Thermal Regulation of Solar Photovoltaic Modules by Incorporating Phase Change Materials to Enhance the Yield

Vishwadeep Chakraborty, Satish Kumar Yadav, and Usha Bajpai

Abstract It is important to use renewable energy technology efficiently for the sustainable development of the society. Presently, the application of rooftop photovoltaic technology is increasing exponentially for energy generation. Government is also promoting lots of scheme for rooftop systems. But the operating performance of these system is limited by some climatic parameters like temperature relatively humidity, wind, and soiling. Temperature highly affects the yield of the photovoltaic module. As temperature of module increases, the output power of module decreases. In this paper, the phase change materials (PCM) are used at the back side of the photovoltaic modules to reduce the cell temperature and increase the yield. Phase changing materials can store extra heat produced during the operation of photovoltaic module in the form of latent heat which can be further utilized for heating or drying purpose. Two si-modules with different PV technology (monocrystalline and polycrystalline silicon modules) and two integrated thermal (PV/T) systems of same configuration were used to study the behavior of PCM. Higher output yield was recorded for the PV/T with the PCM compared to bared PV module. The output water temperature of the monocrystalline PV/T system was recorded less than PV/T with polycrystalline module. PV panel with PCM provides the hot water after the absence of the sun due to the absorbed heat in the PCM that can be further used for low heat application.

Keywords PV module temperature · PV/T systems · Temperature difference · Phase change material

1 Introduction

The energy yield of solar photovoltaic (SPV) module is directly dependent on solar radiation intensity and its availability. When solar photovoltaic module operates into the open environment, its output characteristics vary compared to its laboratory conditions due to the effect of weather parameters especially temperature, which

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highly affects its performance. The output power of the solar photovoltaic modules reduces because it has negative temperature coefficient for the voltage. Due to the temperature increase in PV module, a subsequent drop in the electrical efficiency of it is noted and this efficiency loss boosts the degradation rate of module [1]. There are a number of active and passive ways, which can retardate this degradation rate of PV module by decreasing the cell temperature of module. The passive approaches have boosted the electrical efficiency of photovoltaic module up to 15.5% while through active approaches we can observe an increase of 22% [2].

In recent time, phase change material-based passive PV cooling approach has gained more attention among researchers around the globe. Phase change material (PCM) is the latent heat energy storage material which has been adopted to mitigate the adverse effect of increasing PV temperature on its performance. Maiti et al. [3] worked with paraffin wax and metal wax for the period of 7 h. And they concluded that, the PV-PCM system with embedded metal maintains the temperature around 65–68 °C. Similarly, Hasan et al. concluded that the PV-PCM system enhanced the PV annual electrical energy yield by 5.9% in his experimental work [4]. In this paper, the operating performance of two PVT/PCM systems was analyzed at a different flowrate of water. Moreover, temperature variation and its effect on each solar PV module were also assessed to understand the performance of each PV module.

The cooling of solar modules by phase change material (PCM) is much more efficient as it increases the thermal inertia of the panel which is reported by Yuan et al. [5]. The use of PV module coupled with phase change material increases the power output of the solar module by 7.3% validated by *TRNSYS* software [6]. Hasan et al. got a 10 °C temperature drop for a period of 6 h for a radiation of 415 w/m^2 using the phase change material (PCM) with eutectic combination of capric and lauric acid embedded in an aluminum container [7]. Roslan Eqwan and Aiman investigated the effect of candle wax as phase change material (PCM) for back side cooling of solar photovoltaic module under hot climatic conditions of Malaysia, and their results showed that the power output of the PCM cooled solar module increased by 4.143% [7]. Li et al. analyzed the experimental evaluation of solar module with paraffin wax 35 with PCM poured on the PV module Tedlar surface with a thickness of 5.5 cm, and back sheet was used to cover the PCM surface; the results of the PCM integrated module show that the electrical output of the PV-PCM system increased by 5.18% [8]. Razali et al. used beeswax as the phase change material (PCM) for the cooling of photovoltaic module in the hot climate of Indonesia. The authors observed that the electrical efficiency of the PCM integrated module increased in the range of 0.9–1.8% throughout the length of the entire day with the PCM module being cooler by 17 °C from the reference PV module [9]. Kant et al. developed a thermodynamical model for PCM encapsulated modules which show that angle of inclination, wind speed, and convective heat transfer in PCM play a substantial role in the operating temperature of the modules [10].

