Trending applications of Phase Change Materials in sustainable thermal engineering: An up-to-date review

Original
Trending applications of Phase Change Materials in sustainable thermal engineering: An up-to-date review / Morciano, M., Fasano, M., Chiavazzo, E., Mongibello, L.. - In: ENERGY CONVERSION AND MANAGEMENT. X. - ISSN 2590-1745. - 25:(2025). [10.1016/j.ecmx.2024.100862]

Publisher:
ELSEVIER

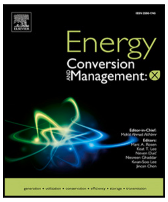
Published
DOI:10.1016/j.ecmx.2024.100862

Energy Conversion and Management: X 25 (2025) 100862

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x



Trending applications of Phase Change Materials in sustainable thermal engineering: An up-to-date review

Matteo Morciano [a,b,*], Matteo Fasano [a,b], Eliodoro Chiavazzo [a,b], Luigi Mongibello [c,*]

[a] Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] Clean Water Center, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[c] Enea Portici, P.le Enrico Fermi, 1 - Località Granatello, 80055, Portici (Na), Italy

ARTICLE INFO

Keywords:
Phase change materials
Energy storage
Sustainable thermal management
Solar thermal energy
Smart textiles

ABSTRACT

The on-going search for increasingly sustainable and efficient thermal energy management across a wide range of sectors leads to continuous exploration of innovative solutions. In this context, phase change materials (PCMs) have emerged as key solutions for thermal energy storage and reuse, offering versatility in addressing contemporary energy challenges. Through this review, we offer a comprehensive critical analysis of the latest developments in PCMs-based technology and their emerging applications within energy systems. First, the conducted investigation highlights the most important drivers stimulating the use of PCMs, namely, the miniaturization of electronic devices, the fluctuating nature of renewable energy sources, and the urge to design smart buildings and textiles. Here, we therefore discuss the integration of PCMs into electronic systems characterized by high heat fluxes, lithium-ion batteries, solar energy systems (including photovoltaic, desalination systems), building materials and textiles to offer wearable solutions for enhanced thermal comfort. Outlining around 100 various cases, PCMs emerge as particularly suitable to ensure optimal operating temperature ranges, to extend lifespan of the devices and ultimately to improve overall system energy efficiency. Beyond potential, challenges such as material leakage, long-term durability, and cost-effectiveness are discussed. By focusing on literature post-2022, the proposed review aims to condense the latest numerical and experimental research findings, spotlight emerging trends, and identify challenges to promote broader and long-term adoption of PCM-based systems. By providing a holistic perspective on PCM applications, we emphasize their potential in achieving sustainable and efficient energy management and provide insights to encourage future cross-disciplinary research and innovation.

1. Introduction

The pursuit of sustainable and efficient thermal energy management across several sectors has positioned phase change materials (PCMs) as a versatile and effective strategy [1–4]. From electronics [5] to solar energy systems [5–7], buildings [8,9], and textile industries [10], the exploration and application of PCMs constantly experience significant progress.

In the field of electronics, the relentless march towards miniaturization and increased performance of devices, which leads to increased power density and heat generation, poses significant challenges to thermal management. Indeed, as electronic components become more compact and powerful, efficient heat dissipation increasingly emerges as one of the most critical factors for ensuring reliable operation and extended operating life. In this context, the use of PCMs offers a flexible and promising solution to improve the thermal performance of devices such as processors, graphics cards, and other electronic components [11,12]. The importance of proper thermal management also emerges in the field of lithium-ion batteries [13,14], which represent increasingly in-demand and fundamental technology in the modern era powering a wide array of applications from portable electronics to electric vehicles. Effective dissipation and regulation of heat generated during battery operation are once again crucial to ensuring battery safety, longevity, and stable performance. To this end, significant pressure has been exerted on traditional air-cooled packs [15,16], which constitute active management strategies. Over the past decades, passive (i.e., not requiring external energy input or mechanical devices to achieve thermal regulation) PCM-based strategies have played a major role in addressing the above critical issues [17–19]. PCMs have proven significantly more effective in maintaining optimal battery temperatures without the need for external systems [20]. The integration of

---

* Corresponding authors.
E-mail addresses: matteo.morciano@polito.it (M. Morciano), luigi.mongibello@enea.it (L. Mongibello).

https://doi.org/10.1016/j.ecmx.2024.100862
Received 13 November 2024; Received in revised form 18 December 2024; Accepted 26 December 2024

PCMs within battery systems offers indeed the potential to mitigate temperature-related issues such as overheating, thermal runaway [21], and capacity degradation, thereby enhancing battery reliability and efficiency [22]. Above all, PCMs are particularly effective during peak usage of these electronic devices, helping to avoid the over-sizing of conventional heat sinks. The first section of this review is therefore dedicated to the use of PCMs in electronic systems characterized by high heat flux (e.g. chipsets, CPUs, diodes), as well as, in the field of lithium-ion batteries. We comprehensively explore the principles behind PCM integration in electronics and the latest advances and innovations in this field. In particular, this review considers and compares the different thermal management strategies used (i.e., conventional active strategies based on air or liquid cooling, passive strategies based precisely on the use of PCMs, and hybrid strategies), the type of research conducted (numerical and/or experimental), and the different types of PCMs mostly employed.

Turning to the solar energy sector, it has seen significant advancements with the integration of PCMs into various technologies [23,24], including solar thermal collectors, photovoltaic (PV) systems, and hybrid configurations. PCMs may play an important role in enhancing heat transfer, stabilize temperature fluctuations, and improve system efficiency by storing excess thermal energy during high solar irradiation and releasing it during low or no solar input. This contributes to continuous operation, reduced thermal stress, extended equipment life, and lower maintenance costs. Particularly in solar desalination systems, increasingly proposed by the scientific community to address the growing global demand for fresh water and mitigate the challenge of water scarcity [25,26], PCMs ensure stable heat sources, mitigate productivity fluctuations, and enable component downsizing for cost-effective installations [27,28]. Recent research has focused on optimizing PCM selection, arrangement, and system design to maximize energy storage [29] and transfer efficiency [30] while reducing environmental impact. This section reviews key developments and challenges in integrating PCMs into solar energy systems, highlighting case studies that illustrate critical factors such as material choice, system configuration, and operational parameters.

Finally, beyond applications in electronics and solar, PCMs have also penetrated the fields of buildings and textiles [31,32]. The building industry is evolving rapidly in response to the global demand for energy-efficient and environmentally sustainable buildings. Among the myriad technologies aimed at enhancing the performance of building envelopes [33], the latter infused with PCMs offer the promise of innovative and energy-efficient structures, capable of responding dynamically to environmental conditions. This feature offers a plethora of advantages, including reduced energy consumption, enhanced occupants comfort, and decreased greenhouse gas emissions [34,35]. Research is still ongoing to develop new PCM compositions, mainly with higher cycling stability and environment-friendly. Several research projects and initiatives worldwide have demonstrated the practical implementation of PCM technology in buildings to increase energy efficiency, improve thermal comfort and reduce dependency on traditional heating and cooling systems. This topic will be addressed in the third section [36].

As far as the textile field is concerned, several studies also involve the use of PCMs to improve the thermal comfort of garments and other textile products. PCMs used in textiles are typically micro-encapsulated within the fibers or introduced through a fabric coating. Incorporating PCMs into fabrics offers several advantages: (i) temperature regulation and increased comfort: PCMs help maintain a comfortable temperature by absorbing excess heat or releasing accumulated heat when needed, reducing temperature fluctuations; (ii) energy savings: by reducing the need for external heating or cooling, PCM fabrics can help save energy and reduce dependence on climate control systems. In the last section of this work, we therefore discuss the most recent developments and applications of PCMs in textiles.

2. PCMs for the management and storage of thermal energy in electronic systems

2.1. Thermal management of processors and other electronic heat sources

Numerical studies. In 2023, a study focused on the investigation and optimization of a metal foam PCM-based heat sink for thermal management of electronic devices was proposed [37]. The thermal power generated was considered equal to 4 kW m^{-2}. Several design parameters, including PCM types (RT31, RT42, and RT55), metal foam porosities (85%, 90%, and 95%), and metal foam materials, were systematically studied to figure out the optimal heat sink parameters across critical temperatures of 40 °C, 50 °C, 60 °C, and 70 °C. Employing the volume-averaged method and a thermal non-equilibrium model, the study simulated heat transfer, phase change, and fluid flow within the heat sink unit, which is schematically represented in Fig. 1. Notably, metal foam integration proved beneficial for enhancing the thermal performance of heat sinks, with PCM types exerting a substantial influence on their efficacy. For instance, heat sinks with RT31 demonstrated a five-fold increase in maximum operating time compared to those with RT55 at a critical temperature of 40 °C. The investigation identified optimal design configurations, emphasizing the importance of PCM type selection, with RT31 and aluminum foam showcasing superior thermal management efficiency across critical temperatures. Despite these promising results, the optimization results also highlight a limitation: while increased porosity improves heat transfer, it can compromise structural integrity or lead to reduced thermal contact with the heat source. This may suggest the need for a more finely-tuned balance in the design criteria of these systems. Moreover, experimental validation of the model used remains crucial to investigate real-world applicability, particularly in the presence of dynamic and variable thermal loads. Future research should aim to experimentally validate these results to assess their practical feasibility.

In the same year, another numerical study [38] focused on addressing the instantaneous thermal shock experienced by electronic devices subjected to transient heat flux through the design of a novel passive PCM-based heat sink, which is represented in Fig. 2. The study systematically explored the thermal control performance, considering maximum temperature reduction, PCM liquid volume fraction, energy storage rate, natural convection heat transfer, and temperature control efficiency. Results indicate that compared to a heat sink without PCM, the PCM-based counterpart can achieve approximately a 10 K reduction in maximum temperature. A key feature of the optimal design was the effective utilization of a fin-filling strategy, in which PCM fills regions around the heat sink fins (see Fig. 2). Analysis revealed that this configuration controlled heat distribution more effectively than conventional heat sink designs. Moreover, findings suggested that PCM-filling width plays a pivotal role in transient performance, with a dimensionless filling width (i.e., $\frac{b}{D}$, being b and D represented in Fig. 2) of 0.3 demonstrating the best thermal management response. These findings provide actionable insights into design strategies, particularly for transient thermal events. Although the study provided valuable guidelines, factors such as PCM aging and material degradation under prolonged use require further exploration to ensure long-term reliability.

These numerical studies reveal how the coupling between PCMs and heat sinks may be prone to continuous refinement by leveraging a myriad of different conceivable configurations obtained by mixing different types of PCMs (organic, inorganic, nano-PCMs, composite) and fins. The studies are therefore intended to provide guidance for the design and development of efficient PCM-based heat sinks. However, it is worth mentioning how these studies also highlight the presence of critical gaps. Most notably, while numerical models effectively capture phase change phenomena and thermal performance, they often simplify practical conditions, such as localized hot spots or non-uniform heat generation, which may limit their direct application. Further integration of computational and experimental approaches is necessary to refine these designs and enhance their robustness.

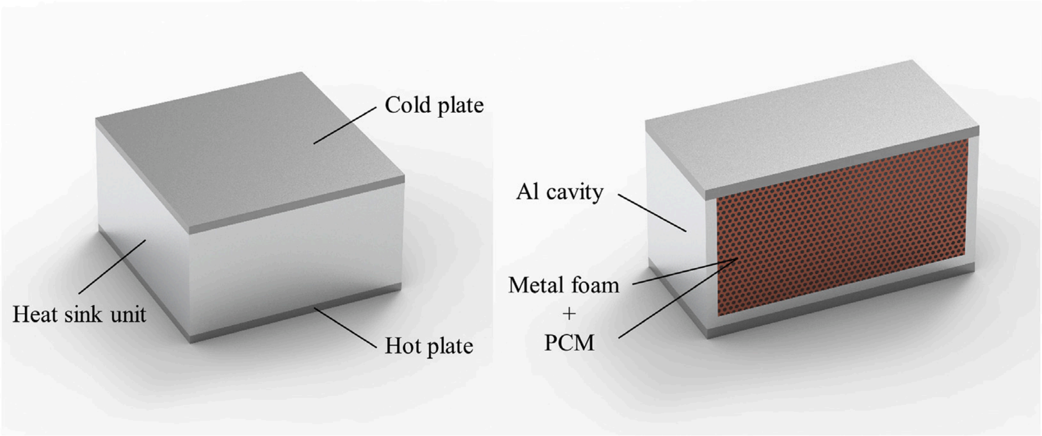


Fig. 1. Thermal control module of the electronic component (a) schematic and (b) section drawing.
Source: Picture taken from Ref. [37], with permission.

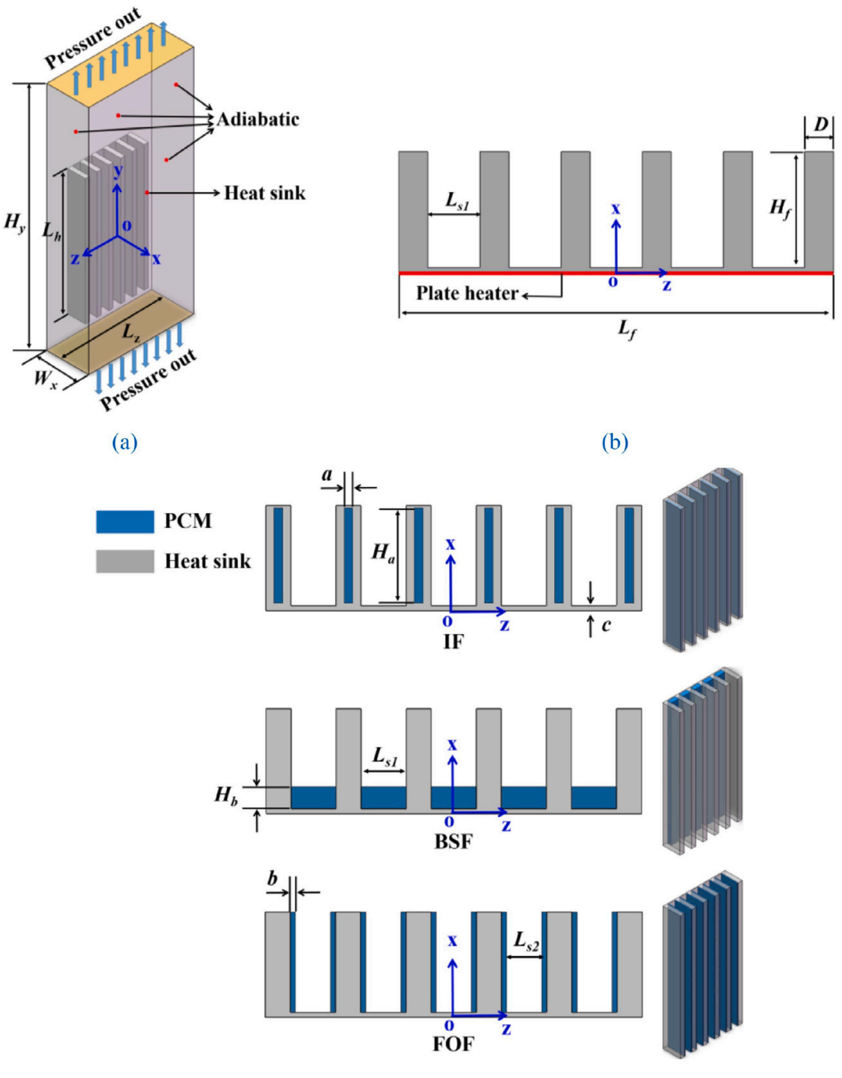


Fig. 2. Schematic of the computational domain. (a) Illustration of the application; (b) top view of the heat sink; (c) scheme of heat sink PCM-based (IF: Inside filling; BSF: Bottom surface filling; FOF: Fin outside filing).
Source: Picture taken from Ref. [38], with permission.

Experimental studies. Experimental studies have demonstrated that PCM-based heat sinks can successfully mitigate high heat fluxes, but they also highlight areas requiring further optimization and exploration. In one recent study, authors fabricated and proposed an innovative passive module for electronic chipset cooling with high heat fluxes ranging from 2 to 4 kW m^{-2} [39]. In detail, the research addressed the most representative issues encountered in conventional passive PCM-based heat sinks, including leakage, corrosion, and low thermal conductivity of PCM. The cooling module integrates a conventional heat sink with a thermal storage unit filled with PCM and nano-additive PCM (NPCM). Horizontal circular copper fins connect the two components, ensuring indirect contact between PCM/NPCM and the heat sink. The study employed image processing to visualize and assess the melting behavior of PCM and NPCM. Results demonstrated that the innovative cooling module significantly reduced steady-state and transient temperatures (by approximately 7 °C and 12 °C, respectively) compared to conventional cooling systems. The inclusion of pure PCM and NPCM, especially ZnO-PCM, further enhanced thermal management. The higher volume fraction of PCM contributed to lower transient and steady-state temperatures and higher efficiency, with substantial effects at lower heat fluxes. However, challenges such as nanoparticle agglomeration and potential long-term compatibility with the heat sink material remain unaddressed. These issues are critical for ensuring the durability and scalability of such systems in practical applications.

A seminal experimental study [40] examined the effect of micro-encapsulated PCM suspension (MPCMS) on the thermal management of Light Emitting Diodes (LEDs) within a Thermoelectric Cooler-Microchannel Heat Sink (TEC-MHS) system. The research explored the morphology, phase-change and thermophysical properties of MPCMS, aiming to enhance the cooling capacity with respect to systems that use water as coolant. Experimental results revealed that the TEC-MHS system employing MPCMS as a coolant outperforms the system using water, demonstrating improved LED cooling. The study interestingly introduced a dimensionless thermophysical factor to assess the influence of MPCMS concentration on cooling performance. The conclusions emphasized the adaptability of the microchannel heat sink with MPCMS for high-power TEC (i.e., up to ≈ 30 kW m^{-1}).

In another noteworthy investigation, authors [41] equipped a thermoelectric generator (TEG) with a PCM to stabilize the output power for unsteady heat sources, such as electronic chips. A schematic of the experimental setup is reported in Fig. 3. In detail, researchers combined a vanadium dioxide (VO_2) sintered body, representing a solid–solid PCM, with the TEG, comparing its performance with conventional solid–liquid PCM paraffin. The TEG with VO_2 demonstrated superior power generation and output power leveling, attributed to its higher thermal conductivity compared to paraffin. The on-chip TEG-PCM system with VO_2 effectively leveled the temperature of the electronic chip while generating electricity, resulting in a 14.4 °C reduction in the maximum chip temperature compared to the scenario without PCM. Authors suggested further research to optimize the size and conditions for solid–solid PCM, evaluate durability under temperature cycling, and explore cost-effective alternatives to maximize the benefits of this innovative approach. Indeed, while VO_2 exhibited high thermal conductivity, its high cost and limited availability pose significant barriers to widespread adoption. Exploring cost-effective solid–solid PCMs with similar properties would enhance the practicality of this approach.

The potential of solid–solid PCM applications in the field of electronic cooling was also explored using Neopentyl Glycol (NPG) (phase transition between 40 °C and 48 °C) in combination with heat pipe-assisted heat sinks under forced air cooling [42]. Experimental and numerical results confirmed that integrating heat pipes with solid–solid PCM achieved enhanced heat transfer rates and improved thermal response during both charge and discharge periods. This configuration outperformed other heat sink designs, demonstrating the promise of combining heat pipes and solid–solid PCM for efficient cooling under variable operating conditions. The study also noted that enhanced heat transfer at the condenser section and incorporation of conductive particles could further optimize the system. This highlights the need for multi-faceted improvements to fully leverage solid–solid PCMs in electronic cooling applications.

