Role of PCM in Solar Photovoltaic Cooling: An Overview

Pragati Priyadarshini Sahu, Abhilas Swain, and Radha Kanta Sarangi

Abstract The present article put forth a comprehensive review of the latest research works carried out on the cooling techniques for maintaining the required temperature of photovoltaic modules for achieving greater efficiency. The conventional cooling technologies such as water cooling, air cooling and water spray are little discussed in this article as these are not preferred in the present scenario due to their power requirement and complicated arrangement. The phase change materials (PCM) have evolved as a better alternative for the cooling of photovoltaic modules due to their advantageous thermo-physical properties. The recent research investigations on using phase change materials as heat absorbing material are critically reviewed in the present article. The investigations include experimental and numerical studies on single PCM, combined PCM (PCM with nanoparticles, graphite powders), PCM as secondary thermal energy storage. The critical review suggests that further research works are necessary for developing a passive design (not using external power) for obtaining optimum temperature of the solar photovoltaic modules.

Keywords Phase change material · Solar photovoltaic · Efficiency of PV · Photovoltaic thermal

1 Introduction

In the era of growing civilization and industrialization, the requirement of energy is growing. Due to this, the demand for the renewable energy and consequently the solar photovoltaics has played a greater role in the energy generation. However, till date, the technological development of photovoltaics is able to achieve a highest efficiency of about 15–20%. Moreover, the part of the irradiation not converted to electricity increases the temperature of the photovoltaics and the efficiency decreases with increase in the temperature. Thus, it is essential to remove heat from the photovoltaics

P. P. Sahu (✉) · A. Swain · R. K. Sarangi
School of Mechanical Engineering, Kalinga Institute of Industrial Technology (KIIT) Deemed to be University, Bhubaneswar, Odisha 751024, India
e-mail: pragatipsahu009@gmail.com

S. Revankar et al. (eds.), *Proceedings of International Conference on Thermofluids*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-7831-1_23

to optimize the electricity generation. For this objective, researchers are continuously investigating and developing technologies for controlling the temperature of the photovoltaic panels. Some of these are heat exchangers, water sprinklers, phase change materials, heat sinks, transparent coating, etc.

The present article presents a concise review of the latest developments made in this field of research for obtaining the best suitable cooling technology. Along with this a greater emphasis is given to the application of the phase change material (PCM) for cooling of PV cell. The comparison of different ways to use PCM for this application is presented.

Sunlight is one of the perpetual renewable energy sources which is converted into electrical energy through the photovoltaic (PV) system. These photovoltaic systems are gaining popularity for electricity generation because of their anti-pollution technology, no effect on global warming, low cost of operation and low maintenance. As already described, a big problem in case of the photovoltaic is the reduction in efficiency with increase in temperature. For each 1 °C temperature rise of the photovoltaic module surface, there is an efficiency reduction of 0.5% [1].

The above discussion leads to the conclusion that there is a strong need for a suitably designed cooling technology with least power consumption for the optimum temperature of the photovoltaic module and best possible efficiency. Thus, the present article presents an discussion on the current trends of the cooling technologies being investigated for cooling of PV modules and more emphasis is given on the use of phase change materials for this purpose.

2 Review of Other Techniques for Cooling of Photovoltaic

Floating-Tracking-Cooling and Concentrating (FTCC) is a concept applied to get the maximum performance of PV modules. In this arrangement, the modules are arranged over the structures made out up of PVC pipes in a water pool. For cooling purpose, the water sprinklers are used to spray water on the panels for cooling purpose. Due to the water spray, the power production increased by 40%. However, the water sprinkling is capable to decrease the temperature of the certain areas of the photovoltaic modules. Another method adopted for cooling of the PV modules is the hybrid solar PV and thermal methodology in which the cooling fluid is usually air or water. The heat recovered by the air or water is used for the domestic purpose. Akbarzadeh and Wadowski [2] have adopted a similar method and observed an increase in the power output by almost 50%. It is also observed that the maximum temperature could be maintained at 46 °C when allowed for power generation for a time span of 4 hour [2]. Tonui and Tripanagnostopoulos [3] have investigated the performance of PV modules with air as the cooling fluid under natural and forced convection conditions. They observed that the arrangement with fins on the panel has performed best considering air as the working fluid [3].