The main objective behind use of PCM is that PCM materials are better equipped to absorbed the excess heat from the modules and absorb the heat as latent heat which can used to release heat for longer time duration. Also, PCM continuously absorbing the heat lowers the module temperature and increases the electrical efficiency.

The research objective is based upon the use of paraffin wax as PCM storage material to lower the heat from the backside of the crystalline modules and lower the cell temperature. The PCM transfers the heat to water flowing through copper pipes which can used for low heating applications. This technique of cooling the solar modules enhances the electrical efficiency and lowers the need for decrease need in cooling energy with thermal energy available for used in requisite applications.

2 System Description

The study conducted in the Centre of Excellence in Renewable Energy Education and Research laboratory located at the new campus of the University of Lucknow (Lucknow) India. Phase change material used to regulate the back module temperature behind two different PV module technologies such as monocrystalline and polycrystalline photovoltaic modules. Phase changing materials absorb the back-module heat and store it in the form of latent heat, which can further utilize for heating or drying purpose. Two si-modules of different PV technologies such as monocrystalline (m-si) and polycrystalline silicon (p-si) modules and two integrated photovoltaic thermal (PV/T) systems of the same technology were used in our work to study the behavior of PCM with the PV module as shown in Fig. 1. The electrical characteristics of the PV modules provided in Table 1.

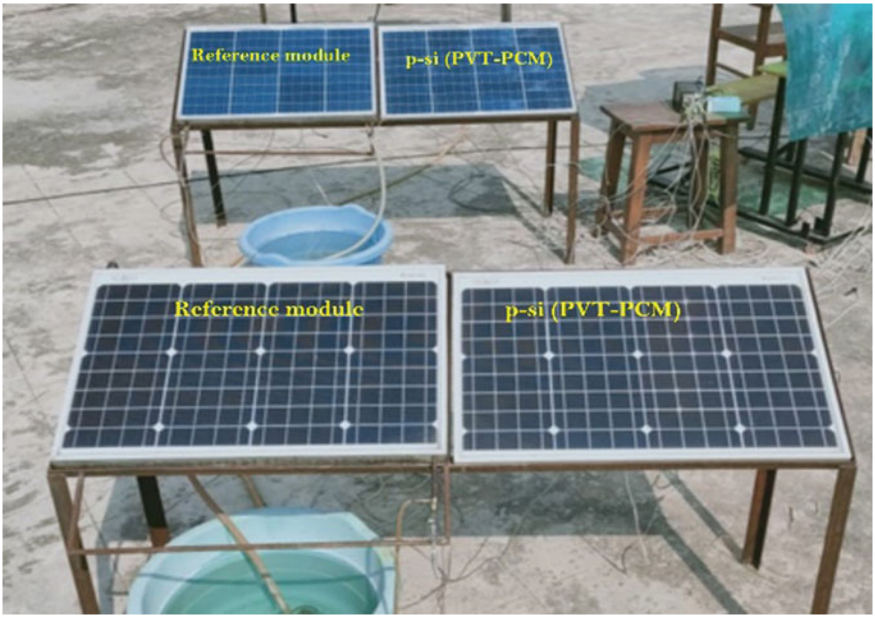

Fig. 1 Monocrystalline and polycrystalline-based PVT/PCM system with reference module