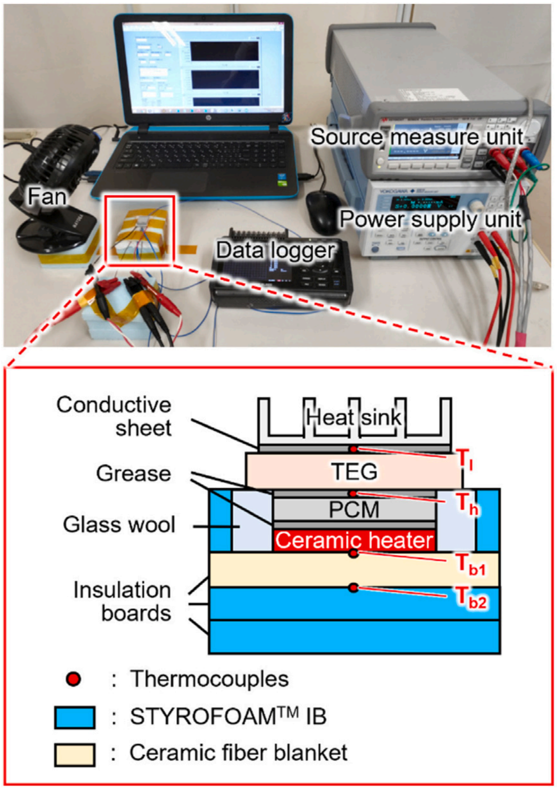


Fig. 3. Experimental setup for on-chip TEG-PCM.
Source: Picture taken from Ref. [41], with permission.

Still, an interesting application was recently explored by Mao and co-workers [43]. In response to the increasing adoption of “more- and all-electric aircraft” driven by the prevalence of airborne electromagnetic actuators such as permanent magnet synchronous machines (PMSMs), authors introduced a novel PCM-based thermal protection strategy for enhancing the thermal management of PMSMs [43]. Two equivalent PMSMs were employed to experimentally validate the proposed PCM-based cooling scheme using commercial wax. Comparative analysis revealed a significant reduction in machine temperature under various operating conditions, with a maximum temperature drop of 13.7 °C. The study further explored the relationship between the utilized PCM and the cooling working mode, introducing a dimensionless correlation to predict temperature peak differences. The study concludes by emphasizing the compatibility of the PCM-based cooling strategy for PMSMs in aircraft applications, proposing future investigations to validate and refine the results presented. Further investigations on non-commercial high-efficiency PCMs tailored for cooling PMSMs could prove very interesting and enrich the state of the art.

The combination of eutectic gallium-indium liquid metal with PCM capsules represents another recent advancement [44]. This composite demonstrated high thermal conductivity and scalability, achieving a 414.3% increase in full-load operating time for CPU cooling (see Fig. 4) compared to conventional designs (i.e., pin-fin heat-sink). The inclusion of liquid metal enhanced thermal buffering performance, reduced temperature differences under operational changes, and led to a 23% energy saving. The authors also suggest future research to explore further applications and optimizations of the proposed innovative PCM-LM composite. Although these results are promising, even in this study, the long-term stability of the PCM-LM composite under cyclic loading

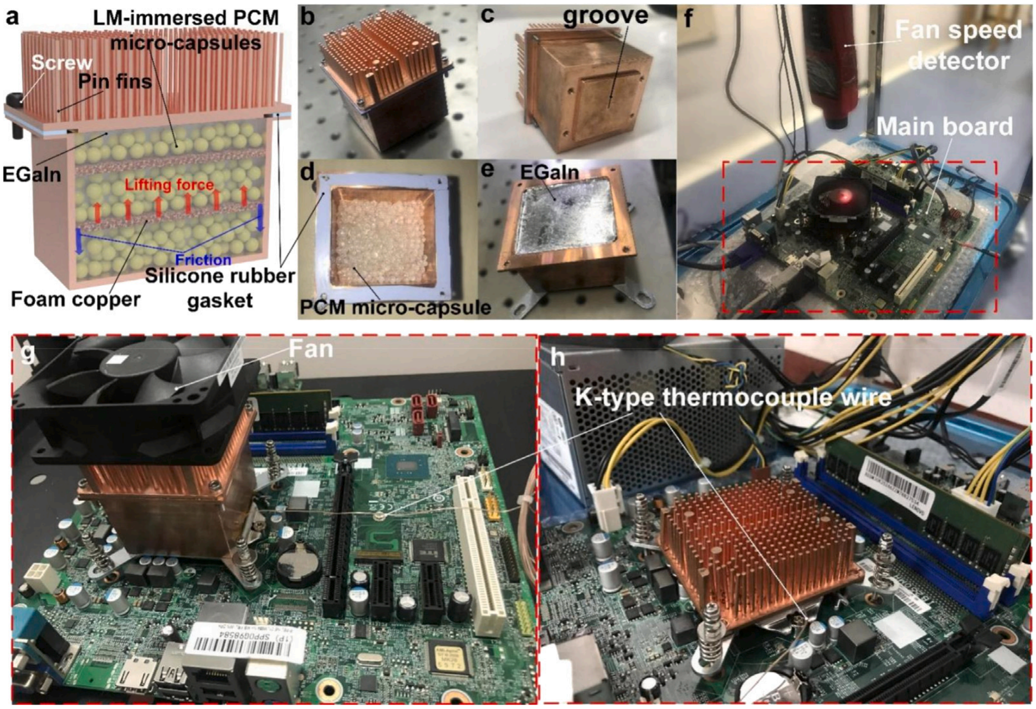


Fig. 4. Experimental setup. (a) Schematic view of the LM-PCM-filled heat mitigator. (b) Photographic view of the heat mitigator. (c) Bottom surface of the heat mitigator. (d) Semi-filled heat mitigator without EGaIn LM. (e) Fully-filled heat mitigator. (f) CPU heat dissipation using pin fin heat sink and fan. (g) CPU heat dissipation using heat mitigator and fan. (h) CPU heat dissipation using pin fin heat sink.
Source: Picture taken from Ref. [44], with permission.

is lacking. This remains a critical recurring area to be studied in the future.

Interestingly, an approach to control the position of the melting front of PCM using pressure-enhanced close-contact melting (CCM), proposed in 2022 by Fu and co-workers [45], was adopted in 2023 [46] for thermal management in high heat flux electronic devices (see Fig. Fig. 5). The conventional PCM-based heat sink and a metal foam-enhanced PCM heat sink were compared with the pressure-enhanced CCM method using paraffin and low melting point alloy. The pressure-enhanced method effectively limited the movement of the melt front, achieving stable temperature control for electronic devices operating under high heat flux (here up to 10 kW m^{-2}). The results demonstrated that the surface temperature of the heat source can be stabilized around the melting point of PCM, and the thermal resistance is minimized to less than 10^{-4} K m^2 W^{-1} at an applied piston pressure of 2250 Pa. This method proved to be superior to conventional PCM heat sinks, where the enhancement in thermal conductivity diminishes over time due to increasing liquid film thickness. The study emphasizes the significance of applied pressures and heat loads on achieving stable controlled temperature and suggests further analysis of thermal properties and in-depth research on liquid–solid heterogeneous interfaces for comprehensive understanding. The focus of the study on paraffin limits its applicability to more demanding systems, highlighting the need for broader material testing.

Another research [47] focused on enhancing heat transfer in paraffin wax by incorporating multilayer graphene (MLG) at different mass fractions (0–10 wt%), aiming to improve thermal buffering in electronic applications. The MLG, obtained through supercritical fluid exfoliation of graphite in alcohol, demonstrated interesting morphological features, indicating close contact between paraffin and graphene. Thermal properties, including phase change transition temperatures, latent heat, and thermal conductivity, were extensively studied. Although a slight decrease in energy storage capacity was observed with graphene addition, a remarkable 150% improvement in thermal conductivity was achieved at the highest graphene loading. The composite was applied as heat sink for an embedded electronic processor, and results indicated a significant reduction in processor operating temperature (up to 20%) with graphene content exceeding 5 wt%.

In 2024, recent analysis [48] of natural convection suppression in liquid PCM embedded in porous media revealed further opportunities for thermal optimization. Using metal foam skeletons or anisotropic carbon foams reduced the temperature of the heat source by delaying natural convection onset and altering the melting front behavior. Anisotropic foams were found to demonstrate directionality in heat transfer properties, emphasizing the need to strategically align these structures to heat sources for optimized thermal management. These insights represent a promising design strategy for applications in next-generation electronics where transient heat dissipation is critical.

Summarizing, the integration of PCMs into electronic systems, ranging from high-performance computing devices to more-electric aircraft components, may represent a good solution to address the thermal challenges associated with the miniaturization and increased performance of such components. The integration of PCMs, whether through innovative heat sink designs, enhancement with metal foams, or the development of composite materials, have demonstrated potential towards enhanced thermal performance and operational longevity of electronic devices. The achievements highlighted across these studies include the optimization of PCM-based heat sinks for effective heat dissipation in high-performance computing environments, the successful application of PCMs in managing transient thermal shocks, and the novel use of PCM composites for cooling CPUs and other high heat flux electronic devices. Notably, the exploration of solid–solid PCMs and the incorporation of nano-additives and metal foams have opened new avenues for enhancing the thermal conductivity and phase change behavior of PCMs, thereby improving their overall performance in thermal management applications. Looking to the future, several promising research lines have been identified. These include further exploration of bio-based and environment-friendly PCMs for sustainable thermal management, advancements in composite PCMs integrating high thermal conductivity materials, refining the integration processes

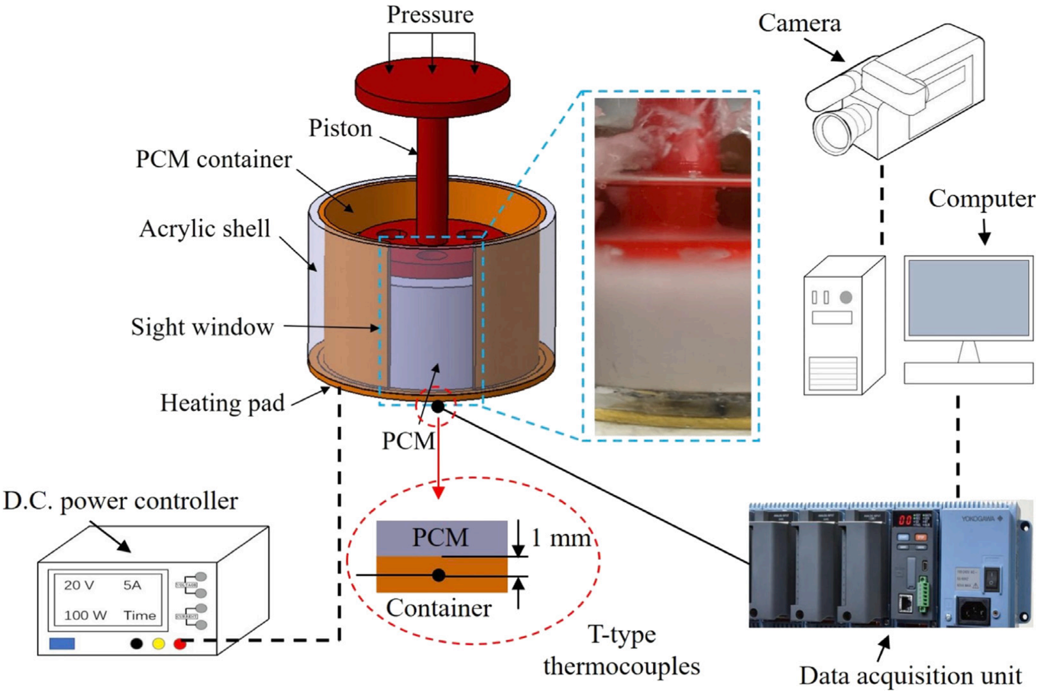


Fig. 5. Schematic of the experimental setup. The PCM container for the experimental test section is made of copper and shows cylindrical structure with the inner diameter of 70 mm and the height of 60 mm. A sight window with the width of 20 mm is designed on the side of the container to visualize the PCM melting process. An acrylic cylinder is covered on the outside of the PCM container to encapsulate the sight window and minimize heat loss. The heating pad (Polyimide heater) with diameter of 70 mm is fixed at the bottom of the PCM container. The heat load of the heating pad can be set to constant values by using a D.C. power controller. The pressure exerted on the solid PCM is provided by the piston, which is coupled to the electro-mechanical actuator.
Source: Picture taken from Ref. [46], with permission.

for electronic devices, and development of more sophisticated modeling and simulation techniques to predict PCM behavior in complex electronic systems accurately. As electronic devices continue to evolve in complexity and performance, the role of PCMs in thermal management will undoubtedly expand, offering exciting opportunities for future research and technological innovations (see Fig. 5).

2.2. Thermal management of lithium-ion batteries

Numerical studies. A comprehensive numerical investigation [49] into the thermal behavior of nano-enhanced PCMs within a circular enclosure housing lithium-ion battery packs (LIBPs) has revealed promising opportunities for advanced thermal management (see Fig. 6). Specifically, graphene nanoparticles were incorporated into $CaCl_2 \cdot 6\ H_2O$ PCM to assess the impact of nanoparticle inclusion on phase change dynamics. Simulation analyses showed that varying blade length influenced both the melting and freezing processes of nano-PCMs under steady conditions with constant thermal loads from the batteries. Findings indicated that introducing nanoparticles enhanced phase-change behavior, with specific blade length configurations optimizing heat dissipation during critical operational periods.

Similarly, finite element method-based simulations [50] of PCM-filled packages within the LIBP were employed, investigating key parameters such as maximum temperature, minimum temperature, and the volume fraction of molten PCM under varying charge and discharge rates (1c, 1.5c, 2c) in transient conditions. Remarkably, even in the most challenging scenario, the maximum temperature did not exceed 325 K within the proposed thermal management system, highlighting its effectiveness in preventing overheating. However, it is worth noting that these numerical results depend heavily on idealized thermal properties and boundary conditions, which must be experimentally validated for practical implementation.

The numerical exploration of these phenomena provides key insights into how PCM distributions, nanoparticle loadings, and system geometry influence the operational stability of thermal management strategies. While the numerical results emphasize the potential of nano-enhanced systems and optimized thermal configurations, future work should explore multi-physics phenomena (e.g., fluid dynamics and phase transitions) under real-world battery cycling conditions to fully capture operational behaviors.

Experimental studies. Among the most recent experimental works, it is worth mentioning that proposed by Wang and co-workers [52]. Authors investigated the charge–discharge performance of lithium-ion batteries and established the critical temperature thresholds for heat preservation and preheating processes. The researchers developed graphite powder/paraffin composite PCM and a more advanced graphite powder/paraffin/nickel foam ternary composite PCM with optimized compositions. A comprehensive thermal management experiment involving large-capacity rectangular lithium iron phosphate batteries spanning a wide range of climatic conditions was conducted. The performance of different thermal management modes, including (conventional) air natural convection, paraffin, graphite powder/paraffin composite, and graphite powder/paraffin/nickel foam ternary composite, was compared. The findings demonstrated that both the binary and ternary composite PCMs effectively control battery surface temperature, ensuring it remains above 0 °C for extended periods in extremely cold environments (−20 °C). However, the ternary composite exhibits superior temperature homogeneity in both high (40 °C) and low-temperature (−20 °C) conditions, making it a promising choice for advanced thermal management systems for lithium-ion batteries.

In the same year, a recent study [51] addressed the need for a detailed comparison and reliability validation of paraffin-based optimization methods for lithium-ion battery thermal management systems. A paraffin was chosen as PCM, and two optimization approaches were explored: one involving expanded graphite (EG) and the other using fins (see Fig. 7). Experiments comparing thermal properties before and after cycling cycles show that these composite systems maintain performance over repeated charge–discharge events. Of particular interest

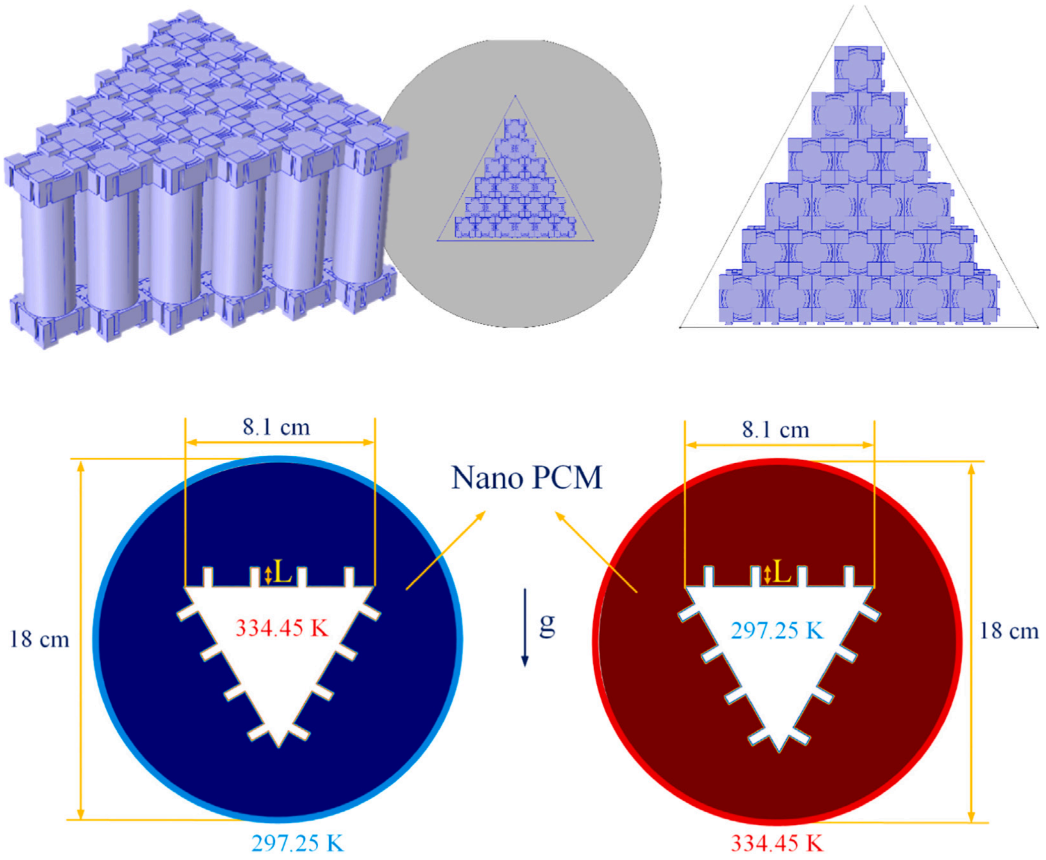


Fig. 6. Schematic of the geometry: charging mode (left) and discharging mode (right).
Source: Picture taken from Ref. [49], with permission.

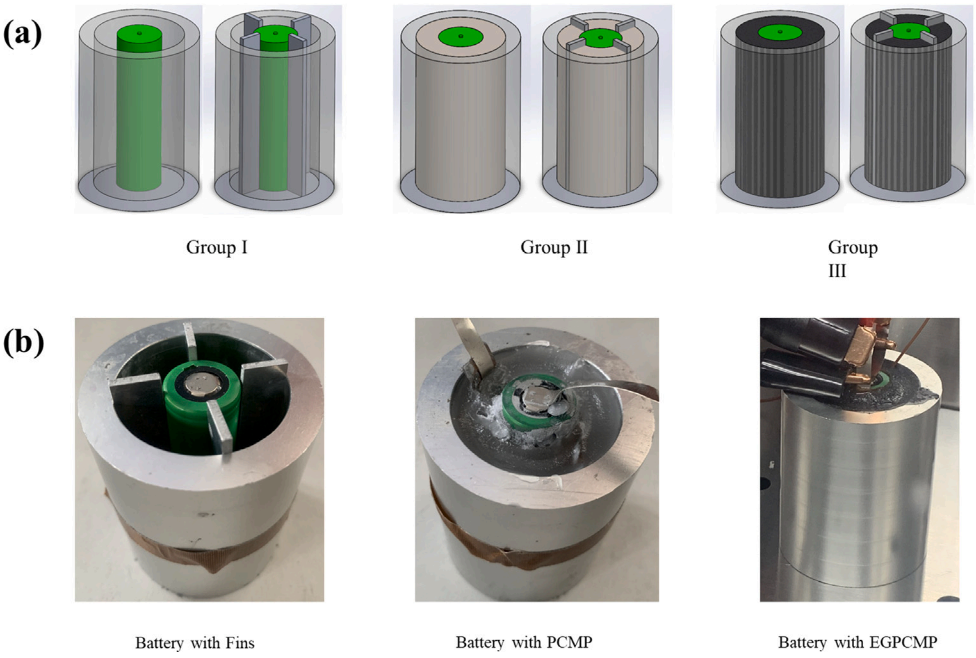


Fig. 7. (a) Sketch of the experimental group; (b) physical view of the group.
Source: Picture taken from Ref. [51], with permission.

is the 35.5% temperature reduction achieved when combining paraffin with expanded graphite and fin structures, demonstrating a synergistic effect between geometry and material design.