3 Cooling of Photovoltaics Using PCM

By considering these problems facing in case of solar photovoltaic cell efficiency, so many works were carried out in order to solve the problems stated and observed that cooling is needed for solar photovoltaic cell as like heat exchanger, to minimize wasted solar radiation and high system temperature. Less numbers of authors have published an extensive literature review on cooling solar PV modules by using various techniques which can increase the overall efficiency of the solar conversion system by implementing these techniques, we can reduce the unwanted temperature rise. Some cooling techniques are Floating-Tracking-Concentrating-Cooling system (FTCC), heat sink, cooling by spraying water, forced water circulation, forced air circulation, water immersion cooling technique, use of phase change materials (PCM), cooling by transparent coating (photonic crystal cooling) and thermoelectric cooling.

Phase change material can be used as a latent heat storage in the temperature range 0–120 °C for low temperature applications like solar cooling, etc. [4]. Duffie and William [5] have suggested to select such a phase change material which do not have a tendency to supercool. In a suitable temperature range, material undergoes in a phase change and absorbing a large amount of latent heat is known as phase change materials (PCMs) which can used for a passive heat storage [5]. Ismail and Goncalves [6] have stated PCM as a latent heat storage unit by changing its states form solid to liquid and regaining it back without any external sources [6]. Wirtz et al. [7] have formulated the performance of a dry PCM and resulted positive use of PCM for more heat storage and temperature control of electronics. Without showing adequate change in temperature, the thermal energy can be stored into latent energy by heating and cooling of phase change material. The stored energy can be repaired when the process is overturned. Due to the high latent heat of phase change material during phase change process, it is popularly used in such thermal energy storing process.

Sarı and Kaygusuz [8] have used lauric acid with 95% of purity as a phase change material which has a small temperature change and no subcooling during the solidification and they studied temperature distribution and thermal characteristics of phase change material [8]. Khodadadi et al. [9] and Kibria et al. [10] have reviewed thermo-physical properties of phase change material with dispersed several nanoparticles. Some reviews has been concise on thermal energy storage capacity, long-term stability, encapsulation, temperature range and system-related issues of phase change materials [11, 12].

Waqas and Jie [13] have investigated numerically phase change materials' effect on cooling of photovoltaics in the hot climatic condition in Pakistan during hottest month of summer. They carried out the computational work using the enthalpy method for the melting of PCM and taking mathematical model for the PV panel. It has been observed that the peak module temperature can be lowered by maximum 30 °C which increases the efficiency of the panel by 9–10%. They concluded that the performance will be best when there is a 10–12 °C temperature difference between the melting temperature of the PCM and the atmospheric temperature. Figure 1 shows

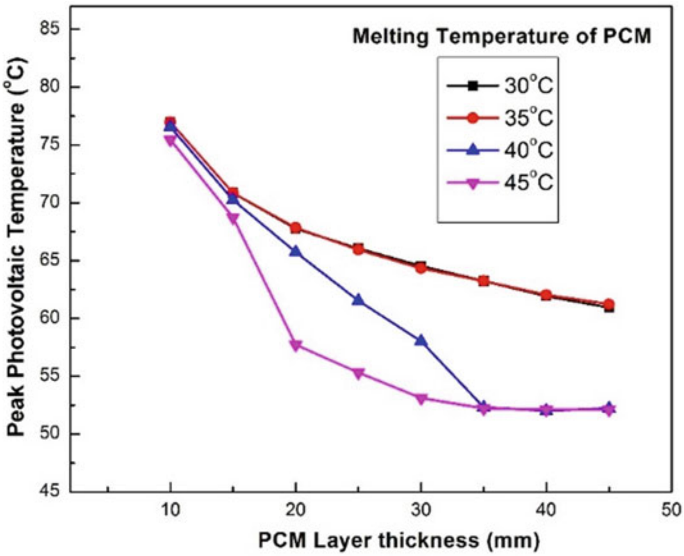

Fig. 1 Melting temperature effect [13]

that with the increase in the melting temperature of PCM, the peak temperature of PV panel decreases. Moreover, higher the thickness of the PCM, the lower will be the peak temperature [13].

