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(REVIEW ARTICLE)

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A comprehensive review on performance evaluation of PV panel using phase change material for thermal energy management

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Abstract

The performance of photovoltaic (PV) systems is significantly influenced by surface temperature, which reduces electrical efficiency under high solar irradiance. Sensitivity of the photovoltaic systems (PV) is affected considerably by the surface temperature, reducing the electric efficiency of PV under high solar radiation. Different methods have been used to overcome this, such as the phase change material (PCM) cooling, nanofluid cooling, forced air, forced water, heat pipes, and natural cooling. Here we assess how effective these methods are in increasing electrical and thermal efficiency. When comparing the use of nanofluid and forced air cooling, the potential increase in electrical efficiency is 11.9% and 11.4%, respectively, whereas with the application of PCM and forced water cooling, the gain is less, at 5.2%. On the other hand, the PCM reveals the highest Δη ther at 72.6% whereas the nanofluids at 67.0%. It is, therefore, reasonable to anticipate promising prospect on combined application of nanofluids and PCMs for enhancing PV system performance especially in hot climatic zones.

Keywords: Photovoltaic Systems; Cooling Techniques; Nanofluids; Phase Change Materials; Electrical Efficiency; Thermal Regulation

1. Introduction

Non-renewable energy is the major source of global greenhouse gas (GHG) emissions, which account for a large proportion of factors causing climate change and global warming. The burning of fossil fuels emits enormous quantities of greenhouse gases (GHGs) such as CO2 and methane and other pollutants in the atmosphere further leading to environmental pollution. Alternatively, with the growing awareness of sustainable development and the call for more environment-friendly options industries are moving toward renewable energy and reducing their carbon emissions, becoming environmentally sustainable. Solar power is one of these options being considered as an alternative, because it is a GHG free and an unbounded energy resource that offers long term economic benefits. The rising deployment of solar energy has driven numerous research and development undertakings to improve the efficiency, storage potential, and integration of solar energy into the current energy grid. Inventions in PV, concentrated solar power (CSP), and energy storage have also contributed, the shift from the analog world has been particularly rapid. This field is witnessing increasing attention from academia and industry as evidenced by number of scientific publications relevant to solar energy over the last two decades. This point illustrates the worldwide dedication to developing solar technologies cheap and efficient enough for broad usage. With solar power advancing, it's an industry subsidy grabs simply can't be tolerated because breaking dependency on subsidized fossil fuels can't wait. This shift not only acts to promote environmental sustainability, but also to ensure long-term energy security and economic resilience. The overall efficiency of the solar photovoltaic (PV) power generation system is hardly between 15% and 20%, which is dependent

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on many other environmental and operating conditions. Among these, include dust deposition on PV panels, shade, wind speed, solar irradiation, environment temperature and panels surface temperature. One of the challenges for the performance of a PV is the over-irradiance of the sun where an excess heat is created, and the panels' surface temperature is raised. PV systems work best at a normal temperature of 25°C, the conversion rate of the electricity starts to drop if the temperature gets too high. In hot and dry areas, PV panel temperature can reach 75°C and efficiency reduction can be as high as 25%. The relative maximum power varies with temperature for mono-crystalline silicon PV cells, and is denoted around -0.002/°C, whereas the efficiency decreases with 0.5% for every 1 °C at temperature increase. Effects of the solar irradiance variation on the efficiency of PV cells of different kinds are different. More precisely, for amorphous, poly-crystalline and mono-crystalline PV cells the drop in electrical yield per 100 W/m^2 of higher solar irradiance is 0.33%, 0.51% and 0.84% respectively. Such thermal and irradiance efficiency deteriorations underscore the need for cooling strategies and novel, integrated systems to maximize PV performance, especially in warmer climates.

The objective of this study is to conduct systematic, quantitative meta-analysis on the thermal management characteristics of PCM for a variety of engineering applications: BTMS, TES and PV cooling. The study is also the first to piece together experimental and simulation data from previously published works using data-mining techniques, and sets out to provide a broad approach for quantifying the temperature clipping effects of PCM utilization in different use cases and environmental contexts. It aims to evaluate not only the average temperature reduction that can be achieved using PCMs, but also other temperature reduction/cooling performance with a specific application along with other performances characteristics derived from the system like energy conversion efficiency, thermal durability and cycle life. In addition, the investigation seeks to find important design parameters (e.g., type of PCM, melting temperature range, method of thermal conductivity enhancement, method of introducing PCM into the host material) that determine how well a PCM can be utilized in practice. The aim is to gather the isolated results into a unified knowledge base, furthering the understanding of PCM results towards their general applicability and bridging the gap to the applications of PCMs, pointing out future research and technological optimization in thermal solutions using phase-change materials.

