

Review

Phase Change Materials for Thermal Management in Lithium-Ion Battery Packs: A Review

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Abstract

In the continuous demand for high-performance lithium-ion batteries (LIBs), thermal management control is, these days, crucial with respect to safety, performance, and longevity. As a promising passive solution, Phase Change Materials (PCMs) have been implemented to overcome the conventional battery thermal management (BTM) approaches, including air cooling, liquid cooling, or refrigerant-based systems. Their ability to transfer the heat during phase change processes makes them ideal candidates for further thermal buffers, thus allowing compact and energy-efficient temperature control without extra power consumption. This work encompasses the recent progress in PCM-based battery thermal management systems, with a particular focus on material selection, structural design, and experimental validation. Current advances in composite PCMs, including the use of high-conductivity additives, porous supports, and encapsulation methods, are here appraised in terms of their thermal conductivity, cycling stability, leakage prevention, and overall safety. Comparisons between organic, inorganic, and hybrid PCM types demonstrate the benefits and drawbacks of each class. Ongoing discussion is also directed towards challenges that include low thermal conductivity, limited heat storage capacity, scalability, cost, and flammability. Future development opportunities are also identified in the areas of multifunctional PCMs, hybrid passive–active cooling approaches, scalable processing, and life-cycle considerations.

Keywords: phase change materials; lithium-ion battery; battery thermal management system; passive thermal management



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1. Introduction

The high demand for continuous improvement of lithium-ion batteries (LIBs) across electric vehicles (EVs), portable electronics, and renewable energy storage systems has also led, at the same time, to increasingly effective thermal management systems. It is well known that LIBs are highly sensitive to temperature variations, in which excessive heat accelerates capacity degradation, raises internal resistance, and may even trigger severe safety hazards, such as thermal runaway [1,2]. Therefore, effective thermal regulation is important not only for performance benefits, but also for reliability, safety, and commercial feasibility. Battery thermal management (BTM) systems and conventional practices are used in the EV automotive industry and stationary storage applications today, including in air cooling systems, liquid cooling systems, and refrigerant-based systems. All of these traditional methods present several relevant disadvantages and important limitations. In terms of energy use and efficiency, they consume additional energy simply through their

auxiliary components (e.g., pumps, fans, and compressors), which all lead to a loss in efficiency. Additionally in regard to weight and volume, they are additive components that add to the overall weight and take up volume, thus placing limitations on the EV range and packaging. Plus, they need complex infrastructure, which increases costs and maintenance needs [3,4].

With these difficulties, there is growing interest in developing new, energy-efficient, and scalable thermal management systems. A practical solution is to utilize phase change materials (PCMs). PCMs absorb high amounts of energy as they undergo their solid–liquid phase transition. When the temperature becomes greater than the PCM melting temperature, it will begin absorbing the excess energy and become molten. When the system cools, the PCM will solidify and reject that energy to the system to dampen the thermal swings [5]. This passive approach keeps battery temperatures in the right range without needing constant external energy, supporting steady performance, safety, and longer battery life.

PCMs offer several advantages for passive thermal regulation: they provide energy-efficient heat control without parasitic power consumption, allow for compact system designs suitable for integration at the module or cell level, and they enhance safety by mitigating thermal hotspots and uneven aging [6]. In Figure 1, we highlight these advantages, in terms of energy efficiency, compactness, and improved operational stability.

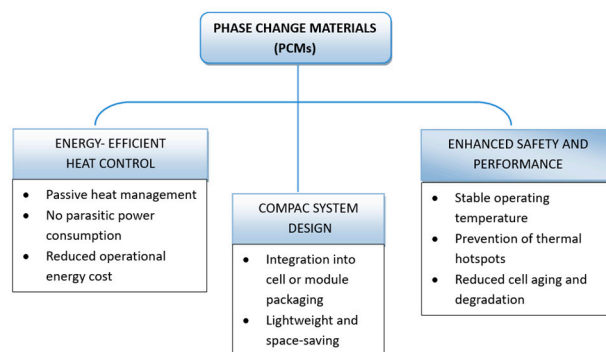


Figure 1. PCM ascendancy in terms of passive thermal regulation implementation.

Recent studies have investigated the current limitations of standard PCMs. Although pure organic PCMs, such as paraffin, support high latent heat, they tend to have low thermal conductivity ($\sim 0.2\text{--}0.4\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and can potentially leak when melting [7]. To address the problems listed above, composite PCMs have been employed, where high conductivity fillers (e.g., graphene, carbon nanotubes, and metal foams) are used to improve heat transfer, porous supports, and polymer encapsulation in order to prevent leaking and hybrid additives (ceramics, flame retardants) to improve mechanical stability and safety [8,9]. These innovations have significantly improved thermal conductivity, structural stability, and cycling performance, broadening PCM applicability in real-world LIB packs. Despite the continued advancements, PCM-based BTM systems still face obstacles to widespread use. Low intrinsic thermal conductivity limits the ability of effective heat dissipation over higher current loads, while repeated melting/solidifying cycles can create increased leaking or degradation [10,11]. Long-term compatibility with cell casings or electrolytes must also be considered to avoid corrosion, while effective thermal runaway mitigation requires PCMs to buffer heat and prevent catastrophic propagation under abuse conditions [11]. Proper selection of PCM melting points ($\approx 20\text{--}50\text{ }^{\circ}\text{C}$) is critical to ensure heat absorption occurs precisely when needed, thereby minimizing uneven temperature distribution, capacity loss, and safety risks [12].

Within a Battery Management System (BMS), thermal management exists in conjunction with the monitoring of voltage, current, state-of-charge (SoC), and state-of-health (SoH)

assessments throughout the BMS ecosystem. The most modern BMS systems proactively interact with the battery thermal management (BTM) subsystems to achieve optimal safety, efficiency, and predictive maintenance [13]. BTM systems are typically characterized as either active, passive, or hybrid systems [14]. Active systems utilize energy from outside sources, such as liquid cooling loops, forced air convection, or thermoelectric devices. For example, a majority of the newer electric vehicles (EVs) use glycol–water coolant loops, while older or budget-friendly cars may solely rely on air cooling, and thermoelectric cooling is used selectively. Active systems offer rapid responsiveness but add weight, cost, and energy consumption. Passive BTM systems, in contrast, exploit materials with high thermal storage capacity, such as PCMs, or high-conductivity heat spreaders (graphite sheets, thermal pastes) to stabilize temperatures without external energy input. Hybrid systems combine both strategies, balancing efficiency and responsiveness by, for example, using PCMs for routine thermal buffering while activating liquid or air cooling during fast charging or extreme loads [14].

In electric vehicles, grid-sized storage systems, and aerospace applications, the optimization of phase change material integration and structural design is important because thermal stability is directly correlated with performance, safety, and lifespan [15]. Recently, battery packs have seen a switch to composite materials utilizing phase change material to address thermal runaway and to improve safety. These changes are undeniably a positive trend, yet many critical challenges still exist, especially relating to conductivity, leaking, compatibility, and durability. However, improvements in composite materials and hybrid systems are advancing PCM-based BTM systems towards actual implementations. Ongoing improvements with multifunctionality, recyclability, and standardization should help to advance BTM systems even further.

Figure 2 illustrates PCM operations, in which the material encapsulates cells, absorbs heat during charge/discharge cycles, and stabilizes temperature via the latent heat plateau. The Battery Temperature vs. Time plots emphasize the flat section of the curve (the temperature plateau during the PCM's phase transition), highlighting its ability to buffer heat and prevent a steep temperature rise. However, the heat arrow labelled Heat → PCM Layer in that simplified schematic does not represent the direction of generation but rather the direction of heat flow being absorbed by the PCM. This simple yet powerful mechanism demonstrates the potential of PCMs as a compact and energy-efficient alternative to traditional cooling systems.

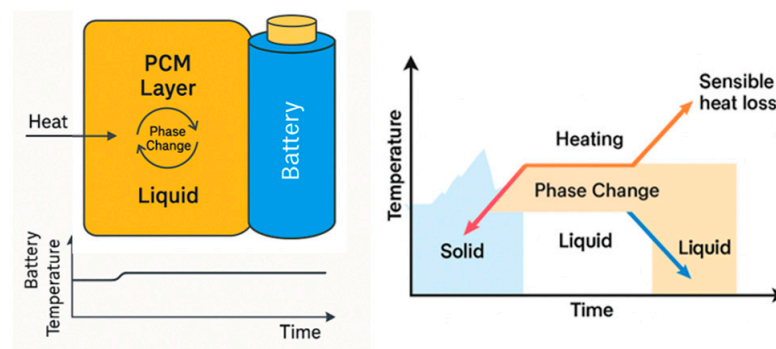


Figure 2. Left—schematic of a PCM working process in BTM; right—the solid–liquid change principle.

In these perspectives, this review highlights important technical challenges, namely low thermal diffusivity and leakage, and it also introduces new research directions for the integration of advanced PCM technologies with next-gen, real-life battery thermal management (BTM) solutions. It provides professional insight and operational guidance with the objective of aiding in the development of efficient, reliable, and safe thermal

management solutions for LIBs. Ultimately, the long-term performance and stability of PCMs is necessary for the commercial adoption of PCMs in lithium-ion battery systems. The long-term stability of PCMs can improve the safety, performance, and lifetime of the battery if the PCM preserves its thermal properties over the course of a few thousand cycles; as such, it is required to consider durability and aging factors, which are key elements in any PCM-based thermal management approach.

2. Fundamentals of Phase Change Materials

2.1. Basic Principle, Applications, and Types

PCMs store and release thermal energy through the latent heat associated with phase changes. In contrast to sensible heat storage, where energy is absorbed simply by raising the temperature of the material, latent heat storage occurs almost isothermally. When a PCM absorbs heat, it undergoes a phase change, usually from solid to liquid, with virtually no temperature increase [16]. When a PCM cools, the stored latent heat is released back to the environment as the material solidifies, buffering temperature variations. In this regard, PCMs can absorb or release large quantities of heat with little or no change in temperature. For example, melting ice requires about 333 J/g of energy at a temperature of 0 °C, but raising the temperature of this mass of water by 1 °C will only require roughly 4.2 J/g [17]. From this example, we see that a PCM like water or ice can store approximately two orders of magnitude greater energy at the melting point than can a typical sensible heat material in the same temperature range.

In practice, the solid–liquid transition is the most commonly utilized in thermal energy storage. They can absorb heat as they melt and return it to the environment upon crystallization, usually over a narrow temperature range. While other transition types, such as solid gas or liquid gas, can store greater latent heats, they are not often viable options due to dramatic changes in volume [18]. Some higher-phase materials can undergo solid–solid phase transitions, in which a change in crystal structure allows for the exchange of latent heat without a phase change. These solid–solid PCMs usually have less leakage and volume variation, although they typically have a lower latent heat capacity than solid–liquid systems [19]. Both mechanisms of thermal energy storage are shown schematically in Figure 3.

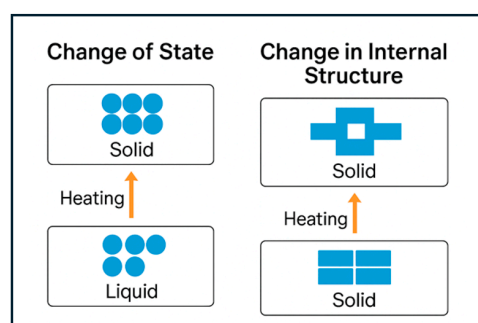


Figure 3. Energy storage via phase or structural change.

Understanding the classifications, characteristics of the materials, and trade-offs are important to implementing PCMs. PCMs can be grouped generally into three classes: organic, inorganic, and eutectic materials [20].

1. Organic PCMs—Carbon-based materials that are characterized by their stability in thermal cycling, chemical inactivity, and non-corrosive properties. Organic PCMs have congruently melting and freezing behavior, which means they will melt and solidify without phase segregation [21]. This makes organic PMCs suitable for repeated thermal cycles, as they are very predictable during the two-phase transformations.

There are many subtypes of organic PCMs, which can generally be divided into the following: (a) paraffin waxes (e.g., octadecane and hexadecane), which are saturated hydrocarbons and have a wide melting point temperature range depending upon the carbon chain length; and (b) fatty acids (e.g., stearic acid and lauric acid), which are essentially the components from natural fats and oils, and these often have sharp melting points. Organic PCMs are safe, easy to work with, and chemically stable, but they are typically not great for thermal conductivity and are flammable [22].

