PAPER • OPEN ACCESS

Effect of Phase Change Material and orientation angles on the efficiency of hexagonal solar Photo-voltaic module

To cite this article: Aditya Raj Chhetri *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **573** 012025

Effect of Phase Change Material and orientation angles on the efficiency of hexagonal solar Photo-voltaic module

Aditya Raj Chhetri[1], Barreto Russell John[1], Arunabha Das[1], T. Venugopal[1], N.Gobinath[1]*

[1] School of Mechanical Engineering, VIT Chennai, Tamilnadu, India – 600127
* Corresponding author

e-mail: gobinath.n@vit.ac.in

Abstract: Electricity has been paid much attention towards its entry in all sectors of human life, ever long since its revolutionary invention. Networking the disconnected hamlets with reliable electricity is still found to be challenging in many countries, due to demographic conditions, where electricity remains elusive. Solar energy, a form of renewable energy that has been proved to be a viable alternative to fossil fuels could bea potential solution for regions with poor distribution of power. The present work aims t augmenting the solar energy harvesting in a PV module with a phase change material. A portable PV module is fabricated based on an innovative design including passive cooling with paraffin wax and arrangements for enhanced solar irradiation. The new design is tested for its performance at different temperatures and it is found that the module with PCM has shown 3% of increase in voltage generation over the conventional one. Also, paraffin wax is found to maintain the module temperature at 5% lesser than the normal one on an average. Five different angles of orientation of the mirrors say, 30°, 45°, 60°, 75° & 90° with module axis are tested and it is observed that 60° is optimum in harvesting the voltage. The results revealed that the new design is more efficient and viable for its usage.

Keywords: Solar energy, Photovoltaics, PV module, PCM, Renewable energy device.

1. Introduction

With the energy requirements of the 21st century having reached unsustainable levels and the use of fossil fuels being discouraged for its harmful effects on the environment, renewable energy has come to the forefront as the most promising source of energy in the world. Renewable energy accounted for up to 26.2 % of the global electricity produced in 2018, with more than 90 countries actively installing a minimum of 1 GW of devices capable of generating energy from renewable sources [1]. Solar energy, a promising form of renewable energy can go functional either as concentrated photovoltaics (CPV) or concentrated solar power (CSP) for heating/cooling applications [2]. Annually, the Earth receives close to 173000 TW of solar energy and roughly receives 1366 W/m^2 of power from the Sun on an average day [3]. Due to the spherical shape and the tilt of the earth on its axis, the poles receive lesser sunlight than equatorial regions and thus it is most suitable to harness solar energy from tropical countries. In accordance with the Paris climate goals, Solar Photovoltaic technology, if deployed with the aim of generating 8500 GW of energy will be capable of sustaining 25% more energy than needed globally. In further, it will contribute a reduction of 4.9 GT of CO_2 emissions by the year 2050, which is approximately 21% of total emission reductions that need to be met [4].

The International Renewable Energy Agency (IRENA) estimates that the global scenario for PV power may change dramatically by as much as 600% by 2030. Asia is set to contribute about 65% of the total global PV installations. In Asia, China is estimated to be the main center for PV energy with about 1412 GW of installed capacity, followed by the United States in North America (437 GW) and then Europe (291 GW) of installed PV capacity [5]. India has tremendous potential to utilize solar energy due to the high overall irradiation, densely populated demographic and the sheer size of the subcontinent. However, solar energy contributes only 4.59% of the total energy produced by renewable energy systems in India [6]. As the country experiences about 250-300 sunny days, which translates to about 2200-3200 hours of sunlight per year, the total electricity needs of the country can be achieved on a land of 3000 km^2, a mere 0.1% of the total land in the country [6].