The Phase Change Materials (PCMs) are widely explored to regulate the heat in numerous applications like battery thermal management systems, thermal storage units and cooling of photovoltaic panels, however the literature in this domain is largely fragmented and highly application centric. The majority of reports are individual case studies without a comprehensive methodology or a universal format for a side-by-side comparison. Moreover, there is no quantitative benchmarking to systematically compare and analyze the reduction of a heat loss temperature in different PCM types, encapsulation approaches, and operating conditions. The material-level problems, such as the narrow phase-changing temperature range, low thermal conductivity, and the low long-term stability, are still not well solved and are far from enough for practicalization in large-scale system integration. Furthermore, scalable, low-cost and system-level performance metrics, such as overall energy efficiency, reliability and life cycle profit, are absent in the existing literature. Meanwhile, the lack of a uniform evaluation protocol and performance criterion makes it difficult to compare across various studies. Additionally, the multi-functional/hybrid applications (e.g., combined energy storage and thermal regulation) for PCMs are rarely reported. These lacunae underscore the necessity of a holistic review that not only compiles the learnings but also quantitatively measures the thermal advantages of PCMs in diverse applications, and also sets a benchmark to define and guide the development process and optimization of PCM based thermal management devices.

This work conducts a systematic and quantitative analysis of PCM used in applications to address the enhanced PV cooling, thermal energy storage, and battery temperature regulation. By pulling together disparate literature into one coherent context, the work closes existing knowledge holes and yields a better understanding of temperature reduction windows, enhanced efficiencies, and trade-offs occurring when implementing cooling strategies. This raises PCMs from being an alternative only applied passively, but as an imperative material that is worth the effort in improving its performance when it is incorporated into novel solutions as nanofluids or hybrid diagnostic tools.

In recent years, the depletion of traditional energy sources has resulted in a surge in the application of alternative renewable energy sources including solar, wind, hydro, geothermal, and biofuels to satisfy the electricity demand, achieve the sustainable development goals (SDGs), and counteract the global warming and climate change [1–3]. Of these, solar photovoltaic (PV) and building technologies have made tremendous progress in both residential and commercial sectors and have contributed to a decrease in national energy use and greenhouse gas emissions [4–6]. The PV panels have recently been considered as one of the significant renewable energy sources for various applications [7,8]. However, the performance of PV panels are significantly affected by the solar radiation intensity and the operating temperature of the semiconductor cells. Overheating causes the module temperature to increase limiting the power output, since efficiency generally decreases by approximately 0.45% for every 1 °C increase above the standard operating temperature of 25 °C [9–11]. In addition, to compensate for this loss, decreasing the PV temperature using

active, passive, or hybrid cooling methods has become important [12,13]. For example, insulating the back surface of a PV panel can result in an elevated temperature (12–20 °C) and decrease in electrical efficiency (7–10%) [14]. In experimental research studies, Wilson and colleagues [7] found that 500mg/kg ARCs did not have the effect of agitated behavior, although that dose and ARCs which were received 300, 150, and 50mg/kg significantly increased spontaneous motor activity levels. [15], water circulation in back of the PV panel led to a decrease in surface temperature from 62 to 30 °C—32 °C was a-or-drop—allowing to an increase of 13% in the power generation. Similarly, Maghrabie et al. [16] reported that, within an operating range of 33–45 °C, an air-cooling system reduced the temperature of the PV cell to approximately 10 and 11% for the front and rear respectively, which consequently improved the overall efficiency. Farhana et al. [17] proposed a passively cooled PV module by adding a brushless DC fan mounted with an inlet and an outlet manifold to distribute the airflow uniformly above the panel module. The results of their experiments revealed that the system was able to reduce the temperature of the PV module by 12 °C.115 Teo et al. [18] who studied the effect of the copper fins from the back side of the PV module integrated with forced convection manner with an air push fan. The findings showed a pronounced decrease in temperature with a decrease of about 30 °C which significantly promoted thermal regulation. In a different study, Fossa and colleagues found that at a median follow-up of 7 years, 13 (2.8%) of 468 patients with seminoma had died of disease compared with 151 (23%) of 648 patients with nonseminoma. [19] experimentally studied the heat transfer modes in a double-skin PV façade. They found that the larger the air channel lo spacing was, the lower the operating temperature was in multiple heating systems. Also, correlations expressing the dependence of local and average Nusselt numbers on the geometry and flow conditions were developed from the experimental data, thus providing predictive power for the convective heat transfer behavior.