2. Inorganic PCMs—Primarily identified as salt hydrates and low-melting metals and alloys. Their notable advantage over organic PCMs is higher thermal conductivity and latent heat storage capacity, and they are generally non-flammable [23]. Types of inorganic PCMs include the following: (a) salt hydrates (calcium chloride hexahydrate and sodium sulfate decahydrate), which are solid and crystalline materials containing water molecules in their structure; and (b) metals and eutectic alloys (gallium and indium-tin), which melt at a specific temperature and provide a rapid thermal response. However, frequent use of these materials can result in phase separation, supercooling, or corrosion [24].
3. Eutectic PCMs—Prepared by mixing two or more components together as an organic, inorganic, or composite combination, thereby removing erratic melting/freezing points and forming a single, sharp melting/freezing point [20]. This preparation method can lead to phase segregation and compatibility issues over time [25]. These materials are designed to meet the appropriate thermal requirements across a variety of applications. An advantage of this PCM subclass is that you can adjust the phase change temperature to stay within the desired operating range.

A comparison summary of the three categories, along with their advantages and disadvantages, are outlined below and in Table 1.

Table 1. PCM comparison summary.

PCM Type	Example Materials	Advantages	Limitations
Organic [21,22]	Paraffin wax, stearic acid	Stable, non-corrosive, non-toxic	Low thermal conductivity, flammable
Inorganic [23,24]	Salt hydrates, metallic alloys	High latent heat, better conductivity	Corrosion, supercooling, phase separation
Eutectic [25]	Organic–organic or salt mixtures	Precise melting point, customizable profiles	Compatibility and segregation risks

Choosing the right PCM is dependent on specific thermal needs being met, the desired operation range, and other system limitations [26]. The versatility of PCMs has even moved PCMs beyond battery systems into a broad range of applications, including the following: buildings and construction [27], energy storage systems [28], waste heat recovery [28], thermo-regulating fibers and smart textiles [29], microelectronics cooling [30], photovoltaic thermal (PV/T) systems [28], space and terrestrial TES applications [31], or in controlling greenhouse temperature [32]. Out of the emerging technologies (see Figure 4), battery thermal management (BTM) has become one of the better-known promising applications of PCMs. In the BTM field, improved organic PCMs (for example, paraffin with graphite or metal foams) and salt hydrates are often discussed due to their amenable transition temperatures and high heat storage capacities [33,34]. They can decrease temperature spikes, improve the thermal homogeneity of batteries, and extend a battery’s lifespan.

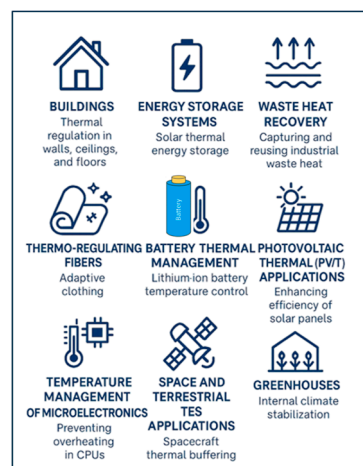


Figure 4. Applications of latent heat storage when using PCMs.

2.2. Key Properties for Lithium-Ion Battery Applications

PCMs are integral components for the thermal management system of lithium-ion batteries. However, to be effective, PCMs must meet a number of rigorous thermal, physical, and chemical criteria. The choice of PCM will affect the battery's performance and safety over the lifetime of the battery.

One of the most important considerations is the temperature of the phase change (melting), where the melting point establishes the operational window in which the PCM can absorb excessive heat. For BTM systems, an ideal melting interval of 20–50 °C is preferred to ensure that the PCM will absorb heat at the exact moment before the battery begins to exceed safe thresholds during charge–discharge cycles, thereby preventing overheating [7,10]. This temperature range also enables the PCM to be effective at the exact moment needed to buffer transient heat loads immediately preceding the time in which power is required from the battery. In typical scenarios, BTM systems utilize a variety of PCMs that may have melting points ranging from around 31 °C and up to 72 °C, depending on the design and application [35].

The latent heat capacity (ΔH) of PCM is also of equal importance. A high latent heat will allow the PCM to absorb a significant amount of thermal energy when melting (likely, the latent heat will be in the range of 150 to 250 kJ/kg). This minimizes a rise in internal temperature, maintains a more constant performance of the cell under variable loads, and minimizes the volume of PCM required for effective cooling [22]. Ultimately, high-latent-heat PCMs provide higher heat absorption properties and flexibility in the design of the systems they comprise. It is important to note that latent heat is closely related to thermal conductivity, which is another key parameter. Many common types of PCMs, especially organic types, like paraffin, have a low thermal conductivity (~ 0.2 W/m·K), preventing efficient heat distribution to or from the PCM. Due to their importance, significant effort has gone into improving this property. For example, many researchers have recently studied various composite PCM systems with conductive additives (e.g., graphite, carbon fibers, metal foams, and carbon nanotubes) as additives that have been able to enhance their conductivity to values of at least 0.5 up to 9.3 W/m·K [35]. For example, paraffin impregnated into a graphite foam matrix and encapsulated with a polymer/boron nitride shell reached a conductivity of approximately 4.5 W/m·K, which significantly enhances the efficiency of heat transfer [36].

Like latent heat and conductivity, specific heat capacity (C_p) affects a PCM's capacity to store sensible heat before and after phase transition. A higher specific heat allows the material to store more thermal energy before and after phase change. Specific heat capacity for organic PCMs is typically around 2 J/g·K, and it can be slightly enhanced

by adding metals or ceramics to achieve marginal benefits in overall thermal storage capacity [37]. Specific heat is acknowledged in overall thermal analyses, but latent heat generally dominates energy storage.

Density (ρ) further contributes to the amount of heat storage per unit volume, as well as to the overall system weight. Organic PCMs generally fall in the 0.8–0.9 g/cm³ density range, while inorganic salt hydrates are mostly 1.5 to 1.6 g/cm³ [38]. PCMs with a higher density can store thermal energy more compactly, but this can lead to heavier systems that must be considered in the design depending on the application. Design decisions must always be made to balance the advantages of compact high-density storage versus marginal increases in weight. In addition, any potential volume expansion that may occur during melting (typically observed with organics at 5–15%) must be structurally accommodated in any design or application to avoid undue structural stresses.

Thermal cycling stability is also an important factor. A PCM in a BTM could experience many hundreds or thousands of melt–freeze cycles; therefore, long-term stability is very important. Ideal PCMs need to be resistant to phase segregation, leakage, and degradation over extended use. Researchers have highlighted form-stable, or shape-stabilized, PCMs that remain intact as a solid structure after melting (e.g., PCMs contained within a porous matrix, or those encapsulated within a shell) [38]. The target for many PCMs is >1000 cycles, which is considered a reliable degree of cycling for the longevity of real-world battery systems. They should not undergo decomposition, degradation, or segregation in their component parts, as any of these changes may potentially reduce thermal performance and raise safety concerns. There has been good cycling stability recently reported in studies. One example is a composite PCM made of paraffin and expanded graphite that was encapsulated in polymer, with a >99.9% mass retention after melting and solidifying multiple times, thus confirming excellent stability [39].

Safety factors, especially flammability, are also important. Organic PCMs, including paraffin, are flammable materials that have implications for fire risk in the use of the battery pack. Fire risk can be addressed by employing PCMs that are non-flammable organically (e.g., hydrated salts, molten salts, or solid–solid PCMs) or by employing additive flame retardants in the organic PCM [40]. Development of flame-retardant composite PCMs have also recently been reported. For instance, Zhang et al. [38] reviewed a paraffin-based composite PCM with additives such as ammonium polyphosphate (APP), chitosan, and aluminum hypophosphite. This formulation exhibited significantly improved flame resistance (self-extinguishing behavior), and it simultaneously demonstrated effective temperature management of the battery. In tests at a rate of 3C discharge, flame-retardant PCMs have successfully mitigated peak cell temperature to around 41 °C with a temperature gradient of <5 °C, i.e., well within acceptable limits [39]. These results contribute to addressing the fire risk of PCM-based BTM systems.

Note that the volume change, as well as the chemical compatibility, needs to be taken into account. Repeated expansion and contraction due to cycling may develop cracks or gaps in the encapsulation that lead to PCM leakage. Encapsulation with flexible, or resilient, arranged containment materials (polymers or foams) can reduce these problems, and they can be utilized to accommodate the, respective, volume changing. Furthermore, the PCM must, from chemically inert to all battery material, inhibit the corrosion or degradation of the encapsulation. For example, salt hydrates can corrode metal casings unless properly sealed [38,40]. An incompatible PCM can affect the container or those of any materials located close by, and they can either react or degrade the materials and produce leaks or corrosion over time. This is why researchers recommend using inert PCMs or protective coating. Recent developments in research have looked to resolve these issues through material advances.

To summarize, an appropriate PCM for lithium-ion battery BTM systems should have an optimal melting temperature, sufficiently high latent heat, substantially higher thermal conductivity, low volume change, exceptional cycle stability, low flammability, and robust chemical compatibility. Recent advances in hybrid and nano-enhanced PCMs have met many of these criteria, supporting safer and more efficient BTM systems in electric vehicles, renewable energy storage, and portable electronics. Key PCM properties for BTM systems are summarized in Table 2. However, implementation will require careful consideration of the ideal choice of PCM, which would be based on relevant thermo-physical properties, safety, and compatibility.

Table 2. Summary table of the key PCM properties for BTM systems.

Property	Unit	Typical Range	Importance for BTM Systems
Melting Temperature (T _m) [35]	°C	30–60	Matches battery operating temperature window
Latent Heat of Fusion (ΔH) [35]	kJ/kg	150–250	High heat absorption capacity
Thermal Conductivity (k) [36]	W/m·K	0.5–9.3	Faster heat transfer; improved system response
Specific Heat Capacity (C _p) [37]	kJ/kg·K	1.5–3.0	Supports pre- and post-melting heat absorption
Density (ρ) [38]	kg/m ³	700–1500	Affects system weight and energy density
Thermal Cycling Stability [38,39]	Cycles	>1000	Durability and long service life
Flammability [39,40]	-	Low or non-flammable	Safety for lithium-ion environments
Volume Change [38,40]	-	Minimal	Avoids mechanical stress or damage to the battery casing
Compatibility with Battery Materials [40]	-	Chemically inert	Avoids risk of corrosion, leakage, etc.

2.3. Advantages of Using PCMs for Li-Ion BTM

PCMs offer multiple specific advantages when included as part of lithium-ion battery thermal management (BTM), especially in electric vehicles, stationary energy storage, and portable electronics products. One of the primary advantages of PCMs is their passive thermal regulation. A PCM can maintain nearly constant temperatures with minimal temperature rise through heat absorption during the melting process. Ultimately, this phase transition minimizes temperature spikes due to high-rate charge or discharge, while not requiring any external power to keep the cells within the safe operating window [34,41,42].

A further benefit is the improved safety. PCMs can absorb the excess heat that may initiate thermal runaway, by either delaying or preventing it, in a Li-ion cell. As localized heat reserves, they can absorb the energy that would initiate possible chain reactions that lead to fire or an explosion. Furthermore, PCMs provide a more uniform temperature distribution across a cell or module, reducing hot spots that may be required to increase local damage or failure. Therefore, it is essential to select an appropriate PCM with a favorable melting point and high latent heat capacity to maximize safety advantages [41–43].

PCMs also help to improve battery performance. When PCMs maintain a stable operating temperature, the electrochemical kinetics of the battery are improved, resulting in more consistent capacity, voltage output, and power delivery. During discharge or rapid cycling, PCMs will take away and prevent overheating, while their heat-release characteristics during solidification might also gently warm cells under ambient cold

conditions, enhancing low-temperature efficiency while improving overall energy delivery. Another key benefit is extended battery life. By damping temperature fluctuations, PCMs operate to reduce the thermal stress on electrodes and electrolytes. Reduced temperature swings slow down detrimental processes like electrolyte decomposition, solid–electrolyte interphase (SEI) formation, and degradation of the electrode materials. Therefore, holding cells in a narrow temperature range extends cycle life and maintains long-term capacity.

Additionally, there is some improvement to energy efficiency because PCM-based cooling is fundamentally passive and, therefore, effectively consumes no additional power. Unlike systems based on active thermal management (e.g., pumps, fans, and compressors) that are designed to transport heat, PCMs absorb or release heat from the ambient environment, thereby reducing parasitic energy losses and improving the overall thermal management system efficiency. PCMs also offer design options, as they can come in one of several forms (e.g., sheets, encapsulated beads, and composite materials with thermally conductive fillers), and they are integrated into battery packs. PCMs can be directly utilized in battery packs in modules or they can be utilized in hybrid cooling systems that use active cooling (e.g., air or liquid) for both steady-state and peak thermal loads. Additionally, PCM operation is silent, maintenance-free, has no moving parts (which reduces operational noise), and decreases ongoing maintenance.