With continued usage over a period of time, kerosene lamps lead to ophthalmic and respiratory problems [7] and hence it is of utmost importance to promote PV lighting systems. Solar water pumping systems have been promoted for used in agriculture and drinking in regions that are disconnected from power grids [8]. Photovoltaic distillation systems for the desalinization of water are also found to be promising in small scale systems [9]. Solar PV technology is also used in space for the generation of electricity in space stations and satellites [10]. PV-PCM modules have recently come to the forefront as promising technology that will definitely change the global scenario of solar power plants. A study conducted by Hasan *et. al.* (2008), using PCM for cooling showed that the temperature at the surface of a PV panel can be maintained below 40^0C for up to 6 hours [11]. Machniewicz et al., analyzed the surface temperature of photovoltaic panels using software (ESP-r), and found that the PCM greatly reduced the system temperature thereby increased the electricity production [12]. The present paper aims at demonstrating the novel techniques to boost the efficiency of a smart solar photovoltaic module for the purpose of lighting. With the objective of proposing clean energy product to rural masses living in tropical and sub-tropical areas, a newly designed p-v module is fabricated and an extensive study on its performance is carried out, and the results are reported.

2. P-V Module: Concepts and Modeling

Incorporating mirrors or cooling loop or both in the solar modules will have positive effects in enhancing the efficiency of the system. Henceforth, in the present work a new design of PV module has been made that has a provision for the mirrors and the passive cooling method. Though parabolic or non-planar mirrors are widely used for commercial purposes, flat mirrors when positioned at appropriate angles at a specific orientation (depends on frame design) could be viable and efficient in radiating the incident light to the panels [13]. A silicon photo-voltaic cell converts only 20% of incident radiations in to electricity whereas the rest dissipates as heat, which further raises the system temperature [14]. A passive cooling system as schematically shown in Fig 1(a), with PCM is found to be a viable solution for this technical issue [15 and16]. Five different angles of the plane mirrors for their effective irradiation on the solar panels were analyzed and the optimum angle is identified. A scaled down model is fabricated using 3-D printing method (Model: Flashforge dreamer NX) as shown by its CAD model in Fig. 1(b) and the capacity of solar panels in voltage generation is studied with and without PCM in the new model.

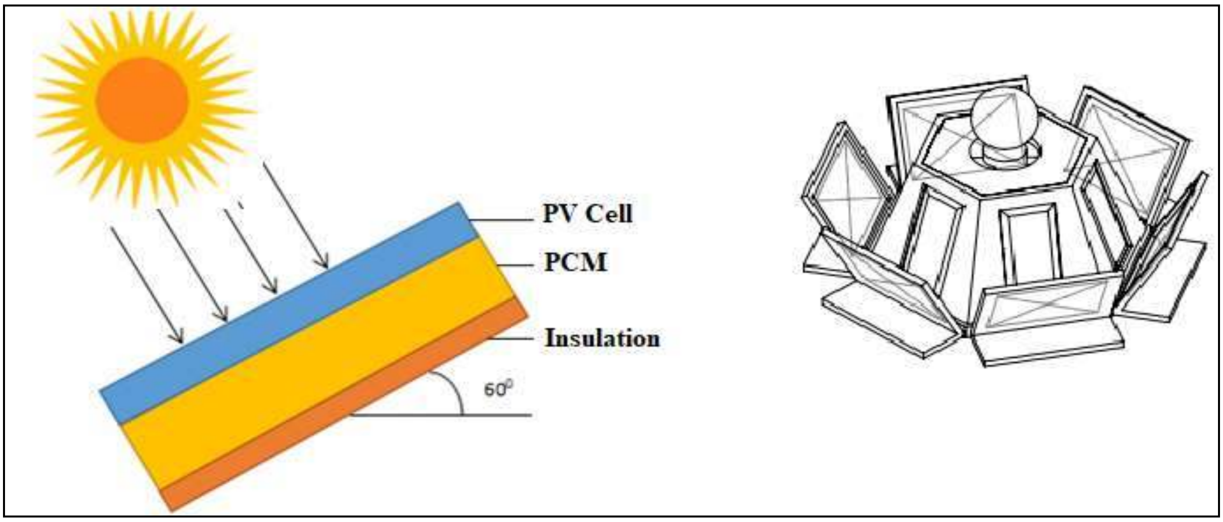

Fig 1. (a) Schematic of passive cooling system with PCM (b) CAD model of the new P-V module

