Cooling Methods for Solar Photovoltaic Modules Using Phase Change Materials: A Review

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1 Introduction

The hazardous effects of power generation on environment can be mitigated by reducing our dependence on fossil fuels. Power generation using renewable sources is gaining a lot of attention recently owing to fast depleting fossil fuel reserves and growing focus towards clean energy and sustainability. It is the need of time to exploit more and more renewable energy sources and reduce our dependence on fossil fuels for power generation to meet the future electricity demand while causing minimal damage to our environment [1]. Global renewable power generation was increased by 6.1% in 2018 as compared to 2017 [2]. In 2019, share of renewables in global electricity generation reached 10.4%, surpassing nuclear power for the first time [3].

Among all the renewable means of power generation such as solar, wind power, geothermal, biomass, and small-hydro, solar energy has been observed as a viable alternative for power generation with a large potential to achieve future goals of clean energy production [4]. According to an estimate, Earth receives a huge amount of energy as sunlight in one hour which is sufficient for the world for an entire year [5]. Hence, the potential of solar energy is infinite, and the only limit is our ability to convert solar radiation into more usable form. Figure 1 provides renewable power breakup in India which shows that nearly 40% of installed renewable power in India comes from solar energy conversion.

Employing solar photovoltaic panels for power generation presents several advantages over solar thermal method as they are silent, static, and directly provide high grade of energy. However, large initial cost and low efficiency of solar panels remain big barriers in widespread deployment of this technology. Table 1 shows

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Fig. 1 **a** Renewable power breakup July 2020 [6] **b** Growth of PV installed capacity in India till March 31, 2020 [7]

Table 1 Efficiencies of various types of solar PV cells [10]

Sr. No	PV cell technology	Conversion efficiency at lab scale (%)
1	Carbon nano-tube (CNT)	10–12
2	Thin film	14–22
3	Crystalline Si	21–25
4	Multi-Junction cells	31–38
5	Perovskite solar cells	22
6	Dye-sensitized solar cells	11
7	Organic solar cells	10

efficiency of various types of PV cells at standard test conditions. While the efficiency of solar thermal power systems may go beyond 35% [8], the maximum conversion efficiency of most popular silicon solar panels is still restricted to 26% at standard test conditions [9]. The actual conversion efficiency achieved by solar PV panels is even lesser than the value attained at standard test conditions.

1.1 Effect of High Temperature on PV Modules

The efficiency of a solar photovoltaic module depends on several factors such as cell material and technology, radiation intensity, ambient temperature, sun tracking, shading, soiling of module, and equipment efficiency. Module surface temperature is a major factor which reduces the conversion efficiency especially at high solar intensity. At STC, the module is kept at 25 °C [9] while in actual practice, module temperature may go well beyond 50 °C during peak hours of solar insolation. PV module efficiency declines significantly with the rise in module temperature. Generally, a 0.5% decline in conversion efficiency occurs with 1 °C increase in

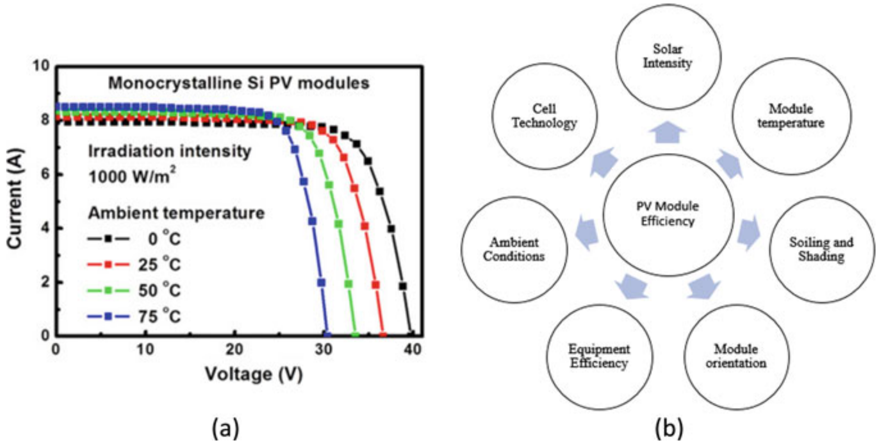

Fig. 2 **a** Effect of temperature on Si solar cell performance [13] **b** Factors affecting PV module efficiency

module temperature [11, 12]. It has also been observed that PV modules working at relatively low temperature works for longer period. So, for high conversion efficiency and longer life, PV module temperature should be kept low during operation. So, a thermal management system for PV modules is essential to ensure high performance and longer life. Figure 2 represents various factors which affect the PV module efficiency and the effect of module temperature on electrical characteristics of a typical Si module.