Finally, PCM-based solutions have the potential to be cost-effective. Compared to complex active cooling systems, a PCM-based solution can be simpler and, potentially, more cost-effective. By eliminating or reducing the need for additional cooling hardware (e.g., complex heat exchangers, blowers, or other cooling loops), this may reduce the overall cost and complexity of the battery thermal management system. Figure 5 summarizes the significant advantages, including passive temperature control, improved performance, longer life, energy efficiency, and flexible integration, with schematic icons for visualization.

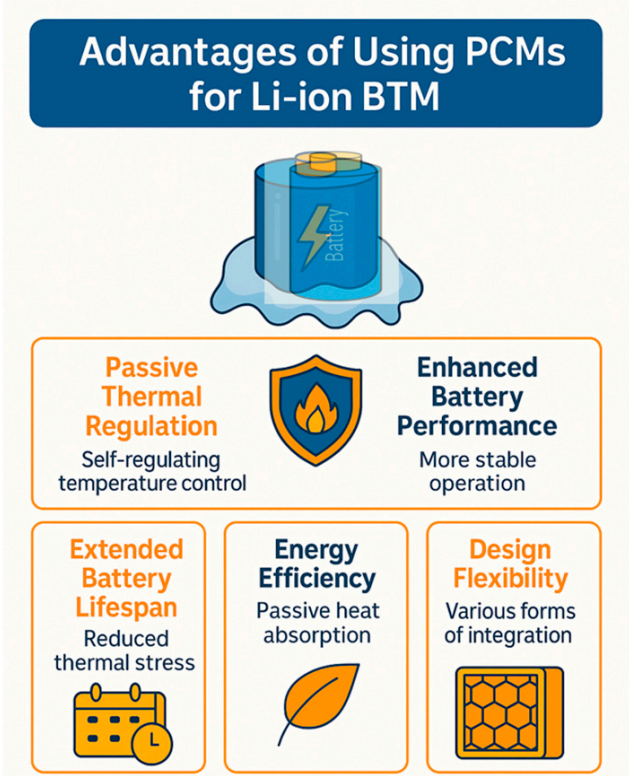


Figure 5. PCM advantages.

For perspective, Table 3 compares PCM cooling with conventional thermal management methods, such as air, liquid, and heat-pipe cooling, across several operational criteria.

Table 3. Comparative advantages of PCM cooling for Li-ion battery thermal management.

Feature/Criterion	PCM Cooling	Air Cooling	Liquid Cooling	Heat Pipes
Temperature Regulation	Excellent peak shaving; maintains narrow range due to latent heat absorption [34,41]	Moderate; depends on airflow and ambient temperature [44]	Very good; can maintain tight temperature control [45]	Good; relies on conduction and evaporation/condensation [46]
Hot Spot Reduction	Very good; distributes heat evenly across cells [14]	Poor–moderate; airflow may miss certain areas [47]	Good; uniform coolant distribution if well designed [48]	Good; point-to-point thermal spreading [49]
Energy Consumption	Zero during phase change; fully passive [50]	Low–moderate (fans require power) [51]	Moderate–high (pumps, chillers) [52]	Low (capillary action passive but may need fans) [53]
Safety Improvement	High; delays/prevents thermal runaway [41–43]	Low–moderate [54]	High [52]	High [55]
System Complexity	Low; simple encapsulation or embedding [56]	Low; ducting and fans [57]	High; requires pumps, reservoirs, hoses [58]	Moderate; requires sealed tubes and vapor chamber [59]
Maintenance Needs	Very low [60]	Low–moderate (fans may fail) [56]	High (fluid leaks, pump wear) [52]	Low [53]
Noise Level	Silent [61]	Noticeable (fans) [62]	Noticeable (pump) [63]	Silent [53]
Weight Impact	Low–moderate (depends on PCM mass) [64]	Low [65]	Moderate–high (fluid and equipment) [66]	Low [67]
Design Flexibility	High; can be molded into any shape [68]	Moderate; ducting constraints [69]	Moderate; plumbing constraints [52]	Limited to linear or planar paths [70]
Best Use Case	Peak load shaving, passive backup for active systems [52]	Low-cost, moderate performance needs [71]	High-power, continuous cooling [52]	High heat flux transport in compact layouts [71]

As summarized in Table 3, PCMs are a more effective thermal management solution that allow thermal peaks to be managed and hot spots to be removed without the mechanical and energy requirements of liquid cooling. PCM-based systems reduce variation in temperature by maintaining a small band of temperature variability, resulting in the improved safe use and longer life of lithium-ion batteries. This is especially beneficial for applications where there are intermittent high-power loads, such as in electric vehicle batteries, hybrid storage modules, and renewable energy buffered systems.

Experimental studies indicate that PCM-enhanced BTM systems can lower peak cell temperatures by, approximately, 5–15 °C, and they can extend the cycle life of batteries by 20–30%, depending on the addition of thermal conductivity enhancers like graphite, carbon fibers, or metal foams [34,41–43]. Additionally, PCM systems are inherently silent, require little maintenance, and can be designed in custom geometries, allowing for their incorporation as encapsulated layers, composite fillers, or structural spacers into modules. However, PCMs come with limitations. Some examples include a finite storage capacity for thermal energy, relatively low intrinsic thermal conductivity, and potential leakage of the phase change material, all of which are active areas of research. Addressing these

challenges has motivated ongoing development of composite PCM solutions and innovative encapsulation solutions to improve both thermal performance, as well as durability and reliability in practical use.

2.4. Challenges and Considerations for PCM-Based BTM

While PCMs have the potential to significantly enhance lithium-ion battery thermal management, owing to their ability to absorb heat while maintaining a nearly constant temperature, significant technical barriers would need to be overcome in order for these materials to achieve widespread use. One major limitation is that, like all thermal buffering materials, PCMs have a limited heat storage capacity. The thermal buffering ability of a PCM can only sustain its latent heat capacity before becoming ineffective. Once the PCM is fully melted, it will no longer be able to absorb heat effectively [72]. This means that, under a continuous high-power operating condition, the material will quickly exhibit a rise in temperature once the PCM has fundamentally changed phases. In other words, the thermal buffering advantage has been “spent” once the latent heat is fully absorbed. Until the released heat is removed or the PCM is permitted to re-solidify, or if cool-down periods are provided, continuing a high-power operating condition will eventually raise the battery temperature once the PCM is fully melted (and, thus, latent heat removed). This means that, under continual higher loads or high ambient temperatures, passive PCM cooling will likely not be effective in sustained periods or during high ambient operating conditions without some type of combination of mechanical and active cooling or sufficient rest periods to allow the PCM to solidify.

Another issue is the low intrinsic thermal conductivity of PCMs. Typical organic PCMs (e.g., paraffin waxes) have conductivities of only $0.2\text{--}0.3\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, such that heat cannot transfer from battery cells to the PCM as rapidly [73] as desired. Low thermal conductivity leads to slowed heat transfer from the battery and a bottleneck in heat dissipation. In practice, a PCM configuration based on wax adjacent to a hot cell may not transfer heat quickly enough to prevent temperature rise at the cell core. Research has addressed PCMs’ conductive limitations through the incorporation of thermal conductive additives or constructs. Common strategies include mixing a PCM with thermally conductive fillers, such as graphite or graphene, and metal particles or carbon fibers, embedding metal foams or fins in the PCM, thus creating composite PCMs that dramatically improve the effective thermal conductivity [46]. These composite configurations can increase thermal conductivity by one order of magnitude or more (for example, impregnating paraffin in a graphite matrix increases the conductivity by hundreds of times) [74]. Such PCM configurations can allow for heat to transfer more quickly through the PCM and, thus, improve overall cooler effectiveness. Nevertheless, increasing the conductivity can decrease the latent heat capacity and create challenges by requiring an appropriate balance between heat transfer efficiency and heat storage. The need for auxiliary structures also adds complexity and may partially offset the passive, simple nature of PCM-based cooling.

When it comes to weight and volume, introducing PCM materials into a battery pack necessarily increases the weight and volume of the system because PCMs (and any container or filler for PCMs) occupy space and mass that does not directly contribute to energy storage capacity. This is related to pack-level energy density, which is a critical issue for electric vehicle applications. Strategically placing PCM in an optimized configuration, particularly near thermal hot spots, can help to alleviate some of the impact; however, trade-offs between thermal performance and total energy density can never be fully avoided [72]. For example, studies have noted that the inclusion of a PCM thermal buffer layer could potentially contribute a $\sim 10\text{--}15\%$ weight increase at the pack level [74]. The advantage of smoother thermal management must always be measured against the potential loss in

driving range or increased battery size and weight. The quantity of PCM must also be carefully selected, with a design to minimize its usage and provide thermal mitigation capabilities in the most strategic locations. Still, the balance between thermal performance and pack energy density is a key consideration, especially for any EV application; as a result, design optimization is necessary to simply incorporate the minimum usable amount of PCM to meet the objectives in providing the desired thermal performance.

Leakage and encapsulation are also major issues. In a battery module, leaking PCM could damage electronics and insulation, and it could lead to a condition where the PCM cannot re-solidify properly around the cells. The common solutions to leakage include impregnating PCMs into porous matrices (e.g., expanded graphite and metal foams) or using microencapsulation methods [72]. These work to minimize leakage of PCM and increase thermal conductivity. The drawbacks of these solutions are added manufacturing processing steps and cost. For instance, filling a graphite matrix with paraffin roughly doubled the thermal conductivity of the composite but also “prevents leakage of the molten phase during melting–solidification cycles” [72]. However, as described, the solution is now a more complex and costly option for PCM. Finding leak-proof yet efficient PCM systems in engineering is ongoing.

Thermal cycling durability is also a major concern. In many instances, after thousands of charge–discharge cycles, repeated melting and solidification can lead to phase segregation, mechanical stresses, or degradation of thermal properties [75]. It is of utmost importance for the thermal properties of a PCM to remain stable within these repetitions. Thermal cycling can invoke multiple degradation mechanisms in PCMs: volumetric expansion/contraction upon each melt–freeze cycle can induce mechanical stresses or potentially creep in due to the phase shift; phase segregation can occur in multi-component PCMs (for example, there may be segregation of the water with the salt in some hydrated salts); or chemical or physical degradation of the PCM structure may occur over extended periods of use. All of these situations could result in a degradation of latent heat, change in the melting point, or loss of thermal contact with the cells. Recent reviews indicate that concerns over long-term stability, such as supercooling (the PCM not undergoing the expected solidification) or compatibility/corrosion (as experienced in the case of inorganic salt-based PCMs) are still a high priority in future studies [75–77]. For example, some salt hydrate PCMs have a level of corrosion to metals, which can damage battery enclosures or components over time if not properly contained. Research is ongoing into the durability of PCMs, with some organic PCMs demonstrating acceptable stability over tens of thousands of cycles [77], but the work to ensure long-term durability equal to the lifespan of the batteries themselves is not yet complete. Thus, stable PCM formulations and encapsulation methods are needed to assure durability equal to that of the battery.

It is also a significant challenge to combine them with other cooling methods. Continuous high-power operation subjects fully melt PCMs to reduce efficiency because, as previously explained, a fully melted PCM cannot absorb heat. Practical EV battery systems do typically combine active cooling methods, such as forced-air or liquid coolant loops with PCMs, to dispose of heat continually and to reset the PCM. Therefore, hybrid methods are more successful in performance and value in cooling and thermal management systems that combine PCMs with active systems (air, liquid, or heat-pipe cooling) [72,73]. For example, a module filled with PCM that has small liquid coolant channels or heat pipes also markedly improves temperature management and uniformity under high discharge rates [72]. The difficulty exists in the intricacy of the design and control: adding passive and active components increases the number of parts in the system and, therefore, the number of possible failure modes. Engineers have to ensure that active cooling is used only when necessary and will solidify the PCM without wasting energy, and if the PCM does

not have adequate time and/or cooling to allow for re-freezing, its ability to absorb heat is significantly reduced during subsequent cycles [73]. Therefore, hybrid designs require accurate thermal coordination and add complexity to the system.

Consequently, building a more effective hybrid BTM requires a more deliberate connection between the PCM and active cooling so that they will work together rather than against each other. The aim is to have a reliable system that does not overheat during peak load while adding no excess weight, volume, or parasitic power loss. Research is progressing in the development of unique configurations (e.g., PCMs with internal fins and coupled airflow, or PCMs with phase change heat exchangers) to take advantage of PCMs while using the least active as possible cooling aid [72,73]. Striking this balance, without significant added complexity, is a major engineering challenge for next-generation BTM approaches.