The new P-V module has a hexagonal-trapezoid 3D printed body that houses 6 photo-voltaic cells. Adjoining mirror stands are placed at 60^0 angles from the base. This maximizes the incident sunlight falling onto the solar panels and thereby directly increases power output. The slots behind the panels store the PCM (Paraffin Wax) which cools down individual panels by absorbing latent heat when changing phase from solid to liquid at 40^0C. At center of the module a bulb holder, the electrical wiring and the battery are placed. When required, the bulb can be pushed down into the central cavity via a corkscrew mechanism by simply twisting. The hexagonal trapezoid shape is unique and ensures that the device receives adequate sunlight from all directions throughout the day and the tilt of the panels ensures that the device receives enough sunlight regardless of the angle of the sun.

3. Experimental Methods

The preliminary experiments are carried out with individual panels to measure the temperature profile using a set-up located under clear and direct sunlight as given in Fig 2(a). The voltage and current generated through the panels are measured throughout the day over the course of two weeks with the help of a thermal imaging camera (± 0.1°C accurate). Paraffin wax (melting range: 38-56^{o}C) was selected for regulating the panel temperature in the system. The wax would thus keep the cell in the range of temperatures optimum for its efficiency. Fig 2(b) shows the plain solar cells and solar cell with PCM (enclosed with red sealing). The PCM solar cell experimentally showed better voltage generation and less heating up which directly correlates to higher efficiency.

Fig 2. (a) Temperature measurement with thermal imaging camera (b) Voltage measurement in a PCM system

4. Results and Discussion

At first, the orientation angle of the crystalline silicon (c-Si) panels to be used in the hexagonal-trapezoidal model, with the horizontal is arrived to be at 60° from the literature [17].The panels are tested for their capability of harvesting solar radiation at the specified angle and the trials are repeated for sufficient number of days. The voltage and surface temperature values from the solar energy radiations on the panels are recorded individually on all days using the energy meters. The average values of voltage and surface temperature obtained from each panel is cross-verified for its repeatability. Table 1 shows the average recorded values of voltage and surface temperature obtained from different panels for a day-time. All the panels show similar trend of energy harvesting that could be observed from the recorded voltage and surface temperature values as shown in Table 1. From the table it is apparent that the deviation of voltage values between panels is 2% (max) at morning hours, 1.4% at noon time while it is 1% at the peak hour (14.30 hrs). Similar trend is observed for the deviation in electric current values generated at the panels with near zero deviation at noon time of the day. From the extensive collection of voltage and surface temperature data from the panels for a period of 14 random sunny days, the average values of for voltage and surface temperature are arrived for the panels. Similarly, the experimental procedures are repeated for the panel which is stacked up with paraffin wax (PCM) on its backside. The voltage and surface temperature from the panel with PCM are recorded for the aforementioned period of 14 random days. It is witnessed that the paraffin wax stacked up behind the solar panel augmented the average voltage harvesting capacity of the panel closely 3%. It is also observed that the paraffin wax decreased the average surface temperature of the panel by 5.10 %.

