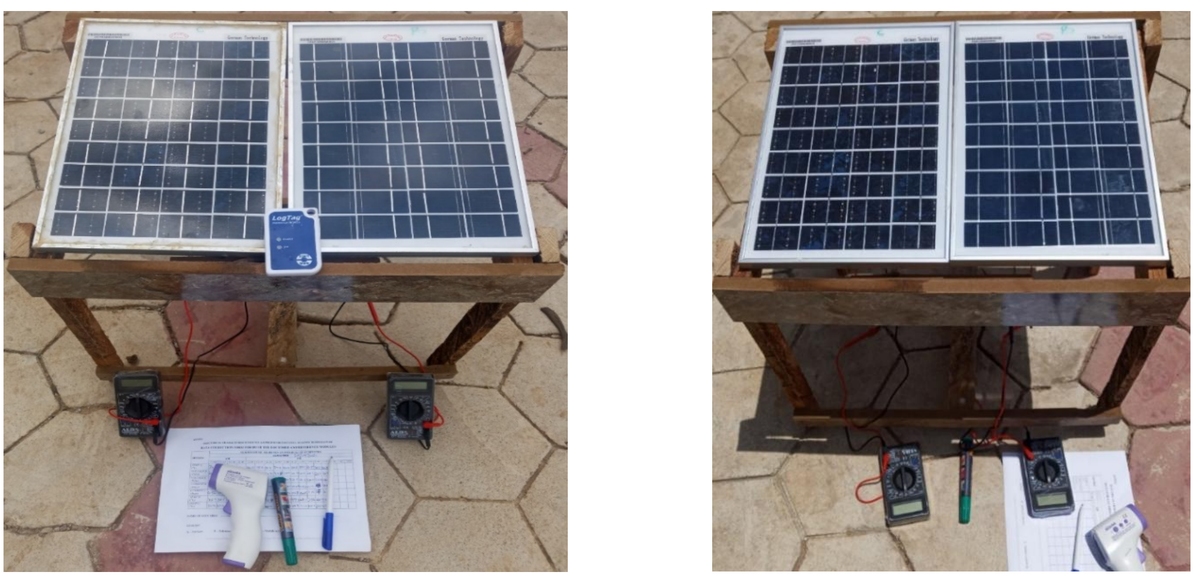


Figure 4: Experimental setup

Table 2: Atmospheric information of the location as at the time of experiment

Site location	Suleja
Solar irradiation	≈1000W/m^2
Latitude	N9.194521^o
Longitude	E7.178624^o
Altitude	442.728261m
Air mass	1.5
average ambient temperature	37^o
Wind speed	3.7ml/h

Source: (weatherspark)

Influence of working temperature on the electrical characteristics of solar PV module can be determined from the measured experimental parameters (Voc), as the open circuit voltage (Voc) seemed to be inversely proportional to the rise in the working temperature.

The maximum power (P_{max}) can be computed as follows:

$$Pmax = (Vmax \times Imax) = (FF)Voc \times Ioc \quad (1)$$

where FF is the fill factor. The Isc and Voc are the short circuit current and open circuit voltage generated by a solar module at certain condition. Nonetheless, under these operating conditions, the power from the module is zero. The fill factor is a parameter that when conjunctionally put together with Isc and Voc can give out the value of Pmax of a solar module in consideration. For equation 1 to be useful, this parameter (FF) can therefore be defined as the ratio of the product of Vmax and Imax from the solar module to that of Voc and Isc as;

$$FF = \frac{Vmax\ X\ Imax}{Voc \times Ioc} \quad (2)$$

A conventional empirical expression for fill factor given below in equation 3 was employed for simplicity in this regards.

$$FF = \frac{voc - In(voc+0.72)}{voc+1} \quad (3)$$

Where *voc* is normalized Voc expressed as;

$$voc = \frac{q}{nkT}Voc \quad (4)$$

Where, q is the electrical charge of magnitude 1.62 x 10^{-19}C, n is the ideal factor given as 1, k is Boltzmann constant given as 1.38 x 10^{-23}JK^{-1} and T is module's surface/working temperature (Green, 1981).

RESULTS AND DISCUSSION

In order to investigate the outcome of incorporating PCM (paraffin wax) beneath a typical silicon-based solar PV module. A solar PV module with PCM attached at it back surface was experimentally tested together with a reference module. The corresponding readings of electrical characteristics and the modules operational temperatures -Temp R and Temp F- for the reference and fabricated modules respectively were recorded. The power generated by each module was computed using equations 1-4 and anlyzed.