Finally, two important factors will drive commercial adoption: cost and scalability of production. While base organic PCMs are inexpensive, advanced composites and encapsulated materials are significantly more expensive [74]. For widespread adoption, PCM materials and products must be produced using a manufacturing process that can be integrated into battery assembly lines without modification and use readily available, low-cost materials [76]. The ability to balance performance benefits with the cost of production and scalability will determine the feasibility of the utilization of PCM-based BTM systems in commercial EV applications. Furthermore, advanced composite materials (e.g., paraffin chemically combined with graphite fibers, or metal foam) and microencapsulated PCMs can significantly increase the cost of development due to materials and processing. In a recent study, PCM (n-octadecane) was estimated to make up around 5–10% of the total cost of a hybrid energy storage module. More generally, there are still concerns with the cost of PCM-based BTM systems when trying to scale them for economic viability in industry [74]. Scaling up from a lab prototype to an automotive production is a significant step and will require that the PCM material and containment are compatible with mass production—mainly for automated filling, sealing, and quality control—while also being produced at high throughput and consistent quality. Designing microencapsulation techniques or vacuum impregnating foams will need to be optimized for large-scale production to avoid becoming cost-prohibitive. The supply chain is another issue to consider: some high-performance PCM additives (e.g., carbon nanotubes and certain flame-retardant PCMs) may not have many suppliers or they may be higher-cost raw material options, making the economic feasibility even more uncertain [76].

In conclusion, the commercial viability of PCM-based thermal management will involve innovations that reduce material and production costs, ensuring that the system-level benefits to safety and performance validate the cost. The cost–benefit ratio is as important as technical performance for PCM integration into future batteries [74]. Figure 6 summarizes all of the primary issues visually.

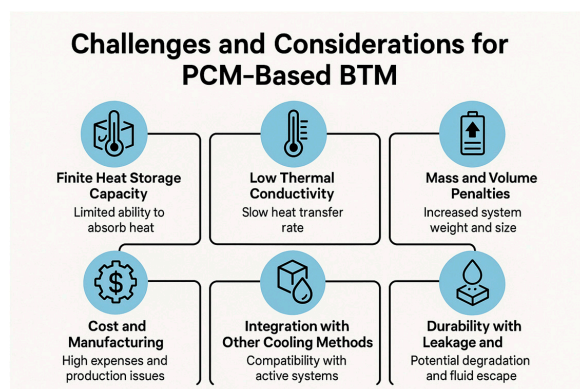


Figure 6. Challenges and considerations for a PCM-based BTM approach.

3. PCM Materials for Li-Ion Battery Applications

A range of PCMs can be designed, including organic, inorganic, and composite or hybrid materials, to meet the specific thermal demands associated with different battery systems. PCMs can be incorporated into the design of the battery as a passive, and reliable, means of mitigating the heat that builds up during charging and discharging. In this regard, Figure 7 represents the general key aspects of PCM materials. In summary, the figure highlights how PCM encapsulation provides thermal management of lithium-ion battery systems, in addition to connecting the essence of encapsulating to the different types of PCMs—organic, inorganic, or compound/hybrid—each with their own advantages and limitations.

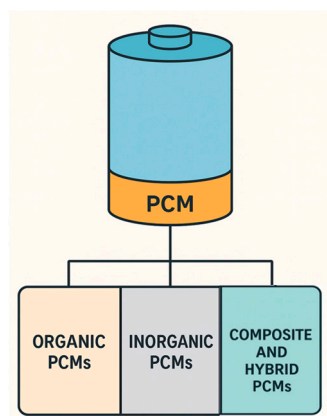


Figure 7. Key components of PCMs.

3.1. Organic PCMs

Organic PCMs are carbon-based materials known for being chemically stable, non-corrosive, and able to undergo multiple phase-changing transitions without significant degradation. Paraffins, fatty acids, and polyethylene glycol (PEG) are the most studied organic PCMs for passive thermal regulation in lithium-ion battery (LIB) applications. The most important properties of these materials are their high latent heat storage capacity, chemical stability, and tunable melting points, all of which contribute to thermal runaway protection during charge and discharge. Organic PCMs also typically melt and freeze congruently, providing stable thermal performance for repeatable cycles over the lifelong period of LIBs [78–80].

Three subtypes of organic PCMs are being developed currently:

Paraffins (n-alkanes)—Paraffins remain the dominant organic PCMs in both research and early commercialization. These long-chain alkanes offer high-energy storage density, affordability, and excellent cycling stability with predictable thermal behavior [80]. However, their main limitation lies in their low intrinsic thermal conductivity, which restricts heat transfer during high-power operations [81]. To address this issue, researchers have developed nano-enhanced and porous composite paraffins. For instance, Pilali et al. achieved a five-fold increase in conductivity using graphene nanoplatelets while retaining >90% of the latent heat [82]. Similarly, Rasool et al. demonstrated paraffin/metal oxide hybrids with rapid thermal response during continuous cycling [37]. Such results highlight that embedding conductive fillers or using porous matrices can overcome the conductivity bottleneck without substantially sacrificing storage potential.

Fatty acids—Examples include stearic, lauric, myristic, and palmitic acids, and they are emerging as biodegradable and environmentally sustainable alternatives to paraffins [83,84]. They exhibit low supercooling and sharp melting/solidification transitions, which are particularly advantageous for maintaining the stable operating conditions required in

electric vehicles. Their affordability and stability mirror those of paraffins, but challenges, such as mild corrosivity towards metallic casings and odor release at elevated temperatures, must be addressed for large-scale deployment [85,86]. Recent advances include Zhao et al., who optimized eutectic mixtures of fatty acids to match EV battery temperature windows [78], and Murali et al., who incorporated expanded graphite to enhance both conductivity and shape stability [87]. Although paraffins still dominate, due to cost and availability, fatty acids offer compelling advantages in systems prioritizing environmental sustainability and recyclability.

Comparatively, paraffins currently dominate commercial and prototype applications due to their stability and availability, but fatty acids are increasingly attractive in contexts where eco-friendliness and recyclability are prioritized. However, comparative studies assessing their long-term cycling, cost-performance ratios, and large-scale integration remain an important research direction [88,89].

Polyethylene glycol (PEG)—PEG has recently attracted attention as a versatile organic PCM for battery thermal management due to its tunable melting temperature, high latent heat, and favorable safety profile [80]. Unlike paraffins, PEG is non-toxic, biodegradable, and non-flammable, aligning with sustainability and safety requirements [61]. Its melting point can be precisely tailored by molecular weight, e.g., PEG-600 (~17–22 °C), PEG-1000 (~37–40 °C), PEG-1500 (~45–50 °C), and PEG-4000 (~55–63 °C), thus allowing close alignment with the Li-ion battery operating range (25–60 °C) [85]. PEG typically exhibits latent heat values of 120–200 J·g^{−1}, with slightly higher density (1.1–1.2 g·cm^{−3}) than paraffins. Like other organics, PEG suffers from low thermal conductivity (~0.2–0.3 W·m^{−1}·K^{−1}) and leakage upon melting [90]. To mitigate these issues, composite PEG systems have been developed: PEG/SiO₂ aerogels achieve shape stabilization and conductivity up to 2 W·m^{−1}·K^{−1} [72], while PEG/graphene and PEG/CNT hybrids demonstrate conductivities up to 10 W·m^{−1}·K^{−1} with >80% latent heat retention [91]. Encapsulation strategies, such as PEG microcapsules with polymeric or silica shells, have shown excellent cycling stability (>500 cycles) with negligible performance loss [92]. At the pack level, PEG-based composites have reduced cell temperatures by 10–15 °C under high-rate cycling, effectively preventing thermal runaway [93]. Nevertheless, hygroscopicity, volume expansion during phase transition, and scalability of composite manufacturing remain barriers to commercialization [94]. Despite these challenges, PEG's safety, tunability, and compatibility with diverse support matrices make it a strong candidate for next-generation EVs, portable electronics, and hybrid PCM systems [95].

Despite these advances, PEG still faces challenges related to moisture sensitivity (due to its hygroscopic nature), volume expansion during phase transitions, and the scalability of composite or encapsulation manufacturing processes. Nevertheless, its tunable phase-transition temperature, high safety, and compatibility with a wide range of support matrices position PEG as one of the most promising organic PCMs for future Li-ion battery systems, particularly in electric vehicles, portable electronics, and hybrid PCM configurations [96,97].

3.2. Inorganic PCMs

While organic PCMs are widely used because of their high latent heat and low melting points, inorganic PCMs (principally, salt hydrates and, for high-temperature systems, molten salts) offer important advantages for battery thermal management (all of which make them attractive for module- and pack-level passive thermal protection where safety and energy density per volume are priorities [98]): higher volumetric latent heat, improved intrinsic thermal conductivity, and far lower flammability. Inorganic salt hydrates, typically, have higher volumetric latent heat storage capacity and intrinsically better thermal conductivity than organic PCMs, and they are non-flammable. These traits make salt

hydrates attractive for module- and pack-level passive thermal protection where safety and energy density per volume are critical [98]. For example, common hydrated salts have phase change enthalpies in the $\sim 100\text{--}300\text{ kJ/kg}$ range (approximately $150\text{--}300\text{ J}\cdot\text{g}^{-1}$) and, owing to their higher density, can store about $45\text{--}120\text{ kWh/m}^3$, outperforming paraffinic PCMs ($\sim 45\text{--}60\text{ kWh/m}^3$) on a volume basis. Moreover, whereas pure organic PCMs often have very low thermal conductivity ($\sim 0.2\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), many salt hydrates exhibit $0.5\text{--}1.0\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ or higher (some $>1\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) in their native state. Finally, unlike hydrocarbons, inorganic hydrates are essentially non-combustible, reducing fire risk in the pack [98].

Salt hydrates (e.g., $\text{CaCl}_2\cdot 6\text{H}_2\text{O}$, $\text{Na}_2\text{SO}_4\cdot 10\text{H}_2\text{O}$, and $\text{MgCl}_2\cdot 6\text{H}_2\text{O}$) form the dominant class of inorganic PCMs for near-ambient to moderately elevated temperatures because their melting points can be tuned into the desired battery operating range (roughly $25\text{--}60\text{ }^\circ\text{C}$) [98]. Many single-component or eutectic salt hydrates melt congruently in this range, and others can be blended to achieve a target transition temperature. On a materials basis, their latent heat values are competitive (often reported on the order of $150\text{--}250\text{ J}\cdot\text{g}^{-1}$), and they are even higher on a volumetric basis when compared to most organic PCMs. However, classical drawbacks have historically limited the direct use of unmodified salt hydrates in battery packs: supercooling (large undercooling needed to trigger solidification), phase separation or hydrate crystallization changes upon repeated cycling, chemical corrosivity towards common metals, and gradual loss of water (change in hydrate state) over long use [99]. These issues can severely reduce the effective stored/released latent heat and the reliability of the PCM over many thermal cycles. For instance, an incongruently melting hydrate, like sodium acetate trihydrate, can remain liquid $40\text{ }^\circ\text{C}$ below its melting point unless a nucleation site is introduced, and it tends to segregate anhydrous salts at the container bottom after melting, which diminishes recoverable latent heat over time [100].

Recent research has made significant progress in mitigating the stability issues of salt hydrate PCMs through material modifications and composites [98,99]. A variety of strategies have been demonstrated to improve cycling reliability: adding nucleating agents (to reduce supercooling by providing crystallization templates), incorporating thickeners/gelling agents or porous supports (to prevent fluid leakage and hold solid hydrates in place) [99], and microencapsulation of salt hydrates in polymer or silica shells (to isolate them from the environment and contain any phase separation) [101]. These interventions preserve much of the material's latent capacity while suppressing undesirable effects. For example, adding a small amount of nucleator (with a similar crystal structure to the hydrate) can virtually eliminate supercooling in some salt hydrates [99]. Likewise, studies on composite salt hydrates (e.g., $\text{Na}_2\text{SO}_4\cdot 10\text{H}_2\text{O}$ with supporting matrices, like expanded graphite or silica microcapsules) report that the materials can retain over $80\text{--}95\%$ of their initial latent heat after dozens to hundreds of melt/freezing cycles, with greatly reduced supercooling compared to the untreated salt [101]. In the same report, microencapsulated magnesium nitrate hexahydrate in a polymer shell showed only $\sim 3\%$ loss of latent heat after 100 thermal cycles, and it remained nearly constant over hundreds of cycles, while also drastically lowering the supercooling degree [101]. Such results underscore the improvements in cycle stability now achievable with tailored salt-hydrate composites.