IOP Conf. Series: Earth and Environmental Science **573** (2020) 012025 doi:10.1088/1755-1315/573/1/012025

Table 1: Average voltage and panel temperature values generated from different panels

Panel	1		2		3		4		5		6	
Time (Hrs)	(V)	(°C)	(V)	(°C)	(V)	(°C)	(V)	(°C)	(V)	(°C)	(V)	(°C)
9:40	6.67	38.6	6.58	39	6.58	40	6.72	38	6.67	39	6.58	40
10:00	6.53	38.6	6.08	40.1	6.45	42	6.5	39	6.53	40.1	6.45	42
10:15	6.65	46.2	6.5	46.8	6.5	47.2	6.54	45.1	6.65	46.8	6.5	47.2
10:30	6.56	50.2	6.48	49.9	6.47	51.5	6.47	47.3	6.56	49.9	6.47	51.5
10:45	6.63	46	6.48	46.5	6.47	46.5	6.53	50	6.63	46.5	6.47	46.5
11:00	6.68	48.6	6.55	48.8	6.55	49.5	6.51	50.2	6.68	48.8	6.55	49.5
11:15	6.56	42.7	6.49	44.2	6.51	47.1	6.54	43.7	6.56	44.2	6.51	47.1
11:30	6.67	43	6.54	43.5	6.55	44.2	6.5	46.9	6.67	43.5	6.55	44.2
11:45	6.48	47	6.52	49.5	6.43	49.2	6.52	47.4	6.48	49.5	6.43	49.2
12:00	6.62	43.4	6.53	47.6	6.53	47.8	6.54	47.4	6.62	47.6	6.53	47.8
12:15	6.5	47.6	6.32	47.6	6.36	48.9	6.44	47.5	6.32	47.6	6.32	47.5
12:30	6.57	47	6.41	46	6.38	45.8	6.36	46.8	6.41	47	6.41	46.8
12:45	6.44	45	6.39	46.2	6.4	46	6.43	45.9	6.39	45	6.39	45.9
13:00	6.45	44	6.3	43.7	6.39	45.6	6.37	46.4	6.3	44	6.3	46.4
13:15	6.37	44.3	6.43	44.5	6.39	45.2	6.34	46.7	6.43	44.3	6.43	46.7
13:30	6.35	43.2	6.46	44.2	6.35	45.2	6.32	46.5	6.46	43.2	6.46	46.5
13:45	6.4	49.5	6.36	49.1	6.41	49.7	6.34	48.9	6.36	49.5	6.36	48.9
14:00	6.33	47.2	6.28	47	6.34	46.2	6.36	46.6	6.28	47.2	6.28	46.6
14:15	6.36	45.2	6.33	43.8	6.35	43.4	6.4	42.5	6.33	45.2	6.33	42.5
14:30	6.34	47.5	6.3	46.6	6.39	48.8	6.37	44	6.3	47.5	6.3	44