Table 1 Electrical characteristics of PV modules

Parameters	Specifications	
Module technology	m-si	p-si
Power at maximum point (P_{mp}) (W_p)	50.0	50.0
Open-circuit voltage (V_{OC}) (V)	23.26	21.77
Short-circuit current (I_{SC}) (A)	2.63	3.04
Voltage at maximum point (V_{mp}) (V)	19.95	17.89
Current at maximum point (I_{mp}) (A)	2.51	2.80
Module efficiency (%)	17.49	13.55
Cell dimensions (mm)	136 × 38	156 × 49
Dimensions (mm)	630 × 435	555 × 665

We have used paraffin wax manufactured by 'Thermo Fisher Scientific Laboratory solutions'. The paraffin wax used in the experiment has congealing point range of 58–60 °C. The main objective behind use of PCM is that PCM materials are better equipped to absorbed the excess heat from the modules and absorb the heat as latent heat which can use to release heat for longer time duration. Also, PCM continuously absorbing the heat lowers the module temperature and increases the electrical efficiency. In monocrystalline module, we have filled paraffin wax in plastic packets with the mass of each individual packet containing the paraffin wax is 125 g. The module consists of total nine number of plastic packets with total mass of paraffin wax ranging to 1125 g. Similarly, in polycrystalline module the backside of the module has been filled with plastic packets consisting of paraffin wax. There are 12 total number of plastic packets with each packet containing 130 g of paraffin wax. The total mass of paraffin wax corresponds to 1560 g in polycrystalline module.

Copper pipes were used in both the crystalline module to convert it into a PVT system, and these pipes were used to absorb heat from the backside of the module and transfer it to the flowing water through these pipes so the water can be used to transfer the heat for useful purpose. The copper pipes have outer diameter of 6 mm and inner diameter of 4 mm which were molded in serpentine pattern.

3 Materials and Methods

The experimental system was analyzed for the period of 1 week from 10 am to 4 pm at composite climate zone of Lucknow. Based on the recorded data, the performance of reference PV modules and PVT/PCMs system analyzed. Collected data are applied to determine the electrical efficiency of PV modules and PVT/PCM systems at various flow rates.

Electrical efficiency (η_e) of PV module has been calculated as below [11]:

$$\eta_e(\%) = \frac{I_{SC} \times V_{OC} \times FF}{A \times I} \times 100 \quad (1)$$

I_{SC} (A), V_{OC} (V), and FF are the short-circuit current, open-circuit voltage, and fill factor of PV module; A (m^2) is the area of PV module; and I is the solar irradiance (W/m^2).

Thermal efficiency of PVT/PCM system was calculated by the following formula [11]:

$$\eta_{th}(\%) = \frac{\dot{m}C_P(T_{out} - T_{in})}{A_M \times I} \times 100 \quad (2)$$

T_{out} and T_{in} (°C) are the inlet and outlet temperature of water. C_p is the specific heat of water, A_M (m^2) is the area of PVT module, and I is the irradiance (W/m^2).

4 Results and Discussion

The experimental work has been performed at clear sunny day in summer to analyze the effect of temperature on the performance of PV module. Different flow rate of water was inlet in PVT system and measured the module temperature along with current and voltage of the same module.

The difference between cell and ambient temperature (ΔT) was recorded as 15 °C for PV/T with PCM in which poly shows slightly higher than that of monocrystalline, while the temperature difference of both (mono and poly) technology PV modules with water was recorded 5 °C more (Fig. 2). Maximum output yield was recorded in PV/T with the PCM material compared to PV/T with water. The output water temperature of the monocrystalline PV/T system was observed more than PV/T with polycrystalline module. Electrical and thermal efficiencies of both PVT/PCM systems were calculated as 24.5% and 25.1%, respectively.

Figure 2 represents that the solar radiation on the experimental day ranged from 725.7 to 402.2 w/m^2 with peak at 12:40. As evident from the figure as the solar radiation increases, the ambient temperature also increases with the maximum ambient recorded as 41.2 °C during 12:20 and minimum value of ambient temperature recorded as 28.4 °C during 16:00. The ambient temperature starts decreasing as the solar radiation continues to dip from 13:40 to 16:00. The higher values of ambient temperatures are associated with increasing values of solar radiation and take a substantial dip as the solar radiation begins to fall.