Several researchers have conducted experiments to quantify and predict the degradation of module performance due to high module temperature. Table 2 summarizes a few of those studies.

1.2 Types of PV Cooling Methods

Various methods of PV module cooling have been developed and implemented by several researchers. These methods can be broadly categorized as active methods and passive methods as represented in Fig. 3. Active cooling methods require external power for their operation because they generally use a coolant circulation over front and/or back side of modules to carry away the heat. They are generally termed as photovoltaic thermal (PV/T) systems. Several PV/T configurations with forced-air cooling, water cooling, water spray, and nanofluids circulation have been extensively reported in the literature. Passive cooling methods do not require external power. These include natural convection cooling, cooling fins, thermoelectric modules (TEM), phase change material (PCM) cooling, spectral beam splitting, etc. Passive cooling methods are less costly but also less effective when compared to active cooling.

Table 2 Studies on degradation of PV modules due to high temperature

Study type	Short description	Effect of module temperature	References
Experimental and numerical	PV module's output was estimated based on the relationship between environmental factors and basic meteorological data of local area	Operating temperature was found to be the major factor for performance degradation in PV modules	[14]
Review	Studied several mathematical correlations between temperature of a PV module and its conversion efficiency	Keeping the module temperature within permissible limit would ensure high conversion efficiency	[15]
Experimental	Studied the degradation of module performance due to various environmental factors, viz., solar intensity, ambient temperature, relative humidity, and soiling of PV module surface	Significant reduction in electrical output of PV module was observed due to high ambient temperature in single day of operation	[16]
Experimental	Studied the drop in PV module output and efficiency with rise in its temperature at various irradiance levels ranging from 400 W/m^2 to 1000 W/m^2	At 1000 W/m^2 irradiance level, the PV module was able to attain maximum temperature of 56 °C resulting in 3.13% reduction in its efficiency	[17]
Experimental	Investigated the effect of PV module surface temperature on its conversion efficiency	Module efficiency was reduced from 12.07% to 10.7% when module temperature rose from 14.9 °C to 51.3 °C	[18]

Selection of a cooling method for PV modules depends on several factors such as ambient conditions, available resources, system durability, and cost to benefit ratio. No clear standards have been reported for cooling of PV modules.

The present work attempts to review and summarize recent research articles focused on phase change materials based cooling systems for PV modules. Research articles on the use of more than one PCM, composite PCM, and PCM with active water cooling have been discussed. Moreover, various methods to enhance thermal conductivity of PCMs such as construction of internal fins, porous metal structures, and use of nanoparticles have also been discussed. Finally, few suggestions for future work on PV module cooling have been included .

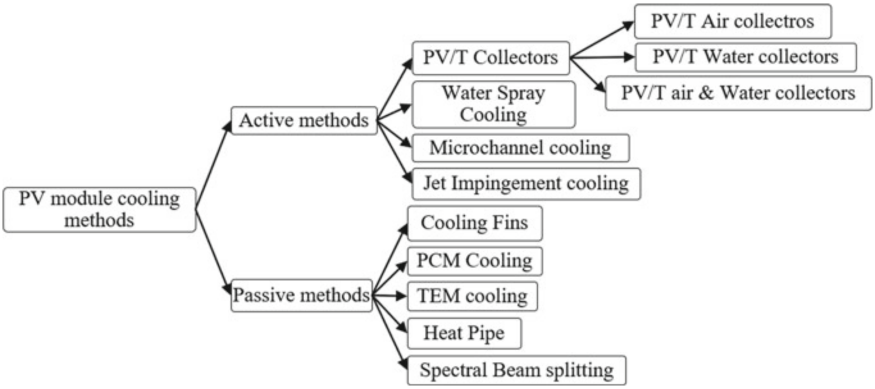

Fig. 3 Various cooling methods for solar PV modules [19]

2 Studies on Pure PCM Used with PV Modules

Phase change materials (PCMs) are most suitable for reducing the temperature of PV modules as they can be easily placed on the rear side of a module by constructing a suitable container. A general schematic of such a system has been shown in Fig. 4. Several designs of containers with different phase change materials have been developed by researchers for PV-PCM modules. Some noteworthy studies are summarized in Table 3.