Concurrently, some other investigators have proposed the PCMs as a passive thermal management technology of the PV modules [20 23]. Some advanced computational and optimization approaches including coupled CFD simulations, ANN and NSGA have been suggested for achieving the optimal PCM thermal storage capacity and the optimum latent heat utilization [24]. Predictive numerical models have also been developed to predict melting kinetics and surface-averaged Nusselt numbers during PCM phase change in spherical thermal storage geometries [24,25]. Bouzennada et al. [26], studied the spatio-temporal distribution of thermal fields in the PCM-enhanced systems, to provide a good understanding of the conduction-convection interrelations and a good perception of the effective heat removal behavior.

In recent years, a lot of experimental works have been done to reduce the surface temperature of PV panels and to enhance the thermal control by using phase change materials (PCMs) [27]. Key to the PCM selection is that large amounts of latent heat can be stored during melting/solidification with a volume expansion usually less than 10%. Pichandi et al. [28] proved experimentally that by adding PCM into PV modules, the effective temperature was reduced 7 °C and the daily average performance increased to 1.21%. Hasan et al. [29] investigated a PV-PCM system (RT-42) under hot weather conditions with a numerical model and an experimental study. They found that, at peak irradiation, the mean device temperatures of PVs reduced by 10.5 °C, leading to a 5.9% cumulative yearly gain in power generation. Indartono et al. [30] studied the effect of PCM thickness in coconut oil and crude palm oil (CPO) as storage materials. They found CPO to perform better than virgin coconut oil at a thickness of 80 mm under an ambient temperature of 27–30 °C, and concluded that an 80 mm thickness would be adequate, similar with Cellura et al. [31] tested different paraffin waxes and observed a maximum surface temperature decrement of 22 °C. Savvakis et al. [32] tested that PCM-27 and PCM-31 combination improved 4.19% and 4.24% of PV generation, respectively, with an overall enhanced efficiency ranging between 2.86% and 4.19%. Khanna et al. [33] have performed a theoretical efficiency investigation of PV-PCM systems with RT-25 HC at various tilt angles. They found that temperatures dropped from 43.4 °C to 34.5 °C and efficiency increased from 18.1% to 19% as the tilt angle was adjusted from 0° to 90°. Waqas et al. [34] experimentally studied PV-PCM panels having RT-24 in copper tubes and reduced the temperature by 8.5 °C for the best PCM mass per unit area of 2.5 kg, resulting in a 3% efficiency improvement. Kumar et al. [35] investigated the use of a mixture of paraffin wax, copper, and silicon carbide (SiC), achieving an enhancement in performance up to 2.8% for nominal PCM use and up to 4.3% for hybrid PCM integration. Khanna et al. [36] numerically optimized the geometry of the systems PV-PCM finned type systems, concluding that optimal results were achieved using a 25 cm fin spacing with a 2 mm thickness for different solar irradiance levels. Huang et al. [37] experimentally investigated PV-PCM panels using RT-25 and granular GR-40. Findings confirmed that it was possible to keep PV temperatures below 29 °C for 130 min using the RT-25 container, but not with the GR-40 container. Preet et al. [38] studied water-based PV/T and PV/T-PCM, and found maximum increments of the electrical efficiency of 10.66% and 12.6%, respectively. Finally, Browne et al. [39] studied a new PV/T-PCM configuration with a capric–palmitic faty acid eutectic PCM and obtained thermal efficacies from 20 to 25%.