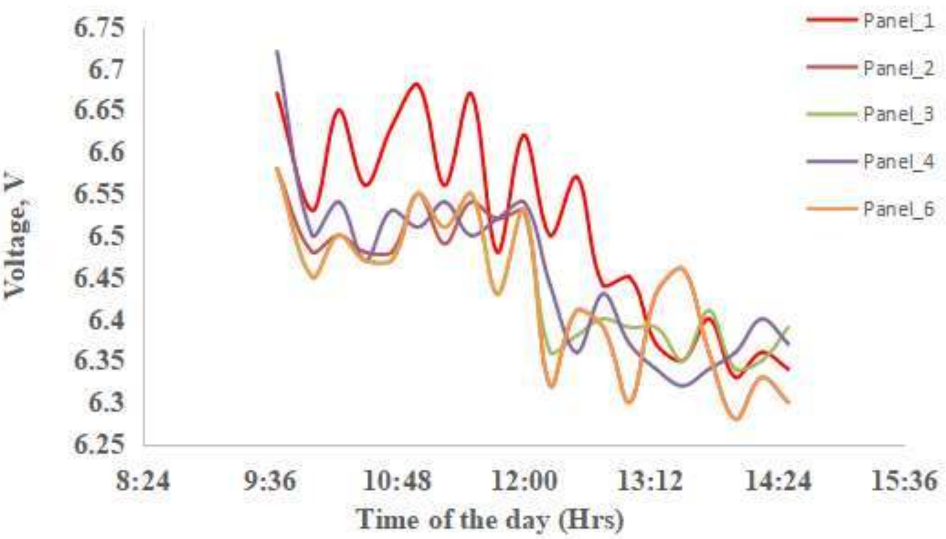

Fig 3. Influence of different time of the day on the changes in panel voltage

Fig 3 shows the variation of the voltage in each panel and the trends in voltage variation with each hour of a day are found to be matched with the results obtained by Patil et al [18]. The values of voltage generated by the panels at the present orientation angle of 60° (with horizontal) are attaining the peak values at the mid of the day while it drops down after 12.00 hours. This trend of decline in voltage after the mid of the day could be due to the data recorded using individual panel and it could be improved when the panels are assembled in the hexagonal-structure.

The voltage variation of the panels throughout the day follow a similar trend wherein peak values are obtained earlier in the day between 10:00 hrs to 12:30 hrs. The values of voltage then begin decreasing non-linearly with several aberrations due to the inconsistent pattern of sunlight received. In Fig 4, the average of the aforementioned curves has been taken and compared with the curve for the PCM reinforced panel marked as Panel 5. There is a noticeable visual difference in the values of voltage obtained throughout the day. Panel 5 consistently shows a higher voltage output as is evident from the graph made in accordance with experimentally obtained values.

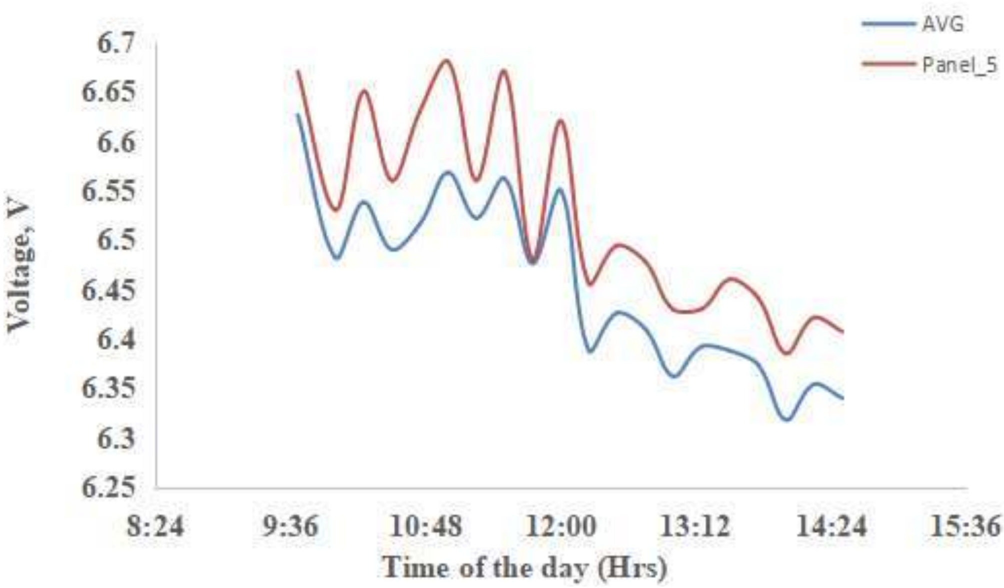

Fig 4. Average value of voltage curves in comparison with the PCM reinforced panel

Surface temperature values were recorded throughout the day and were found to be more evenly distributed than panel voltage which achieved peak values around mid-day. The trends in temperature of the 5 panels excluding Panel number 5 were observed as displayed in Fig 5. These were regular panels without PCM additions. Subsequently a comparison was made between the average value of the curves from Fig 5 and the curve for the temperature profile of the PCM reinforced panel as displayed in Fig 6.