Figure 3 represents the difference between module and ambient temperature (ΔT) for all the crystalline modules. The maximum ΔT for monocrystalline PV reference module is 28.3 °C, whereas the maximum ΔT recorded for monocrystalline PV/T system is 19.9 °C. In view of polycrystalline modules, the maximum value of ΔT reaches 29.6 °C; for reference module and for PV/T system, the highest value of ΔT is observed as 20.5 °C. The above represented case shows that the ΔT values

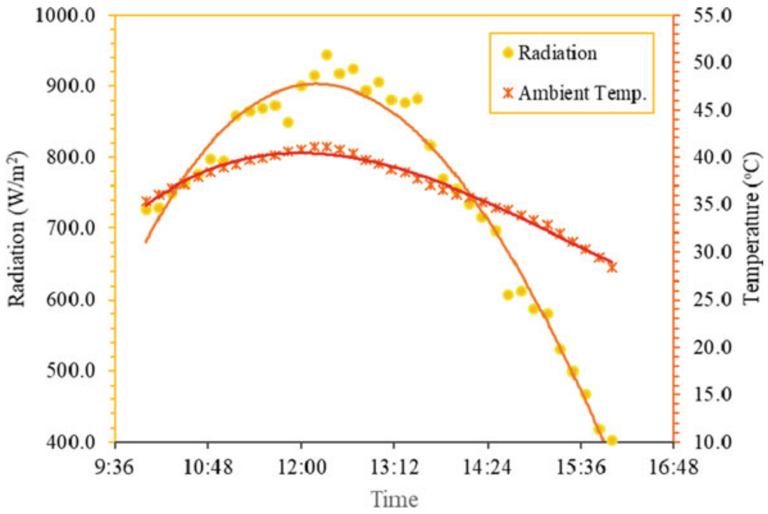

Fig. 2 Ambient temperature and radiation of the experimental day

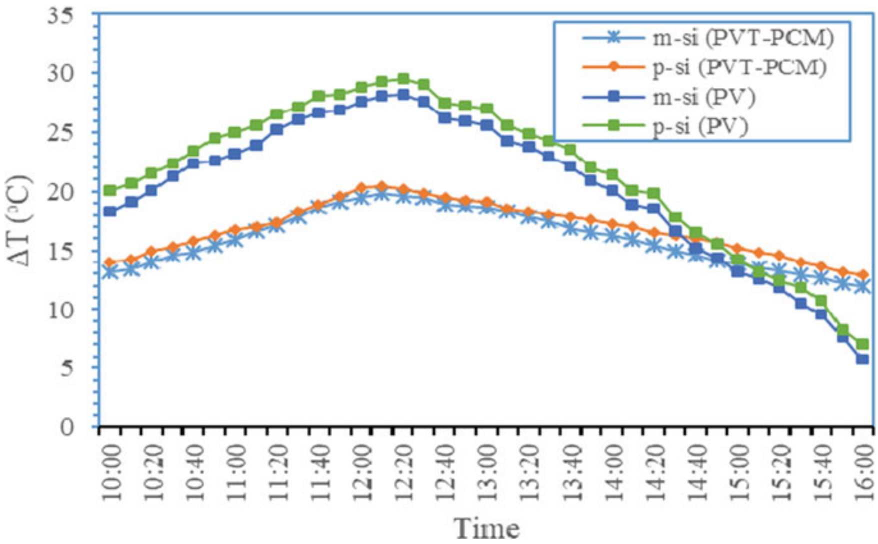

Fig. 3 Variation of temperature of different PV/*T* systems with the time

are smaller for PV/*T* systems as compared to PV systems for both monocrystalline and polycrystalline systems. The ΔT values are higher for polycrystalline systems as compared to monocrystalline systems for both the reference and PV/*T* systems indicating higher heating of polycrystalline system as compared to monocrystalline systems.