1.1. Progress of Phase Change Material and their research growth in last 10 year.

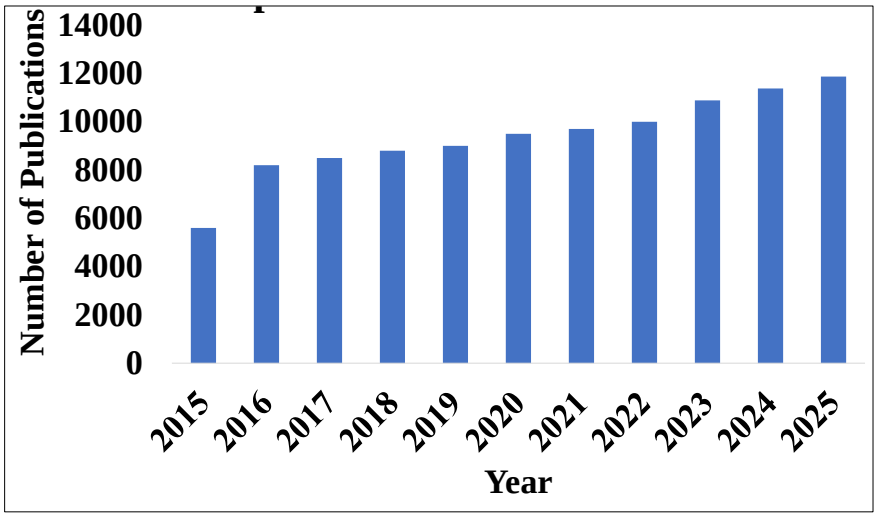


Figure 1 Paper Publications On PCM

The annual trends regarding papers published about PCMs from 2015 to 2025 are shown in Fig. 1. From 2015 to 2022, a consistent rise trend is observed due to the increase of articles from 5600 in 2015 to 10,000 in 2022, which represents the growing interest in PCMs in the field of energy storage, battery thermal management, and photovoltaic cooling. This increasing trend reflects a transition from exploratory to applied and system level studies. According to the trend, the forecast data for 2023–2025 shows an upward trend with approximately 12,000 publications in 2025. This underscores PCMs being a rapidly growing area of research in response to the worldwide need for effective thermal management for renewable energy and green industries.

1.2. Application of Phase Change Material in Battery Cooling corresponding to number of publications.

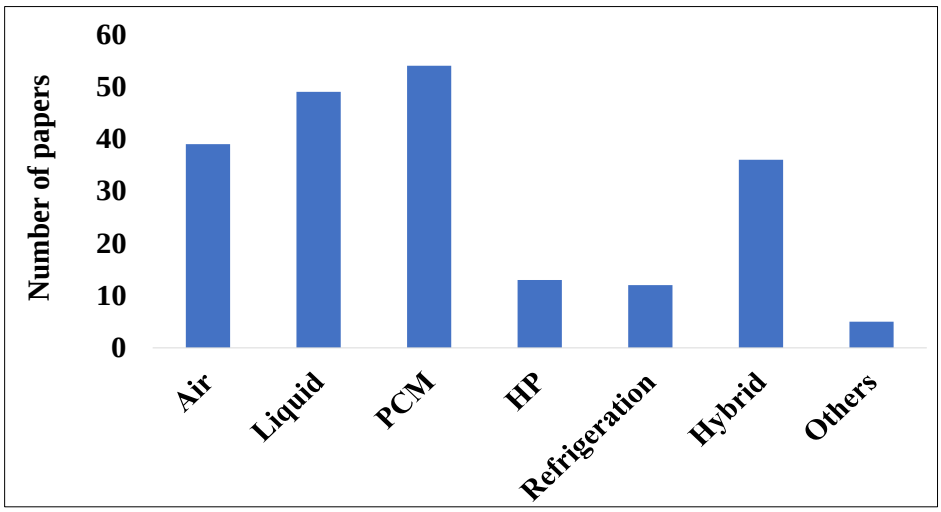


Figure 2 Application of PCM in Battery Cooling

Battery Cooling Techniques Fig. 2 shows the various cooling techniques that have been proposed for use in battery thermal management, concentrating on using Phase Change Material (PCM). Of various approaches reported PCM is the most well-studied approach being reported in 54 % of the publications to enhance battery cooling performance. Liquid cooling occupies the second place with 49 papers, whereas air cooling contributes with 39 works. Hybrid approaches that bring together more than one method are represented in 36 papers and included as an indication of an increasing trend in combined solutions. Heat Pipe (HP) and refrigeration approach, in contrast, are much less studied with 13 and 12 articles, while Others are still rare with only 5 articles. In general, the picture can suggest that the PCM is the most attractive research area for its potential of thermal management of battery systems.