Energy balance equation for the solar cell is given in Eq. (1).

$$S * \alpha\tau * \beta_c + S * \alpha\tau * (1 - \beta_c) = U_T * \left(T_c - T_g\right) + U_T * (T_c - T_{bs}) + E \quad (1)$$

In Eq. (1), the first factor represents the solar energy absorbed by the solar cell after transmission, second factor represents the solar energy absorbed after transmission, third factor represents conductive heat transfer between glass and solar cell, fourth section represents rate of energy conducted from solar cell to the back surface of the module, and E suggests the rate of electrical energy available from PV module.

The rate of thermal energy transferred from the conventional PV cell to the back surface of the PV module and then transferred to the ambient can be obtained by following equation

$$U_T * (T_{bs} - T_c) = h_w * (T_{amb} - T_{bs}) \quad (2)$$

where the rate of energy conducted from solar cell to the back surface of PV module is equal to the rate of heat transferred from the back surface of ambient.

Sainthiya and Benewal [14] have carried out an experimental investigation studying effect of front surface cooling of PV panels by flowing water for different flow rate conditions. During their experimentation, a thin layer of water is allowed to flow over the PV panel from top to bottom. The power output and the efficiency

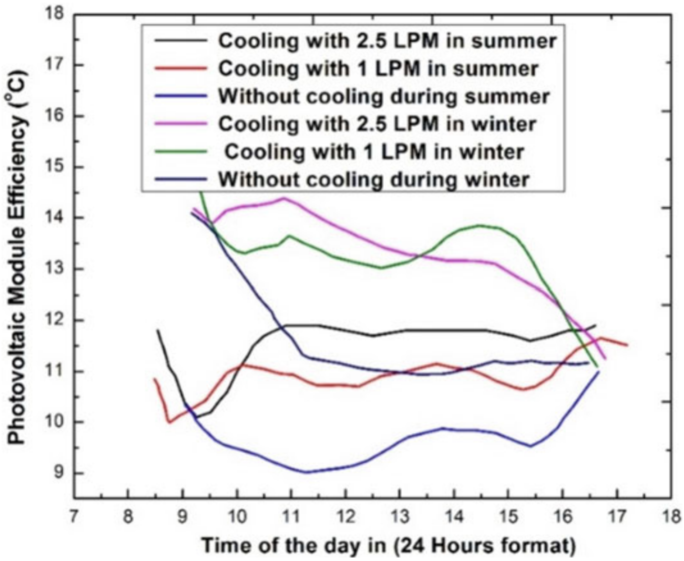

Fig. 2 Effect of water flow cooling or PVT [14]

are observed in both summer and winter weather conditions under four flow rate conditions (1–2.5 LPM). They observed an increase in efficiency of about 20–40%. It was observed that in winter the water cooling is more effective than the summer. Figure 2 shows the variation of the module efficiency during the whole day in both winter and summer for a different water flow rate.

Ahmed et al. [15] have investigated photovoltaic in combination with thermal heat recovery by using water flow at the back surface of the photovoltaic cell in a hot climatic condition of Egypt. The efficiency and the power output showed an improvement because of the water cooling arrangement. They evaluated the overall efficiency of the system by considering the thermal heat gain. One important point needs to be mentioned here that the electrical power consumption for the pump used for the flow of water. The variation of the peak temperature is shown in Fig. 3.

$$\eta_{\text{tot}} = \frac{Q_{\text{th}} + P_{\text{ele}}}{P_{\text{act}}} \tag{3}$$

Abdollahi and Rahimi [16] have investigated a cooling technology for photovoltaics by using water and PCM. The water is allowed to flow at the back side of the PV cell to receive heat. The hot water exits from the cooling path is allowed to pass through a helical coil present in a cylinder for receiving heat by placing phase change material. The PCM consists of 82% coconut oil and 18% sunflower oil leading to a melting temperature of 25–26 °C and latent heat of 308 kJ/Kg. The schematic of the setup is presented in Fig. 4. They compared the performance of the arrangement