Another central engineering challenge is the relatively low thermal conductivity of, even, inorganic PCMs in their pure form ($\sim 0.5\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for many hydrates, as noted above). Although salt hydrates conduct heat better than paraffins, their native conductivity is still insufficient to absorb/dissipate the intense heat pulses during high-power battery operation [98]. To address this, practical composite designs incorporate high-conductivity fillers or frameworks: for instance, expanded graphite, carbon fibers, metal foams/meshes, or thermally conductive ceramic matrices are combined with the salt hydrate to create

a percolating heat conduction network [98]. These conductive scaffolds dramatically enhance the effective thermal conductivity (often by an order of magnitude) and help spread heat quickly during fast charge/discharge events. As an example, adding 20–25 wt% expanded graphite to a sodium sulfate decahydrate PCM can raise its conductivity from $\sim 0.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ to over $4 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (a $\sim 5\text{--}6\times$ increase) [102]. Even larger enhancements have been reported using nano-graphite additives—one study achieved $\sim 5.9 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ in a graphite-infused salt hydrate, more than ten times the base material's value [103]. These carbon–salt composites have been directly tested in battery thermal management scenarios, showing tangible benefits: in one high-power cell experiment, a graphite-enhanced PCM reduced the peak cell temperature from 55°C (with no PCM) down to $\sim 38\text{--}40^\circ\text{C}$, outperforming an equivalent thickness of pure PCM and maintaining much better temperature uniformity among cells [104]. In short, combining salt hydrates with conductive and porous supports both limits migration of the melt and boosts thermal transport, yielding composite PCMs that can arrest temperature spikes more effectively than the PCM alone.

For higher temperature thermal management (beyond typical Li-ion battery ranges), molten salt PCMs (usually inorganic nitrate/nitrite salts or eutectic mixtures thereof) provide extremely high thermal stability and heat storage capacity. Molten salts have been widely studied in concentrated solar power and industrial thermal storage systems because they are non-flammable, inexpensive, and can operate at $>300^\circ\text{C}$ for thousands of cycles without decomposition. However, their melting points are often well above 100°C ; for example, common solar salt ($\text{KNO}_3/\text{NaNO}_3$) melts around 220°C , which makes it unsuitable as a PCM in conventional ambient-temperature Li-ion battery packs [105]. It remains solid and inert at normal battery operating temperatures and will not activate in time to buffer thermal excursions. Thus, molten salt PCMs are generally limited to high-temperature batteries (such as ZEBRA Na/NiCl₂ batteries that run at $250\text{--}350^\circ\text{C}$, or Na-S batteries at $\sim 300^\circ\text{C}$) and other specialized thermal-buffering systems where the operating environment is maintained above the salt's melting point [104,105]. These batteries actually rely on a molten salt electrolyte to function, exploiting the salt's excellent ionic conductivity at elevated temperatures. While molten salts are attractive for large stationary energy storage (due to low cost and long life), their use in low-temperature battery contexts is precluded by the need for continuous heating and heavy thermal insulation, as well as the risk of corrosion to metal components at high temperatures. In summary, inorganic molten salts are a critical class of PCMs for thermal applications, but they fall outside the practical range for passive thermal management in EV or consumer Li-ion packs.

The latest literature shows promising developments aimed at bringing salt-hydrate PCMs closer to real-world battery pack integration. Researchers are exploring multi-scale encapsulation techniques; for instance, they are combining microencapsulation (to stabilize individual salt particles) with macro-encapsulation or compartmentalization at the module level to ensure leak-proof and reliable operation over long durations [101]. New manufacturing approaches have emerged, such as direct ink writing of salt-hydrate composite inks, which allow printing of complex PCM structures that already contain nucleating agents and conductive additives pre-distributed in a polymer matrix. One recent study demonstrated a 3D-printable salt-hydrate “ink” loaded with ~ 70 wt% salt plus carbon black and polymer binders; the printed composite showed, while being non-corrosive and formable into custom shapes, suppressed supercooling and stable latent heat over multiple melt–freeze cycles [106].

There is also progress in creating hybrid supports, such as silica aerogels combined with carbon networks, to host the salt hydrate. Silica aerogels offer a lightweight, thermally insulating scaffold that can prevent liquid leakage and segregate the salt, whereas embedded carbon fibers or graphene layers provide thermal conduction paths—together, these

hybrid aerogel/carbon frameworks can maintain PCM integrity and improve its thermal response in cell-scale tests (often dubbed “composite phase change thermal pads”) [107]. Early prototypes of battery modules containing such composite PCMs, showing improved safety in thermal runaway scenarios and more uniform temperature distribution during fast charging (without the need for active cooling power), have been reported [108].

Despite these advances, several critical knowledge gaps remain before inorganic composite PCMs can see wide deployment in EV and consumer battery packs. There is a need for standardized aging and cycling protocols to assess how the latent heat and thermal performance degrade (if at all) after hundreds or thousands of real-world charge–discharge cycles. Likewise, long-term corrosion compatibility data between candidate salt-hydrate PCMs (or their additives) and typical battery materials (cell cans, current collectors, bus bars, etc.) are still limited, and any risk of material interactions over years must be quantified. Techno-economic comparisons to established organic PCM solutions are also important: although hydrated salts are inexpensive in raw form, the added costs of encapsulation, fillers, or special packaging need evaluation to ensure the overall system remains cost-effective and lightweight. Finally, comprehensive life-cycle and environmental impact assessments will be required—including end-of-life recycling or disposal considerations—since introducing any new thermal management material at pack scale implicates safety and sustainability beyond just performance metrics. Addressing these questions through further research and prototype testing will be crucial for translating the promising lab-scale results into robust, commercial battery thermal management systems in the coming years.

3.3. Composite and Hybrid PCMs

Eutectic PCMs, combining paraffins or fatty acids with thermally conductive fillers, aerogels, or foams in order to achieve balanced performance, have emerged in composite organic PCM research. Conventional passive PCMs, such as paraffins, fatty acids, and some salt hydrates, can absorb large amounts of latent heat, but their low intrinsic thermal conductivity, leakage during melt, and—in some cases—flammability or phase-segregation issues limit practical pack-level performance.

Composite and hybrid PCMs address these shortcomings by combining a high-enthalpy PCM core (organic or inorganic) with thermally conductive fillers or structural supports, or by encapsulating the PCM in robust shells or porous matrices. Carbonaceous fillers, such as expanded graphite (EG), graphene nanoplatelets (GNPs), and carbon nanotubes (CNTs), have been widely reported—while typically retaining the majority of the PCM’s latent heat (commonly reported enthalpy retention of ~70–90% for well-designed composites [109,110])—to increase apparent thermal conductivity from the order of $0.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ (pure organics) to values ranging from ≈ 2 up to $>10 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ depending on filler type and loading. Such conductivity gains enable faster spreading of transient heat and meaningfully reduces peak cell temperatures under high C-rate operations.

Beyond carbon fillers, metal foams/particles and thermally conductive ceramics (e.g., Al, Cu foams, SiC, or BN additives) have been used to create composite PCMs (CPCMs) with exceptional heat-spreading ability. These systems trade off added mass and cost for higher conductance, and they are attractive for high-power or aerospace applications where weight/volume constraints differ from automotive pack design. Recent experimental reports demonstrate that multiphase composites (e.g., paraffin + EG + ceramic/ceramic coating) can achieve both improved conductivity and structural stability under repeated thermal cycling, making them promising for fast-charging electric vehicles [109]. Shape-stabilized supports and aerogel-based matrices (PEG or paraffin impregnated into silica, polymer, or carbon aerogels) represent another class of hybrids that mitigate leakage and improve mechanical/thermal resilience. Work on PEG–silica aerogels and similar aerogel–

PCM hybrids has demonstrated high PCM loading with minimal leakage, improved fire safety, and excellent cycling stability—many report an enthalpy retention of >95% of the initial value, even after tens or hundreds of melt–freeze cycles in the laboratory [111]. These aerogel–CPCM systems are attractive for both cell-level and module-level passive thermal protection, and they can serve as thermal barriers to help stop the propagation of thermal runaway between adjacent cells [111,112].

Micro- and nano-encapsulation of PCMs (encasing an organic PCM core within polymeric or inorganic shells) offers another route to create composite PCMs with excellent dispersibility and manufacturability for battery applications. Encapsulated PCMs can be more easily integrated into the composite binders, adhesives, or potting compounds used in battery packs. Recent research on encapsulated PCMs shows improved cycling stability (e.g., ~98% latent heat retention after 100 cycles) and reliable integration into battery components without leakage [111]. Several experimental studies have demonstrated that applying encapsulated or shape-stabilized CPCM around cylindrical and prismatic cells can notably reduce peak cell temperatures during operation compared to baseline designs without PCM [113]. These advances suggest that encapsulated CPCM can be scaled up in battery modules while avoiding free-liquid leakage and preserving ease of manufacturing [111,113].

Despite impressive progress, outstanding challenges remain: (i) the filler vs. latent-heat trade-off—more conductive filler generally reduces gravimetric and volumetric latent capacity; (ii) cost and scalability, i.e., many high-performance additives (graphene, CNTs, and engineered aerogels) remain expensive or difficult to process at gigawatt-hour scale; and (iii) long-term durability under combined mechanical, electro-thermal, and chemical stresses, i.e., realistic pack-level aging datasets are still limited. There have been recent literature calls for standardized cycling/aging protocols, life-cycle assessments, and techno-economic analyses to guide selection of the composite formulations that balance thermal performance, safety, weight, and cost [114–116].

In summary, organic PCMs (e.g., PEG) provide tunability and safety, inorganic PCMs offer high latent heat but face stability issues, while composite/hybrid PCMs represent the most balanced approach for near-term Li-ion battery applications. The design of future thermal management systems is likely to involve multi-functional hybrids, combining high enthalpy storage with rapid heat spreading, leakage prevention, and structural integrity.

A comparative table of PCM materials for Li-ion battery applications, with their key properties, pros, and cons, is shown below (Table 4).

Table 4. Comparative table of PCM materials for Li-ion battery thermal management.

Category	Material Examples	Melting Point (°C)	Latent Heat (J/g)	Thermal Conductivity (W/m·K)	Advantages	Drawbacks
Organic PCMs	Paraffins (n-alkanes, C16–C28) [117]	30–60	150–250	~0.2	Abundant, chemically stable, negligible supercooling, tunable melting point	Low conductivity, flammable, leakage
	Fatty acids (lauric, palmitic, stearic acids) [118]	30–65	150–220	~0.2–0.3	Renewable, higher safety than paraffins, good compatibility	Odor, cost, possible phase separation
	Polyethylene glycol (PEG) [119]	20–65	140–200	~0.3	Wide tunable range, stable, flexible use	Hydrophilic (absorbs moisture), leakage without encapsulation
Inorganic PCMs	Salt hydrates (CaCl ₂ ·6H ₂ O, Na ₂ SO ₄ ·10H ₂ O) [120]	25–50	150–300	0.5–1.0	High latent heat density, higher conductivity than organics	Supercooling, phase segregation, corrosive
	Molten salts (LiNO ₃ –KNO ₃ –NaNO ₃) [121]	>100	100–200	0.5–1.0	Stable, high-capacity, non-flammable	Too high T _m for EV use, corrosive

Table 4. Cont.

Category	Material Examples	Melting Point (°C)	Latent Heat (J/g)	Thermal Conductivity (W/m·K)	Advantages	Drawbacks
Composite/ Hybrid PCMs	Paraffin + Expanded Graphite/Graphene [122]	30–60	120–200	2–10	Greatly improved thermal conductivity, leakage prevention	Reduced latent heat, higher cost
	Fatty acid + Graphite/CNTs [123]	30–65	120–180	2–8	Balance between heat storage and transfer	Additive cost, possible agglomeration
	PEG/SiO ₂ Aerogel, Polymer-encapsulated PCMs [124]	25–60	100–180	0.5–5.0	Shape-stabilized (no leakage), lightweight, tunable	Lower latent heat, fabrication complexity
	Nano-encapsulated PCMs (silica, polymer shells) [125]	25–60	100–160	0.5–3.0	Stable, good distribution, scalable for packs	Expensive, lower capacity per weight

Moreover, a recommendation matrix showing which PCM materials are best suited for different Li-ion battery applications (EVs, stationary storage, and consumer electronics), along with reasoning, is detailed below in Table 5. For a more visually intuitive presentation, a visual flowchart was created, as shown in Figure 4.

Table 5. Recommendation matrix for PCM materials in Li-ion battery applications.