The computed values of the average power generated by each module during the period of the experiment are given in comparison to the manufacturer's rating. The two modules were rated to be 10W by the manufacturer. Due to the negative effect of temperature on electrical performance (voltage) of a typical solar PV module, the R-module generated an average of 8.12W. Similarly, F-module (cooled module) generated an average of 9.58W.

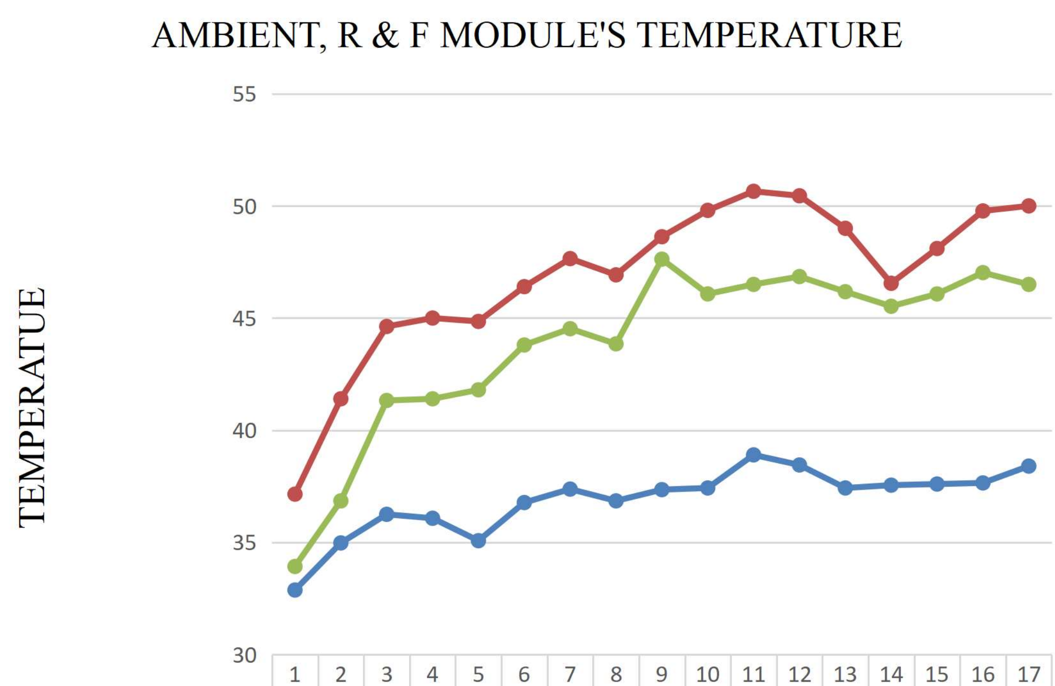
The percentage power (W) gained (P_g) from the average performance of F-module over R-module was discovered using below expression as 18%, With a variance of 1.45W.

$$Pg\% = \frac{Pf - Pr}{Pr} \times 100 \quad (5)$$

Where, P_f and P_r power in watt for F and R modules respectively.

The graphical chart in Figure 4 represent the electrical characteristics (Voc) fluctuations of both the modules in response to the irregular variation of atmospheric temperature, otherwise referred here as ambient temperature. It is clearly seen that; temperature critically affects the electrical performance of solar photovoltaic cells. There is relatively about twelve degrees (12°C) difference between the atmospheric temperature (Temp. A) and working temperature of the R-module (Temp. R). Conversely, there is variance of about 8°C rise in temperature between atmospheric and F-module temperatures, which is lower than R-module. The average atmospheric temperature recorded throughout the period of experiment was 38.4°C, whereas the corresponding average temperature of R-module was 50°C and seemingly that of the accompanying F-module was 46.5°C.

There is also difference of moderately 4°C rise in temperature between the R-module and the F-module. This significant progress brings about the realization of one of the initial experimental objectives, which focuses on keeping the operational temperature of solar photovoltaic cells at the lowest degrees possible when compared to atmospheric or ambient temperature.