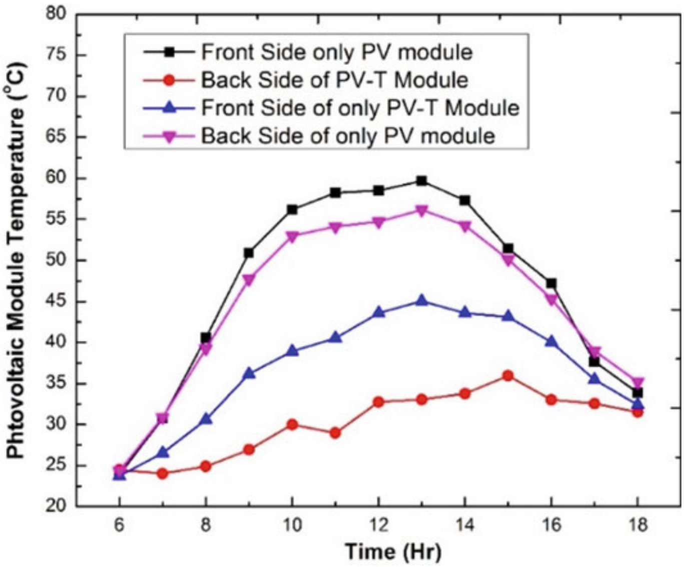

Fig. 3 Comparison of the front and back surface temperature of the photovoltaic cell for (1) only PV cell and (2) PV cell with water cooling (PV/T) [15]

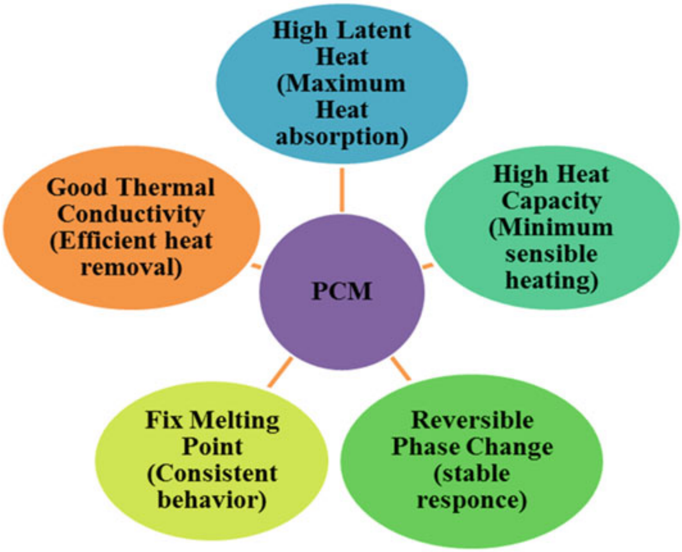

Fig. 4 Properties of a PCM desired for photovoltaic thermal regulation

Table 1 Thermal properties of pure and combined PCM

Properties	Pure PCM	Combined PCM
Thermal conductivity (W/m K)	0.18	92.1
Density (kg/m^3)	900	957
Specific heat (J/kg K)	2500	1900
Melting temperature (^{o}C)	36–60	36–60

with that of only PV by using a term COE which is the efficiency considering the power consumption by pump.

As per the studies, 25–28 °C is the suitable operating temperature of PV cell which provides 80–90% of efficiency. By violating this range and constant solar radiations, it results decrease in conversion rate and efficiency by 0.5% per each degree Celsius rise of surface temperature [17].

Heng et al. [18] have decreased the operating temperature and increase in efficiency of solar panels by using phase change materials (PCM) and developed a 2D finite volume heat transfer model for framing integrated photovoltaic cell with the use of PCM.

Hachem et al. [19] have experimented and stated that pure PCM enhance electrical performance of PV cell by an average of 3%, where transient energy balance presented to analyse thermal behaviour and an average of 5.8% improvement of efficiency while using combined PCM. The thermal conductivity of phase change material which is 0.18 W/m K is enhanced by combining mass ratio of 20% copper powder and 10% of graphite powder with 70% of pure PCM and the enhanced thermal conductivity will be 92.1 W/m K (Table 1).

A PCM (paraffin-based) with 38–43 °C of melting range is integrated at the backside of the solar PV panel and its cooling effect is monitored. The increased PV power output due to cooling produced by PCM is quantified and PV annual electrical energy enhanced by 5.9% in the hot climatic condition [20].