Rajvikram et al. tried to augment PV module efficiency by placing a container on backside of the module filled with PCM-HS29 having melting point of 29 °C [32]. The container was further attached to an aluminum heat sink to dissipate the heat stored in PCM to the atmosphere. Mahamudul et al. [33] conducted numerical simulation on PV modules integrated with PCM for its thermal regulation for Malaysian weather conditions. Paraffin RT35 with 2 cm layer thickness was placed on rear side of the PV module. Simulation results were validated by comparing them with the experimental data. Maximum temperature reduction of 10 °C was obtained for 6 h of module operation.

The PV-PCM system was found to be effective in keeping low module temperature thus ensuring high output. Maximum efficiency of nearly 17% was achieved by employing the PV-PCM cooling system with aluminum heat sink. Hasan et al. developed a PV-PCM module for extremely hot climate of UAE [34]. It was built by placing a paraffin container on the module back. Melting temperature range of PCM was 38–43 °C which was optimum according to ambient conditions of the location. Tests were conducted for yearlong period in order to evaluate performance and economic feasibility of PV-PCM module. PV-PCM system showed variable performance during different months of the year. It was especially least effective in months of extreme weather owing to its partial melting and solidification. Maximum drop of 13 °C and average drop of 10 °C in module temperature were achieved resulting in 5.9% increase in annual power output.

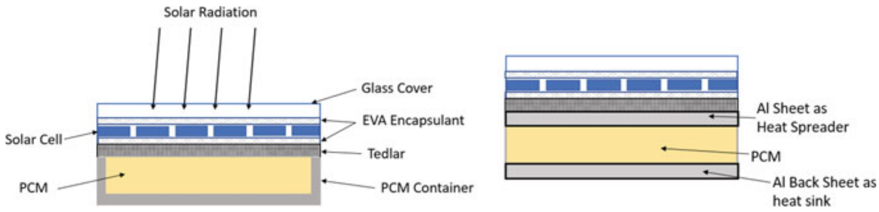

Fig. 4 Schematic representation of PCM container in PV-PCM systems

Table 3 Summary of noteworthy research articles on PCM based cooling systems for Solar PV modules

Author	Cooling method and PCM used	Major findings
Al-Waeli et al. [20]	Paraffin wax	6.5% improvement in electrical efficiency
Indartono et al. [21]	Petroleum jelly	Average increase of 7.3% and 6% in electrical output and conversion efficiency, respectively
Choubineh et al. [22]	Salt hydrate (PCM 32/280) with forced-air cooling	9% increase in PV electrical efficiency
Bayrak et al. [19]	$CaCl_2.6H_2O$ with fins and TEM	7.7% improvement in module electrical output
Waqas et al. [23]	Macro-encapsulated organic PCM	9 °C reduction in peak module temperature and 2% improvement in conversion efficiency
Hasan et al. [24]	RT 42 with water cooling	9 °C reduction in peak temperature and 1.3% improvement in conversion efficiency
Hossain et al. [25]	Lauric acid with water cooling	1.2% increase in PV module conversion efficiency
Sarafraz et al. [26]	Paraffin with multiwalled CNT	0.2% (by weight) carbon nanotube suspension in PCM showed maximum improvement in performance of PV-PCM module
Abdollahi and Rahimi [27]	Coconut oil and sunflower oil Boehmite nanoparticles	48.23% increase in module output
Al-Waeli et al. [28]	Paraffin wax and SiC nanoparticles	PV efficiency was improved when SiC nanoparticles were used as coolant
Eisapour et al. [29]	Ag/water nanofluid and microencapsulated nano-PCM slurry	8.58% and 0.6% increase in thermal efficiency and electrical efficiency, respectively, compared with simple water cooling
Sharma et al. [30]	CuO nanoparticles with RT 42 PCM in micro-finned heat sink $CaCl_2H_{12}O_6$ with Al_2O_3	18.5% reduction in PV module temperature
Salem et al [31]	Nanoparticle and/or water cooling	Water cooled PV module which utilized 1% mixture of nanoparticles in PCM showed the highest performance