1.3. Implementation of Phase Change Material in thermal and energy storage management

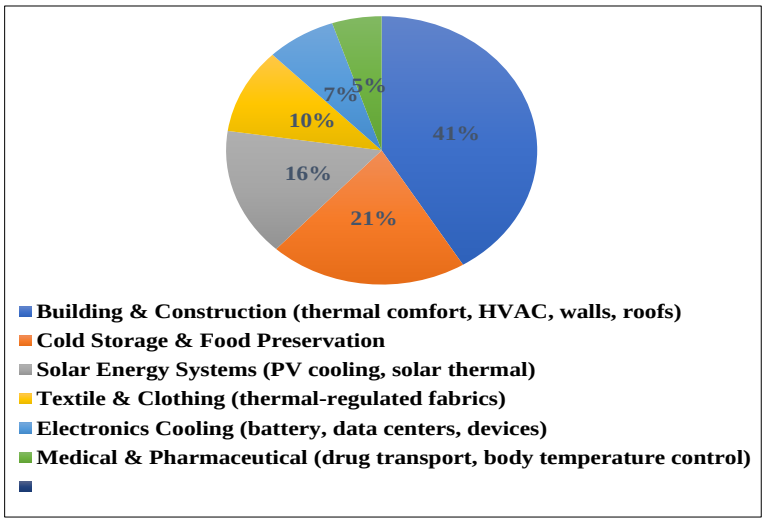


Figure 3 PCM applications in different Area

Figure 3 the pie chart illustrates the multiple uses of PCMs in various applications. The largest end use (41%) is in building and construction, where PCMs improve thermal comfort and efficiency, in buildings and HVAC systems, walls and roofs. Cold storage and perving of food are next (21%), as it allows the stability of temperature for perishable products. Solar applications, such as PV cooling, solar water heating, and MP PCM technologies, represent 16% of the contributions, demonstrating the importance of PCMs to renewable energy efficiency. For the textile industry, 10% of the applications are based on the development of thermal-regulated fabrics that achieve an increased comfort and performance. In the meantime, those batteries, data centers and devices make up 7% of electronics cooling usage. The other 5% is used for other applications that have newly emerged, which implies the increasing and expanded applications of PCMs in technology and energy systems.