At an adequately constant temperature, PV panel is maintained with the help of high latent heat capacity of PCM. The stored heat later can be used for water heating, space heating and many more. It is viewed that forced air and water cooling techniques are widely used to cooling PV panels as compared to natural ventilation-based cooling as an inadequate method. Without any additional electricity consumption, PCM has the advantages to delaying the temperature rise of PV panels.

Japs et al. [21] have experimented by considering PV with and without PCM and resulted that the generated energy by the panel with PCM is higher than the panel without PCM for 5 out of 25 days while with PCM+ graphite-PV. They got the results that the average energy and economic yields were positive at peak temperature means at the afternoon while it is negative for the rest. Later, Japs et al. [22] have concluded that PCM rigged with graphite, accomplished better than that have not with it. As graphite improves the conductivity of the phase change material which causes expeditious dissipation of heat results better output.

Thermal management performance and the heat transfer characteristics of dry-packed MEPCM were investigated by Tanuwijava et al. [23] via CFD simulations.

And stated that by consolidating the appropriate MEPCM layer in PV module gives improvement in thermal and electrical performance as the output. Ho et al. [24] have concluded that the layer thickness with 5 cm PCM has the best PV cooling performance with a melting temperature of 30 °C. Though, PCM could not fully solidify at night after certain thickness causes poor cooling performance. Experiment was carried out by installing microencapsulated phase change material (MEPCM) which is water insulated, attached to the back of PV panel and floats on a water surface (Table 2).

A noticeable drop in temperature results efficiency improvement while cooling the solar PV module using PCM technique. PCM being restrained by many researchers due to its higher cost for PV module cooling application. Pork fat, a cheaper phase change material have been numerically used by Nižetić et al. [30] and they have developed a numerical model by showing comparison study between conventional PCM and pork fat for cooling PV models. However, not much convincing results have been found, but concluded that the pork fat can be used as a potential PCM. 10–26 °C temperature drop and efficiency increases up to 3.73% have been resulted by Arıcı et al. [31] by developing a numerical model and analysing the performance of PV module cooling using phase change material technique. Many researchers have also used PCM as a cooling agent to improve the efficiency of hybrid PVT. Preet [32] has used water-based PCM cooling technique for cooling of PVT system (Table 3).

Some research articles are mentioned in Table 4 by the use of different types of PCM. They are petroleum jelly, coconut oil and palm oil and RT35.

The above discussion expounds the use of phase change materials in different ways for the cooling of photovoltaic modules such as directly on the back side, combined PCM, PCM with fins, PCM as secondary heat recovery material, etc. It is also observed that different types of PCMs are also used for different ambient conditions and application methodologies. Still, further research is needed to design and develop a passive cooling system for the photovoltaic modules which is possible by using phase change material.

Table 2 Various techniques used for solar PV cooling

Technique used for cooling PV cell	Highlights	References
Water and air-based cooling	• Conventional cooling techniques were reviewed • With limited temperature, degradation of PV cells was studied • Performance of low PV cell was studied which create difficulties • PV cooling using micro-channel, automotive radiator and thermoelectric modules need extensive research which are in developing stage	[25]
Natural/forced, hydraulic, heat pipe and PCM cooling	• To maintain cell temperature, surface area must be raised to maintain the concentration ratio • In ventilated facade system, large temperature fluctuation of PV cell was found • The heat removed from PV cell by PCM-based cooling system was not used properly	[26]
Phase change material	• Large capital investment needed during its low service life and low heat transfer, high maintenances cost which may affect overall efficiency of PV cell • Need to find out its benefit and reliability in a real environmental condition to find market potential	[27]
Single phase fluid	• Less than 10% of efficiency has been achieved by most of the cooling techniques • Air-based cooling is less effective than water-based cooling • Due to irregularity of different conditions tested it is difficult to state the comparison	[28]
Jet, micro-channel, PCM, heat sink and heat pipe	• PCM deteriorates from toxicity, corrosiveness and inflammability • Dumping of PCM after their uses is a problem • For attaining uniform lower temperature in PV panel, micro-channels can be used • Minimum cell temperature can be carried out by hybrid micro-channel jet impingement technique	[29]