More recently, innovative studies have further explored hybrid strategies combining PCM with active cooling elements [53], such as liquid cooling or airflow-assisted cooling mechanisms. For instance,

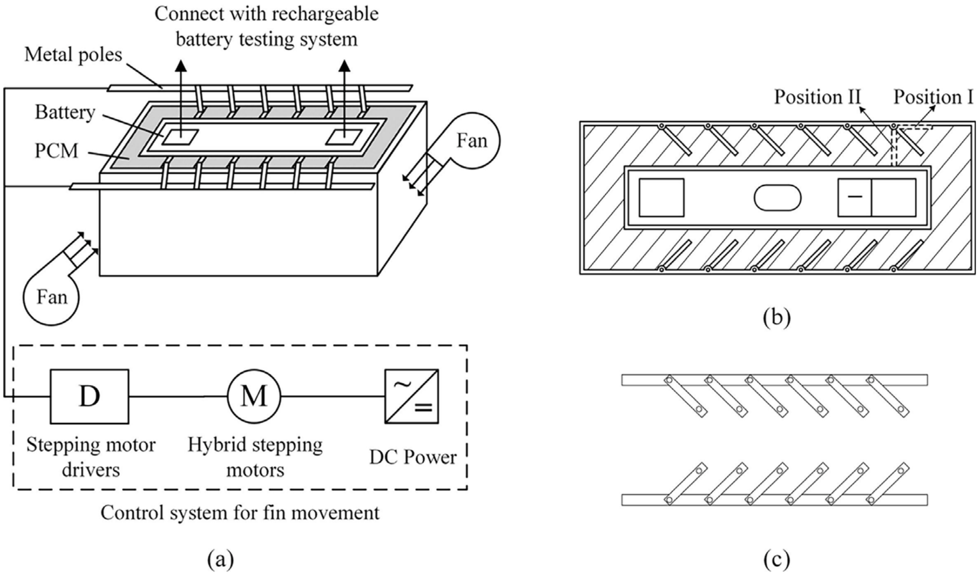


Fig. 8. Proposed PCM-based battery thermal management design with adjustable fins. (a) Design schematic; (b) Container with the battery, PCM and fins; (c) Two aluminum poles used to drive fins. Schematic of the geometry: charging mode (left) and discharging mode (right).
Source: Picture taken from Ref. [53], with permission.

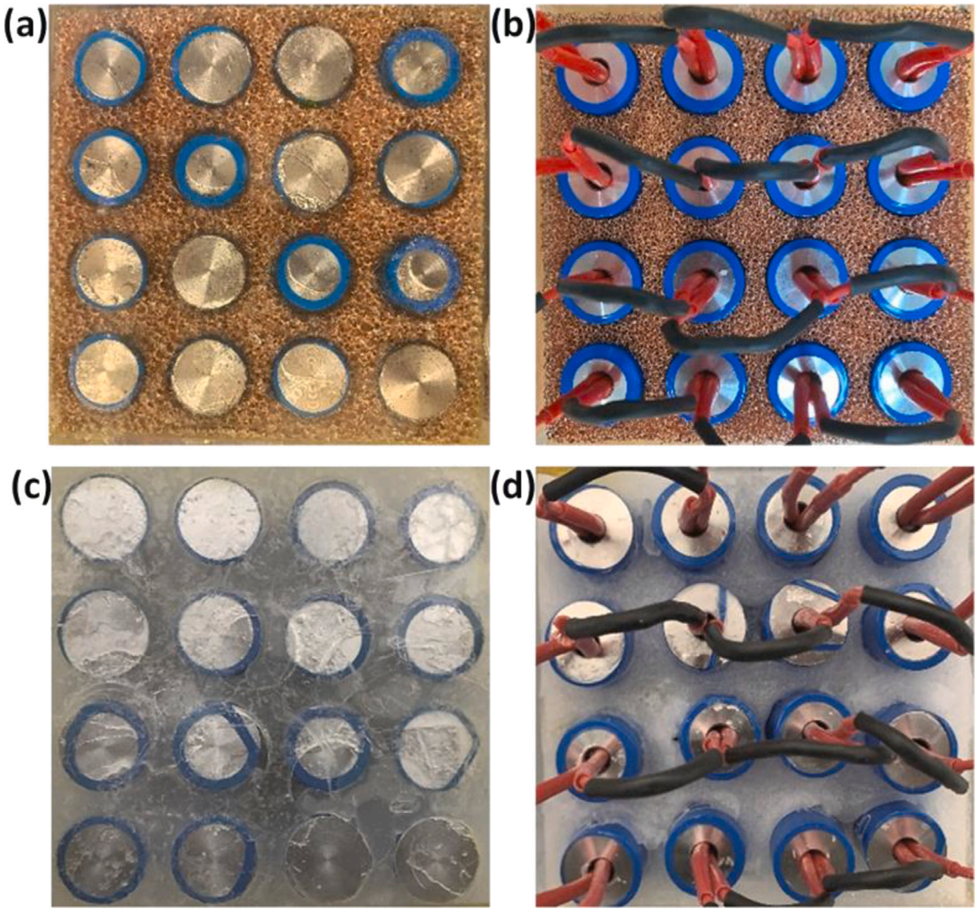


Fig. 9. Battery module with cooling material: (a) copper foam-PCM, bottom view; (b) copper foam-PCM, top view; (c) pure PCM, bottom view (d) pure PCM, top view.
Source: Picture taken from Ref. [54], with permission.

movable fin structures within PCM pools demonstrated effective forced convection during melting periods, maintaining operational temperatures below 40 °C during typical discharge conditions. The proposed PCM-based battery thermal management design with adjustable fins is represented in Fig. 8. These designs not only reduced maximum operating temperatures but also enhanced thermal uniformity across the system, offering a promising and cost-effective method for large-scale thermal management.

Another study published in 2023, explored the use of paraffin-based PCM embedded within copper foam to enhance heat dissipation. Comparative investigations were conducted to assess the thermal responses of a battery module under different thermal management solutions, including natural air, pure PCM, and copper foam-PCM. The battery module, consisting of 16 thermal dummy cells (TDC), designed to replace commercial 21,700 NMC battery cells, is represented in Fig. 9. The results demonstrated that such systems reduced peak temperature responses by up to 10.4%, achieving a significant improvement in thermal stability. Furthermore, these composite solutions optimized cell-to-pack ratios, addressing both performance and packaging efficiency challenges for large-format battery systems.

Several other advanced composite strategies integrating unique nanomaterials such as boron nitride, silicone gel and carbon nanotubes have been explored [55]. This composite leveraged the high latent heat of PCM combined with the heat-conductive properties of silicone gel as a thermal interface material. These materials demonstrated enhanced heat conduction properties while maintaining key features like anti-leakage and flexibility, thus addressing multiple performance metrics simultaneously. Experimental observations suggest that these composites can reduce operational peak temperatures during intense thermal cycling, highlighting their potential for next-generation battery thermal management designs.

Several other advanced composite strategies have been proposed. For instance, a novel composite material composed of a paraffin, carbon nanotube, boron nitride, and silicone gel was introduced in 2023 [55]. This composite leveraged the high latent heat of PCM combined with the heat-conductive properties of silicone gel as a thermal interface material. Notably, this composite material offered several advantages, including anti-leakage, mechanical flexibility, re-ignition resistance, and impressive waterproofing capabilities. Experimental observations suggest that these composites can reduce operational peak temperatures during intense thermal cycling, surpassing the performance of modules without composite material, highlighting their potential for next-generation battery thermal management designs. Another paper on composite [56] addressed the limitations such as rigidity, assembly challenges, high thermal resistance, low thermal conductivity, and potential leakage. The study introduced a novel flexible composite PCM designed to overcome these issues effectively. The composite PCM was obtained by combining a thermoplastic styrene-based polymer (TPS) as a support material, paraffin as the PCM, and expanded graphite as a thermally conductive filler. The results revealed that this composite exhibits excellent flexibility and extensibility at room temperature while maintaining shape stability at high temperatures and under pressure. The contact thermal resistance of the composite PCM was significantly lower than that of similar materials, making it highly efficient for thermal management. Experiments conducted on both single batteries and square battery modules demonstrated that the composite PCM thermal management system can effectively reduce battery module temperatures.

Recent experimental study [57] focused instead on the approach of coupling PCMs with liquid cooling technology. Micro-encapsulated PCM (MPCM) was developed to create MPCM slurry (MPCMS), and various base liquids were evaluated, with silicone oil proving to offer the best stability without sedimentation over a seven-day period. Furthermore, graphene (GE) was incorporated into the slurry to enhance its heat transfer properties. The results demonstrated that increasing the MPCM concentration in the slurry led to improvements in latent heat, thermal conductivity, and specific heat capacity. Remarkably, the viscosity of the slurry remained relatively stable at concentrations below 40 wt%. When applied to a prismatic lithium-ion battery module, the GE-MPCMS-Si slurry effectively reduced the temperature and its variation of the battery module. Additionally, the study investigated the impact of coolant flow rate with the aim of determining the most economical and efficient option.

Furthermore, innovative approaches employing hybrid thermal management strategies combining composite PCM and liquid cooling showed superior performance under challenging thermal loads. For example, an interesting study [58] found that this hybrid approach could reduce maximum operational temperatures by nearly 5 °C, even at high discharge rates and ambient temperature extremes. The optimal parameters influencing this hybrid system's performance include composite PCM thickness and ambient conditions, with simulations and experiments pointing to 4 mm as an effective thickness that maximized thermal dissipation while minimizing system weight.

Finally, the development of composite PCMs leveraging advanced nanomaterials such as highly oriented N-doped carbon nanotubes derived from metal–organic frameworks has marked a significant advancement [59]. These composites demonstrated enhanced thermal conductivity (up to 197.47% higher than the base PCM) and excellent phase stability, retaining over 99.95% of their latent heat over numerous charge–discharge cycles. The composite PCM was successfully applied to create a flexible thin film for thermal management in lithium-ion batteries, reducing the maximum battery temperature by approximately 2 °C during charge–discharge cycles. These features support their viability as flexible thermal management solutions, especially for applications requiring consistent performance during repeated phase transitions under dynamic thermal loads.

The various types of PCMs developed and thus most proposed, the operating methods of thermal management (i.e., passive, active, or hybrid), the type of research conducted (i.e., numerical, experimental or hybrid), the main purpose (i.e., investigating thermal management — TM, cyclability — CYL, stability — STAB and flexibility — FLEX) behind the study leading to the integration of PCMs into the battery systems, and finally the year of publication of all the research papers discussed are well-organized for clarity in the Table 1.

In summary, the recent literature reveals an intensive effort within the research community. The most recent studies collectively emphasize the role of PCMs in mitigating the risks associated with overheating, thermal runaway, and capacity degradation, thereby enhancing the safety, efficiency, and longevity of lithium-ion batteries. A major achievement highlighted by the analysis is the development and optimization of PCM formulations and composites, tailored to operate within the optimal temperature ranges of lithium-ion batteries. These advancements include the incorporation of organic and inorganic PCMs, enhanced with nanomaterials such as graphene, to improve thermal conductivity and phase change behavior. Additionally, innovative designs combining PCMs with active and passive cooling strategies have been explored, demonstrating significant potential in achieving superior thermal management performance. In perspective, the field is expected to explore several promising research directions. Among others, the development of hybrid thermal management systems integrating PCM with other cooling technologies for more efficient and robust temperature control seems to be the most dynamic. Moreover, the application of computational modeling and machine learning to optimize PCM integration and performance in lithium-ion batteries may represent an exciting frontier for future investigations, potentially providing insights into PCM system design and operation under evolving thermal management needs.

3. PCMs in solar energy systems

3.1. PCMs in solar thermal collectors

Numerical studies. The successful use of passive PCMs in buildings depends on factors such as thermo-physical properties, material distribution and amount, and climate conditions, thus place where the building element is located, its typology and daily thermal cycle [61]. Tailored analyses are essential for effective application. Peralta et al. [61] investigated PCM integration into Massive Solar-Thermal Collectors (MSTCs), which are cement-based devices converting solar radiation

Table 1
Recent application of PCMs in lithium-ion batteries (LIBs) for thermal management (TM).

PCM type	Method	Research	Purpose	Year
Nano-enhanced salt hydrates	Pass	Num.	TM	2022 [49]
Organic (generic)	Pass	Num.	TM	2022 [50]
Paraffin-based composite	Act/Hyb	Exp.	TM	2022 [52]
Paraffin-based composite	Pass	Exp.	TM/RL	2022 [51]
Paraffin-based	Pass/Hyb	Exp.	TM	2023 [53]
Paraffin-based composite	Act/Pass	Exp.	TM	2023 [54]
Paraffin-based composite	Pass/Hyb	Exp.	TM/CYL/STAB	2023 [55]
Paraffin-based composite	Act/Pass	Exp.	TM/CYL/FLEX	2023 [56]
Paraffin-based composite	Hyb	Exp.	TM	2023 [57]
Paraffin-based composite	All	Num/Exp.	TM	2023 [58]
Paraffin-based composite	Pass	Exp.	TM/CYL/FLEX	2023 [59]

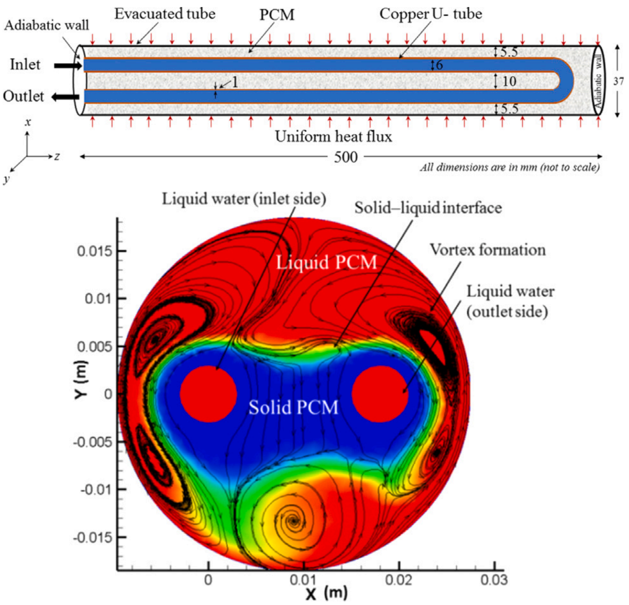


Fig. 10. Top: schematic diagram of the computational domain of the evacuated tube illustrating all the dimensions. Bottom: Contour of solid–liquid fraction with streamline for the paraffin wax across a plane drawn at z = 250 mm.
Source: Picture taken from Ref. [60], with permission.

into thermal energy. Numerical simulations assessed the performance of MSTCs in two locations with distinct climates: Sauce Viejo (Argentina) and Frankfurt am Main (Germany). The study included a parametric analysis of cement-based absorbing materials to optimize energy efficiency. Results highlighted that correct PCM incorporation can enhance MSTC performance, with maximum improvements of 38.9% in warm climates and 27.4% in cold climates, identifying optimal melting temperatures of 34 °C and 53 °C. Conversely, improper PCM use hindered performance. The findings suggest consistent efficacy across diverse weather conditions, with superior performance observed in Sauce Viejo's warmer climate.

More recently, a multi-objective optimization approach was adopted [62] to improve solar thermal collector performance and PCM utilization for hot water production [63]. Unlike prior studies that optimized collectors or PCM independently, this research employed a multi-objective evolutionary algorithm, focusing on energy discharge time and stored energy. Simulation outcomes revealed a trade-off between these objectives, influenced by parameters such as PCM mass and water mass flow rate. Notably, minimizing PCM mass while increasing water flow rate enhanced performance. Additionally, the study examined tube diameter variations within the collector system, identifying a nonlinear relationship with discharge time, where larger diameters extended the discharge period. Various PCM materials, including hybrid salts and fatty acids, were also evaluated, providing insights into their effects on stored energy and discharge dynamics.

Further, the integration of PCMs into evacuated tube solar collector was numerically explored by Uniyal and co-workers [60]. Author employed three-dimensional computational fluid dynamics simulations to investigate the performance of the aforementioned solar system integrated with different PCMs: lauric acid, paraffin wax, and stearic acid. The simulations, conducted using a copper U-tube-based collector, considered varying solar radiation conditions. A schematic of the simulated system is reported in Fig. 10. The research compared the heat transfer rates and melting characteristics of the three PCMs, revealing distinct behaviors influenced by their physical properties and the evolution of natural convection currents and vortexes within the collector. Lauric acid exhibited faster liquefaction, making it preferable in locations with lower solar radiation. The study also analyzed the impact of heat transfer fluid flow rates on the outlet temperature and melting processes of the PCMs. Key findings highlight the significance of natural convective currents in PCM melting and indicate that lauric acid absorbs 25.09% more total energy than stearic acid during the considered time period.

Experimental studies. In the field of solar water heating systems, Pawar and co-workers [64] explored the enhancement of heat pipe evacuated tube solar collectors (HPETCs) by integrating PCM with copper porous metal. The schematic of different configurations of the proposed system is represented in Fig. 11. The performance of this novel system was experimentally compared to a conventional HPETC system under similar conditions, revealing significant improvements. The integrated PCM + copper porous metal system achieved a peak temperature increase of nearly 21 °C during maximum solar radiation, showcasing its efficacy in enhancing heat transfer capability. After sunset, the proposed system demonstrated a substantial temperature difference of 36.1 °C compared to the conventional system. Additionally, the proposed system exhibited a maximum water outlet temperature difference of 11 °C, contributing to enhanced energy efficiency. The daily energy efficiency reached an impressive 85.64% for the proposed system, while the conventional system achieved a maximum of 36.91%. The integrated system also showed substantial savings in hot water production cost for different lifetimes and interest rates.

Whereas Prakash and co-workers [66] introduced a cost-effective design modification for flat plate solar thermal collectors, implementing a Step Serrated Fin Plate Integrated Trough Array (SSFPT) on the sun-facing side. This design concentrated heat on a PCM-filled copper pipe, achieving outlet temperatures between 44.5 and 74.5 °C, with energy and exergy efficiencies of 66.32% and 23.06%, respectively. Economic analysis indicated a cost per kWh of 0.10 USD, which is 0.18 USD lower than the conventional FPC SAH. The SSFPT collector proved to be a simple, efficient, and economically viable solution, with potential applications in solar drying of agricultural produce, benefiting economically weaker processes involved in farming. Further improvements could be explored through the introduction of nano-PCM for enhanced heat storage.

A novel self-storing design for an evacuated tube solar collector (ETSC), employing collector tubes filled with a PCM-metal foam (PCM-MF) composite was also introduced in the same year, see Ref. [65]. A

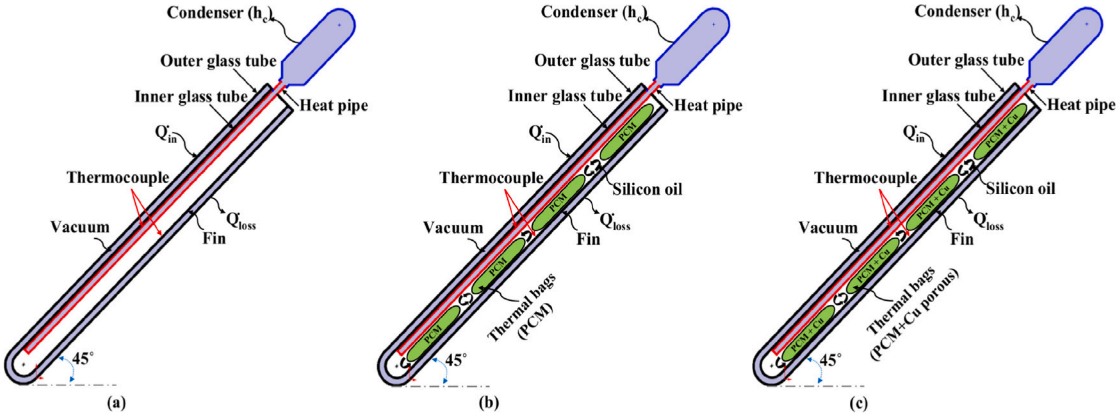


Fig. 11. Schematic of different configurations of HPETC system: (a) Conventional HPETC, (b) HPETC integrated with PCM, and (c) HPETC integrated PCM + copper porous metal. *Source:* Picture taken from Ref. [64], with permission.