Application	Best-Fit PCM Type	Examples	Why Suitable	Limitations
Electric Vehicles (EVs)	Composite/Hybrid PCMs (organic + fillers) [73]	Paraffin/graphite, fatty acid/graphene, PEG/SiO ₂ aerogel	-Operating range (30–60 °C) matches Li-ion safety window -High latent heat for heat spikes during fast charging/discharging -Additives improve conductivity (2–10 W/m·K) for rapid heat spreading -Shape-stabilized → no leakage in dynamic environments	Higher cost, reduced latent heat due to additives, fabrication complexity
Stationary Energy Storage (grid, renewable integration)	Inorganic PCMs (salt hydrates, molten salts) [126]	CaCl ₂ ·6H ₂ O, Na ₂ SO ₄ ·10H ₂ O, LiNO ₃ –KNO ₃ mixtures	-Can tolerate wider temperature ranges -High volumetric energy storage -Low flammability and safer in large installations -Cost-effective for large-scale systems	- Supercooling and segregation (salt hydrates) - High melting point (molten salts) unsuitable for low-temp ops - Corrosion issues
Consumer Electronics (laptops, phones, drones, power tools)	Organic PCMs (low-melting paraffins, fatty acids, PEG) [127]	Paraffin (C16–C20), lauric acid, PEG-600	-Lightweight, compact -Low melting range (30–45 °C) ideal for small Li-ion cells -Easy integration into casings or encapsulated composites -Less complex manufacturing than composites	- Low thermal conductivity → may require micro/nano-encapsulation - Flammability of paraffins
High-power/Extreme Applications (fast-charging EVs, aerospace, defense)	Advanced nano-composite PCMs [128]	Paraffin + graphene nanoplatelets, PCM in metal foams, nano-encapsulated PEG	-Ultra-fast heat dissipation needed -Graphene/metal foam structures boost conductivity >10 W/m·K -Stable and reliable under extreme thermal cycling	Expensive, not yet mass-produced, weight concerns (metal foams)

Figure 8 illustrates how different PCM types are selected for Li-ion battery applications depending on the use case, ranging from EVs to stationary storage, consumer electronics, and high-power systems. It highlights the tailored match between application requirements and PCM materials, such as organic, inorganic, hybrid, or nano-composites, to optimize thermal management, safety, and performance.

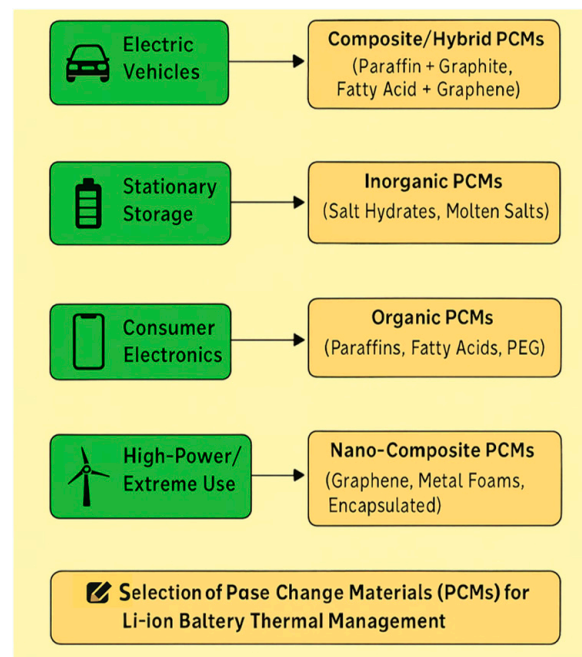


Figure 8. PCM selection for Li-ion battery applications.

3.4. Future Directions in PCM-Based BTM

Ongoing research aims to overcome the intrinsic limitations of conventional phase change materials (PCMs) and enable their broader use in lithium-ion battery packs for electric vehicles and stationary energy storage. Several key development pathways are being pursued to improve PCM-based battery thermal management (BTM) systems. These include new high-conductivity nano-enhanced PCMs, shape-stabilized composites to prevent leakage, active-passive hybrid cooling architectures, climate-tailored PCM blends, structural integration of PCMs into battery modules, advanced encapsulation techniques for scalable manufacturing, and the use of modeling and AI-driven optimization. The sections below discuss each of these directions in detail.

Nano-Enhanced and High-Conductivity PCMs—The incorporation of thermally conductive nanomaterials, such as graphene, carbon nanotubes, expanded graphite, or metal nanoparticles, in nano-enhanced and high-conductivity PCMs can increase the PCMs' effective thermal conductivity by up to an order of magnitude, all while preserving their latent heat storage capacity. Proper optimization of filler dispersion and loading is essential to avoid excessive viscosity or phase segregation. While there are several review papers that encompass these novel materials in various different applications [96,129,130], our main focus is on BTM systems that incorporate nano-enhanced phase change materials. Below, in Table 6, are several recent real-world examples of BTM systems that incorporate nano-enhanced PCMs.

Table 6. Summary table of nano-enhanced PCM-based BTM examples.

System Type	Nano-Enhanced PCM (nePCM) Integration	Key Advantage
Emulsion-based liquid cooling [4]	NPCME (octadecane/eicosane)	Lower $T_{\max}$ and ΔT vs. water cooling
Expanded Graphite/PCM/Graphene Composite [131]	Solid nePCM + radiative layer	26% temperature reduction, passive performance
Air-Assisted Hybrid nePCM System with Nano Powder Enhancements [132,133]	nePCM with graphite/nano powder	Maintains safety under real-cycle conditions

Table 6. Cont.

System Type	Nano-Enhanced PCM (nePCM) Integration	Key Advantage
Hybrid PCM/Liquid Cooling Plate with Graphite Composite [19]	PCM impregnated in graphite matrix	Efficient thermal removal via channels
Fin-PCM-Expanded Graphite Composite Heat Sink [134]	Expanded Graphite-enhanced nePCM with fins	Superior under high discharge rates
Hybrid Nanofluid + nePCM Cooling for Pouch Cells [135]	Nanofluid + PCM in cold plates	Effective for high C-rate pouch cells
Hybrid Nanofluid + nePCM in Cylindrical Packs [136]	Nanofluid + PCM hybrid in cylindrical pack	Enhanced lifespan and thermal uniformity

Shape-Stabilized and Leakage-Proof Designs—Embedding PCMs into porous matrices, such as metal foams, aerogels, or polymer scaffolds, mitigates leakage and enhances structural stability during phase transitions. Shape-stabilized PCMs may be directly integrated into module casings or cell spacers, eliminating the need for additional containment structures. A concise summary containing the most recent developments is detailed in Table 7.

Table 7. Summary table of shape-stabilized and leakage-proof PCM designs.

System Type	Matrix Material	Key Outcome and Highlights
Metal Foam-PCM Composite [137]	Copper/Nickel Foam	Embedding PCM into metal foams significantly improves thermal conductivity and shape stability, achieving lower peak temperatures and more uniform cooling across battery modules
Hybrid Metal-Foam and Active Cooling [138]	Metal Foam + Water Channels	A hybrid system embedding PCM in metal foam and integrating water-cooled channels reduces maximum battery temperatures and improves thermal distribution, especially under high discharge rates
Aerogel-PCM Composite [139]	Biomass Aerogel Scaffold	A Ge/SA biomass aerogel coupled with a flexible CPCM provides exceptional thermal insulation (~120 °C temperature difference across 1 cm), high latent heat, and robust shape stability—delaying thermal saturation effectively
Gelatin/Sodium Alginate Aerogel + CPCM [139]	Biopolymer Aerogel	This multi-network aerogel combined with CPCM performs as a highly insulating, flame-retardant stabilization system, absorbing heat while maintaining structural integrity during thermal events
Hierarchical Macro-Nanoporous Metal + PCM [140]	Copper Macro-Nanoporous Matrix	Achieves leakage-free PCM loading (90 vol%) with high energy density, a three-fold thermal conductivity increase, and effective temperature control in simulated battery pack models
Ternary MWCNT/Graphene Aerogel-PCM [141]	Carbon Aerogel (MWCNT + Graphene)	This composite PCM achieves up to a 124% increase in thermal conductivity and a 63% reduction in operational temperature in battery applications owing to enhanced heat dispersion and stability

Active–Passive Hybrid Systems—These combine PCMs with air cooling, liquid loops, or thermoelectric modules, thus enabling rapid heat dissipation once the PCM is fully melted, and they also maintain effectiveness during continuous operation. Moreover, intelligent control algorithms can only trigger active cooling when PCM storage capacity

is exhausted, thereby minimizing parasitic energy consumption. In Table 8, some recent examples that blend passive thermal storage with active cooling methods are described.

Table 8. Hybrid PCM-based BTM examples.

System Type	Hybrid Configuration	Key Highlights and Outcomes
Air Cooling + PCM with Fins [58]	PCM buffer + air convection via biomimetic fins	Reduced power consumption by ~59%; maintained $T_{\max} \approx 40\text{ }^{\circ}\text{C}$ and $\Delta T \approx 3\text{ }^{\circ}\text{C}$
Air Cooling + PCM + Copper Foam [137]	Air flow + PCM in metal foam (prismatic cells)	Hybrid reduced $T_{\max}$ by $24\text{ }^{\circ}\text{C}$ vs. $+13\text{ }^{\circ}\text{C}$ (active) and $+11\text{ }^{\circ}\text{C}$ (passive)
Liquid Cooling Plate + PCM Composite [66]	PCM impregnated graphite between cells + microchannel liquid plates	Enhances heat transfer via PCM to coolant, improving thermal dissipation
Heat Pipe + PCM [142]	PCM reservoir integrated with heat pipes and fin jackets	Maintains lower temperatures at high discharge power, with airflow variation
Water Channels + Dual-PCM in Metal Foam [143]	Active water cooling + metal foam with two PCMs	Reduces $T_{\max}$ by $\sim 2\text{--}2.7\text{ }^{\circ}\text{C}$; improved thermal uniformity by $1.2\text{ }^{\circ}\text{C}$
Liquid Nanofluid + PCM (Nanofluid Cooling) [144]	Nanofluid coolant + PCM in foams and microchannels	Achieves $\sim 3.44\text{ }^{\circ}\text{C}$ lower $T_{\max}$ at 1C discharge; 6–15% longer cycling; only 5% more power use
Liquid + PCM + Nanofluid (Simulated Hybrid BTM systems) [143,145]	Hybrid with PCM, liquid assist, and Al_2O_3 nanofluid	Hybrid BTM systems improves $T_{\max}$ by $\sim 28\%$; only it and PCM achieve $\Delta T < 5\text{ }^{\circ}\text{C}$

Tailored Melting Points for Different Climates—PCMs are blended with application-specific melting temperatures (e.g., $30\text{--}45\text{ }^{\circ}\text{C}$ for EVs, higher for aerospace or defense systems), improving thermal management efficiency and operational safety across diverse environments. Table 9 highlights the recent strategies for tuning PCM melting temperatures to optimize performance across diverse environments.

Table 9. Tailored melting points for different climates—BTM examples.

BTM System Strategy	Melting Point Tuning Approach	Key Benefit and Outcome
Multi-PCM Hybrid Systems [145]	Dual-layer PCM set with distinct melting temperatures embedded in metal foam and water channels	Enhances thermal regulation via staggered heat absorption; reduces $T_{\max}$ by $\sim 2.7\text{ }^{\circ}\text{C}$ and homogeneity improves by $1.2\text{ }^{\circ}\text{C}$ under 3C discharge
Modular PCM in Aviation Packs [138]	Carefully selected PCM with melting point tailored just above ground ambient ($42\text{--}50\text{ }^{\circ}\text{C}$) for triggering phase change only during high thermal loads	Prevents premature melting in cool conditions; provides sufficient latent capacity during critical flight phases
EV-Friendly PCM ($\sim 40\text{ }^{\circ}\text{C}$) [146]	Use of PCM melting near $40\text{ }^{\circ}\text{C}$ to maintain optimal battery operation; supports life extension and capacity stability	Maintains battery within safe thermal window, particularly in mild-to-warm climates
Solar-Climate PCM ($75\text{ }^{\circ}\text{C}$) [147]	PCM with $\sim 75\text{ }^{\circ}\text{C}$ melting point for engine pre-heating in cold climates	Retrieves waste heat effectively, reducing combustion-related fuel use in cold starts ($<0\text{ }^{\circ}\text{C}$)
Low-Melting Inorganics ($10\text{--}20\text{ }^{\circ}\text{C}$) [148]	Salt hydrates and organics with low melting temps tailored for ambient-sensitive thermal storage	Maintains thermal equilibrium in temperate or cooling-demand sequences

Structural Integration in Battery Packs—The PCM composites are designed as load-bearing or vibration-damping components in order to reduce system-level weight penalties. In this respect, multifunctional pack structures combining thermal management with crash protection, or acoustic insulation, seem particularly interesting. Incorporating PCMs into battery pack structural components, including flexible sleeves or foam matrices, achieves both thermal management and mechanical performance or protection, arranging for compact, safe, and multifunctional battery module designs. Some recent examples are presented in Table 10.