Kawtharani et al. [35] experimentally investigated capric acid as PCM to regulate its temperature in indoor test conditions. The organic fatty acid-based PCM had melting point ranging from 27 to 32 °C. It was found to be effective for keeping module temperature within permissible limit. Further, a numerical simulation model was also developed and validated to theoretically predict the temperature variation of PV module and its electrical characteristics. The PV-PCM module was able to save 16% energy as compared to the conventional PV module. Hendricks and Van Sark [36] conducted tests on several PCMs in order to investigate the possibility of using them to limit the PV module temperature. A simple heat balance model was applied to PV-PCM modules to analyze net energy gain for different runs of cooling system. Several numerical simulations were run on PCMs namely: Rubitherm RT-27, RT-42 BASF micronal DS5001, and Thermusol HD35. Rubitherm PCMs were found to be effective in keeping relatively low module temperature. However, economic feasibility was not reached for a practical scenario. Integration of PCMs in BIPV systems for inside climate control of the building was suggested as future scope for further research. Hasan et al. designed and developed PV-PCM systems with two different PCMs and conducted experimental investigations on these systems in cold as well as hot climatic conditions [37]. PCM stores the excessive heat generated by the module for sufficiently long duration. While the PV-PCM systems were found to be effective in keeping low module temperature, they were not found economically feasible in cold climatic conditions. So, mass production of such systems was not suggested for cold climates. However, in hot climates PV-PCM systems can be economically viable over a considerable operating period. Stropnik and Stritih [38] conducted simulation as well as experimental investigations on PV-PCM module using paraffinic organic PCM RT28HC. A 250 W solar PV module was modified to contain PCM on the back side. Simulations were carried out on TRNSYS software and a comparison of experimental and simulation data was also conducted. Annual increment of 7.3% in electrical output and 0.8% increment in conversion efficiency were reported for climatic conditions of Ljubljana, Slovenia.

Zhao et al. [39] conducted simulation study on PV-PCM system for varied PCM layer thickness. One dimensional thermal resistance model was used for performance analysis of PV-PCM system while RT35HC was used as PCM. A maximum temperature drop of 24.9 °C was achieved in one day of operation with PCM layer thickness of 30 mm (Fig. 5). Sharma et al. [40] conducted experimental study to investigate feasibility of using PCM for thermal management of low concentration building integrated concentrated photovoltaic system (BICPV). A PCM container filled with paraffin wax RT42 was integrated to the BICPV system for an indoor experimental setup. BICPV-PCM system achieved an average temperature reduction of 3.8 °C and 7.7% enhancement in electrical efficiency when compared to naturally ventilated BICPV system. Klugmann-radziemska and Wcisło-kucharek [41] conducted several experiments in laboratory conditions on PV-PCM systems in order to analyze the effectiveness of various PCMs for temperature control. Module temperature reduction of 7 °C was achieved without using active water cooling. Paraffin RT 42–44 were recommended as PCMs for PV module thermal

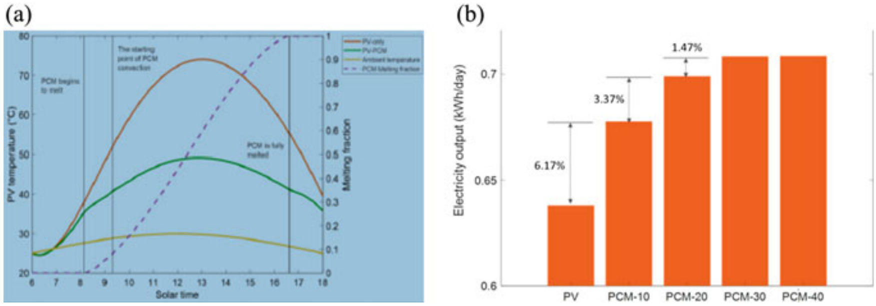

Fig. 5 **a** PV Module temperature with and without PCM system (30 mm PCM) **b** Electrical output of PV-PCM module with increasing PCM layer thickness (10, 20, 30, 40 mm) [39]

management as they were able to maintain low module temperature for most of high-intensity solar radiation period.