1.4. Effect of organic and inorganic phase change material on PV panel surface temperature reduction.

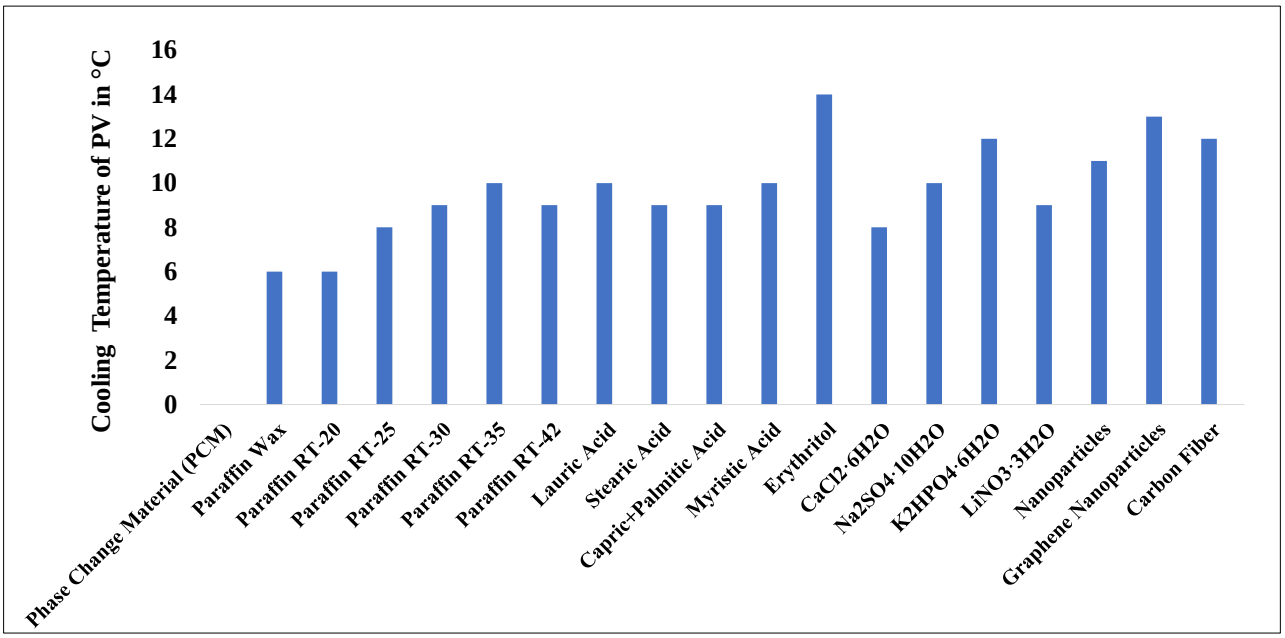


Figure 4 Different Types of Phase change material and temperature reduction

Table 1 Shows each PCM's cooling temperature reduction (°C) under comparable PV operating conditions and overall suitability. Covers paraffin grades, fatty acids, and inorganic/advanced (hydrates/nanoparticle-enhanced) PCMs, highlighting performance–stability–cost trade-offs [40-50].

PCM tested, melting point (0C)/Latent Heat (kJ/kg)	PV-panel specifications	Nature of Work and Duration	Type of PV system	Key Findings	Ref
PCM, 218 kJ/kg~54 °C/~49 °C	30Wmonocrystalline PV-panels	Outdoor experiment in summer at Paderborn, Germany from 15th Jul to 16th Aug	PCM filled in bags attached to back of PV-panel	PCM brought uniformity in panel temperature and peak reduction was 7 °C	[40]
RT35, 35 °C	PV-module	Numerical Simulation	PV-module with PCM integrated at its back	PV-PCM system showed 35 °C temperature drop as compared to PV system.	[41]
RT28 HC, 28 °C/245 kJ/kg	250 W CS6P-M PV-panel with dimensions 340 × 280 (mm)	Outdoor experimentatLjubljana, Slovenia, from 14th to 21th October 2013	PV with PCM box attached on behind and enclosed with acrylic glass	PVsurface temperature reducd by 35.6°C.Electricalefficiency enhanced by 23.2%.	[42]
RT42, 38–43 °C/145 ± 7% kJ/kg	40 W polycrystalline EVA encapsulated panels, 53 × 63(cm)	Outdoor experiment at Al-Ain, UAE for a complete year 2015	PV with PCM container attached at behind	PV-cell temperature dropped by maximum 13 °C in April. Average increase in electrical power output was 5.9% for complete year.	[43]
RT44, 44 °C (peak)/250 kJ/kg	Conventional-PV Panels with PCM filled shutters on back	Numerical simulation using conditions of 1st week-Jan and 2nd week-Jun in Islmbd, Pakistan	PV with PCM-filled shutters on back	In June, PCM with Tm = 35 °C gave maximum efficiency as PV temp. reduced by 35 °C while in January, PCM with Tm = 30 °C was found most efficient with 17 °C drop in temp.	
RT35, 35 °C/240 kJ/kg	PV-module	Numerical simulation with climatic conditions of May in City of Allahabad, India	PV-module coupled with PCM at its back	During melting stage of PCM, convective mode enhanced heat transfer more than by conduction (i.e. 6 °C). Moreover, increasing the tilt angle also increased convection.	[44]
RT20, 20 °C	Conventional-PV-panel	Indoor experiment using Solar simulator (500, 750, 1000 W/m2) for 6 h and a half	PV using PCM in aluminum container at back	By increasing solar irradiations, cell temp dropped more due to PCM (i.e. 8 °C, 9 °C and 13 °C for 500, 750 and 1000 W/m2 respectively).	[45]

RT25 HC, 26.6 °C/232 kJ/kg	PV-module	Numerical simulation for 3 h	PV with PCM box attached at behind	Increasing tilt angle from 00 to 90 °C increased convection rate in PCM. Temp. reduced by 19 °C while efficiency enhanced by 11.8%.	[46]
MEPCM, 26 °C and 34 °C/172 kJ/kg	PV-module	Numerical simulation	PV-module with MEPCM attached at back	Both PCMs (Tm = 26 °C and 34 °C) showed almost equal increase in average efficiency. Efficiency enhanced with 0.277 AR while reduced with 1.	[47]
PCM1: 30 °C, PCM2: 28 °C	PV-module	Numerical simulation with 2-day summer conditions of Taiwan	MEPCM-PV module floating on water surface	5 mm thickness of PCM layer resulted inbest performance.	[48]
RT 42, 38–43 °C/174 kJ/kg	5 LGBC crystalline Si cells (116 mm × 6 mm) connected in series	Indoor experiment with Wacom Solar Simulator (1000 W/m2) for 2 h	PCM containment integrated with BICPV-module	PV-surface temp. reduced by max. 12 °C. Electrical power and efficiency enhanced by 16.67% and 7.7% respectively.	[49]
25 °C/184 kJ/kg	Two 10.9 W monocrystalline panels, 350 × 280 (mm)	Outdoor experiment at Songdo, Incheon, South Korea, from 17th May to 17th June 2012	PV/PCM module installed on a vertical wall surface	Cell temp. lowered by 5 °C. Optimum Tm of PCM was 25 °C. Increase in PCM thickness from 30 to 50 mm had little effect on efficiency.	[50]