Table 10. Structural integration of PCMs in battery packs—examples.

System Type	Structural Integration Approach	Key Highlights and Outcomes
Flexible Dual-Layer FPCM Sleeve [149]	PCM embedded in a flexible composite sleeve with outer conductive and inner insulating layers	Achieves $\Delta T_{\max}$ reduction of 14.5 °C at 5C discharge; maintains flexibility and adaptability across climates
PCM-Negative Poisson's Ratio Laminboard [150]	PCM encapsulated in a modular laminboard structure integrated with liquid cooling plates	Reduces $T_{\max}$ by 3.8 °C and ΔT by 2.5 °C; also decreases mechanical stress and deformation
Metal Foam + Dual PCM + Water Channels [143]	Dual PCMs impregnated in metal foam integrated into structural water-cooled channels	Enhances cooling uniformity and reduces $T_{\max}$ by ~2.7 °C, while providing structural rigidity
PCM-Composite Cell Spacers [151]	Shape-stabilized PCM integrated into load-bearing cell spacers	Improves pack compactness and minimized leakage risk, while ensuring both thermal buffering and vibration damping
Multifunctional PCM Barriers [152]	PCM-based crash-protection barriers within modules	Provides both thermal runaway mitigation and structural reinforcement under mechanical impact

Encapsulation at Pack-Level Manufacturing Scale—Integration of novel advances in microencapsulation, vacuum-assisted filling, and additive manufacturing has led to this development. It has great potential for cost-effective, scalable integration of PCMs in large-format batteries used for EV and grid-storage applications. These techniques are listed in Table 11, with the methods shown to be best suited for scalable battery pack integration being listed.

Modeling, AI Optimization, and Digital Twins—Leveraging high-fidelity thermal-electrochemical simulations with machine learning can allow for optimum geometry, distribution, and the material selection of PCM for different duty cycles. In addition, a digital twin framework can provide real-time predictions of the saturation state of the PCM, as well as facilitate predictive cooling management and adaptive battery thermal management system operation. A summary and recent advancements related to the modeling, AI optimization, and digital twins specific to battery thermal management systems are provided in Table 12.

Table 11. Encapsulation for scalable PCM deployment in battery packs.

Encapsulation Technique	Description and Outcome
Multi-Scale Inorganic PCM Encapsulation [153]	Sodium acetate trihydrate (inorganic PCM) is first micro-encapsulated with expanded graphite to → thermal conductivity $\sim 4.96 \text{ W/m}\cdot\text{K}$ and prevent leakage; then, it is macro-encapsulated with silicone sealant to ensure long-term chemical stability
Microencapsulated PCM Suspensions (MPCMS) [154]	Microcapsules (e.g., paraffin/melamine resin) are dispersed in base liquid to form a latent heat-enhanced coolant; demonstrates $\sim 14.5^\circ\text{C}$ reduction in module temperature and a $\sim 3.8^\circ\text{C}$ reduction in temperature variance compared to plain coolant
Encapsulated PCM with Enhanced Thermal Conductivity [155]	Use of graphene or CNTs in micro-epoxy or polymer shells; silver-coated nano-PCM improves thermal conductivity from 0.246 to $1.346 \text{ W/m}\cdot\text{K}$; CNT-enhanced microcapsules preserve PCM latent heat and improved uniformity
Semi-Penetrating Composite Shell Encapsulation [76]	Core-shell PCM structures using CaCO_3 or SiO_2 shells around octadecane core; increases durability, thermal conductivity, and leakage protection—scalable and cost-effective encapsulation

Table 12. Modeling, AI optimization, and digital twins for battery thermal management examples.

Strategy	Description and Outcomes
Cooling-Guided Diffusion Model for Cell Arrangement [156]	A generative AI framework using a diffusion model to optimize battery cell layouts for enhanced thermal diffusion. Achieves superior cooling efficiency—outperforming TabDDPM by $5\times$ and CTGAN by $66\times$ in feasibility and thermal performance
Physics-Informed ML Surrogate for Temperature Distribution [157]	Integrates physics laws into ML surrogate modeling (via convolutional neural networks) to predict battery pack temperature. Delivers 15% better accuracy than purely data-driven models using less training data
Digital Twin with ROM and ML Integration [158]	Combines reduced-order models from CFD with supervised machine learning (decision trees, SVR, and neural nets) to create a predictive digital twin for thermal dynamics. Offers fast updates and high accuracy
Real-World BTM System Optimization via Driving Prediction [159]	Uses neural networks to predict driving profiles for real vehicle BTM systems, enabling adaptive thermal management optimization in real time
Review of AI/ML in BTM System Optimization [160]	Highlights the utility of ML models (ANN, LSTM, NSGA-II, and Kriging) for optimizing BTM system performance—achieving an R^2 of up to 0.99 and temperature reductions up to 31.7%. Identifies gaps in real-world validation and system variability
Hybrid ML-CFD Models for Digital Battery Modeling [161]	Reviews the fusion of physics-based modeling and ML to accelerate battery digitalization—balancing accuracy and computation speed in design and real-time control
Surrogate Models for PCM-Liquid Hybrid BTM Systems [162]	Employs surrogate modeling (Adaptive Kriging HDMR) alongside AI (SVR optimized with PSO) to predict and optimize thermal performance, cooling capacity, and system COP
AI Prediction for PCM + Air Cooling System Behavior [161,162]	Neural network trained to predict average and peak battery temperatures under varying conditions with $<10\%$ error and $R \approx 0.997$. Inputs include discharge rate, coolant flow, and inlet temperature

Research efforts are underway to address some of these limitations in a few exciting ways. Nano-enhanced PCMs that incorporate additives such as graphene, carbon nanotubes, or even metal alternatives have been proven to enhance thermal conductivity by a factor of 10 while maintaining latent heat storage characteristics, and shape-stabilized designs—or porous substrates (e.g., metal foams, aerogels, or polymer substrates)—have been produced that are less prone to leakage and can be immediately used in a battery module form factor [163]. Hybrid cooling systems that combine PCMs with an active system (i.e., air and liquid loops) have been used to rapidly dissipate heat after systems become saturated with PCMs, thereby extending performance, while minimizing parasitic energy expenditure, in rigorous use cycles. Advancements in innovative materials are achieving PCM blends with specific melting points tailored for distinct climate zones or operational profiles, while the pursuit of multifunctional composites are filling in the roles of load bearing or vibration damping to offset weight. Progress on encapsulation and additive manufacturing techniques are increasing manufacturability in aim to scale. Development of modeling and AI-based optimal placement and geometry of PCMs create more predictable bonding within the frame for better thermal uniformity and efficiency.

Overall, PCM-derived thermal management is a compelling building block for next-generation BTM systems, especially when incorporated in hybrid systems and multifunctional pack configurations. As materials, encapsulation, and predictive design advance, their application will likely continue to expand from niche peak-load buffering into mainstream EV and stationary storage platforms. Figure 9 captures all of this.

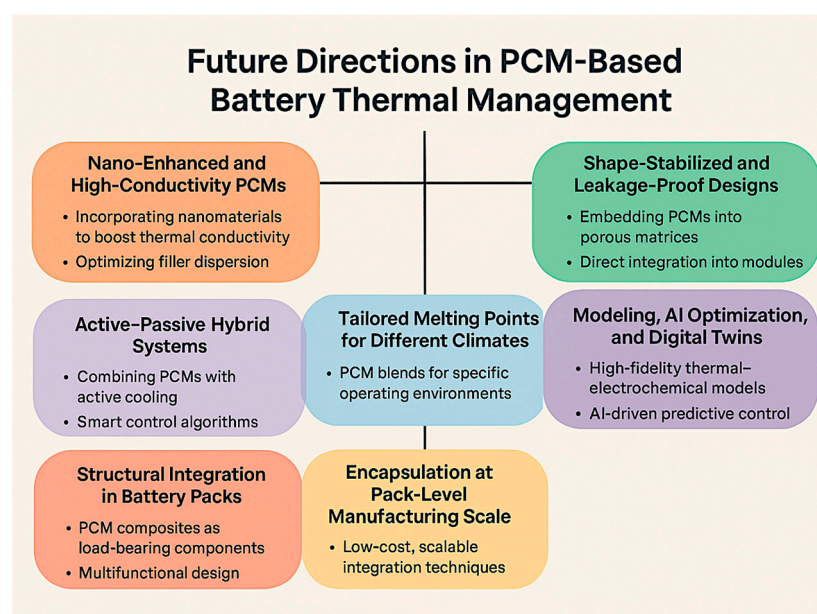


Figure 9. Future directions in PCM-based BTM approaches.

As one can see, there is a clear logical relationship between the left-hand blocks and the right-hand blocks. The left-hand blocks discuss the practical and system levels when considering PCMs: how best to implement the materials inside a battery pack. They concern themselves with things like enhancing the thermal performance of the PCMs, combining them with active cooling systems in the battery pack, and their structural integration into the design of the battery. In other words, they will deal with the practical aspects of implementation and application. The right-hand side of the chart has more emphasis on the design, optimization, and stability aspects. These would include developing shape-stabilized PCMs to prevent leakage, programming the melting point to suit the climate; and modeling, artificial intelligence, and digital twins for predicted and optimal performance.

The right-hand side of the chart emphasizes the refinement, control, and adjustments of the PCM system for reliability and efficiency performance aspects. In all, the two sides are complementary: the left describes what we build and integrate into the battery system, and the right describes what we need to do to design, optimize, and stabilize those solutions. While challenges related to thermal conductivity and shape stability exist, ongoing research and development efforts are currently focused on overcoming these limitations and optimizing PCM-based systems for various battery applications.

4. Battery–PCM Integration Strategies

The performance of phase change materials (PCMs) for thermal regulation in lithium-ion battery systems not only clarifies on the thermal and physical properties within the phases of a PCM, but also how these materials are structured within the cell, module, or pack. The structure of the PCM will define how efficiently heat is absorbed, the uniformity of temperature distribution, and the overall applicability of larger systems. Multiple design techniques have been demonstrated for PCMs in battery systems, from direct encapsulation to varying degrees of complexity in composite designs.

4.1. Direct-Contact Integration

In configurations involving direct contact, the PCM is in immediate physical contact with each battery cell or the battery casing, promoting optimal thermal conductivity. Heat is quickly taken up, not only during the charge/discharge cycle, but also when inserting into a localized hot spot [151,153]. PCMs in both cylindrical and prismatic cell formats are typically cast or infiltrated into the spaces between battery cells to capture localized heat while promoting temperature uniformity or to minimize the temperature differences across the pack. This mechanism affords the fastest PCM response in cases of transient heat, making it particularly useful during high C-rate charge/discharge events. Direct-contact PCM configurations are commonly applied in laboratory prototypes or demonstration systems, while also serving as the basis for most passively cooled PCM-based designs. The only drawback is that these designs require reliable leak-proof encapsulation to prevent the risk of an electrical short circuit. Organic PCMs, ranging from paraffins to polyethylene glycol (PEG), are often utilized in conjunction with microencapsulation or polymeric supports to provide a built-in safety to the operation of organic PCMs [145].

Multiple design options for direct-contact PCM integration have been created for various battery geometries and packaging approaches. One of the prevalent designs includes cell jackets or sleeves (wrapped or molded). Pre-formed jackets, normally silicone or thermoplastic shells filled with PCM or shape-stabilized PCM sleeves, are wrapped or molded around individual cells. This approach provides good thermal contact at the cell level, and it also works well in automated assembly situations like those commonly used for cylindrical cells, such as 18,650 or 21,700 [151]. Another prevalent design is interstitial or gap filling, where PCMs are cast or injected into modules between each cell within the module enclosure and spacing has been optimized to maximize PCM volume and thermal uniformity. This approach improves thermal uniformity across the module cooling surface, but it may have drawbacks due to the need for careful leak-proofing and vacuum filling processes. The ideal PCM layer thickness will vary depending on the cell geometry and operating C-rate, but it is generally in the ~2–8 mm thickness range. The optimal thickness is often referenced for small-format cells and falls within the 3–4 mm range for the best compromise [145].

More recently, PCM layers based on thin-film or coatings have been of more interest because of their low weight and high thermal conductivities. Thin PCM layers, usually made from microencapsulated or solid–solid PCM composites, are applied directly to the

surface of the cells for a small and preventable thermal interface. Since solid–solid PCMs are structurally stable during phase transition, they completely eliminate leakage risk, contributing to a more efficient and lightweight or flexible battery module design [154]. The encapsulated microcapsules dispersed around cells and composites, for example, in potting or adhesives or polymers also represent an elegant alternative because they satisfy inherent leakage protection while concurrently permitting co-integration with electrical insulation or structural materials. A schematic overview of these direct-contact PCM strategies is shown in Figure 10.