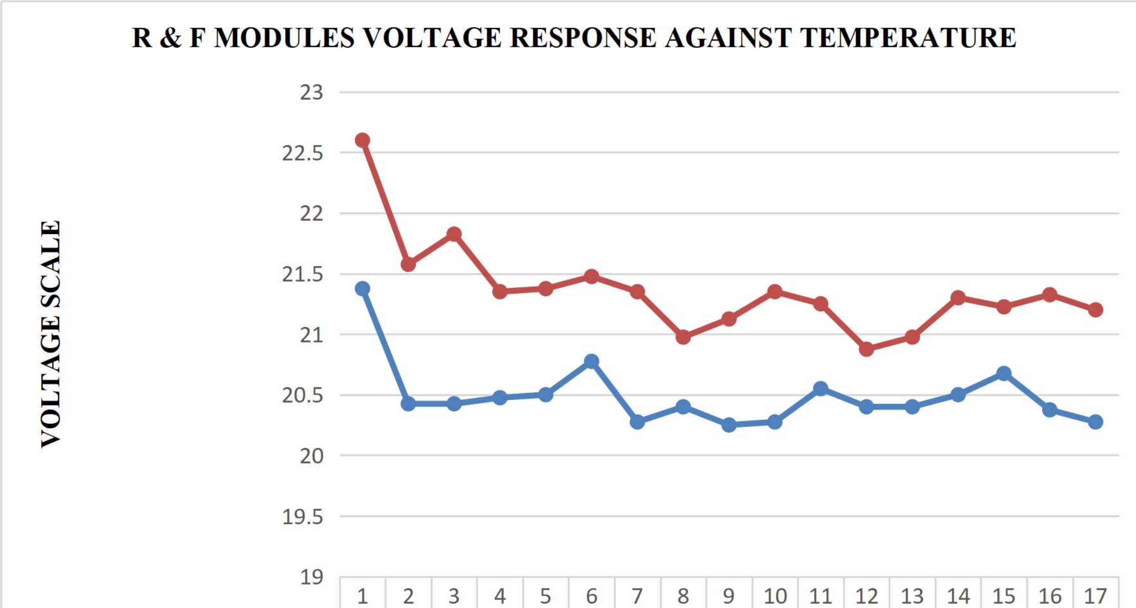


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
TEMP A (OC)	32.8	34.9	36.2	36.0	35.0	36.7	37.3	36.8	37.3	37.4	38.9	38.4	37.4	37.5	37.6	37.6	38.4
TEMP R (OC)	37.1	41.4	44.6	45	44.8	46.4	47.6	46.9	48.6	49.8	50.6	50.4	49	46.5	48.1	49.7	50
TEMP F (OC)	33.9	36.8	41.3	41.4	41.8	43.8	44.5	43.8	47.6	46.0	46.5	46.8	46.1	45.5	46.0	47.0	46.5

Figure 5: Graphical illustration of ambient and modules' (R and F) operational temperatures relationship.

This affirms that, atmospheric temperature is directly proportional to the working or operational temperature of solar photovoltaic cells.

Figure 6 below gave the graphical interpretation of the experimental results. The trend of the electrical characteristics of a typical solar PV module is directly proportional to the atmospheric temperature. This is because, when the ambient temperature rises, the module surface temperature also rises. This feature tends to reduce the electrical performance of the module as it was also being observed in this research.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
VOLTAGE R (volts)	21.3	20.4	20.4	20.4	20.5	20.7	20.2	20.4	20.2	20.2	20.5	20.4	20.4	20.5	20.6	20.3	20.2
VOLTAGE F (volts)	22.6	21.5	21.8	21.3	21.3	21.4	21.3	20.9	21.1	21.3	21.2	20.8	20.9	21.3	21.2	21.3	21.2

Figure 6: Graphical charts displaying temperature voltages fluctuations of both reference and fabricated modules.

SUMMARY

The paper presented a solar PV module cooling model that incorporates a phase change material (PCM), paraffin wax. It was tested through an experiment with both the fabricated and reference module arranged side-by-side. The experiment lasted for the period of 5 consecutive days. The model, (based on the ability of the PCM utilized to absorb and dissipate heat) was used to monitor the thermal effect of attaching paraffin wax at the bottom of a solar PV module. It is ascertained that, incorporation of PCM in the system helps in controlling the operational temperature and thereby improving the efficiency as well as expanding the lifespan of a typical solar module. During the experiment, an average of 4^oC reduction in the operational module temperature under cooling in contrast to that without cooling was achieved. Similarly, an average of 18% output power was obtained from the cooled module over uncooled one during PSH.

CONCLUSION

Effective cooling technique is essential in combating the danger of overheating in solar PV technologies. According to the results of this experiment, electrical performance and reliability of photovoltaic module can be enhanced through PCM's back-surface cooling technique (The average power gained by the F-module over the R-module is 18% and there is a significant improvement in keeping down the surface temperature of F-module due to the effect of cooling technique employed). This can also benefit in extending the module's life cycle. Taking into considerations, the very low cost of paraffin wax, its abundance in terms of availability and its cooling effect are very good factors capable of instigating researchers to further intensify efforts on finding effective means of combating this negative effect of solar PV module overheating.

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