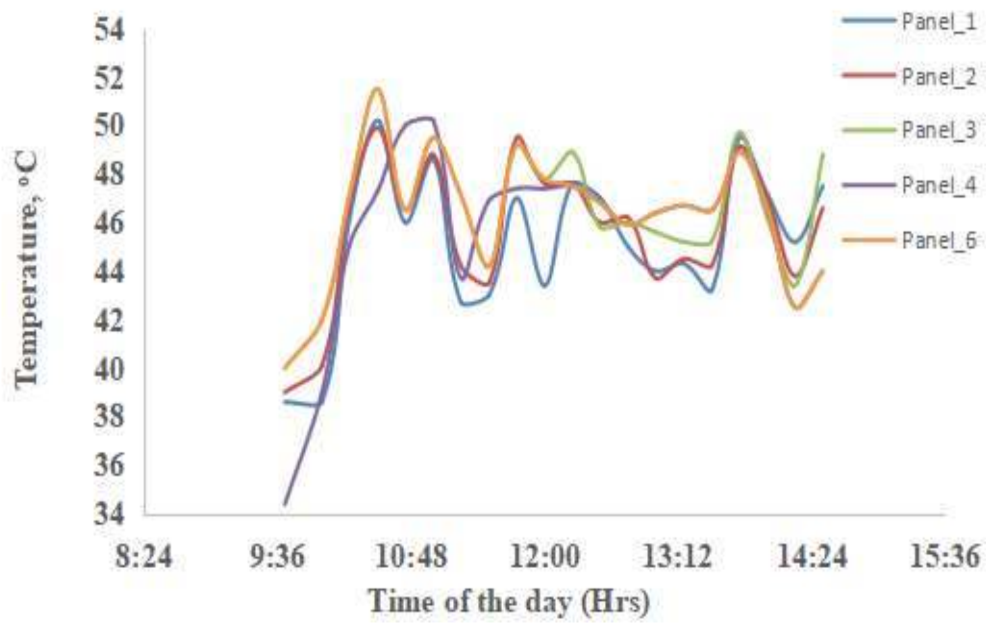

Fig 5. Influence of different time of the day on the changes in panel surface temperature

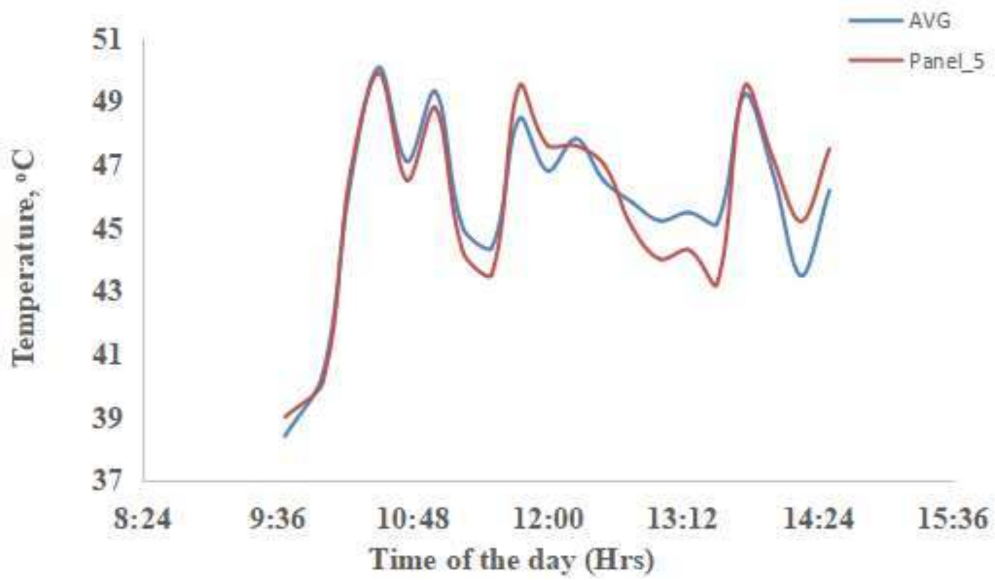

Fig 6. Average value of temperature curves in comparison with the PCM reinforced panel

It can be observed that the PCM backed panel consistently showed lower temperature values throughout the day compared to non- PCM based regular solar panels. This result is found to be consistent with results obtained from previous studies that were performed on PCM based cooling systems for photovoltaic cells, in which, the phase-change materials were found to be effective in maintaining the temperature of photovoltaic cells.