3 Studies on Heat Transfer Enhancement in PV-PCM Modules

Various techniques have been used by researchers in past few years to enhance the heat transfer rate of PCM to improve the performance of PV-PCM modules. Rajvikram et al. [42] conducted experimental investigation on a 5 W PV-PCM module, placing an aluminum plate at the module back as thermal conductivity enhancer. Paraffinic organic PCM OM-29 with a thickness of 30 mm was placed at the module back. The aluminum plate was found to enhance the thermal dissipation capacity of PCM. An average temperature reduction of 10.35 °C was observed during experiments with 2% improvement in overall efficiency of PV module. In order to develop an effective passive cooling system for PV modules, Bayrak et al. [19] conducted various experiments on PV-PCM modules using two different PCMs with several fin configurations (Fig. 6). Biphenyl and calcium chloride hexahydrate ($CaCl_2.6H_2O$) were used with thermoelectric modules and a number of aluminum fins on the module back. Calcium chloride hexahydrate was found to

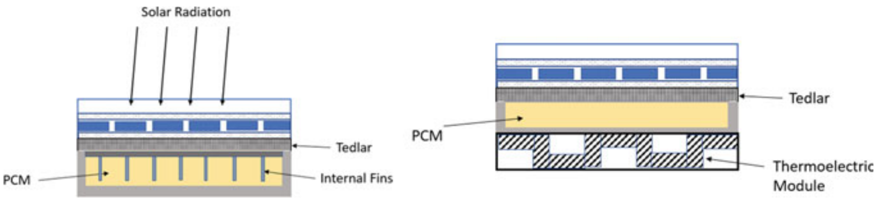

Fig. 6 Different configurations of PCM with fins and TEM

improve the PV module performance. Moreover, increasing the number of fins resulted in high-cooling performance. Highest improvement of 7.72% in PV module output was observed when $CaCl_2.6H_2O$ was used with fins and thermoelectric module .

In order to enhance thermal conductivity of paraffin wax PCM, Shastry and Arunachala [43] utilized aluminum matrix in PV/T-PCM system. Aluminum matrix, with honeycomb structure filled with paraffin wax PCM, was placed on the back side of PV module to store the heat generated by the PV module. Figure 7 shows the matrix placed in PCM container to enhance its thermal conductivity. Maximum improvement of 8.6% in module output was reported as compared to conventional PV-PCM system. Wongwuttanasatian et al. [44] utilized low-cost palm wax as PCM in three different designs of PCM container placed on PV module back. Palm wax has a melting temperature ranging from 50 to 55 °C which makes it suitable for PV module cooling. Three designs were basically three different fin configurations with provision of active water cooling. The module with finned PCM container was able to reduce the module surface temperature by 6 °C which resulted in 5.3% improvement in conversion efficiency when compared to a non-cooled PV module. Atkin and Farid [45] conducted experimental and simulation studies to investigate viability of PCM infused graphite along with external-finned heat sink for thermal management of PV modules. PV-PCM configuration which used 92% (by weight) PCM infused in graphite block and external Aluminum fins was reported to be most effective with 12.97% increase in overall efficiency of PV module.

In order to enhance thermal characteristics of PCM used in PV cooling systems, Numan [46] utilized aluminum matrix foam to modify a 67.5 W PV module into the PV-PCM module. Paraffin wax was embedded in pores of foam to store excess heat. Optimum thickness of PCM layer was found to be 3 cm at which maximum reduction in peak module temperature was achieved. Khanna et al. [47] constructed a PCM container of paraffin RT 25 HC with internal finned structure. They conducted simulation study on finned PV-PCM system to optimize several fin parameters such as fin thickness, fin length, fin spacing, and depth of PCM layer. Maiti et al. [48] used paraffin wax PCM with PV panel to limit the temperature while taking benefit of high solar intensity. Paraffin wax with melting temperature of 58 °C was incorporated at the back side of the PV collector. An attempt was made to enhance thermal conductivity of paraffin wax by spreading metal turnings

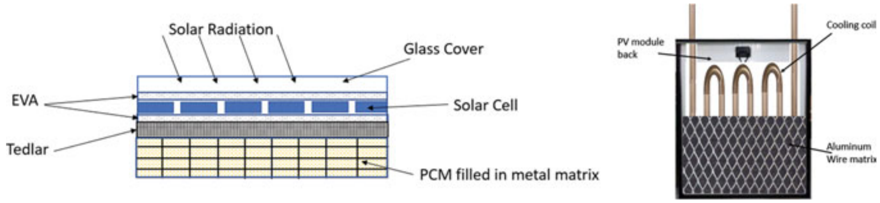

Fig. 7 PCM embedded in Al metal matrix [43]