Table 3 Summary of current research trends

Important observations	Results	References
• The combined effect of water and phase change material on the PV panel performance is investigated • Effect of Al_2O_3 nanoparticles loading in the phase change material on PV cell performance is conducted • Behind the PV panel, PCM/water implemented and occupation ratio is presented • Phase change material can be an excellent solution for the PV cooling	Compound technique; Al_2O_3 ($\varphi = 1\%$)/PCM mixture ($\lambda_{PCM} = 25\%$) + 75% water (5.31 kg/s m^2) obtains the highest PV performance	[33]
• Optimum option can be PVT and PVT-PCM systems for both heat and electricity • Experimentally, the PV cell temperature reduced to 12 °C • 13.98% and 13.87% are the efficiency of PVT-PCM numerically and experimentally founded, respectively • PVT-PCM systems increases electrical efficiency around 7% with compared to PVT system • Thermal collector with aluminium is used by presenting a design to get better heat transfer performance, which is in PVT-PCM and PVT systems	The module temperature dropped 12.6 and 10.3 °C For PV, the numerical and experimental electrical efficiency are 13.72 and 13.56% and in case of PVT system is 13.85 and 13.74%	[34]
• Sugarcane wax and Al_2O_3 composite have been used as phase change material • Gelatin-gum Arabic used as the polymer shell material	Enhancing the composite, PCM layer thickness by 7 mm from 4 mm could lower the cell's front-facing surface temperature by 4% resulting in raised the PV cell power generation by 12% at the peak time, due to the temperature storage capacity of the composite phase change material	[35]

(continued)

Table 3 (continued)

Important observations	Results	References
• Mathematical model and ANN model have been presented for nanofluid and nano-PCM cooling PVT • The expected linear models are consistent with ANN model and experimental results • The linear predicting models diverse from simple and accurate results	The expected predicting models gained an excellent R^2 result of 0.99 and MSE value of 0.006 RSME of 0.009 for both P-M1, P-M2 models The expected linear prediction models help to decrease the error in furcating future results and determine the best conditions for any solar system in an easier and faster way	[36]
• For a concentrated PV cooling, a combined PCM and water cooling system are developed • Efficiency and thermal power output raised while water flow rate is low • Cell temperature decreases by 60% and the system efficiency is raised by 224% • By using nanofluid, power output enhanced by 2.5% and PCM melting time lowers by 12%	Average temperature reduced up to 60% in case of CPV while comparing with PCM-PV and water cooling system Concentration ratio (CR) at 10 and HTF velocity at 0.01 m/s, the panel temperature did not exceed 78 °C Nanofluid has been used as HTF enhancer which helps to enhances the CPV efficiency by 2.7%	[37]
• Efficiency of conventional PV and the water-based PVT-PCM have been compared • Thermal energy, electrical energy and equivalent thermal exergy have been analysed throughout the year • Efficiency of embodied energy, energy payback time and lifecycle conversion have been analysed • Investigation have been carried out for DC electrical energy production cost and annual cost	Water-based PVT-PCM has 27% longer life cycle transformation efficiency as compared with conventional PV module	[38]

(continued)

Table 3 (continued)

Important observations	Results	References
• Efficiency increased by implementing PCM as PV cooling • PV performance further improved by adding nanoparticle (Al_2O_3) to PCM • Efficiency enhanced by 5.7 and 13.2% in PV-PCM and PV-PCM/nanoparticles, respectively	Efficiency improved with the use of PCM along with Al_2O_3 nanoparticles. Temperature drop measured in case of PV-PCM and PV-PCM/nanoparticle is 8.1 and 10.6 °C, respectively. Similarly, the efficiency gained by 5.7% and 13.2%, respectively	[39]

Table 4 Types of PCM used in some research studies

Details of research work/findings	PCM used	References
Up to 21.6% efficiency improvement has been shown due to heat removal by PCM in Indonesian climatic condition	Petroleum jelly	Indartono et al. [40]
For an ambient temperature range 27–30 °C, palm oil considered as the better PCM which can reduce the cell temperature by 9.6 °C having 102 mm of thickness. And gives an enhanced power output of 23%	Coconut oil and palm oil	Indartono et al. [41]
Experimenting for around 4 h in a peak temperature of 53 °C it gives reduction of cell temperature by 10 °C	RT35	Mahamudul et al. [42]

4 Conclusion

Low heat dissipation rate is the major affecting parameter which increases the temperature of solar PV panel and decreases the system efficiency. Various cooling techniques have been investigated by many researches resulted in the enhanced system efficiency. Latest researchers stated some advantages and disadvantages which is listed in the conclusion section.