Figure 4, the bar graph shows the decrease in cooling temperature for various Phase change materials (PCMs) used for the PV panels. The decrease falls between 6°C and 11°C for the organic paraffin PCMs and Paraffin RT-30 and RT-42 have the most significant cooling potential in this type of PCMs [51]. These PCM can achieve the moderate reduction (approximately 7-11 °C) when they are absorbed in various supporting materials.Fat PCMs (as lauric acid, stearic acid and capric-palmitic acid) have higher value of phase transition temperature (m.p) when compared with Chloride salt hydrates (as $CaCl_2 \cdot 6H_2O$ and $Na_2SO_4 \cdot 10H_2O$) and a select agent have range of melting (PCM), are included and which have showed the effective reduction (approximately 7-12 °C) that suitable potential is used for cooling application due to having an excellent own latent HR storage. Applications of advanced composites, nanoparticle enhanced paraffin, and graphene doped paraffin PCMs can result in more than 15°C cooling, proving the capability of enhancement, although conventional paraffin and fatty acid exhibit stable performance, the composite PCMs are much better than them in in terms of thermal. Taken together, the graph demonstrates the importance of the PCM in improving the efficiency for the cooling of PV and prolonging the system operation under different weather circumstances. PCM's cooling temperature reduction (°C) under comparable PV operating conditions and overall suitability as discussed in Table 1.

1.5. Effect of different cooling techniques on performance enhancement of electrical efficiency of PV panel

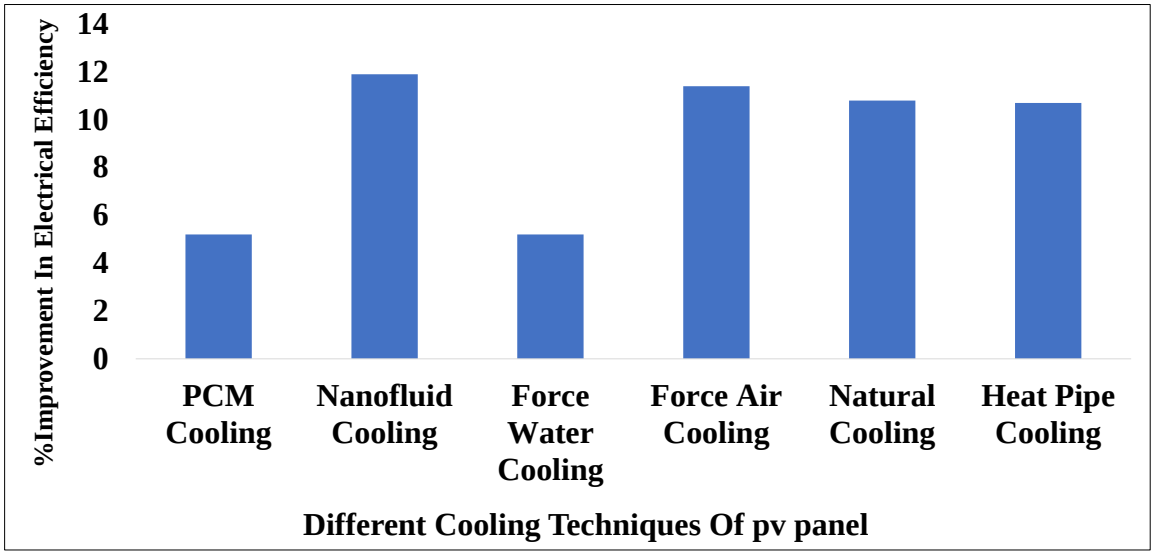


Figure 5 Improvement in Electrical Efficiency

The Figure 5. illustrates the percentage increase in electrical efficiency of photovoltaic panels employing various cooling strategies. Nanofluid cooling shows the highest improvement in efficiency among the cooling methods (11.9%), followed by forced air cooling (11.4%), natural cooling (10.8%), and heat pipe cooling (10.7%). PCM cooling Recover Abs FWC These 14.9% and 23.1% improvements are the highest whereas those for PCM cooling and forced water cooling are the lowest, both with 5.2%. This comparison also reveals that advanced techniques such as nanofluids and forced air markedly improve PV output, while PCM and water-based methods provide moderate enhancement.