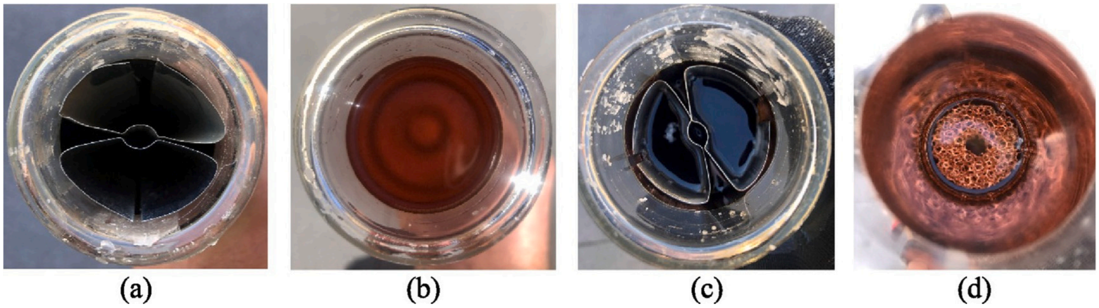


Fig. 12. Photos of the tubes for each of the four cases studied, (a) conventional ETSC, (b) ETSC-PCM, (c) ETSC-PCM-fin, (d) ETSC-PCM-MF. *Source:* Picture taken from Ref. [65], with permission.

schematic of the proposed system is represented in Fig. 12. Despite containing less PCM mass, the PCM-MF composite outperformed pure PCM and PCM-fin composites, achieving a 35% higher maximum output temperature and storing 10% more thermal energy. Thermal efficiency during solar energy input reached 57%, with prolonged temperature maintenance during periods without solar input. This design holds promise for practical solar water heating applications, offering superior performance compared to conventional systems. Similar activity is reported in Ref. [67].

3.2. PCMs in PV, CPV, and hybrid PV/T systems

Numerical studies. Numerical studies have explored various innovative designs integrating PCMs with solar energy systems to enhance efficiency and thermal management. For instance, a concentrated solar system comprising a PVT module with PCM and a solar thermal collector (ST) equipped with thermoelectric generators (TEG) [68] was proposed in 2022. The PV/T-ST system generates both electricity and low-temperature thermal energy, utilizing the PCM in the PV/T module to absorb heat during the daytime, thereby reducing the temperature of the PV cells. The secondary outputs, including heated water and additional electrical power from TEG on the ST module, enhance the overall performance. The structure of the PV/T-ST system is represented in Fig. 13. The study highlighted the effectiveness of the system in generating both electricity and low-temperature thermal energy, providing a comprehensive analysis from energy and exergy perspectives, as well as an economic evaluation. Future work is suggested to include experimental validation and further optimization for increased electrical and thermal output and cost reduction. More recently, the same authors [69] also proposed a novel PV and thermoelectric generator (PV-TE) system with a micro-channel heat pipe (MCHP). Regarding the existing research on PV-TE integrated systems mostly focus on their daytime behaviors. Here, the PV-MCHP-TE system is integrated with PCM to enable continuous electrical output throughout the day. Detailed structure of the PV-MCHP-TE system with PCM is represented in Fig. 14. The system achieved two-level power generation during the day, utilizing both PV and TE modules, while PCM releases stored heat at night to sustain TE operation, ensuring uninterrupted 24-hour power generation. The results indicate that PCM enhances daytime PV performance, raising TE component temperatures at night and improving overall system power acquisition. The study compares systems using free cooling, forced air cooling, and water cooling, revealing varying electrical efficiencies and maximum TE efficiencies. Additionally, a comparative analysis explored the impact of different PCM parameters on system behavior. The findings suggest that PCM contributes to increased overall system efficiency and power output throughout the day, laying the groundwork for the potential application of TE in solar systems. Future work is proposed to optimize system structures and enhance heat storage capabilities for improved nighttime TE output, particularly with advancements in TE properties, which could significantly elevate system performance.

Research into PV-PCM systems has also investigated the impact of structural modifications, such as fin shapes and PCM cavity dimensions, on thermal and electrical performance. Advanced configurations, including fractal fins [70] (see Fig. 15) and nano-PCM technologies [71], demonstrate that the choice of design parameters significantly influences cooling efficiency and electrical performance. For example, the introduction of fractal fins is found to significantly enhance the thermal management compared to conventional straight fins, resulting in a remarkable 2 °C reduction in the PV panel temperature [70]. Obviously, a suitable PCM thickness and number of fins should be evaluated, balancing the trade-off between enhanced thermal performance and the weight and cost of the PV-PCM system. Moreover, nano-PCM with various nanoparticles (specifically RT25HC paraffin wax infused with

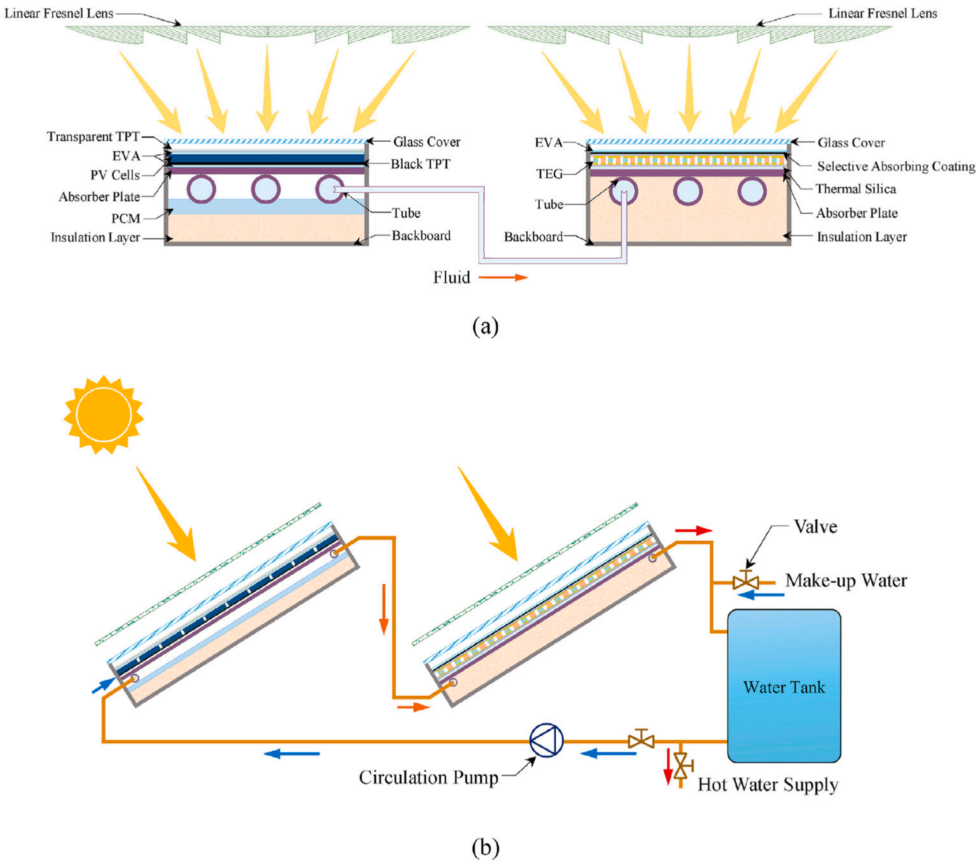


Fig. 13. Structure of the PV/T-ST system.
Source: Picture taken from Ref. [68], with permission.

MgO, TiO_2, ZnO, and CuO nanoparticles) has been shown to maintain PV panel temperatures effectively [71], though panel orientation heavily affects performance outcomes. These findings underscore the importance of tailoring PCM-based solutions to specific operational conditions. Future research avenues could explore different nanomaterial compositions and smart control systems for dynamic adjustments based on environmental conditions. Similar analysis focused on the role of thermal properties of fins on the cooling process of a PV system were performed by same authors and reported in Ref. [72]. Moreover, heat sink design has emerged as a critical factor for enhancing the thermal management capability of PCM heat sinks integrated in PV systems. In this context, Hong et al. [73] explored a novel T-shaped fin. The study conducted a numerical investigation to evaluate the temperature control performance of PCM heat sinks with various T-shaped fin layouts, comparing them with heat sinks without fins and with traditional rectangular fins. Key findings revealed that the T-shaped fins significantly influence the melting front in the heat sink cavity, improving PCM temperature uniformity and reducing melting time compared to unfinned and rectangular fin systems. The T-shaped fins showed a maximum reduction in melting time of 25.5% compared to rectangular fins and enhance electrical conversion efficiency by 11.1%. The research provided valuable insights for optimizing PCM heat sink designs in PV systems, with implications for future studies involving multi-layer PV panel structures, shape optimization, and the use of nano PCMs.

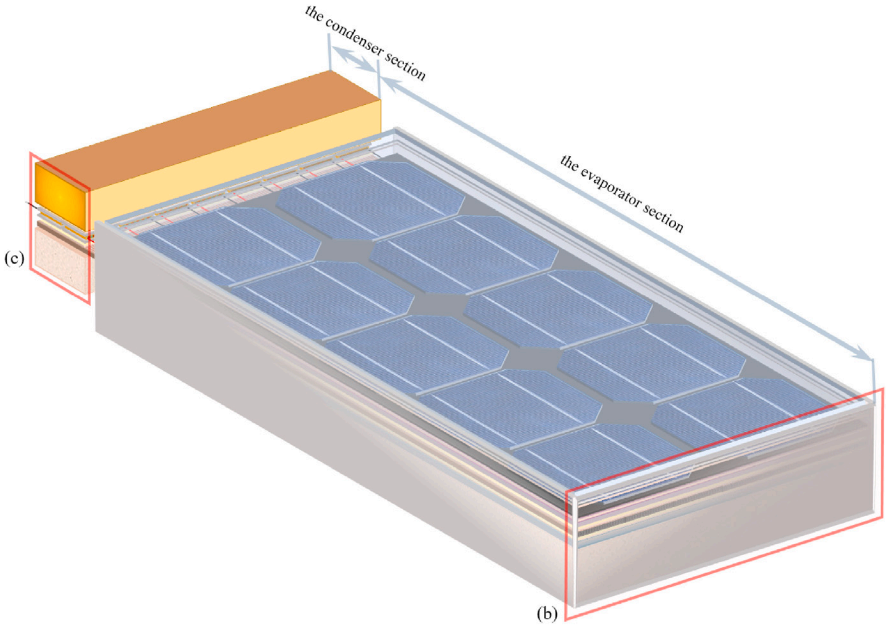
It is worth discussing also an interesting research [74], where authors explored the synergistic application of solar tracking and PCMs in a PV system to enhance power generation while mitigating temperature-induced efficiency losses. A numerical model of a tracking PV-PCM system was developed, enabling an in-depth analysis of PCM temperature variations in three distinct time intervals. The inclusion of PCM effectively reduces the PV panel temperature, with an average decrease of 6.9 K compared to a system without PCM. These insights pave the way for optimizing solar energy systems through synergistic design approaches.

Experimental studies. Experimental investigations of novel hybrid PVT collector integrated with PCM (PVT-PCM) [75], designed to meet diverse building energy needs, have been proposed. A cross-season test revealed an impressive overall system efficiency of 39.4%, and energy-saving efficiency of 64.2%. Economic analysis indicated an additional investment payback period of 13.1 years, demonstrating promising application potential.

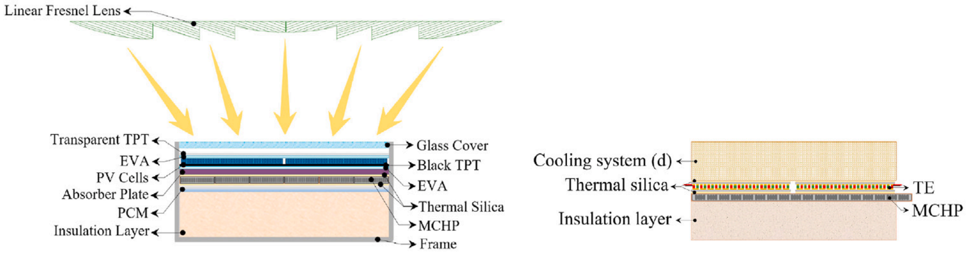
Similarly, Hamada et al. [76] introduced a water-based PVT system integrated with PCM capsules, operating in both active and passive cooling modes, to optimize the performance of PV panels in terms of power generation and thermal utilization. Real-world experiments demonstrate that the integration of PCM with advanced cooling techniques can result in cumulative efficiency gains, further emphasizing the need for tailored designs based on location-specific requirements.

In greenhouse drying applications, PCM-enhanced systems were also proposed [77] to address operational challenges by ensuring functionality beyond daylight hours. Systems incorporating materials such as lauric acid exhibit quick energy payback times and significant carbon credit potential, showcasing their environmental and economic viability. This research emphasized the need for further improvements in PCM technology to address challenges related to heat transfer rate, stability, and cost, potentially through the incorporation of nanoparticles and exploration of alternative materials. Geographical conditions must also be considered for the feasibility of solar thermal systems in different locations.

More recently, the application of Cantor fractal fins, inspired by fractal theory, to enhance the thermal management of PV panels in

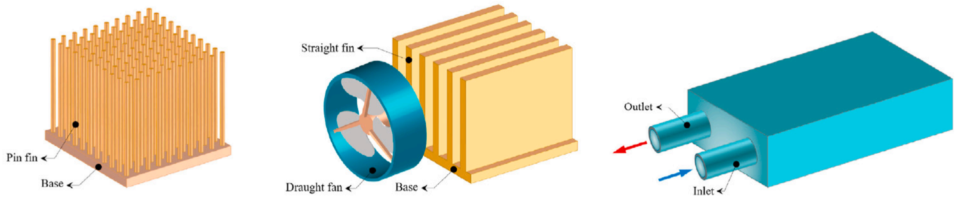


(a) The overall structure.



(b) The evaporator section.

(c) The condenser section.



Free cooling

Forced air cooling

Water cooling

(d) The cooling method.

Fig. 14. Detailed structure of the PV-MCHP-TE system with PCM.
Source: Picture taken from Ref. [69], with permission.

conjunction with PCMs was experimentally analyzed [78]. The study conducted an experimental analysis using lauric acid as the temperature control medium, comparing the performance of Cantor fractal fins with rectangular fins and a finless cavity. Results showed that Cantor fins outperform rectangular fins, offering advantages such as improved temperature uniformity in the PCM, reduced PV panel temperature, and enhanced wall temperature uniformity. The adoption of Cantor fins resulted in a substantial decrease in wall temperature by 9.1 °C and an increase in electrical energy efficiency by up to 5.2%. Horizontal arrangement of Cantor fins was found to be more beneficial than vertical arrangement in improving temperature uniformity, reducing PV panel temperature, and enhancing electrical efficiency. The study provided valuable insights into the design considerations for optimizing the thermal management of PV-PCM systems, offering a promising avenue for future research in outdoor experiments and optimization of geometric parameters.

Experimental studies validated by numerical models. Integrated studies combining numerical models with experimental validation offer a comprehensive understanding of PCM-based solar systems. In 2023, a

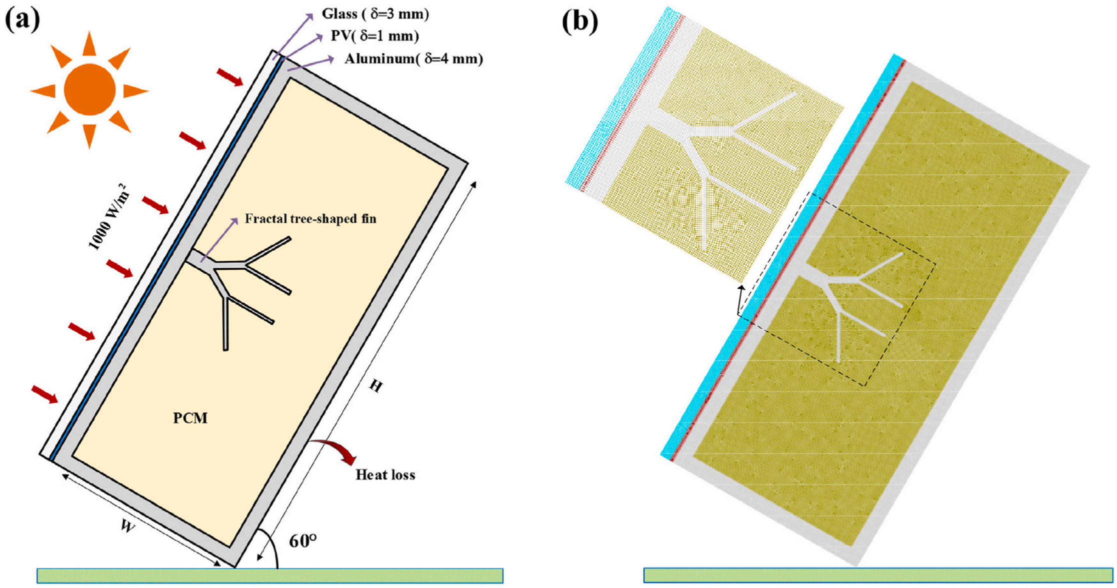


Fig. 15. The 2D view of the fractal fin PV-PCM system: (a) physical model (b) mesh details.
Source: Picture taken from Ref. [70], with permission.

research [79] explored the use of PCMs in two different applications. First, authors numerically and experimentally studied the performance of direct and indirect passive cooling systems employing PCM and flat heat pipes (FHP) for low-concentrated PV panels (LCPV) with and without a compound parabolic collector (CPC). The layouts explored are represented in Fig. 16. The study compared the two cooling approaches, where the indirect PCM-heat sink system outperformed the direct system in terms of cell temperature, conversion efficiency, and power generation. Without a CPC, both systems effectively reduced the solar panel operating temperature compared to the reference panel. The indirect cooling system kept the cell temperature within safe limits even with the integration of a CPC, whereas the direct system failed. In the second research work [80], authors numerically and experimentally investigated the thermal regulation of PV panel, via a hybrid cooling system of flat heat pipes (HP) coupled with PCM without and with the inclusion of hybrid nanoparticles. In detail, two PCM were used, namely SP31 and SP15-gel. The proposed cooling system with hybrid nanoparticles maximally achieved a daily energy efficiency of 56.45% and 54.45%, compared with 8.77% and 7.84% for the conventional solar cell system using SP31 and SP15-gel, respectively. Also, cost analysis indicated that the PV/HP-PCM-hybrid nano system produced electricity at 0.0899 USD/kWh compared with 0.0905 USD/kWh and 0.105 USD/kWh for the PV/HP-PCM and traditional cooled PV, respectively.

Through a different approach, Asefi and co-workers [82] expanded the horizon by investigating the integration of Porous PCM (PPCM) into PVT systems. Authors presented a comprehensive investigation of annual performance, environmental impact, and economic viability of the proposed systems and its impact on cooling cycle temperature throughout the year. The mathematical model developed was validated experimentally. Various systems were assessed, including PV-only, PVT, and PV integrated with PCM (PV-PCM). The results showed that PVT-PPCM exhibited the highest annual power output and CO_2 reduction. The study emphasized the importance of considering multiple factors in evaluating the performance and economic feasibility of solar PVT systems, providing suggestions for policymakers and industry professionals in the sustainable energy sector.