- PCM can store large amount of heat at a tiny temperature change
- Changing of phase can occur at stable temperature
- Further, the utilization of absorbed heat can be done
- Maintenance free
- During off sunshine also PCM can works
- High cooling capacity
- Absorption capability of the material degrades over time
- May not attain the same output during hot and cold climate

- Disposal problem after life cycle
- Due to toxic nature of some PCMs cause fire safety issue
- Segregation reduces active volume for heat storage.

Future research must focused on to find suitable techniques for cooling a different solar PV module. Finding of suitable phase change materials will also be a challenging work, and of course, the further utility of harvested heat from PCMs in a broader way.

References

1. Kumar K et al (2007) Standalone photovoltaic (PV) module outdoor testing facility for UAE climate. Submitted to CSEM-UAE Innovation Centre LLC
2. Akbarzadeh A, Wadowski T (1996) Heat pipe-based cooling systems for photovoltaic cells under concentrated solar radiation. Appl Therm Eng 16(1):81–87
3. Tonui JK, Tripanagnostopoulos Y (2007) Improved PV/T solar collectors with heat extraction by forced or natural air circulation. Renew Energy 32(4):623–637
4. Abhat A (1983) Low temperature latent heat thermal energy storage: heat storage materials. Sol Energy 30(4):313–332
5. Duffie JA, Beckman WA (1991) Solar engineering of thermal processes. Wiley, New York
6. Ismail KAR, Goncalves MM (1999) Thermal performance of a PCM storage unit. Energy Convers Manage 40(2):115–138
7. Wirtz RA, Zheng N, Chandra D (1999) Thermal management using "dry" phase change material. In: Fifteenth annual IEEE semiconductor thermal measurement and management symposium (Cat. No. 99CH36306). IEEE
8. Sarı A, Kaygusuz K (2002) Thermal and heat transfer characteristics in a latent heat storage system using lauric acid. Energy Convers Manag 43(18):2493–2507
9. Khodadadi JM, Fan L, Babaei H (2013) Thermal conductivity enhancement of nanostructure-based colloidal suspensions utilized as phase change materials for thermal energy storage: a review. Renew Sustain Energy Rev 24:418–444
10. Kibria MA et al (2015) A review on thermophysical properties of nanoparticle dispersed phase change materials. Energy Convers Manage 95:69–89
11. Zalba B et al (2003) Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl Therm Eng 23(3):251–283
12. Fan L, Khodadadi JM (2011) Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. Renew Sustain Energy Rev 15(1):24–46
13. Waqas A, Jie J (2018) Effectiveness of phase change material for cooling of photovoltaic panel for hot climate. J Sol Energy Eng 140(4):041006
14. Sainthiya H, Beniwal NS (2019) Efficiency enhancement of photovoltaic/thermal module using front surface cooling technique in winter and summer seasons: an experimental investigation. J Energy Res Technol 141(9):091201
15. Salem Ahmed M, Mohamed ASA, Maghrabie HM (2019) Performance evaluation of combined photovoltaic thermal water cooling system for hot climate regions. ASME J Sol Energy Eng 141:041010-1–10
16. Abdollahi N, Rahimi M (2020) Using a novel phase change material-based cooling tower for a photovoltaic module cooling. J Sol Energy Eng 142(2):1–20
17. Ozakin AN, Yakut K, Khalaji MN (2020) Performance analysis of photovoltaic-heat pump (PV/T) combined systems: a comparative numerical study. J Sol Energy Eng 142: 021010-1–10
18. Zhang H, Liu H, Chen H, Guo X, Liang K, Yao P (2018) Research on the performance of flat-box photovoltaic/thermal collector with cooling channels, ASME J Sol Energy Eng 140: 021002-1–10