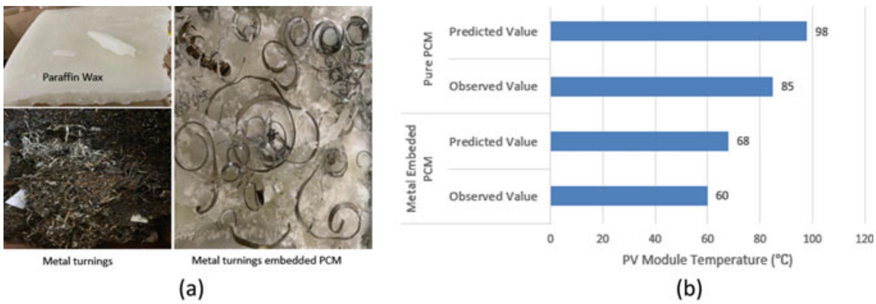

Fig. 8 **a** PCM embedded with metal turnings **b** Maximum temperature of PV module [48]

(shown in Fig. 8) in the PCM container. PCM was able to keep relatively low module temperature during indoor as well as outdoor testing of the module.

In order to test the effectiveness of activated alumina (Zeolite) as a heat storage medium, Ragab et al. [49] conducted experimental study on different configurations of PV modules. Tests were conducted in indoor conditions with four different zeolite layer thickness on back of the PV module. Metal fin structures, metal mesh and metal particles were used inside the zeolite container to further enhance the effectiveness of the system. Significant drop of 15 °C and 9 °C in module surface temperature with 10% and 7% improvement in efficiency was reported at radiation intensities of 600 W/m^2 and 1000 W/m^2, respectively. Singh et al. [50] designed a number of small aluminum containers for PCM in order to augment its thermal conductivity.

4 Studies on Composite PCMs/Nano-Enhanced PCMs

Composite PCMs which are mixture of two or more PCMs sometimes provide better thermal characteristics than a single PCM. Zhang and Zhang [51] conducted indoor experiments on composite PCM of $CaCl_2.6H_2O$ and $MgCl_2.6H_2O$ for thermal management of PV modules. Composite PCM was made by physical mixing of the two PCMs with expanded graphite as the carrier. The composite PCM showed excellent thermal characteristics and performed better than a single. The composite PCM was able to maintain PV module temperature less than 40 °C for most of the operational time which resulted in nearly 8% more electrical power output. Luo et al. [52] used a form-stable paraffin (RT28)/expanded graphite composite, to develop a PV-PCM system and conducted experiments as well as CFD simulations in order to control the temperature of PV module. Composite PCM was able to keep the temperature of module below 50 °C throughout the experiment. Figure 9 presents the findings of this study.

Siahkamari et al. [53] conducted experimental study on sheep fat utilized as PCM in water cooled PV/T system. Copper microchannels were placed on the back

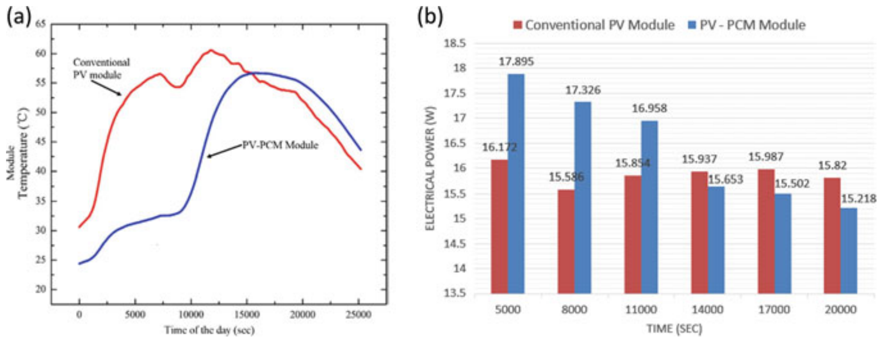

Fig. 9 **a** Temperature of conventional PV module and PV-PCM system **b** Power output comparison [52]