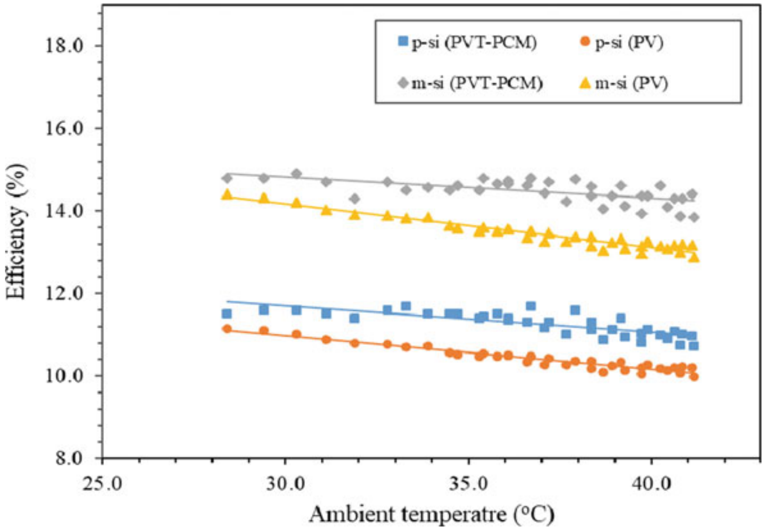

Fig. 4 Variation of electrical efficiency with the temperature

Figure 4 represents that PV/*T* PCM systems have higher electrical efficiency as compared to PV systems taking in view the account of ambient temperature. Monocrystalline PV/*T* PCM system has highest electrical efficiency of 14.8%, whereas monocrystalline PV system has 14.4% as its maximum value when the ambient temperature begins to drop at the end of the day. In view of polycrystalline system, the PV/*T* PCM system marks its highest electrical efficiency as 11.7% compared to PV system which has electrical efficiency of 11.2%.

The electrical efficiency of PV/*T* PCM systems in both cases of monocrystalline and polycrystalline does not represent a sharp dip as the reference PV systems exhibit when the ambient temperature increases. At the highest ambient temperature of 41.2 °C, the electrical efficiency of monocrystalline PV/T system is 13.8%, whereas PV system has an efficiency of 12.9%, in polycrystalline PV/T PCM system has an electrical efficiency of 10.7%, whereas PV system has an electrical efficiency of 10% only.

Figure 5 shows that the maximum thermal efficiency of monocrystalline PV/*T* system is 45.1%, and it increases gradually with time. The maximum thermal efficiency of polycrystalline PV/*T* system is 53.3% which also increases with time. The thermal efficiency of polycrystalline PV/*T* system is high as compared to monocrystalline PV/*T* system which suggests that polycrystalline PV/*T* system has much more heat capacity to carry compared to monocrystalline PV/*T* system.

Figure 6 represents that the maximum outlet temperature of water in monocrystalline PV/*T* system is observed as 61 °C, whereas for polycrystalline PV/*T* system, the maximum outlet temperature is 60 °C. The inlet water is flowed at ambient temperature and is at the same temperature for both the PV/*T* systems. On an average, the outlet water temperature of polycrystalline PV/*T* system is slightly higher than