19. Hachem F et al (2017) Improving the performance of photovoltaic cells using pure and combined phase change materials—experiments and transient energy balance. Renew Energy 107:567–575
20. Hasan A et al (2017) Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate. Sol Energy 146:417–429
21. Japs E et al (2014) Energy-economic comparison of photovoltaic modules equipped with a layer of conventional and improved phase-change material. In: 2014 IEEE 40th photovoltaic specialist conference (PVSC). IEEE
22. Japs E et al (2013) Technical investigation of a photovoltaic module with integrated improved phase change material. In: Proceedings of the 28th European photovoltaic solar energy conference and exhibition, vol 28. Paris, Frankreich
23. Tanuwijava A et al (2013) Numerical investigation of the thermal management performance of MEPCM modules for PV applications. Energies 6(8):3922–3936
24. Ho C-J, Chou W-L, Lai C-M (2015) Thermal and electrical performance of a water-surface floating PV integrated with a water-saturated MEPCM layer. Energy Convers Manage 89:862–872
25. Chandrasekar M, Rajkumar S, Valavan D (2015) A review on the thermal regulation techniques for non-integrated flat PV modules mounted on building top. Energy Build 86:692–697
26. Du D, Darkwa Jo, Kokogiannakis G (2013) Thermal management systems for photovoltaics (PV) installations: a critical review. Sol Energy 97:238–254
27. Ma T et al (2015) Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: a review and outlook. Renew Sustain Energy Rev 43:1273–1284
28. Reddy SR, Ebadian MA, Lin C-X (2015) A review of PV–T systems: thermal management and efficiency with single phase cooling. Int J Heat Mass Transf 91:861–871
29. Bahaidarah HMS, Baloch AAB, Gandhidasan P (2016) Uniform cooling of photovoltaic panels: a review. Renew Sustain Energy Rev 57:1520–1544
30. Nižetić S et al (2018) Investigation of pork fat as potential novel phase change material for passive cooling applications in photovoltaics. J Clean Prod 170:1006–1016
31. Arıcı M et al (2018) Phase change material based cooling of photovoltaic panel: a simplified numerical model for the optimization of the phase change material layer and general economic evaluation. J Clean Prod 189:738–745
32. Preet S (2018) Water and phase change material based photovoltaic thermal management systems: a review. Renew Sustain Energy Rev 82:791–807
33. Salem MR et al (2019) Performance enhancement of the photovoltaic cells using Al_2O_3/PCM mixture and/or water cooling-techniques. Renew Energy 138:876–890
34. Fayaz H et al (2019) Numerical and outdoor real time experimental investigation of performance of PCM based PVT system. Sol Energy 179:135–150
35. Tangsiriratana E et al (2019) Thermal properties and behavior of microencapsulated sugarcane wax phase change material. Heliyon 5(8): e02184
36. Al-Waeli AHA et al () Mathematical and neural network modeling for predicting and analyzing of nanofluid-nano PCM photovoltaic thermal systems performance. Renew Energy 145:963–980
37. Nasef HA, Nada SA, Hassan H (2019) Integrative passive and active cooling system using PCM and nanofluid for thermal regulation of concentrated photovoltaic solar cells. Energy Convers Manag 199:112065
38. Maatallah T, Zachariah R, Al-Amri FG (2019) Exergo-economic analysis of a serpentine flow type water based photovoltaic thermal system with phase change material (PVT-PCM/water). Sol Energy 193:195–204
39. Nada SA, El-Nagar DH, Hussein HMS (2018) Improving the thermal regulation and efficiency enhancement of PCM-Integrated PV modules using nano particles. Energy Convers Manage 166:735–743
40. Indartono YS, Suwono A, Pratama FY (2016) Improving photovoltaics performance by using yellow petroleum jelly as phase change material. Int J Low-Carbon Technol 11(3):333–337

41. Indartono YS et al (2015) Simulation and experimental study on effect of phase change material thickness to reduce temperature of photovoltaic panel. In: IOP conference series: materials science and engineering, vol 88(1). IOP Publishing
42. Hasan M et al (2014) Development of a temperature regulated photovoltaic module using phase change material for Malaysian weather condition. J Optoelectron Adv Mater Rapid Commun 8:1243–1245