Noteworthily, the surface temperature variations in the panel circuits showed gradual increase from the morning hours, reaching the peak value at 10.30 hrs and showed decrease in value thereafter. However, it is observed from the experimental data that surface temperature values though decrease after 10.30 hrs the magnitude is still higher than the value obtained at the morning hours. This trend of surface temperature variation proved that the present orientation of panels is optimal in harvesting the solar energy during an operational day. It was apparent that the voltage from the panel with paraffin wax consistently increased while the surface temperature was found to be reduced. This may probably be due to the phase change of the wax material induced by latent heat which plays a major role in maintaining the panel temperature at a reduced value. Furthermore, the reduction in temperature of the panel surface at all hours, leads to better efficiency of the solar panel.

The improvement in efficiency after incorporating the PCM panel was found by firstly find the efficiency of the panel without PCM and then comparing it with the efficiency of the PCM incorporated panel. Standard test conditions were assumed under which the working surface temperature of the panel is assumed to be 25^0 C, Incident Solar Radiation as 350 W/m^2 , surface area of each panel is found out to be 0.004 m^2 , current flowing through each panel is 60mA and the thermal coefficient is -0.4.

CASE – I:

Here, the voltage and surface temperature are reported for non-PCM panels. The average value of voltage is found to be 6.45 V and average surface temperature is 45.78^0 C. The Standard Test Conditions (STC) efficiency (in %) can be obtained using the formula (1) as given below,

$$\frac{(Current)\times(Voltage)}{(Incident\ Solar\ Radiation)\times(Surface\ area\ of\ \ panel)}\times 100 \tag{1}$$

By substituting the aforementioned values for Current, Voltage, Incident Solar Solar Radiation and Surface area we find the the STC efficiency to be 27.66%. The formula for Efficiency drop is given below,

$$(P\max)\times(Average\ surface\ temperatur\,e - STC\ surface\ temperatur\,e)$$

Substituting the aforementioned values in this formula we get Efficiency drop as 8.312. We obtain the final Operating efficiency of the non- PCM solar panel by subtracting this efficiency drop from the STC efficiency. Hence, the Operating efficiency for non- PCM solar panel used for this experiment was found to be 19.34%.

CASE – II:

Here, the voltage and surface temperature are reported for PCM reinforced panels. The average value for voltage was found to be 6.60 V and average surface temperature was 43.45^0 C. We use the above formula for STC efficiency again to obtain STC efficiency for PCM reinforced panels as 28.294 %. The efficiency drop is found to be 7.37 and hence the final Operating efficiency for the PCM panel was found to be 20.99%

5. Conclusions

The effects of phase change material and orientation angles are experimentally analyzed with a newly designed solar P-V module and the following outcomes are arrived,

The addition of PCM based cooling system drastically improved the voltage output of the panels of the P-V module. The new design ensured that a minimum of 3 faces have moderate to good exposure to sunlight in a day. PCM enhanced the voltage harvesting around 3% while it reduced the surface temperature of the panels by around 5%.

The Operating efficiency of the non-PCM panel was found to be roughly 19.3% and that of PCM based panel was found to be roughly 21%. This change translates into an increase in efficiency by 0.1%. This value was obtained under Standard test conditions.

The features included in the present design of the P-V module will ensure adequate power generation even at minimal operating conditions.