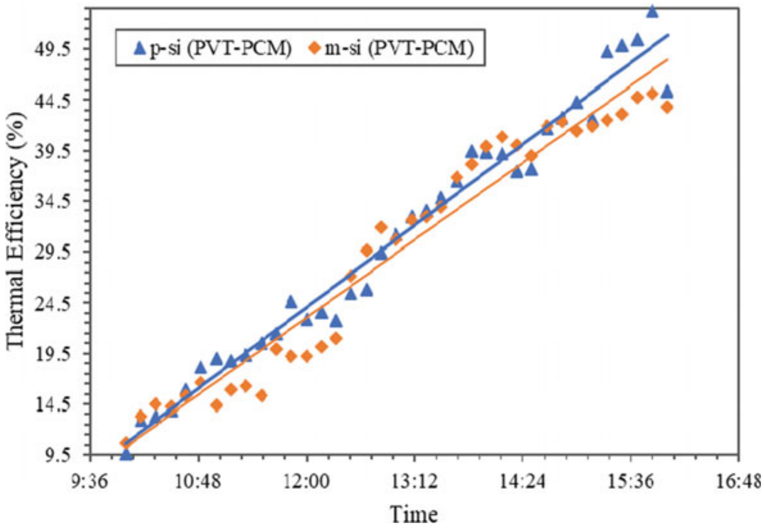

Fig. 5 Variation of thermal efficiency of PV/*T* systems with time

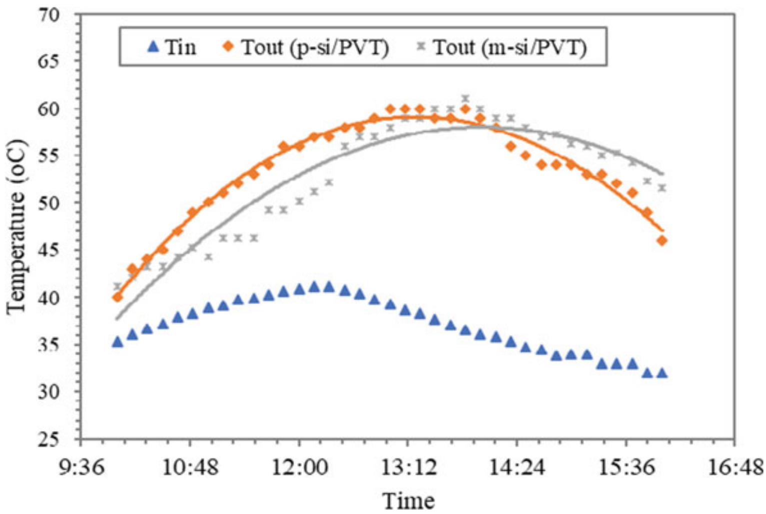

Fig. 6 Variation of inlet and outlet water temperature of PV/*T* system with time

monocrystalline systems The outlet water temperature of both the PV/*T* systems gradually increases with time as the heat of the PV/*T* system increases and starts dipping during the day as the modules start to cool due to decreasing ambient energy.

Figure 7 represents the average electrical and thermal efficiency of both PV/*T* systems for all seven days of the week. Electrical efficiency of both monocrystalline and polycrystalline PV/*T* systems has the highest electrical efficiency on 29th May