Then, it is worth mentioning the use of multilayered PCM system with a combination of low and high melting point PCMs to address the reduced power conversion efficiency and shortened lifetime of PV modules due to high temperatures [81]. The study involves different configurations, reported in Fig. 17. While previous studies have primarily relied on simulations, this work included systematic experiments to validate the efficacy of the multilayered PCM arrangement. Experimental results demonstrated a lower maximum temperature of the PV module by 4 °C and 7.2 °C compared to single-layer PCM and PV reference, respectively. The multilayered PCM system is shown to regulate the operating temperature of PV modules in all seasons, offering a 3.3% higher yearly electric output, an extension of PV life by almost ten years, and nearly double the lifetime earnings. Similarly, Khanegah and co-workers [83] focused on enhancing the efficiency of concentrated photovoltaic/thermal (CPV/T) systems by employing a novel hybrid cooling approach using water and PCM. The concentrators in this study were designed with linear flat mirrors, providing an innovative configuration. The investigation included both numerical simulations and experimental validations of the proposed system, comparing it with a CPV system cooled solely by PCM. The results demonstrated an 18.5% improvement in performance for the hybrid cooling system. The study explored the impact of thermophysical properties of the PCM and different coolant inlet conditions on system efficiency. Seasonal analysis revealed that the proposed system performs optimally during cold months, with January, November, and March showing the highest efficiency. The technical, economic, and environmental aspects of the system were also assessed, revealing a significant increase in productivity and a reduction of 0.02 kg per hour in CO_2 emissions. This study lays the groundwork for the development and application of efficient and environmentally friendly CPV/T systems with innovative cooling solutions.

Last but not least, the integration of PCM and multichannel tube technology into PV modules, referred to as the MPCM-PV, represents an innovative approach for addressing the temperature-related efficiency challenges [84]. Through CFD modeling and experimental validation, authors analyzed the thermal and electrical behaviors of the MPCM-PV module under varying parameters. The results indicated that increasing the number of channels enhances heat transfer, resulting in a more even distribution of temperature in the PCM zone. The MPCM-PV module with five channels achieved a significant reduction in the PV surface temperature, improving electrical efficiency by up to 1.46%. Additionally, the study highlights the influence of channel shape, heat storage capacity (HSC), and PCM melting point on the module's performance. Rectangular-shaped channels are recommended for optimal electric energy production, while higher HSC and lower melting points

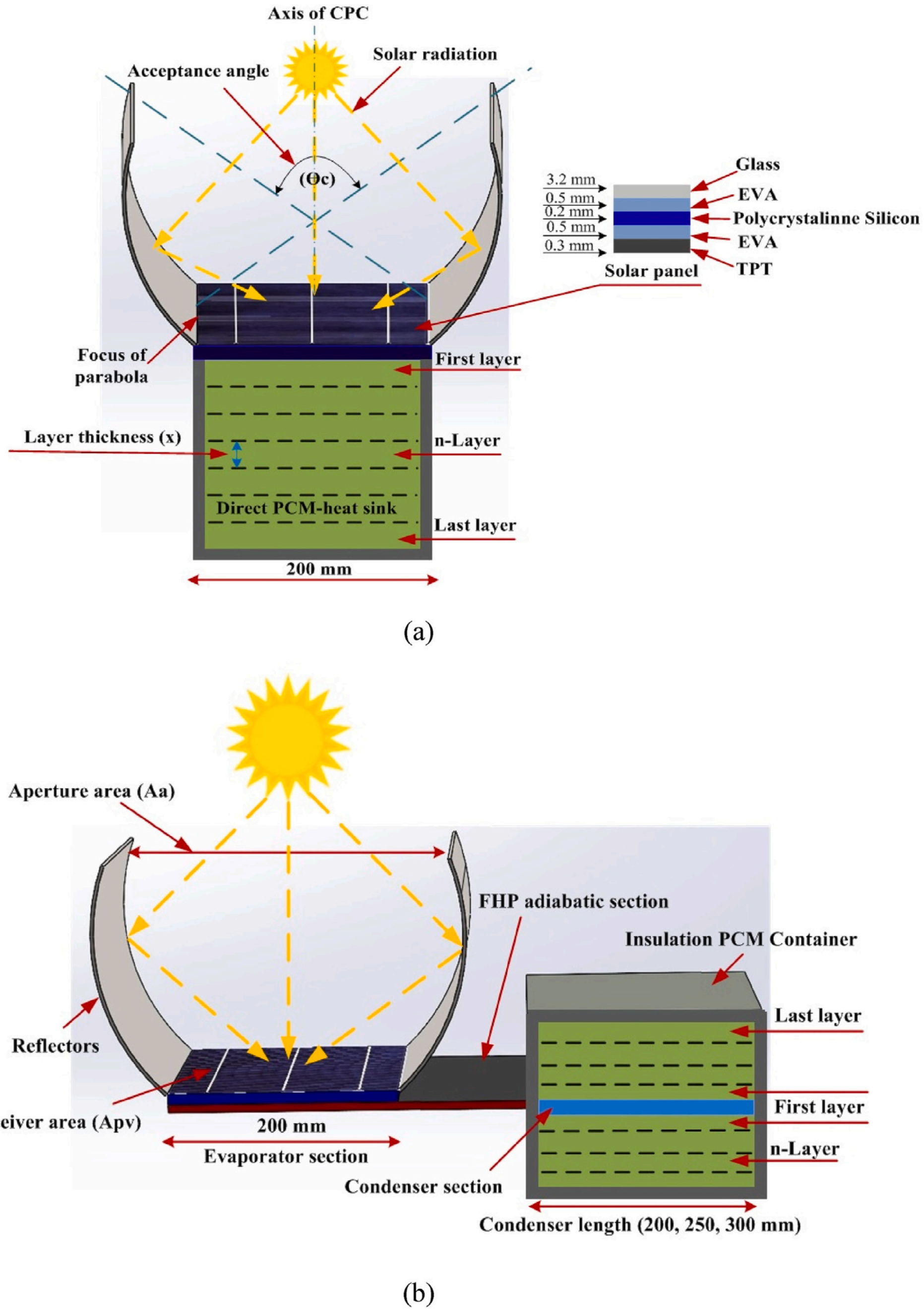


Fig. 16. Schematically layout of (a) direct PCM-heat sink cooling system (CPV-PCM) and (b) indirect PCM-heat sink cooling system (CPV-PCM/FHP).
Source: Picture taken from Ref. [79], with permission.

contributed to improved electrical efficiency. The sensitivity analysis underscored the significance of channel shape, channel number, HSC, and PCM melting point.

3.3. PCMs in solar desalination systems

Numerical studies. In this field, performance of a solar still featuring a PCM layer were recently investigated through transient numerical simulations [85]. COMSOL software was used to perform the analysis. In detail, the PCM (n-Eicosane) layer was envisioned at the bottom of the desalination unit, with varying thicknesses between 10 and 50 mm. Aluminum nanoparticles were introduced into the water, and a two-phase mixture model was employed to simulate fluid flow. A schematic of the solar still integrated with PCM is represented in Fig. 18. The study explored the influence of glass angle (10–45 degrees) and heat transfer coefficients on the glass surface on parameters such as PCM temperature, volume fraction, and moisture temperature. Results indicated that increasing PCM thickness reduced the molten PCM volume fraction by 35%, while variations in glass angle decreased PCM temperature, especially during morning and afternoon hours. PCM thickness significantly influenced moisture temperature, particularly during evening periods.

Experimental studies. Kumar and co-workers [86] presented an interesting advancement in solar still technology, comparing conventional solar stills with advanced solar stills incorporating a nano-paraffin-based PCM, specifically ZnO-PCM (i.e., paraffin wax with zinc oxide nanoparticles). Under identical climatic conditions, the advanced solar stills with ZnO-PCM outperformed the conventional solar stills in

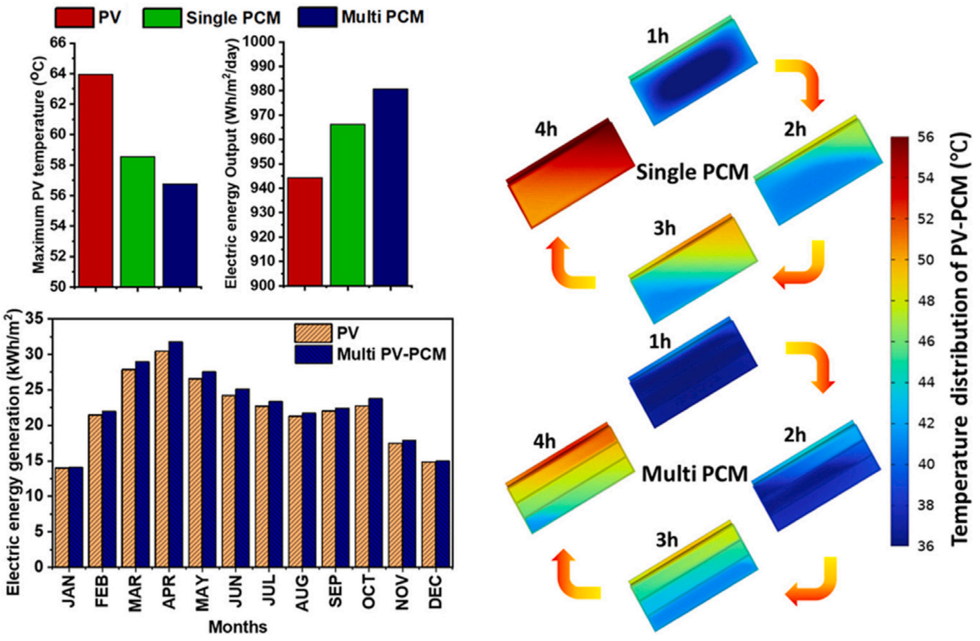


Fig. 17. Simulated temperature profiles of single and multilayered PV-PCM systems.
Source: Picture taken from Ref. [81], with permission.

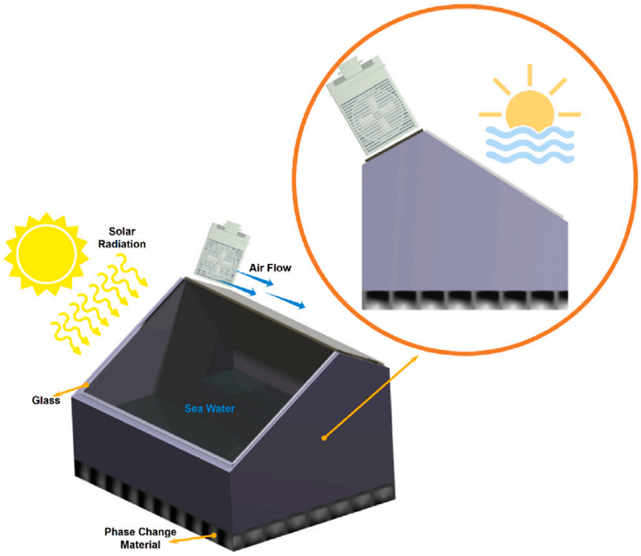


Fig. 18. A schematic of the solar still integrated with PCM.
Source: Picture taken from Ref. [85], with permission.

terms of yield, thermal efficiency, and freshwater productivity. The advanced solar stills-ZnO-PCM achieved an impressive 113% increase in cumulative yield compared to the conventional system. Authors also experimentally investigated the influence of different parameters, such as nano-PCM concentration in base fluid and volume ratio of ZnO and PCM in hybrid nanocomposite.

Yet, with the aim of enhancing the productivity and efficiency of conventional tubular solar stills, a recent research [87] proposed a novel oval tubular solar still design, incorporating paraffin-based PCM and a cover cooling. The system was designed to extend the operating time. Experiments conducted in Cairo, Egypt, revealed optimal conditions – a 0.5 cm saltwater depth and 2 L h^{-1} cooling water flow rate – yielded a 22% productivity increase compared to systems without cooling. Adding PCM at the optimal saltwater depth further boosted productivity by approximately 30%, achieving a daily efficiency of 61.59% and a cost of $ 0.017 per liter of desalinated water. The study recommends exploring different nanoparticle materials and concentrations to enhance PCM thermal conductivity and investigating various PCM masses, thicknesses, and oval tube aspect ratios for further optimization.

More innovatively, Zhang and co-workers [88] proposed a bifunctional solar absorber leveraging microcapsules with n-docosane PCM cores, a compact SiO_2 shell coated with sodium alginate (SA), and MXene nanosheets (MXene/SA/SiO_2-MEPCM). These microcapsules achieved over 97% light absorption, high latent heat capacity (≥ 150 J g^{-1}), and an evaporation rate of 2.11 kg m^{-2} h^{-1} under one-sun illumination. The system demonstrated effective water evaporation under intermittent sunlight and recyclability for long-term use, offering a notable increase in evaporation mass compared to non-PCM evaporators.

In the same years, authors [89] developed and proposed another solar-driven interfacial evaporator for efficient and continuous seawater desalination. The evaporator utilized microencapsulated PCM consisting of n-tetracosane and n-eicosane as twin PCM cores within a SiO_2/Fe_3O_4 composite shell. The system incorporated a surface-coated polypyrrole layer and surface-decorated MXene nanosheets, serving as both a solar absorber and a latent-heat storage material. The microcapsules demonstrated an exceptional light absorption efficiency of 95.4%, enabling high evaporation rates of 2.04 and 4.11 kg m^{-2} h^{1} under 1.0-sun and 2.0-sun illumination, respectively. Importantly, the proposed design allowed the evaporator to continue evaporating water even in the absence of solar illumination, thanks to the photothermal energy released by the PCM cores. Compared to conventional evaporators without PCM cores, the developed system achieved a 0.45 kg m^{-2} increase in distilled water yield under 2.0-sun illumination and subsequent darkness. The integration of magnetic Fe_3O_4 nanoparticles in the SiO_2 shell facilitated easy separation of microcapsules from accumulated salt crystals. The research presented a promising approach for sustainable solar-driven seawater desalination and wastewater treatment, addressing above all challenges related to intermittent solar illumination and salt accumulation.

Finally, it is worth discussing the research proposed by Li and coworkers [90]. Authors developed an interesting solar-driven interfacial evaporator integrated with an electricity generation system using modified carbon black-decorated magnetic PCM composites (MCB-MPCC). The designed system offered a dual-purpose approach for sustainable seawater desalination and clean electric power generation under intermittent solar illumination. MCB-MPCC, fabricated with a SiO_2/Fe_3O_4 composite shell encapsulating n-docosane as a PCM, exhibited excellent latent heat capacity (over 145 J g^{-1} for the resulting composite), making it ideal for consequent seawater evaporation. The system achieved a high evaporation rate of 2.67 kg m^{-2} h^{-1} under one-sun illumination and demonstrated excellent salt resistance. Moreover, MCB-MPCC served as a hydrovoltaic functional coating, allowing the generation of electric power under sunlight. The various types of PCMs developed and proposed for this application area, along with any composite materials used, the solar-powered systems, the type of research conducted (numerical, experimental, or hybrid), the main purpose of the study, and the year of publication of all discussed research papers, are well-organized for clarity in the Table 2.

In conclusion, PCMs show great compatibility with solar systems. Their use in systems such as, solar thermal collectors, PV, CPV, PV/T hybrid systems, and desalination systems, holds tremendous potential in improving efficiency. A wide variety of PCM-based materials, ranging from paraffin waxes and fatty acids (e.g., lauric acid, stearic acid) to salt hydrates (e.g., disodium hydrogen phosphate dodecahydrate) and hybrid composites (e.g., obtained through the use of nanoparticles such as MgO, TiO_2, ZnO, CuO), have been proposed and extensively analyzed through numerical and experimental studies. Each PCM was selected for its specific thermal properties, including melting temperature, heat of fusion, and thermal conductivity. Tailoring the choice of PCM to the case study is critical, as it directly influences the efficiency and effectiveness of energy storage and release, thermal management, and overall performance of the solar energy system. In solar thermal collectors, the integration of PCMs has been shown to significantly augment thermal energy storage and release as well as the ability of PCMs to stabilize temperatures, thereby enhancing the reliability of the system across varying climatic conditions. Similarly, for PV, CPV and hybrid PV/T systems, the incorporation of PCMs has been crucial in coping with the critical challenge of thermal management. By effectively reducing PV module operating temperatures, PCMs help maintaining higher electrical efficiencies and extended solar panel lifetimes. In addition, innovative designs that combine PCMs with advanced cooling strategies, such as hybrid cooling approaches and multifunctional materials, demonstrate the potential to achieve continuous power production, even under fluctuating environmental conditions. Moreover, in the field of solar desalination, PCMs have emerged as a key component for extending hours of operation and increasing the overall freshwater yield. Although the effectiveness and flexibility of such a solution hold great promise, challenges related to optimization of PCM properties and integration into various systems, and cost remain. Addressing these challenges through continued research and innovation will be key towards wider adoption and implementation of PCM-based solar-powered energy technologies.

4. Integration of PCMs in buildings envelopes

Numerical studies. Interestingly, a significant number of numerical studies have explored the fascinating integration of PCMs into building envelopes to evaluate their potential for improving energy efficiency across diverse climatic conditions. A study published in 2022 [91] presented a comprehensive analysis of the integration of PCMs (i.e., microencapsulated PCM with cement, bio PCM, and a mixture of hexadecane and diatomite) into building envelopes to enhance energy efficiency, particularly in North African climates. Through numerical simulations using EnergyPlus software, the research evaluated the impact of PCM in four different building envelope types (brick, concrete block, reinforced concrete, and earth) across three climatic zones (Mediterranean, arid, and sub-arid). The findings revealed that PCM incorporation leads to reduced total energy consumption, with the reinforced concrete building exhibiting higher energy consumption due to varying thermal inertia. The average energy savings with PCM were approximately 251.82 kWh/year, with the most significant energy saving rate of 10.5% observed in the arid climate when using an earth envelope. PCM proved more effective for cooling in arid regions, reducing cooling energy by up to 7.3%, while in sub-arid and Mediterranean climates, it was more efficient for heating, with a maximum reduction of 10.7%. Moreover, PCM integration demonstrated environmental benefits, reducing CO_2 emissions by about 707 kg/year, and offered economic advantages with a 10% reduction in energy costs. Based on results, the payback period for PCM implementation ranged from 7 to 43 years, well within the typical building lifespan of 60 years. Despite the economic feasibility suggested by a payback period, variations in thermal inertia across the different building envelope types influenced these savings.

Further investigation using paraffin PCMs assessed their influence on key metrics such as average temperature fluctuation reduction (ATFR), thermal load leveling reduction (TLLR), and operative temperature reduction (OTR) [93]. These numerical studies showed substantial improvements in indoor thermal comfort metrics, including a reduction in ATFR by up to 6 °C and OTR by 6 °C during extreme summer heat events. Additionally, this integration yielded daily CO_2 emission reductions of approximately 2 kg and financial savings of up to 250 Iraqi dinar. These findings emphasize role of PCM in achieving energy savings and improving indoor comfort, although it is necessary to critically analyze long-term performance across different geographic locations. In the same year, the same authors studied [92] the synergistic effect of combining paraffin PCMs with thermal insulation (i.e., traditional expanded polystyrene — EPS), to enhance the thermal performance of building envelopes in the context of energy-efficient and nearly-zero energy buildings (NZEBs). The study conducted a comprehensive numerical investigation, considering various thicknesses of EPS insulation to determine their impact on indoor temperature improvement and envelope resistance. A schematic of the simulated stratigraphy is represented in Fig. 19. The findings indicated that the integration of PCM-EPS systems outperformed PCM alone, achieving up to 143% higher indoor temperature reduction and extending the daily thermal lag by up to 3.2 h. The results further demonstrated that optimizing insulation thickness had significant effects, with climate and thermal cycling as key determinants in maximizing energy performance. This study underscores the importance of material layering strategies and optimized insulation design for efficient energy management. For example, the research showed that installing EPS directly after the PCM layer on the inner side ensures efficient melting and solidification of the PCM, offering potential advantages for the design of energy-efficient buildings.