References

[1] Edenhofer, O., Pichs-Madruga, R., Sokona, Y. (2011), *Special Report on Renewable Energy Sources and Climate Change Mitigation: summary for policymakers and technical summary.* p. 230, Intergovernmental Panel on Climate Change, Geneva

[2] Venkatakrishnan, G. R. and Rengaraj, R. (2014), Overview of Solar Energy in India. *International Journal of Development Research,* 4 (3): 605-608.

[3] Appa Rao, A.P. V., Rama Mohan, J., L Malleswara Rao, J. L., Ram Narayana K., Ch. Sundar Singh, C. S. and P Ramakrishna Rao, P. (2018), Solar Energy In India - Present And Future. *International Journal of Engineering Science Invention*, 2319 – 6734: 6-11.

[4] Pandey, A., Tyagi, V., Selvaraj, L., Abd Rahim, Nasrudin A. R. and Tyagi, S. (2016), Recent advances in solar photovoltaic systems for emerging trends and advanced applications. *Renewable and Sustainable Energy Reviews.* 53: 859–884.

[5] IRENA (2019), Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), *International Renewable Energy Agency*, Abu Dhabi, p.72.

[6] Yadav, H. K., Kumar, V. and Yadav, V. K. (2015), Potential of Solar Energy in India: A Review. *International Advanced Research Journal in Science, Engineering and Technology,* 2 (1): 63-66.

[7] Mills, E. (2003), Technical and economic performance analysis of kerosene lamps and alternative approaches to illumination in developing countries. *Lawrence Berkeley National Laboratory Report*.

[8] Bucher, W. (1996), Aspects of solar water pumping in remote regions. *Energy and Sustainable Development,* 3, 8–27.

[9] Al-Karaghouli, A., Renne, D. and Kazmerski, L. L. (2010), Technical and economic assessment of photovoltaic-driven desalination systems. *Renewable Energy,* 35, 323–328.

[10] Karam, N., Ermer, J., King, R., Haddad, M., Cai, L. et al.(1998), High efficiency GaInP2/GaAs/Ge dual and triple junction solar cells for space applications. in *Proceedings of the 2nd world conference & exhibition on photovoltaic solar energy conversion,* pp. 6–10, Vienna, Austria

[11] Hasan, A., McCormack, S. J., Huang, M. J. and Norton, B. (2008), Experimental design for integrating phase change materials into building integrated photovoltaics for thermal control; in *Proceedings of the 3rd photovoltaic science, applications and technology conference,* pp 105-108, Durham, UK.

[12] Machniewicz, A, Knera, D. and Heim, O. (2015), Effect of Transition Temperature on Efficiency of PV/PCM Panels. *Energy Procedia*, 78, 1684-1689.

[13] Pathmika, G. D. M. and Gamage, M. V. (2016), Efficiency Improvement of a Typical Solar Panel with the Use of Reflectors. *European Journal of Advances in Engineering and Technology*, 3(3): 1-13.

[14] Senthil Kumar, M, Balasubramanian, K. R., Ajith Krishnan, R, Maheswari, L., Sivakumaran, N. (2019), Thermal Performance of Phase Change Material Based Heat Sink for Solar Photovoltaic Cooling. *International Journal of Innovative Technology and Exploring Engineering,* 8(9), 3320-3323.

[15] Hasan, A., McCormack, S. J., Huang, M. J. and Norton, B. (2010), Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaic. *Solar Energy*, 84(9), 1601-1612.

[16] Farahat, M. A. (2004), Improvement the thermal electric performance of photovoltaic cells by cooling and concentration techniques. In *Proceedings of the 39th International Universities Power Engineering Conference*, 1, pp. 623-628, Bristol, UK.

[17] Jacobson, M.Z., and Jadhav V. (2018), World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Solar Energy,* 169, 55-66.

[18] Patil, A, Singh, G.,Bhardwaj, S. and Lembhe, S. D. (2019), Improvement of solar energy by mirror reflection technique. *International Journal for Research in Applied Science & Engineering Technology,* 7(VI).