1.6. Effect of different cooling techniques on performance enhancement of thermal efficiency of PV panel

The Figure 6. presents the effect of different cooling media on the thermal efficiency improvement of photovoltaic systems. PCM cooling achieves the highest enhancement with 72.6% improvement, followed by nanofluid cooling (67.0%), forced water cooling (61.5%), forced air cooling (55.2%), and heat pipe cooling (52.1%), while natural cooling shows no improvement (0.0%). The results indicate that phase change materials and nanofluids are the most effective in dissipating heat and enhancing thermal efficiency, whereas natural cooling is ineffective. Overall, active and advanced cooling techniques significantly outperform passive approaches in maintaining lower panel temperatures and improving system performance.

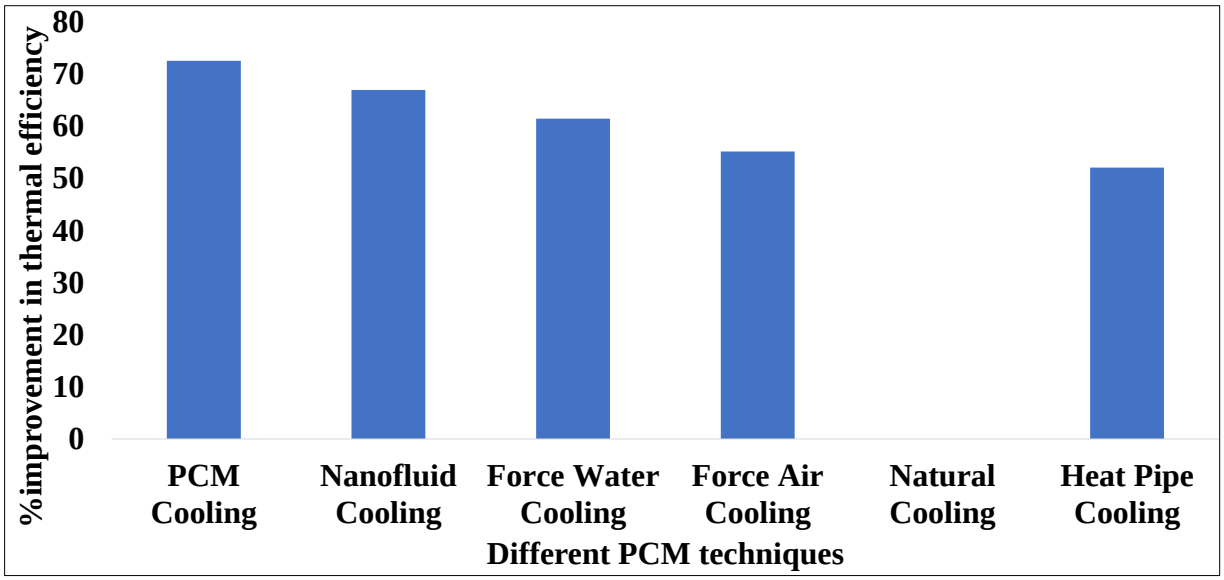


Figure 6 Improvement in thermal efficiency

2. Conclusion

In this paper, a review on the state of the art of Phase Change Materials (PCMs) and other cooling techniques applied for (PV) systems is introduced. This paper summarizes various experimental results with simulations to evaluate the efficiency mitigation of various thermal management techniques including nanofluids, forced air, forced water, heat pipes, and natural cooling against temperature-induced losses. The findings show that PCMs offer the best materials for performance enhancement of thermal efficiency (upto 72.6%) and that nanofluids and forced air cooling produce the best improvements for electricity outputs of upto 11.9% and 11.4%, respectively. The scope of the paper also contrasts the PCM applications in different engineering fields, e.g., battery thermal management, thermal energy storage, and building cooling, providing a benchmarking for knowledge. The results emphasize the potential of hybrid schemes employing the merits of active and passive cooling for improved performance of PV systems in hot climates. Integration of PCMs as part of active cooling methods looks very promising for the optimum compromise between an immediate increase in efficiency and thermally stable performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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