Efforts have also focused on identifying suitable porous materials for PCM encapsulation in concrete applications [94], while meeting specific criteria such as high PCM absorption capacity, strength, resistance to seepage and acidification. The research systematically evaluated five different porous materials for encapsulating capric acid (CA) to develop Form Stable PCM (FSPCM) cement composites for concrete panels. A comprehensive comparison of these FSPCM integrated lightweight concrete panels based on six indicators, including absorption, thermal conductivity, strength, thermal inertia, latent heat storage, and thermal storage, was conducted. Among the tested porous materials, silica aerogel granules (SAG) exhibited the highest PCM absorption capacity at 80 wt%. While the Capric acid-Silica Aerogel Granule (CASAG) integrated concrete panel had the lowest compressive strength, it excelled in terms of thermal conductivity, storage capacity, and thermal inertia. On the other hand, the Capric Acid/Hydrophobic expanded

Table 2
Recent application of PCMs in solar energy systems.

PCM type	Resulting material	Solar-powered system	Research	Purpose	Year
RT35-54-6HC	PCM-based cementitious composite	Massive STC	Num.	Water/space heating	2022 [61]
Hybrid salt ($Na_2HPO_4 \cdot 12H_2O$), Paraffin (C20-C33), Fatty acid (uric acid)	Pure PCM	Flate plate STC	Num.	Water heating	2023 [62]
Lauric acid, Paraffin wax, Stearic acid	Pure PCM	Evacuated STC	Num.	ND	2023 [60]
Organic paraffin $C_{33}H_{68}$	PCM-copper metal foam composite	Heat pipe evacuated STC	Exp.	Water heating	2023 [64]
Paraffin wax	Pure PCM	Flat plate STC with stepped serrated fin assembly	Exp.	Air heating for agricultural crop drying	2023 [66]
RT42	PCM-copper metal foam composite	Evacuated STC	Exp.	Water heating	2023 [65]
Not declared	Pure PCM	PCM-PVT and STC-TEG	Num.	Electricity production and water heating	2022 [68]
Not declared	Not declared	PV-TEG micro-channel heat pipe	Num.	Electricity production and others	2023 [69]
RT42	Pure PCM	PV and fractal fins	Num.	Thermal management/Cooling	2023 [70]
RT25HC	nano-infused PCM (MgO, TiO_2, ZnO, CuO)	Concentrator PV-PCM	Num.	Thermal management/Cooling	2023 [71]
RT44HC	Pure PCM	T-shaped finned heat sink PCM with PV	Num.	Thermal management/Cooling	2023 [73]
PC29	Pure PCM	tracking PV-PCM	Num./Exp.	Thermal management/Cooling	2023 [74]
Paraffin	Pure PCM	PVT-PCM integrated water/air-based system	Exp.	Electricity production and heat generation	2022 [75]
RT35	Copper capsules filled with PCM	Water-based PVT-PCM	Exp.	Electricity production and heat generation	2023 [76]
Lauric acid	Pure PCM	Bifacial PVT	Exp.	Greenhouse dryer	2023 [77]
Lauric acid	Pure PCM	Cantor fractal fins-based PV	Exp.	Thermal management/Cooling	2023 [78]
SP31	Pure PCM	PCM-flat heat pipe integrated with low-concentrated PV via CPC	Exp./Num.	Thermal management/Cooling	2023 [79]
Paraffin wax	PCM-Cu/Al/Graphite foam composite	PVT	Exp./Num.	Thermal management/Cooling	2023 [82]
RT28-35-45-54-55HC and OM37-42	Multilayered PCMs	PV	Exp./Num.	Thermal management/Cooling	2023 [81]
Polyethylene glycol 1000	Pure PCM	CPVT	Exp./Num.	Thermal management/Cooling	2023 [83]

(*continued on next page*)

Perlite (CAHEP) panel demonstrated a balanced performance, offering moderate compressive strength, thermal conductivity, and competitive thermal properties. Consequently, CAHEP was recommended as the most suitable porous material for absorbing polar PCMs such as CA and developing FSPCM-integrated concrete panels for building envelope applications, offering a well-rounded combination of properties.

Table 2 (*continued*).

PCM type	Resulting material	Solar-powered system	Research	Purpose	Year
RT35HC	PCM embedded into multichannel tube	PV	Exp./Num.	Thermal management/Cooling	2023 [84]
n-Eicosane	Pure PCM	PCM-based solar Still with aluminum nanoparticles in water	Num.	Thermal management and water yield enhancement	2023 [85]
Paraffin wax	nano-PCM (ZnO-PCM)	Solar Still	Exp.	Water yield enhancement	2023 [86]
Paraffin wax	Pure PCM	Oval tubular solar Still	Exp.	Water yield enhancement	2023 [87]
n-docosane	MXene-decorated and sodium alginate-coated PCM microcapsules	Bifunctional solar absorber for interfacial evaporator	Exp.	Water yield enhancement	2023 [88]
n-tetracosane and n-eicosane	PCMs cores in SiO_2/Fe_3O_4 composite shell, along with a surface-coated polypyrrole layer and surface-decorated MXene nanosheets	Interfacial solar evaporator	Exp.	Water yield enhancement	2023 [89]
n-docosane	PCMs cores in SiO_2/Fe_3O_4 composite shell, followed by coating a polydopamine layer and surface-depositing modified carbon black nanoparticles	Interfacial solar evaporator	Exp.	Water yield enhancement and electricity generation	2023 [90]

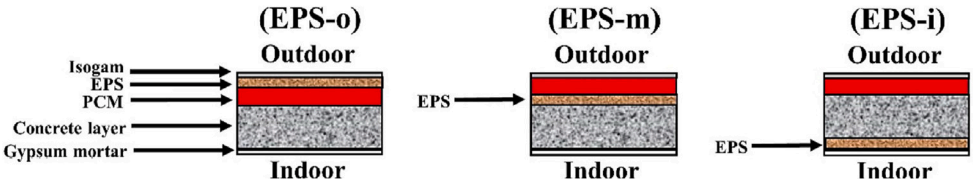


Fig. 19. EPS position cases in the roof combination.
Source: Picture taken from Ref. [92], with permission.

Research on the effects of PCM types in exterior walls also demonstrated their varied impact on heating and cooling demands. Analyses compared multiple PCM types (InfiniteRPCM and BioPCM27) across configurations with varying thickness, melting temperatures, and layering positions [95]. The findings revealed that the heating energy demand reduction was maximized with BioPCM27 in a three-layer wall system (21.32%), while InfiniteRPCM proved more effective in cooling scenarios, achieving a 19.9% reduction in cooling energy demand under certain external conditions. PCM integration in the exterior walls contributed to improve thermal comfort by reducing heat flux peaks, which was particularly beneficial during the discharge period. The annual average optimum melting temperature for PCMs ranged between 18 and 19 °C, depending on exterior wall and material types, with variations in monthly optimum melting temperatures based on the number of layers and material type. These insights suggest that both type selection and thermal configuration have critical implications for PCM-based energy savings.

Interestingly, the study of Khan et al. [96] focused on addressing the energy inefficiency in the residential sector of Pakistan by exploring the integration of PCM into building envelopes. The study employed numerical simulations using EnergyPlus and evaluated 15 different PCMs to identify CrodaTherm24 as the optimal choice due to its melting temperature and latent energy characteristics. PCM integration was assessed in single-story and two-story multi-zone residential buildings across five major cities in Pakistan, considering factors such as PCM placement, thickness, and location within the building envelope. The results indicated substantial energy savings, with single-story buildings achieving an average monthly energy reduction ranging from 32% to 49.6% across different cities. For two-story buildings, energy savings were slightly lower due to increased internal loads and infiltration rates. Economic feasibility assessments, based on static and dynamic payback periods, revealed that PCM integration was economically viable in Lahore, Karachi, and Peshawar but not suitable for Islamabad and Quetta.

Several studies extended this understanding by investigating broader energy flexibility strategies, considering both design and operational aspects. For instance, multi-objective optimization approaches analyzed demand-side management strategies like pre-cooling and flexible air conditioning operations under varying pricing structures [97]. These analyses demonstrated energy flexibility improvements, achieving load reduction of up to 92.87% and flexibility indices ranging from 24.21% to 32.78%. These results are promising, as they illustrate how PCM-integrated strategies can improve grid stability and energy savings by leveraging time-shifting strategies to smooth peak demands. Summing up, this comprehensive research offered knowledge into selecting control strategies and parameter designs for PCM-integrated buildings, contributing to the advancement of energy-efficient building practices.

Further investigations [98] also discussed the building energy flexibility, but with a focus on air-conditioner loads to mitigate the peak-to-valley differences. To achieve this, the integration of PCM into office building walls and the implementation of pre-cooling strategies were examined. A comprehensive heat transfer model of PCM-integrated walls was developed and validated through experiments. The research investigated the energy flexibility and energy-saving potential of these PCM-integrated walls under different pre-cooling strategies and analyzed the impact of several PCM parameters. The results revealed that optimizing the pre-cooling strategy, in conjunction with varying peak-to-valley electricity tariff differences, can elevate the energy flexibility index of PCM-integrated walls to an impressive 69.7%, while reducing the total load by 1.3% and cutting electricity costs by 51%. Notably, PCM location and melting point were identified as key factors influencing energy flexibility and savings under precooling conditions, with specific recommendations for PCM properties, such as a melting point of 25 °C, a 5 mm thickness, and placement in the middle of the insulation. This analysis sheds light on the operational flexibility that PCM integration offers, particularly for energy-intensive cooling demands, emphasizing the need to explore dynamic integration strategies under varying demand patterns.

Finally, the application of multi-stage sensitivity analysis (MSA) and multi-objective optimization (MOO) has proven effective in identifying key design parameters for energy-efficient strategies in arid climates [99]. The MSA involves three global sensitivity analysis approaches in the first stage, followed by local sensitivity analysis in the second stage. This two-stage MSA identifies the most crucial parameters for early design, such as envelope thermal properties, energy-efficiency measures, and building layout. Subsequently, MOO using a genetic algorithm is performed to obtain the Pareto frontier, yielding two sets of solutions: the most energy-efficient and the most cost-effective. The results demonstrated a substantial reduction in total energy consumption ranging from 11.1% to 34.6%, along with a payback period reduction of 17.6 to 48.5 years when compared to reference buildings. Key findings included specific recommendations for PCM parameters, such as melting points, thickness, and placement, depending on the climatic zone. Additionally, insights were provided for window properties, wall and roof specifications, and building orientation, emphasizing the importance of tailored design parameters for significant energy demand and payback period reductions. This approach was poised to advance the design of energy-efficient buildings, potentially incorporating more complex models and diverse performance objectives in the future. Such methods offer a systematic approach for design decision-making, especially for regions where climate-specific energy strategies are paramount.

Experimental studies. Turning then to analyze the experimental studies, among them it is worth mentioning the study proposed by Al-Yasisi and Szabo [100]. Authors investigated passive incorporation of paraffin PCMs into building envelopes to improve thermal performance in a severe hot climate, focusing on southern Iraq. The PCM was macroencapsulated using metal containers. They conducted experimental studies on two test rooms (see Fig. 20), one equipped with PCM-enhanced roofing and brick walls and the other serving as a reference without PCM. The findings revealed substantial benefits of PCM integration, including an average indoor temperature reduction (AITR) of approximately 2 °C and a significant thermal load leveling reduction (TLLR) of up to 8.71%. The study also demonstrated that the effectiveness of the PCM is more pronounced in the roof compared to walls, emphasizing the importance of optimizing PCM quantity and placement based on orientation and outdoor conditions. Furthermore, the PCM-enhanced room exhibited an average heat gain reduction of up to 56 W, resulting in substantial CO_2 emission savings of 1.35 kg/day and electricity cost savings of 80.64 Iraqi dinar (IQD)/day.

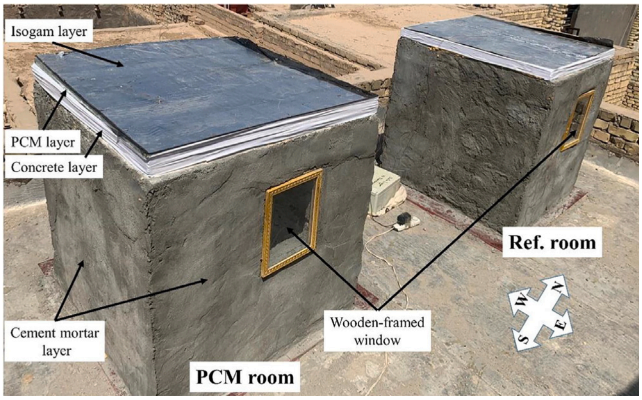


Fig. 20. Pictures of the two test rooms investigated: one with PCM-enhanced roof and brick walls and the other serving as a reference without PCM.
Source: Picture taken from Ref. [100], with permission.

Additionally, the incorporation of microencapsulated PCMs into gypsum plasterboards has shown great promise [101,102]. Authors discussed the fabrication, characterization and use of gypsum plasterboards integrated with microencapsulated PCM to assess their benefits in thermoregulation and energy savings in buildings [103]. The proposed boards were observed to buffer indoor thermal fluctuations effectively, reducing cooling loads by maintaining indoor temperatures up to 3 °C cooler during peak hours, with a lag effect extending the thermal stability of the room for up to 7 h. Notably, their stability up to 140 °C confirms their reliability for long-term deployment in diverse thermal environments. This study suggests the potential of integrating microencapsulated PCM with construction materials to reduce thermal demand with minimal intrusion to structural designs.

Furthermore, in another experimental work, the potential of PCM in managing thermal energy within building envelopes during hot summer days in Iraq was addressed [104]. Two cubicles, one incorporating PCM and the other serving as a reference, were analyzed under non-ventilated conditions, with a focus on the optimal PCM thickness and placement in the roof and high-performing PCM bricks in the walls. The results revealed time-dependent PCM effectiveness, with the east wall exhibiting the best performance, achieving a maximum hourly temperature reduction (HTR) of 9.1% and hourly heat gain reduction (HHGR) of 16%. Additionally, the PCM-integrated roof demonstrated impressive HTR and HHGR of 15.1% and 34.9%, respectively, contributing significantly to overall heat gain reduction. The indoor temperature when using PCM was lowered by up to 4 °C compared to the reference, demonstrating the significant thermal improvement enabled by PCM compaction, even in high diurnal temperature and non-ventilated conditions. These results further confirm the spatial importance of PCM placement, as well as time-dependent performance influenced by ventilation and thermal load cycles. Authors suggested future investigations to explore various aspects, including larger cubicle/room sizes, night ventilation, and additional passive techniques.

In conclusion, the integration of PCMs into building envelopes, as explored through a combination of numerical simulations and experimental studies, presents an interesting and promising avenue for enhancing energy efficiency, thermal comfort, and environmental sustainability. Numerical studies have revealed the significant impact of PCM integration across diverse climates, showcasing its effectiveness in reducing total energy consumption, enhancing thermal performance, and providing insights into potential energy savings. Experimental investigations further validated these findings, demonstrating tangible benefits such as substantial reductions in indoor temperatures, thermal load leveling, and electricity costs, particularly in hot climates. The optimization of PCM placement, material selection, and dynamic strategies emerges as a key trend. However, challenges persist, requiring further investigation, including the development of standardized guidelines for material selection, optimized configuration based on climate considerations, and assessing the economic viability of PCM integration in various contexts. Indeed, over-generalization of results should be prevented. Many numerical studies assume static, idealized conditions. Real-world scenarios introduce variability (e.g. occupancy, local weather deviations or changing urban environment) that may lead to different results. Moreover, while numerical studies suggest economic benefits, the payback periods (ranging from 7 to 43 years) can be long, especially in regions with low energy prices. This may hinder large-scale implementation unless additional subsidies or incentives are provided. Additionally, as far as the experimental studies is concerns, many of these are based on small-scale test rooms or short-term simulations. Scaling these results to full-scale buildings across diverse climatic zones remains challenging. These often focus on short-term thermal performance (e.g., temperature reductions over a few days) rather than examining long-term field durability, degradation of PCM materials, or sustained performance under repeated cycles. Long-term effects of PCM performance under daily and seasonal cycles are not well-explored. Finally, exploration of bio-based PCM types or advanced encapsulation techniques could lead to better thermal performance, safety and longevity. As PCM technology advances, interdisciplinary research efforts and collaboration between academia and industry will be crucial to overcome these challenges and unlock the full potential of PCM integration in building envelopes, contributing to sustainable and energy-efficient construction practices.

5. Recent application of PCMs in textiles

Numerical studies. The impact of free water on fire protective clothing (FPC) incorporating PCM, particularly under heat and humidity exposure, has recently been explored through mathematical modeling [105]. While previous research has shown the benefits of PCMs in dry FPCs, the presence of water in firefighting garments has been overlooked. The study employed a novel mathematical model, assuming the PCM (here, Rubitherm RT42) incorporated in the thermal inner layer of a 3-layer PCM FPC assembly. Numerical analyses were conducted, varying factors such as PCM textile latent heat, water distribution, and heat flux intensity. Results revealed that the presence of free water can significantly affect PCM efficiency. Steam condensation at the skin reduces PCM liquid fraction at the critical second-degree burn time, diminishing the protective capabilities of the PCM. The study underscored the importance of considering moisture management in PCM FPC design to maximize thermal performance, guiding the selection of suitable PCMs and design strategies in scenarios where free water may be present. The numerical insights suggest promising pathways for integrating PCMs into firefighting garments but underscore challenges such as the interaction between PCM states and environmental conditions. These insights could lead to the selection of PCM compositions better suited for managing heat stress in humid or wet conditions. However, the modeling approach assumes certain uniformities, such as a constant distribution of PCM and specific heat profiles, which may not fully capture all real-world scenarios. Thus, experimental validation is essential to corroborate these findings and account for environmental variability. Finally, future studies for a comprehensive assessment of most affecting factors such as latent heat, heat flux, and water distribution are required in future design strategies.

Experimental studies. In the field of experimental studies, significant advancements have been made in creating functionalized textiles through PCM integration, showing promising thermal and environmental performance. A novel approach [106] introduced this area involves creating thermo-regulated cotton fabric by incorporating an inorganic eutectic mixture of $Na_2HPO_4 \cdot 12\ H_2O$ and $Na_2CO_3 \cdot 10\ H_2O$ as a PCM directly into the structure of the fabric, eliminating the need for microencapsulation. A coating technique using silicone rubber was employed to prepare this thermally-managed fabric. The study investigated the thermo-physical properties of the fabric, revealing a significant enhancement in thermal performance, including a 150% enhancement in the time required to reach a specific temperature. Differential Scanning Calorimetry (DSC) indicated a melting temperature of 28.9 °C and a latent heat of fusion of 14.9 J g^{-1} for the treated cotton fabric. Additionally, the fabric demonstrated durability over multiple thermal cycles without losing its thermal capacity. Analysis confirmed that there was no chemical interaction between the materials in the silicone rubber matrix. While the thickness of the fabric and bending properties remained largely unchanged, air transfer and water permeability were significantly reduced posing challenges for breathability and long-term user comfort. This highlights the need for further material modifications to balance thermal regulation with other performance metrics. The study demonstrated the uniform distribution of PCMs across the textile structure through FESEM-EDS mapping.

Similarly, multifunctional textiles with flexible thermal responses and electromagnetic interference (EMI) shielding properties were developed [107]. A schematic diagram of the proposed smart multifuncional textiles is represented in Fig. 21. Traditional silicone resin encapsulation of textiles can often hinder thermal responses, limiting their versatility. In this study, a solid–solid PCM coating was developed by self-crosslinking polyethylene glycol (PEG) using highly reactive silanol groups. This innovative PCM coating retained the phase change properties of the original PEG while ensuring excellent shape stability. These solid–solid PCM-coated textiles were then decorated with silver nanowires (AgNWs) through a scalable dip coating process. Remarkably, these textiles exhibited an outstanding EMI shielding effectiveness of approximately 72 dB with a thickness of 0.26 mm, coupled with an impressive energy storage density of 86.6 J g^{-1}. Furthermore, these textiles displayed flexible thermal responses, including high joule heating efficiency, excellent heat storage and release, efficient heat dissipation, and infrared anti-counterfeiting features. Overall, these multifunctional textiles hold great promise for various applications, including wearable smart clothing, electromagnetic radiation protection, and personalized thermal management. While promising, the addition of nanomaterials like AgNWs introduces concerns regarding scalability, environmental stability, and long-term performance. A deeper investigation into their environmental impact and stability under repeated thermal cycling is necessary to evaluate their full potential.