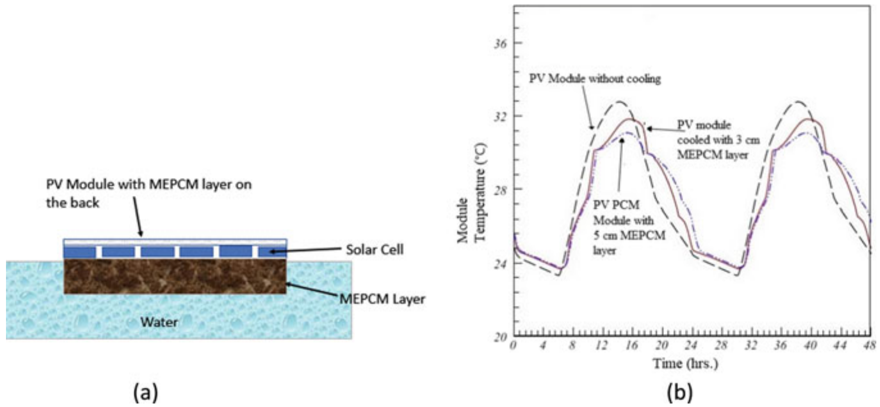

Fig. 10 **a** MEPCM layer used with floating PV module **b** Average PV module temperature with increasing MEPCM layer thickness (3 cm and 5 cm) [54]

of module through which cooling water flows. In order to improve the effectiveness of sheep fat as PCM, CuO nanoparticles were added. The nano-enhanced PV-PCM module reported 26% increment in power output when compared to PV module without cooling. Ho et al. [54] conducted numerical simulations to investigate the effect of micro-encapsulated PCM (MEPCM) layer on the surface temperature of PV module. A PV-PCM configuration was designed in which MEPCM layer was attached to the back of the module and whole system floats in water (Fig. 10). So a combined cooling effect of MEPCM and water cooling was analyzed through numerical method. Maximum reduction of 18 °C was achieved in module temperature with 5 mm thick MEPCM layer.

Tanuwijava et al. [55] conducted CFD simulation study on the use of MEPCM for temperature reduction of PV modules. A valid CFD model was developed to simulate PV module integrated with MEPCM layer on the back of the module.

Sharma et al. [30] used RT 42 as phase change material and enhanced its properties by adding nanoparticles and employing micro fins.

5 PCMs Used with Active Cooling

In order to enhance the rate of heat transfer from the module back, several researchers have used phase change materials with active cooling. Figure 11 represents a typical configuration of PV-PCM module with active cooling. Water is commonly used as coolant in case of active cooling but some authors have even used nanofluids as cooling medium. Preet et al. [56] conducted experimental studies on three different PV/T systems. First one was conventional water cooled PV/T system, second one with double absorber, and third was water cooled PV/T system with paraffin PCM. Thermal and electrical performance of all the three configurations were observed and compared with varying flow rate of water.

The PCM-based cooling system was found to be very effective in bringing down the module operating temperature and enhancing the efficiency of PV/T system. A reduction of 53% in peak module temperature was achieved with PV/T-PCM cooling system. Abood and Shahad [57] constructed aluminum pockets on the rear side of PV module with provision of coolant circulation. SiC/water nanofluid was used to remove excess heat from the module back. System was tested under outdoor conditions with different flow rates of nanofluid coolant in order to optimize the system parameters. Performance of nanofluid-cooled PV module was compared with that of conventional module under same operating conditions. Nanofluid coolant with 0.5% SiC nanoparticles at a flow rate of 2 LPM provided maximum improvement of nearly 33% in PV efficiency. Aberoumand et al. [58] developed a PV/T system in which nanofluids were circulated through several channels on module back in order to remove the excess heat. Significant improvements in thermal characteristics were observed when Ag nanoparticles were mixed in water.