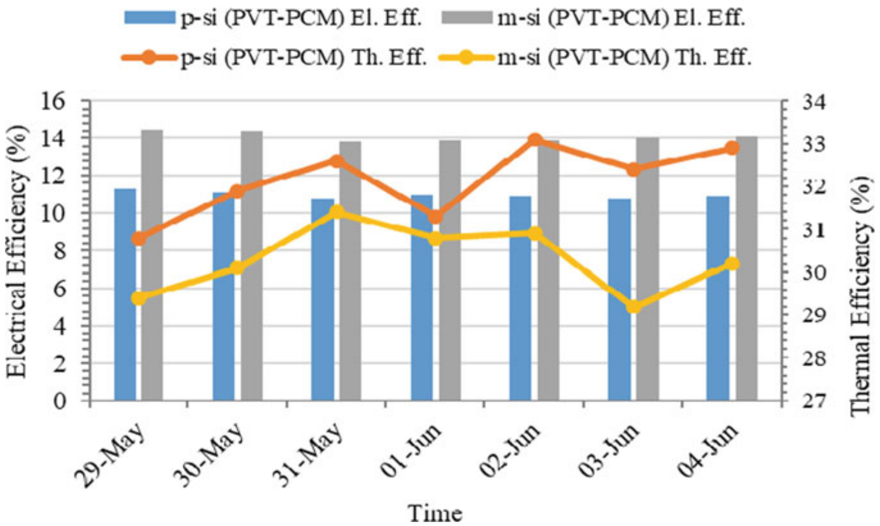

Fig. 7 Overall efficiency of PV and PV/*T* systems

with values of 14.5% and 11.3%, respectively. The overall efficiency of both systems also calculated, and it was seen that monocrystalline PV/T on 29th May is 43.9% and polycrystalline PV/T is 42.1%. The highest thermal efficiency of monocrystalline PV/T system is 31.4% on 31st May, and for polycrystalline PV/T system, it is 33.1% on 2nd June. Both the PV systems have the highest electrical efficiency on 29th May.

5 Conclusion

The module temperature of the PVT/PCM system was observed 15 °C lower than the reference PV module. The maximum outlet water temperature of m-si (PVT/PCM) and p-si (PVT/PCM) system was found 61.2 °C and 60.1 °C, respectively at 41.2 °C ambient temperature. The average thermal efficiency of p-si (PVT/PCM) system recorded 30.8% that was higher than 29.4% thermal efficiency of m-si (PVT/PCM). The maximum temperature of m-si PV module and p-si PV found 76.9 °C and 77.8 °C, respectively. It has been observed that p-si (PVT/PCM) system shows higher electrical efficiency of 11.3% than reference PV modules 10.4% similar as monocrystalline PVT system. The overall system efficiency of both systems also calculated and seen that highest efficiency p-si (PVT/PCM) and m-si (PVT/PCM) was 65.4% and 66.7%, respectively. It has been proposed that PVT/PCM technology can be used to reduce the operating temperature of PV systems and enhance the energy generation of the PV system.

References

1. A.C. Nanakos, A weighted-efficiency-oriented design methodology of flyback inverter for AC photovoltaic modules. IEEE Trans. Power Electron. **27**(7), 3221–3233 (2012)
2. M. Hasanuzzaman, Global advancement of cooling technologies for PV systems: a review. Sol. Energy **137**, 25–45 (2016)
3. S. Maiti, Self-regulation of photovoltaic module temperature in V-trough using a metal–wax composite phase change matrix. Sol. Energy **85**(9), 1805–1816 (2011)
4. A. Hasan, Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate. Sol. Energy **146**, 417–429 (2017)
5. W. Yuan, J. Ji, M. Modjinou, F. Zhou, Z. Li, Z. Song, X.Zhao, Numerical simulation and experimental validation of the solar photovoltaic/thermal system with phase change material. Appl. Energy **232**, 715–727 (2018)
6. U. Stritih, Increasing the efficiency of PV panel with the use of PCM. Renew. Energy **97**, 671–679 (2016)
7. A. Hasan, S.J. McCormack, M.J. Huang, B. Norton, Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics. Sol. Energy **84**(9), 1601–1612 (2010)
8. Z. Li, T. Ma, J. Zhao, A. Song, Y. Cheng, Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material. Energy **178**, 471–486 (2019)
9. R. Thaib, S. Rizal, T.M.I. Mahlia, N.A. Pambudi, Experimental analysis of using beeswax as phase change materials for limiting temperature rise in building integrated photovoltaics. Case Stud. Thermal Eng. **12**, 223–227 (2018)
10. K. Kant, A. Shukla, A. Sharma, P.H. Biwole, Heat transfer studies of photovoltaic panel coupled with phase change material. Sol. Energy **140**, 151–161 (2016)
11. B.J. Huang, Performance evaluation of solar photovoltaic/thermal systems. Sol. Energy **70**(5), 443–448 (2001)
12. M.R. Eqwan, Z.R. Aiman, Experimental investigation of the effect of solar photovoltaic back plate cooling using passive heatsink and candle wax as phase change material. IJSRSET **5**, 26–40 (2017)