Another notable experimental approach [108] involves producing PCMs through one-step bulk-suspension polymerization, focusing on grafting polyethylene glycol (PEG) onto a polystyrene/maleic anhydride copolymer (SMA) matrix. The process involves using poly(vinyl alcohol) as a suspending agent. The resulting SMA-g-PEG phase change microspheres can be used in combination with fibers to produce smart thermoregulated phase-change fabrics. The proposed material displayed remarkable thermal properties, with a melting enthalpy of 79.3 J g^{-1} and excellent stability, as evidenced by minimal changes in latent heat after 1000 thermal cycles. These microspheres, with smooth surfaces and particle sizes ranging from 100 to 150 μm, could be directly utilized as PCMs without further processing. Moreover, the study established a quantitative relationship between grafting rate and enthalpy for PEG-based PCMs, which represents a novel contribution. Nevertheless, future studies could benefit from exploring alternative encapsulation strategies that maintain or enhance these thermal properties while improving environmental sustainability and reducing material costs.

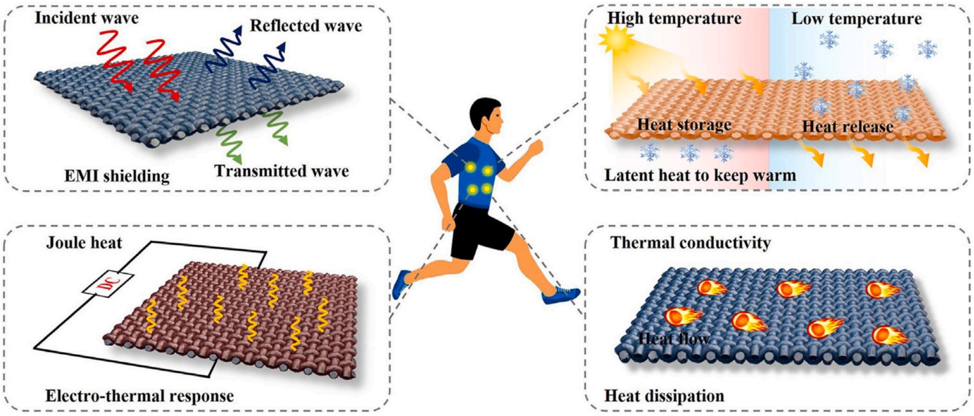


Fig. 21. Schematic diagram of proposed smart multifuncional textiles.
Source: Picture taken from Ref. [107], with permission.

Further exploration into smart thermoregulated fabrics is represented by the study proposed by Kong et al. [109]. The research presents a significant advancement in the development of smart textiles with structural colors, emphasizing high color visibility, stability, and thermoregulating capabilities. The structural colored textiles achieved their vibrant appearance through amorphous photonic structures (APSs) assembled on the textile surface, utilizing polysulfide microspheres of varying sizes to produce purple, green, orange, and red structural colors. Waterborne polyurethane (PEG2000-based) PCM (WPUPCM) played a crucial role as an adhesive, ensuring the stability of APSs on the textiles. The flexibility and durability of these textiles were demonstrated through folding, rinsing, and kneading tests. The WPUPCM exhibited a phase change temperature of 37.0 °C and a melting enthalpy of 74.7 J g^{-1}, enabling the textiles to efficiently regulate body temperature by absorbing and releasing energy near the phase change temperature. This thermoregulating capability was confirmed through heating and cooling tests, highlighting the potential of the textiles for personal thermal management and energy-efficient clothing solutions, ultimately contributing to the alleviation of energy consumption concerns. However, any variation in water permeability, which may affect their practical application, was not investigated. Nevertheless, these multifunctional textile designs open opportunities for wearable energy-efficient clothing solutions, highlighting the convergence of thermoregulation and visual functionalities.

Finally, incorporating cellulose-based materials into PCM applications is gaining momentum. The work of Samanta et al. [110] proposed thermo-regulating cellulose nanofibril (CNF) fibers with incorporated cellulose nanocrystal (CNC)-stabilized PCM microspheres. The PCM, a paraffin wax, was effectively dispersed within CNF suspension to form a stable and spinnable dope, thanks to a Pickering emulsion approach using CNC as a stabilizer. The resulting fibers demonstrated excellent thermo-regulating properties, effectively absorbing and releasing heat without undergoing structural changes while preserving the integrity of the PCM domains. The study revealed a correlation between CNF concentration and the size and dispersion of the PCM microspheres, with lower CNF content leading to larger PW domains and higher enthalpies of fusion, indicative of superior thermo-regulating capacity. This work highlighted the trade-off between efficient thermo-regulation and mechanical performance, which can be fine-tuned by adjusting the PW content. Even at a high PCM content of 40 wt%, the fibers exhibited impressive breaking tenacity. Furthermore, they demonstrated resistance against thermal leaching and good wash fastness. The results achieved show the engineered material as promising for a wide range of applications, particularly in textiles, where the renewable nature of CNF makes it an environmentally friendly choice. The authors state that future research could focus on optimizing paraffin wax content and its localization within fibers, as well as exploring post-treatment operations to further improve mechanical properties.

Therefore, the integration of PCMs into textiles represents an innovative approach for the development of smart textiles for thermal regulation, enhanced safety, and multifunctional applications (see Table 3). Through numerical and experimental studies, recent research significantly advanced the understanding of PCM-integrated fabrics, showing new methodologies, integration strategies, novel materials, several PCM materials, and promising results. In detail, a variety of PCM materials have been explored, including paraffin wax, eutectic mixtures of inorganic salts and solid–solid phase change coatings based on polyethylene glycol (PEG). Interestingly, the development of phase change microspheres and the use of silicone rubber and waterborne polyurethane as matrices for PCM incorporation highlight a trend towards enhancing the compatibility and efficiency of PCMs within textile structures. Among the most relevant results were the development of fire protective clothing that considers moisture management, thermo-regulated cotton fabrics with enhanced thermal performance, and multifunctional textiles offering both thermal regulation and electromagnetic interference (EMI) shielding. These achievements demonstrate the potential of PCMs to revolutionize the textile industry by providing solutions that meet the specific thermal and functional needs of users in various environments. The path forward calls for a deeper exploration of novel PCM materials and composites with improved thermal properties, environmental sustainability, and cost-effectiveness. Moreover, there is a growing interest in enhancing the durability and stability of PCM-incorporated textiles under real-world conditions and prolonged exposure scenarios, including resistance to repeated washing, humidity and mechanical stress. Additionally, the development of smart textiles that can dynamically adjust their thermal properties in response to environmental changes remains a promising area of research. Despite significant progress, gaps remain in understanding and quantifying the long-term performance and environmental impact of PCM-incorporated textiles. Still, the balance between thermal regulation capabilities and other textile properties such as breathability, flexibility, and comfort needs further exploration. Future work could explore hybrid approaches or multifunctional composites to achieve an optimal balance between thermal management, breathability, durability, and environmental sustainability. Additionally, more research is needed to explore the interactions between different PCM chemistries and textile matrices and optimize the encapsulation and integration techniques of PCMs into textiles to prevent leakage and degradation over time, while maintaining the desired thermal performance. Furthermore, bridging the gap between numerical modeling insights and experimental validation will strengthen the confidence in these technologies.

Table 3
Recent applications of PCM in textiles.

PCM type	Research	Mode	Purpose	Year
Organic s-l (RT42)	Num.	Encapsulated	TM with moisture/Fire	2023 [105]
Inorganic s-l mixture ($Na_2HPO_4 \cdot 12H_2O$, $Na_2CO_3 \cdot 10H_2O$)	Exp.	Coating	TM/CYC	2023 [106]
Organic s-s (PEG-based)	Exp.	Direct	TM/CYC/EMI	2023 [107]
Organic s-s (PEG-based)	Exp.	Direct	TM/CYC	2023 [108]
Organic s-s (PEG-based)	Exp.	Encapsulated	TM/CYC	2023 [109]
Paraffin-based	Exp.	Encapsulated	TM/CYC	2023 [110]

6. Conclusions

Key findings. This review has highlighted the significant advancements in the application of PCMs across diverse sectors, including electronics, solar energy systems, buildings, and textiles. The findings illustrate the versatility of PCMs in addressing critical thermal management challenges and their potential to enhance energy efficiency and sustainability. The key findings in the various sectors are summarized below:

- electronics: PCMs have proven effective in mitigating thermal shocks and enhancing the safety and performance of electronic devices and lithium-ion batteries. Specifically, PCM-based solutions prevent overheating and thermal runaway while maintaining optimal operating temperatures, especially during peak usage. These systems demonstrate significant advantages over traditional air-cooled methods by avoiding the need for oversized heat sinks.
- solar energy systems: in photovoltaic panels, PCMs stabilize and reduce temperatures, extending system longevity. When integrated into solar desalination technologies, PCM-based systems enhance freshwater yield by increasing evaporation over time and ensuring stable operation despite intermittent solar energy availability.
- buildings: the integration of PCMs into building envelopes offers dynamic thermal regulation, reduced energy consumption, and improved thermal comfort, contributing to the development of energy-efficient and environmentally sustainable structures.
- textiles: PCM-embedded fabrics enhance thermal comfort by regulating temperature fluctuations, offering energy-saving solutions and improved usability in various applications.

Insights from comparative performance of PCMs in various applications. For the sake of completeness, an overview is provided on the performance in the different application fields considered of various types of PCM (organic, inorganic and composite). Being cost-effective, non-corrosive, stable under varying operating conditions, and characterized by high latent heat, organic paraffin-based PCMs were extensively used in a wide range of electronic systems, solar energy systems and buildings. Indeed, they have proven effective in maintaining thermal equilibrium under various operating conditions. However, their thermal conductivity remains a limitation, reducing their response time, especially in electronic devices and solar collector systems with very high heat fluxes. Moreover, their compatibility with electronic materials and the mechanical stability of encapsulated forms need to be explored more systematically and methodologically. Conversely, inorganic PCMs, such as salt hydrates, although offering superior thermal conductivity, may present problems related to corrosion, phase separation, and thus cycle stability, particularly under extreme temperature variations. Paraffin-based composite PCMs, engineered by incorporating conductive agent, are emerging as suitable candidates especially for electronic systems, showing the promise of overcoming the aforementioned limitations by combining the advantageous properties of organic and inorganic PCMs while enhancing thermal management capabilities. Finally, in emerging textile applications, polyethylene glycol (PEG)-based solid–solid PCMs were mostly tested. These showed promise in maintaining temperature stability. Yet, issues like reduced breathability and mechanical properties limit their widespread implementation. Also, bio-based or natural PCMs such as cellulose nanocrystals combined with paraffin wax also demonstrated excellent environmental sustainability and functionality. These systems balance thermal regulation performance with environmental impact considerations. However, challenges such as durability under mechanical stress and repeated wash cycles remain prominent. This comparison illustrates that although all these PCMs offer specific advantages in terms of thermal energy management, flexibility or environmental sustainability, their performance is highly dependent on the application context. The comparative analysis emphasizes the need for tailored solutions that take into account application requirements, material properties, thermal performance, environmental impact and durability. Recently, an interesting study was published, that systematically reviews the results of research on the chemical modification of organic PCMs at the molecular level, discussing the progress of research in adjusting thermophysical properties, improving stability and developing multifunctional materials [111]. Future research should prioritize the development of hybrid and multifunctional PCMs to optimize these properties in all fields of application.

Expected innovation. It is worth noting that the results obtained in each area do not depend solely on material selection, but are also strongly related to the integration techniques and synergy between PCM and other materials or technologies used concurrently (e.g., metal foams, nanomaterials, and hybrid cooling systems). As anticipated, the materials commonly utilized across these sectors include organic compounds such as paraffin waxes and fatty acids, inorganic salts, and innovative composites enhanced with nanomaterials such as graphene and metal foams [112]. These materials have been selected for their specific thermal properties, including melting temperature, latent heat of fusion, and thermal conductivity, tailored to meet the unique requirements of each application. Given the current state, further fascinating developments are expected in the short-term future, with research focusing on hybrid thermal management systems, optimization of integration processes, application of advanced computational modeling [113] and machine learning techniques for performance optimization, and exploration of new biodegradable and environmentally friendly PCM-based materials with improved thermal properties. In perspective, one promising avenue for advancing the utilization of PCMs in sustainable thermal engineering lies in harnessing generative artificial intelligence (AI) for topology optimization [114]. By leveraging AI algorithms, particularly those capable of generative design, researchers can explore novel PCM-based solutions with optimized material distribution and geometric configurations. This approach holds significant potential for enhancing the efficiency and effectiveness of PCM systems, ensuring optimal heat transfer characteristics and structural integrity. The integration of generative AI in PCM design not only streamlines the optimization process but also opens new frontiers for developing innovative thermal management solutions that are tailored to specific applications and performance requirements.

Challenges and future directions. Despite these achievements, gaps remain in understanding and exploring the long-term performance, environmental impact, economic feasibility of PCM solutions and the development of standardized guidelines for material selection and application. Indeed, to date, a limited number of studies have focused on the long-term stability, durability, and shape and chemical stability of PCM systems under real operating conditions and repeated thermal cycling, as well as the environmental impact and lifecycle of PCM-enhanced systems (including production, operation, and end-of-life stages). Prevention of phase separation and degradation under repeated thermal cycling may, e.g., be accomplished through chemical modifications or encapsulation techniques. In this context, studies such as the recent investigation into ester-based phase change cold storage materials, synthesized by combining polyethylene glycol and lauric acid, demonstrate promising approaches for tailoring melting points through molecular weight adjustments and reactant molar ratios [115]. In addition, the economic analysis of integrating PCMs into various systems is often ignored. Future studies should include detailed cost-benefit analyses to assess the commercial feasibility of PCM-enhanced technologies. Another aspect to study in more detail is the synthesis of novel PCMs with tailored melting points to better accommodate the specific temperature requirements of various applications and/or different climatic conditions. Finally, a significant gap exists between studies of laboratory-scale systems and studies that approach the scalability of PCM technologies for real-world applications. Research is needed to bridge this gap by focusing on pilot-scale demonstrations and field testing. Addressing these challenges and concretely fulfilling the potential of PCMs in various applications will require an interdisciplinary approach, combining insights from materials science, engineering, and sustainability studies. In conclusion, in conducting this comprehensive exploration of PCM applications, we aim to condense the latest research findings, particularly focusing on the post-2022 literature, highlight emerging trends and identify challenges requiring further investigation aiming at a more widespread and definitive use of PCM-based systems. Through this review, authors attempt to provide a holistic perspective, encouraging future efforts towards sustainable and efficient thermal energy management in response to technological advancements and climate change challenges.

CRediT authorship contribution statement

Matteo Morciano: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Fasano:** Writing – review & editing, Validation. **Eliodoro Chiavazzo:** Writing – review & editing, Validation. **Luigi Mongibello:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We acknowledge the financial support of the research contract PTR 2022/24 - ENEA (Studio di sistemi di accumulo termico innovativi basati sull’utilizzo di nano-PCM dinamici: Modellazione e analisi sperimentale delle proprietà termofisiche, realizzazione e testing di un prototipo, e analisi delle possibili applicazioni di tale tecnologia nell’ambito dell’accumulo termico) funded by Ministero dell’Ambiente e della Sicurezza Energetica (MASE).

Data availability

No data was used for the research described in the article.

References

[1] Kumar N, Gupta SK, Sharma VK. Application of phase change material for thermal energy storage: An overview of recent advances. Mater Today: Proc 2021;44:368–75.

[2] Shi J, Qin M, Aftab W, Zou R. Flexible phase change materials for thermal energy storage. Energy Storage Mater 2021;41:321–42.

[3] Morciano M, Alberghini M, Fasano M, Almiento M, Calignano F, Manfredi D, et al. 3D printed lattice metal structures for enhanced heat transfer in latent heat storage systems. J Energy Storage 2023;65:107350.

[4] Ribezzo A, Bergamasco L, Morciano M, Fasano M, Mongibello L, Chiavazzo E. Experimental analysis of carbon-based phase change materials composites for a fast numerical design of cold energy storage systems. Appl Therm Eng 2023;120907.

[5] Ling Z, Zhang Z, Shi G, Fang X, Wang L, Gao X, et al. Review on thermal management systems using phase change materials for electronic components, li-ion batteries and photovoltaic modules. Renew Sustain Energy Rev 2014;31:427–38.

[6] Kahwaji S, Johnson MB, Kheirabadi AC, Groulx D, White MA. A comprehensive study of properties of paraffin phase change materials for solar thermal energy storage and thermal management applications. Energy 2018;162:1169–82.

[7] Pandey A, Hossain M, Tyagi V, Abd Rahim N, Jeyraj A, Selvaraj L, et al. Novel approaches and recent developments on potential applications of phase change materials in solar energy. Renew Sustain Energy Rev 2018;82:281–323.

[8] Wang X, Li W, Luo Z, Wang K, Shah SP. A critical review on phase change materials (pcm) for sustainable and energy efficient building: Design, characteristic, performance and application. Energy Build 2022;260:111923.

[9] Gencel O, Sarı A, Ustaoglu A, Hekimoglu G, Erdogmus E, Yaras A, et al. Eco-friendly building materials containing micronized expanded vermiculite and phase change material for solar based thermo-regulation applications. Constr Build Mater 2021;308:125062.

[10] Mondal S. Phase change materials for smart textiles–an overview. Appl Therm Eng 2008;28(11–12):1536–50.

[11] Bianco V, De Rosa M, Vafai K. Phase-change materials for thermal management of electronic devices. Appl Therm Eng 2022;214:118839.

[12] Kandasamy R, Wang X-Q, Mujumdar AS. Application of phase change materials in thermal management of electronics. Appl Therm Eng 2007;27(17–18):2822–32.

[13] Bibin C, Vijayaram M, Suriya V, Ganesh RS, Soundarraj S. A review on thermal issues in li-ion battery and recent advancements in battery thermal management system. Mater Today: Proc 2020;33:116–28.

[14] Shahjalal M, Shams T, Islam ME, Alam W, Modak M, Hossain SB, et al. A review of thermal management for li-ion batteries: Prospects, challenges, issues. J Energy Storage 2021;39:102518.

[15] Sharma DK, Prabhakar A. A review on air cooled and air centric hybrid thermal management techniques for li-ion battery packs in electric vehicles. J Energy Storage 2021;41:102885.

[16] Akinlabi AH, Solyali D. Configuration, design, and optimization of air-cooled battery thermal management system for electric vehicles: A review. Renew Sustain Energy Rev 2020;125:109815.

[17] Talele V, Thorat P, Gokhale YP, Mathew V. Phase change material based passive battery thermal management system to predict delay effect. J Energy Storage 2021;44:103482.

[18] Luo J, Zou D, Wang Y, Wang S, Huang L. Battery thermal management systems (btms) based on phase change material (pcm): A comprehensive review. Chem Eng J 2022;430:132741.

[19] Chen F, Huang R, Wang C, Yu X, Liu H, Wu Q, et al. Air and pcm cooling for battery thermal management considering battery cycle life. Appl Therm Eng 2020;173:115154.

[20] Shen Z-G, Chen S, Liu X, Chen B. A review on thermal management performance enhancement of phase change materials for vehicle lithium-ion batteries. Renew Sustain Energy Rev 2021;148:111301.

[21] Srivastava G, Nandan R, Das MK. Thermal runaway management of li ion battery using pcm: A parametric study. Energy Convers Manage: X 2022;16:100306.

[22] Chen M, Yu Y, Ouyang D, Weng J, Zhao L, Wang J, et al. Research progress of enhancing battery safety with phase change materials. Renew Sustain Energy Rev 2024;189:113921.