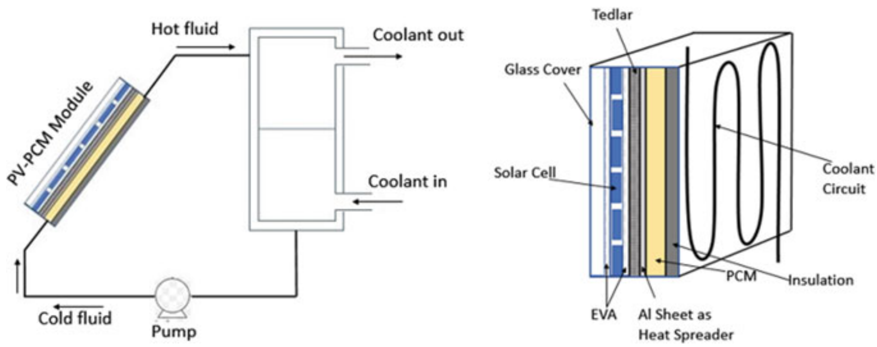

Fig. 11 Active cooling of PV modules

Increasing the concentration of Ag nanoparticles in water was found to have further improved the effectiveness of cooling system. An improvement of nearly 14% in electrical efficiency of PV module was reported with nanofluid circulation having 4% concentration of Ag nanoparticles. Nasef et al. [59] developed and modeled an integrative system for concentrated PV module thermal regulation which utilizes PCM and active water cooling. PCM RT35HC was used with different configurations of cooling fluid circulation on rear side of the module. In order to improve the overall efficiency of cooling system, CuO nanofluid with 4% concentration in water was also circulated as heat transfer fluid. CPV efficiency was increased by 2.7% with a 4 °C reduction in maximum PV temperature. Abdulmunem et al. [60] developed a passive cooling method for PV modules by employing PCM within the copper foam matrix. Phase change material was also enhanced by mixing 0.2% multi–walled carbon nanotubes. Three different configurations of PV-PCM module were developed and compared experimentally with conventional PV module. First one consisted of only a PCM on PV module back. In second design, PCM was embedded in copper foam matrix which augmented its thermal characteristics. Finally, third configuration consisted of nano-enhanced PCM embedded in copper foam matrix which was placed on module back. Improvement in conversion efficiency of PV module over that of conventional PV module in three cases were found to be 4.5%, 1.97%, and 5.68%, respectively. It was reported that copper foam matrix and carbon nanotubes are effective in improving the performance of PV modules, but their economic feasibility still remains to be explored. In order to take advantage of active and passive cooling methods at the same time, Rajaee et al. [61] integrated six different cooling methods and constructed one novel cooling system for PV modules. The novel system utilized a thermoelectric generator on module back with provision of nanofluid cooling. Paraffin wax enhanced with alumina powder was also incorporated in the integrated cooling system. The combined unit was found to be very effective in utilizing the incident solar radiation. The cooling system which utilizes nano-enhanced PCM with 1% Co_3O_4/water nanofluid as coolant improved the overall efficiency by 12.28% when compared to PV/T water system. Use of TEG further improves the effectiveness of integrated cooling system for PV modules.

6 Conclusion

Following conclusions can be drawn as per the literature survey on PCM-based cooling systems for PV modules:

- There is no single universally accepted cooling method for PV modules which can be commercialized for large PV installations. Active cooling methods are more effective than passive cooling methods, but their economic feasibility needs to be explored before employing these in practical situation.

- Phase change materials are suitable and effective in improving the efficiency of PV panels as they do not require external power input and sophisticated equipment for their operation. However, their economic feasibility could only be justified for hot climatic conditions.
- Several cooling systems employ PCMs with an active cooling system. These methods utilize benefits of active cooling as well as passive methods.
- Use of phase change materials provide many advantages but their low thermal conductivity remains a big issue. Several methods such as fins, metal matrix, and nanomaterials can be used to improve their thermal conductivity.
- Use of nanoparticles in PCM improves its thermal performance significantly, but the economic feasibility was not achieved in most of the cases.
- Mass production of PV-PCM modules is justified only for hot climatic conditions as the payback period of these systems was found to be relatively low when employed in tropical regions.

7 Future Scope

- Long-term experiments need to be conducted to evaluate the economic feasibility and durability of PV-PCM systems with seasonal variations.
- Low-cost innovative methods can be developed to address the general problem of low thermal conductivity in almost all the types of phase change materials.
- There is a need for a simple, low cost, and durable cooling system for PV panels to maintain its operating temperature within the desirable limit especially during the peak hours of solar radiation. An integration of passive and active cooling methods can be useful to achieve this.
- Various simulation studies can be conducted to establish set of standards for selection of PCM as per ambient conditions and PV cell material.
- Standard methods for performance evaluation of PV-PCM modules can be developed so that the effectiveness of a cooling system can be easily analyzed.

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