[23] Sikiru S, Oladosu TL, Amosa TI, Kolawole SY, Soleimani H. Recent advances and impact of phase change materials on solar energy: A comprehensive review. J Energy Storage 2022;53:105200.

[24] Javadi F, Metselaar H, Ganesan P. Performance improvement of solar thermal systems integrated with phase change materials (pcm), a review. Sol Energy 2020;206:330–52.

[25] Jamil F, Hassan F, Shoeibi S, Khiadani M. Application of advanced energy storage materials in direct solar desalination: A state of art review. Renew Sustain Energy Rev 2023;186:113663.

[26] Kumar R, Pandey A, Samykano M, Aljafari B, Ma Z, Bhattacharyya S, et al. Phase change materials integrated solar desalination system: An innovative approach for sustainable and clean water production and storage. Renew Sustain Energy Rev 2022;165:112611.

[27] Aljehani A, Razack SAK, Nitsche L, Al-Hallaj S. Design and optimization of a hybrid air conditioning system with thermal energy storage using phase change composite. Energy Convers Manage 2018;169:404–18.
[28] Pasupathy A, Velraj R, Seeniraj R. Phase change material-based building architecture for thermal management in residential and commercial establishments. Renew Sustain Energy Rev 2008;12(1):39–64.
[29] Mourad A, Aissa A, Abed AM, Smaisim GF, Toghraie D, Fazilati MA, et al. The numerical analysis of the melting process in a modified shell-and-tube phase change material heat storage system. J Energy Storage 2022;55:105827.
[30] Liu C, Geng L, Xiao T, Liu Q, Zhang S, Ali HM, et al. Recent advances of plasmonic nanofluids in solar harvesting and energy storage. J Energy Storage 2023;72:108329.
[31] Ismail KA, Lino FA, Machado PLO, Teggar M, Arıcı M, Alves TA, et al. New potential applications of phase change materials: A review. J Energy Storage 2022;53:105202.
[32] Faraj K, Khaled M, Faraj J, Hachem F, Castelain C. Phase change material thermal energy storage systems for cooling applications in buildings: A review. Renew Sustain Energy Rev 2020;119:109579.
[33] Aridi R, Yehya A. Review on the sustainability of phase-change materials used in buildings. Energy Convers Manage: X 2022;15:100237.
[34] Yan S-R, Fazilati MA, Samani N, Ghasemi HR, Toghraie D, Nguyen Q, et al. Energy efficiency optimization of the waste heat recovery system with embedded phase change materials in greenhouses: a thermo-economic-environmental study. J Energy Storage 2020;30:101445.
[35] Yan S, Fazilati MA, Toghraie D, Khalili M, Karimipour A. Energy cost and efficiency analysis of greenhouse heating system enhancement using phase change material: An experimental study. Renew Energy 2021;170:133–40.
[36] Tyagi V, Chopra K, Kalidasan B, Chauhan A, Stritih U, Anand S, et al. Phase change material based advance solar thermal energy storage systems for building heating and cooling applications: A prospective research approach. Sustain Energy Technol Assess 2021;47:101318.
[37] Hu X, Gong X, Zhu F, Xing X, Li Z, Zhang X. Thermal analysis and optimization of metal foam pcm-based heat sink for thermal management of electronic devices. Renew Energy 2023;212:227–37.
[38] Zhang D-X, Zhu C-Y, Huang B-H, Duan X-Y, Gong L, Xu M-H. Thermal control performance evaluation of a phase change material-based heat sink for the electronic device suffering transient heat flux shock. Appl Therm Eng 2023;230:120760.
[39] Etminan E, Alimohammadi M, Barani E, Taheri A, Passandideh-Fard M, Sardarabadi M. On the performance of an innovative electronic chipset thermal management module based on energy storage unit concept utilizing nano-additive phase change material (npcm). J Energy Storage 2022;50:104244.
[40] Ye J, Mo S, Jia L, Chen Y. Experimental performance of a led thermal management system with suspended microencapsulated phase change material. Appl Therm Eng 2022;207:118155.
[41] Nemoto K, Takeuchi R, Baba M, Takeda M, Yamada N. Output power leveling of on-chip thermoelectric generator using a solid–solid phase change material. J Energy Storage 2022;56:106119.
[42] SR AK, Sivan S, Midhun V, Behera SR. Experimental and numerical investigation of solid–solid phase change material assisted heat sink with integrated heat pipe for electronic cooling. J Energy Storage 2023;59:106494.
[43] Mao Y, Zhong M, Wang JX. Dimensionless study of phase-change-based thermal protection for pulsed electromagnetic machines: Towards heat absorption-dissipation matching. Appl Energy 2023;352:121882.
[44] Wang J-X, Qian J, Wang N, Zhang H, Cao X, Liu F, et al. A scalable microencapsulated phase change material and liquid metal integrated composite for sustainable data center cooling. Renew Energy 2023.
[45] Fu W, Yan X, Gurumukhi Y, Garimella VS, King WP, Miljkovic N. High power and energy density dynamic phase change materials using pressure-enhanced close contact melting. Nat Energy 2022;7(3):270–80.
[46] He J, Chu W, Wang Q. Experimental study on pressure-enhanced close contact melting with pcms for stable temperature control of high heat flux electronic devices. Appl Therm Eng 2023;230:120707.
[47] Balan AE, Al-Sharea A, Lavasani EJ, Tanasa E, Voinea S, Dobrica B, et al. Paraffin-multilayer graphene composite for thermal management in electronics. Materials 2023;16(6):2310.
[48] Qu J, Liu Y, Zhang J, Jin Z, Chen Y, Zhao X. Experimental study on heat transfer during melting in metal and carbon foam saturated with phase-change materials for temperature control in electronic devices. Appl Therm Eng 2024;236:121681.
[49] Alqaed S, Almehmadi FA, Mustafa J, Husain S, Cheraghian G. Effect of nano phase change materials on the cooling process of a triangular lithium battery pack. J Energy Storage 2022;51:104326.
[50] Daneh-Dezfuli A, Pordanjani AH. Investigation of passive method in thermal management of lithium-ion batteries at different discharge rates by changing the number of cavities containing phase change materials. J Energy Storage 2022;52:104758.
[51] Mei J, Shi G, Liu H, Wang Z, Chen M. Investigation on the optimization strategy of phase change material thermal management system for lithium-ion battery. J Energy Storage 2022;55:105365.
[52] Wang Z, Du C, Qi R, Wang Y. Experimental study on thermal management of lithium-ion battery with graphite powder based composite phase change materials covering the whole climatic range. Appl Therm Eng 2022;216:119072.
[53] Chen G, Shi Y, Ye H, Kang H. Experimental study on phase change material based thermal management design with adjustable fins for lithium-ion battery. Appl Therm Eng 2023;221:119808.
[54] Sun Z, Guo Y, Zhang C, Whitehouse J, Zhou Q, Xu H, et al. Experimental study of battery passive thermal management system using copper foam-based phase change materials. Int J Thermofluids 2023;17:100255.
[55] Ge X, Li X, Jin Y, Zhang G, Deng J, Ge J. Experimental investigation on thermal management system of composite phase change material coupled with serpentine tubes for battery module. Appl Therm Eng 2023;219:119501.
[56] Yang X, Deng G, Cai Z, Li H, Zeng J, Yang H. Experimental study on novel composite phase change materials with room-temperature flexibility and high-temperature shape stability in a battery thermal management system. Int J Heat Mass Transfer 2023;206:123953.
[57] Chen R, Ge X, Zhong Y, Jiang L, Zhang G, Zhang J, et al. Experimental study of phase change microcapsule-based liquid cooling for battery thermal management. Int Commun Heat Mass Transfer 2023;146:106912.
[58] Xin Q, Yang T, Zhang H, Yang J, Zeng J, Xiao J. Experimental and numerical study of lithium-ion battery thermal management system using composite phase change material and liquid cooling. J Energy Storage 2023;71:108003.
[59] Hu L, An Y, Zhang L, Mai L, Ma T, An Q, et al. Shape-stabilized phase change material based on mof-derived oriented carbon nanotubes for thermal management of lithium-ion battery. J Energy Storage 2023;72:108520.
[60] Uniyal A, Prajapati YK, Suman S. Heat transfer and melting characteristics of the phase change material inside u-tube based evacuated tube solar collector. J Energy Storage 2023;62:106918.
[61] Peralta I, Fachinotti VD, Koenders EA, Caggiano A. Computational design of a massive solar-thermal collector enhanced with phase change materials. Energy Build 2022;274:112437.
[62] Assareh E, Riaz A, Ahmadinejad M, Hoseinzadeh S, Abdehvand MZ, Keykhah S, et al. Enhancing solar thermal collector systems for hot water production through machine learning-driven multi-objective optimization with phase change material (pcm). J Energy Storage 2023;73:108990.
[63] Nair AM, Wilson C, Kamkari B, Hodge S, Huang MJ, Griffiths P, et al. Energy and exergy analysis of a multipass macro-encapsulated phase change material/expanded graphite composite thermal energy storage for domestic hot water applications. Energy Convers Manage: X 2024;24:100788.
[64] Pawar VR, Sobhansarbandi S. Heat transfer enhancement of a pcm-porous metal based heat pipe evacuated tube solar collector: An experimental study. Sol Energy 2023;251:106–18.
[65] Aramesh M, Shabani B. Experimental evaluation of a self storage integrated evacuated tube solar thermal collector. J Energy Storage 2023;62:106920.
[66] Prakash R, Kamatchi R. Design, fabrication and investigations of natural convection step serrated fin plate integrated trough array low-cost collector for solar air heating: An application to agricultural crop drying. Sol Energy 2023;254:42–53.
[67] Senobar H, Aramesh M, Shabani B. Evacuated tube solar thermal collector with enhanced phase change material thermal storage: An experimental study. J Energy Storage 2022;46:103838.
[68] Wen X, Ji J, Li Z, Song Z. Performance analysis of a concentrated system with series photovoltaic/thermal module and solar thermal collector integrated with pcm and teg. Energy 2022;249:123777.
[69] Wen X, Ji J, Li Z, Song Z. Performance assessment of the hybrid pv-mchp-te system integrated with pcm in all-day operation: A preliminary numerical investigation. Energy 2023;278:127932.
[70] Jiang J, Hong Y, Li Q, Du J. Evaluating the impacts of fin structures and fin counts on photovoltaic panels integrated with phase change material. Energy 2023;283:129143.
[71] Chibani A, Merouani S, Laidoudi H, Dehane A, Bendada L, Lamiri L, et al. Numerical simulation and analysis of heat transfer and melting rate of nano-enhanced pcm composite embedded in a concentrator photovoltaic system. J Energy Storage 2023;73:109247.
[72] Chibani A, Merouani S, Laidoudi H, Dehane A, Morakchi MR, Bendada L. Analysis and optimization of concentrator photovoltaic system using a phase change material (rt 35hc) combined with variable metal fins. J Energy Storage 2023;72:108283.
[73] Hong Y, Bai D, Huang Y, Du J. Effect of t-shaped fin arrangements on the temperature control performance of a phase change material heat sink. Int Commun Heat Mass Transfer 2023;148:107073.
[74] Adibpour S, Raisi A, Sajadi A, Rosengarten G. A numerical examination on the use of phase change materials to improve the sun-tracking photovoltaic panels' performance. J Energy Storage 2023;70:108075.
[75] Li J, Zhang W, Xie L, Li Z, Wu X, Zhao O, et al. A hybrid photovoltaic and water/air based thermal (pvt) solar energy collector with integrated pcm for building application. Renew Energy 2022;199:662–71.
[76] Hamada A, Emam M, Refaey H, Moawed M, Abdelrahman M. Investigating the performance of a water-based pvt system using encapsulated pcm balls: An experimental study. Energy 2023;284:128574.

[77] Sehrawat R, Sahdev RK, Chhabra D, Tiwari S, Khargotra R, Singh T, et al. Environmental and economic management study of phase change material integrated bifacial photovoltaic thermal-greenhouse drying system: A thermal approach. Energy Convers Manage 2023;286:117065.

[78] Du J, Bai D, Meng X, Jiao F, Hong Y. Effect of cantor fractal fin arrangements on the thermal performance of a photovoltaic-phase change material system: An experimental study. Int J Heat Mass Transfer 2024;219:124853.

[79] Gad R, Mahmoud H, Hassan H. Performance evaluation of direct and indirect thermal regulation of low concentrated (via compound parabolic collector) solar panel using phase change material-flat heat pipe cooling system. Energy 2023;274:127323.

[80] Gad R, Mahmoud H, Ookawara S, Hassan H. Evaluation of thermal management of photovoltaic solar cell via hybrid cooling system of phase change material inclusion hybrid nanoparticles coupled with flat heat pipe. J Energy Storage 2023;57:106185.

[81] Ranawade V, Nalwa KS. Multilayered pcms-based cooling solution for photovoltaic modules: Modelling and experimental study. Renew Energy 2023;216:119136.

[82] Asefi G, Ma T, Wang R. Techno-economic evaluation of photovoltaic thermal system integrated with porous phase change materials: Case studies in China. Energy Convers Manage 2023;290:117227.

[83] Khanegah MR, Ashrafizadeh A, Borooghani D, Torabi F. Performance evaluation of a concentrated photovoltaic/thermal system based on water and phase change material: Numerical study and experimental validation. Appl Therm Eng 2023;120936.

[84] Hu Z, Li K, Wang Z, He W, Zhu M, Liu X. Numerical study on using multichannel tube and pcm for improving thermal and electrical performance of a photovoltaic module. Sol Energy 2023;265:112058.

[85] Mustafa J, Alqaed S, Sharifpur M. Two phase simulation of solar still in the presence of phase change materials in its bottom and aluminum nanoparticles in the water. Case Stud Therm Eng 2023;49:103357.

[86] Kumar A, Kushwah A. A novel reduced nano-phase change material based absorber for enhancing the water productivity and performance of solar desalination system. Mater Lett 2023;341:134298.

[87] Aly WI, Tolba MA, Abdelmagied M. Experimental investigation and performance evaluation of an oval tubular solar still with phase change material. Appl Therm Eng 2023;221:119628.

[88] Zhang M, Sun K, Zheng Z, Liu H, Wang X. Development of mxene-decorated sodium alginate/sio2@ n-docosane hierarchical phase-change microcapsules for solar-driven sustainable seawater desalination. Desalination 2023;550:116380.

[89] Liu H, Tian D, Zheng Z, Wang X, Qian Z. Mxene-decorated magnetic phase-change microcapsules for solar-driven continuous seawater desalination with easy salt accumulation elimination. Chem Eng J 2023;458:141395.

[90] Li W, Zheng Z, Liu H, Wang X. A solar-driven seawater desalination and electricity generation integrating system based on carbon black-decorated magnetic phase-change composites. Desalination 2023;562:116713.

[91] M'hamdi Y, Baba K, Tajayouti M, Nounah A. Energy, environmental, and economic analysis of different buildings envelope integrated with phase change materials in different climates. Sol Energy 2022;243:91–102.

[92] Al-Yasiri Q, Szabó M. Building envelope-combined phase change material and thermal insulation for energy-effective buildings during harsh summer: Simulation-based analysis. Energy Sustain Dev 2023;72:326–39.

[93] Al-Yasiri Q, Szabó M. Numerical analysis of thin building envelope-integrated phase change material towards energy-efficient buildings in severe hot location. Sustainable Cities Soc 2023;89:104365.

[94] Kumar D, Alam M, Sanjayan J, Harris M. Comparative analysis of form-stable phase change material integrated concrete panels for building envelopes. Case Stud Constr Mater 2023;18:e01737.

[95] Terhan M, Ilgar G. Investigation of used pcm-integrated into building exterior walls for energy savings and optimization of pcm melting temperatures. Constr Build Mater 2023;369:130601.

[96] Khan M, Khan MM, Irfan M, Ahmad N, Haq MA, Khan I, et al. Energy performance enhancement of residential buildings in pakistan by integrating phase change materials in building envelopes. Energy Rep 2022;8:9290–307.

[97] Wang P, Liu Z, Liu R, Zhang F, Zhang L. Energy flexibility of pcm-integrated building: Combination parameters design and operation control in multi-objective optimization considering different stakeholders. Energy 2023;268:126753.

[98] Dong Y, Zhang L, Wang P, Liu Z, Su X, Liao H, et al. Potential evaluation of energy flexibility and energy-saving of pcm-integrated office building walls. J Build Eng 2023;107857.

[99] Saurbayeva A, Memon SA, Kim J. Integrated multi-stage sensitivity analysis and multi-objective optimization approach for pcm integrated residential buildings in different climate zones. Energy 2023;127973.

[100] Al-Yasiri Q, Szabó M. Experimental study of pcm-enhanced building envelope towards energy-saving and decarbonisation in a severe hot climate. Energy Build 2023;279:112680.

[101] Gencel O, Hekimoglu G, Sarı A, Ustaoglu A, Subasi S, Marasli M, et al. Glass fiber reinforced gypsum composites with microencapsulated pcm as novel building thermal energy storage material. Constr Build Mater 2022;340:127788.

[102] Gencel O, Subasi S, Ustaoglu A, Sarı A, Marasli M, Hekimoğlu G, et al. Development, characterization and thermo-regulative performance of microencapsulated phase change material included-glass fiber reinforced foam concrete as novel thermal energy effective-building material. Energy 2022;257:124786.

[103] Gencel O, Bayram M, Subaşı S, Hekimoğlu G, Sarı A, Ustaoglu A, et al. Microencapsulated phase change material incorporated light transmitting gypsum composite for thermal energy saving in buildings. J Energy Storage 2023;67:107457.

[104] Al-Yasiri Q, Szabó M. Hourly analysis of temperature and heat gain reduction for building envelope-compacted phase change material in extremely hot conditions. J Energy Storage 2023;68:107838.

[105] Malaquias AF, Neves S, Campos J. Incorporation of phase change materials in fire protective clothing considering the presence of water. Int J Therm Sci 2023;183:107870.

[106] Kazemi Z, Mortazavi SM, Shahmoradi Ghaheh F. Developing a novel thermo-regulating cotton fabric using inorganic eutectic phase change material. Cellul 2023;30(2):1287–303.

[107] Liang C, Zhang W, Liu C, He J, Xiang Y, Han M, et al. Multifunctional phase change textiles with electromagnetic interference shielding and multiple thermal response characteristics. Chem Eng J 2023;471:144500.

[108] Zhou G, Zeng J, Tang S, Bai Z, Jiang J, Zhang H, et al. One-step bulk-suspension polymerization of polyethylene glycol-based copolymer microspheres for phase change textiles. Polym 2023;15(9):2090.

[109] Kong M, Guo X, Zhang S, Zhang Y, Tang B. Structural colored textiles with high color visibility and stability for intelligent thermoregulating performance. Chem Eng J 2023;473:145332.

[110] Samanta A, Nechyporchuk O, Bordes R. Wet spinning of strong cellulosic fibres with incorporation of phase change material capsules stabilized by cellulose nanocrystals. Carbohydr Polymers 2023;312:120734.

[111] Geng L, Cui J, Zhang C, Yan Y, Zhao J, Liu C. Chemistry in phase change energy storage: Properties regulation on organic phase change materials by covalent bond modification. Chem Eng J 2024;153359.

[112] Ribezzo A, Falciani G, Bergamasco L, Fasano M, Chiavazzo E. An overview on the use of additives and preparation procedure in phase change materials for thermal energy storage with a focus on long term applications. J Energy Storage 2022;53:105140.

[113] Sadr AN, Shekaramiz M, Zarinfar M, Esmaily A, Khoshtarash H, Toghraie D. Simulation of mixed-convection of water and nano-encapsulated phase change material inside a square cavity with a rotating hot cylinder. J Energy Storage 2022;47:103606.

[114] Parrott CM, Abueidda DW, James KA. Multidisciplinary topology optimization using generative adversarial networks for physics-based design enhancement. J Mech Des 2023;145(6):061704.

[115] Geng L, Xiao T, Jiang J, Luo K, Yan Y, Liu C. Wide temperature range phase change cold energy storage by using esterification between polyethylene glycol and lauric acid. Chem Eng J 2024;496:154005.