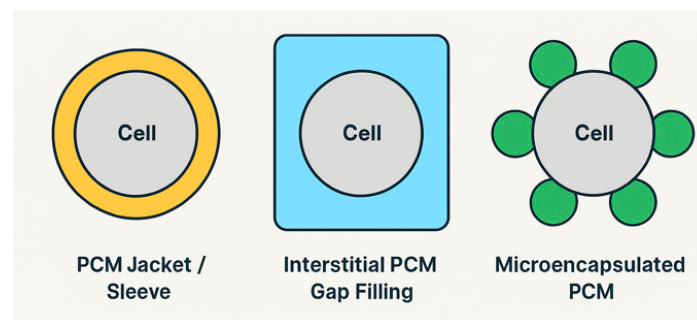


Figure 10. Direct-contact PCM integration strategies: **left**—PCM jacket/sleeve around the cell (orange); **middle**—PCM interstitial gap filling between cells (blue); and **right**—microencapsulated PCM dispersed around the cell (green).

In order to support the design selection, Table 13 encompasses the recommended PCM grades, thickness ranges, and target conductivities suitable for direct-contact LIB integration.

Table 13. Recommended PCM grades, thickness ranges, and conductivity targets for direct-contact Li-ion battery integration.

PCM Type/Grade	Melting Range (°C)	Form/Example	Recommended Thickness (Cell Contact Layer)	Target Effective Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Notes/Application
Paraffin (C18–C28) [164–166]	28–55	Commercial paraffin wax, shape-stabilized with EG or polymer	3–5 mm (cylindrical); up to 8 mm (prismatic)	≥ 1 –3 (with EG/graphene)	Widely used; simple; risk of leakage without stabilization
PEG (PEG-1000, PEG-1500) [167–169]	30–50	Solid–solid PEG, PEG/SiO ₂ or PEG/EG composites	3–4 mm typical; up to 6 mm for high C-rate	≥ 1 –5 (with EG, GNPs, BN)	Stable cycling, reduced leakage; effective for cylindrical and pouch cells
Salt Hydrates (e.g., CaCl ₂ ·6H ₂ O, Na ₂ HPO ₄ ·12H ₂ O) [170,171]	25–40	Encapsulated or polymer-stabilized	2–6 mm	≥ 1 –2 (with graphite/metal foam)	High latent heat but requires encapsulation to avoid leakage and phase separation
Shape-stabilized Organic–Inorganic Hybrids [172,173]	30–45	Paraffin/PEG + silica, aerogels, polymer matrices	2–4 mm	1–3	Leak-free, mechanical stability, suitable for direct coating or jackets
Metallic PCM (low-melting alloys, e.g., Ga–In–Sn) [174,175]	25–35	Encapsulated alloy droplets in polymer or graphite foam	1–3 mm	10–30	Very high conductivity, but cost, toxicity, and corrosion issues limit use
Microencapsulated PCM (paraffin, PEG in polymer shells) [176,177]	28–45	Dispersed microcapsules in polymer resin or adhesive	Thin coating ≤ 1 mm	0.5–2	Leak-proof, scalable, good for thin direct-contact layers; lower volumetric enthalpy

4.2. Indirect-Contact Integration

In an indirect-contact configuration, the phase change material (PCM) heats the battery cell through an intermediate structure. This intermediary structure can take the form of

a metal foam, fin array, or heat spreader to thermally couple the PCM instead of direct contact with the cell surface. This configuration improves mechanical strength and safety, helping to avoid the potential for PCM leakage into the electrochemical system, while still enabling efficient thermal management [153]. Most PCMs have intrinsically low thermal conductivities, so a material such as expanded graphite, aluminum foils, or embedded fins are often used to bridge the thermal conductivity from the cell casing to the PCM while enabling quick thermal transfer and transient response during charge–discharge; in addition, they are able to manage the heat more uniformly than if there was no inducing structure to facilitate improved heat transfer [168]. Indirect integration is especially beneficial for pouch-cell modules because providing structural support, minimizing deformation, and allowing for an even distribution of pressures are significant design variables [151]. Additionally, it is often the preferred solution when the design focuses more on leakage resistance, electrical insulation, or ease of manufacturing, rather than solely on maximizing the heat absorption rate. Even though the thermal coupling is somewhat lowered relative to direct-contact systems, indirect configurations has great design flexibility, mechanical stability, and safety margins.

The heat spreader and PCM pocket design is one of the most common configurations. This design has a thin, high-conductivity plate (graphite sheet, Cu/Al foil, or plated metal) located in direct contact with the cell surface. The plate then conducts heat rapidly into pockets or reservoirs filled with the phase change material that are located some distance away from the cell surface (for example, interstitial pocket/PCM filled tray type of reservoirs). The PCM pockets, which are typically embedded in interstitial layers or trays, absorb heat. The heat spreader would act to thermally distribute the heat evenly to the spreader layer across the module.

An alternative design that is also commonly utilized is the fin/plate and PCM behind barrier configuration. In these designs, the long fins or plates are used to conduct heat away from the cell casing towards the PCM enclosure. The PCM is retained within a container, which has a thermal barrier between the PCM and cell casing. The PCM acts as a thermal buffer, absorbing peak loads, while the fins can be cooled on the other side by air or liquid channels (the design is typically used in conjunction with air/liquid channels on the other side of the fins). This combined design is especially interesting for modules that need both steady-state temperature control by the PCM and emergency thermal buffering due to unpredictable loads, such as in electric vehicles. Metal foam bridges are a further development of those designs, where a porous metal foam (Al or Cu foam) is pressed between the cell casing and the PCM, acting as both a thermal bridge while providing containment for the PCM. The PCM is imbibed into the foam (above the cell casing and away from direct contact), thereby enhancing safety and mechanical stability while providing even heat distribution and latent heat storage [143]. The foam also creates a good mechanical interface that can withstand vibration and thermal stress while preventing PCM leakage. This design offers a solid compromise between reliability, safety, structural rigidity, and thermal responsiveness.

In applications requiring elevated lateral heat conduction, graphite sheets or flexible thermal straps with excellent in-plane conductivity are adhered to the surface of the cells, redistributing heat laterally towards a central PCM reservoir or heat sinks that are adhered to busbars. This strategy reduces the chances of hot spot formation [150]. This arrangement is an effective way to reduce hot spot formation in modules that are densely packed together or when they have limited space and airflow. More sophisticated designs utilize integrated passive and active thermal regulation systems. For example, in heat pipe or vapor chamber and PCM systems, the heat generated by the cells with elevated power levels is transferred into a distant PCM reservoir via embedded heat pipes or vapor chambers. Once the heat

has been transported into the PCM, the thermal energy is absorbed and stored into the PCM, which limits temperature fluctuations and the need for constant active cooling. Hybrid strategies of heat pipe and PCM are particularly well suited to densely packed, high-power modules, where compactness and rapid heat removal is essential [142].

Lastly, a very strong option is a cold plate with PCM backup. In this hybrid configuration, a liquid cold plate offers active cooling, and the PCM, located behind the plate, is passive. In the case active cooling is not available, the PCM only temporarily augments passive heat removal, so there is enough time to avoid thermal runaway [66]. Such a safeguard offers additional dependability and safety to the system, especially valuable in the case of mission-critical and high-power use cases. In summary, by integrating PCM indirectly, a satisfactory equilibrium is achieved amongst thermal efficiency, structural durability, and safety. The resulting package successfully adds conductive pathways combined with cleverly engineered PCM reservoirs, achieving controlled, even removal of, heat without sacrificing mechanical design or manufacturability. They represent a practical and scalable solution for modern LIB modules, particularly those used in EVs and stationary energy storage systems. A schematic representation of several indirect PCM architectures, including the heat spreader with PCM pockets, metal-foam bridge, and the heat pipe plus PCM design, is shown in Figure 11. A comparative summary of the direct and indirect integration approaches is also provided in Table 14.

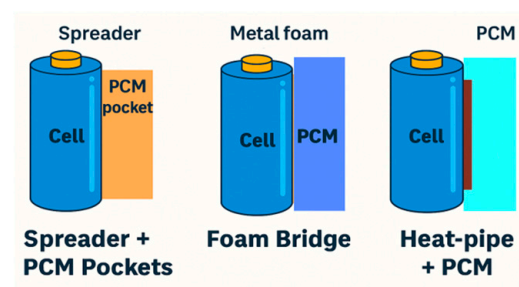


Figure 11. Schematic illustration of the three indirect PCM integration variants.

Table 14. Indirect vs. direct PCM integration performance.

Criterion	Direct-Contact PCM	Indirect-Contact PCM
Thermal performance	Very high heat absorption efficiency (low thermal resistance, rapid response) [12,42]	Moderate efficiency (extra thermal resistance via spreaders/foams), but better spatial heat spreading [178]
Temperature uniformity	High local absorption, but may cause uneven distribution if PCM placement is non-uniform [10]	Better lateral heat distribution (graphite/metal spreaders reduce hotspots, ΔT typically $< 3\text{--}5\text{ }^{\circ}\text{C}$) [5]
Recommended PCM grades	Paraffins (C16–C28), PEG (MW 1000–6000), fatty acids; composite PCMs with expanded graphite (EG) or BN for conductivity [140]	Paraffins/paraffin–EG composites, hydrated salts (PCM pockets), metallic foams impregnated with PCM, graphite-enhanced PCMs [6,141]
Typical PCM thickness	2–6 mm jackets or sleeves; 1–3 mm interstitial fills; microcapsules dispersed within 0.1–0.5 mm matrix [179]	PCM pockets/trays: 5–15 mm; foam bridges: 3–10 mm; spreader-linked PCM reservoirs: 10–20 mm [6,180,181]
Target effective conductivity	$\geq 1.0\text{--}2.0\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (with fillers) to ensure rapid absorption [182]	$\geq 3.0\text{--}5.0\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for spreaders/foams; PCM pocket conductivity less critical, focus on latent enthalpy [180,181]

Table 14. Cont.

Criterion	Direct-Contact PCM	Indirect-Contact PCM
Weight impact	Lower mass (PCM applied directly, no extra spreader components) [10,179]	Higher due to spreaders, foams, or heat pipes [6]
Cost impact	Lower material and manufacturing cost; simpler assembly [179]	Higher due to added conductive materials, TIMs, and assembly steps [6]
Safety	Risk of leakage and direct contact with conductive PCMs; electrical insulation required [182]	Safer (PCM isolated in pockets/trays); lower leakage and contamination risks [6]
Reliability	Long-term stability depends on PCM encapsulation quality; mechanical stress may damage PCM layer [183]	More robust mechanically; easier to service/replace PCM modules [180,181]
Integration complexity	Simple to implement in small packs (e.g., consumer electronics) [179]	More complex, suitable for EV packs and aerospace modules [6]

4.3. Hybrid Integration

Hybrid thermal management systems incorporate phase change materials (PCMs), along with active cooling approaches (e.g., liquid cold plates, forced air, heat pipes, and thermoelectric coolers), to provide reliable and adaptive thermal management. In these systems, the PCM mainly acts as a transient heat buffer to absorb certain rapid thermal surges during the charge–discharge peak periods, as well as the active subsystem to maintain steady-state heat rejection. Therefore, the hybrid system provides additional short-term stability and long-term temperature management, allowing for consistent operation at varying load profiles [184]. These techniques are effective in reducing PCM volume and extending the thermal protection time of the PCM. Hybrid PCM systems, which combine passive latent heat storage with active heat release, can result in a significantly reduced PCM mass requirement while also extending the thermal protection duration. PCM–liquid cooling systems, for example, have reported up to a 15 °C decrease in peak battery temperature and <3 °C inter-cell temperature gradients in a high C-rate cycling for lithium-ion batteries [185]. These designs are especially well suited to battery thermal systems, such as in electric vehicles (EVs), high-power energy storage systems, and industrial batteries (where repetitive charge–discharge cycles require stable and low maintenance load cooling).

One of the most straightforward and affordable hybrid configurations is PCM and forced air, consisting of PCM layers or trays situated between cells, either in interstitial trays or jackets, with forced air flowing through module channels to fight against the latent heat and to re-solidify the PCM after high-load events. It is a relatively inexpensive method that is not complex to retrofit, but the overall heat removal rate is less than the other options utilizing liquid [186]. With PCM and liquid cold plate (direct or indirect), the liquid coolant is the main steady-state sink, while the PCM layer is used for passive buffering during transient peaks or pump failure. PCM reservoirs are often placed behind heat spreaders or incorporated into cold plates, resulting in faster response times. All examples can consistently be shown to provide dramatic reductions in peak temperature using relatively small PCM volumes that will suit EV battery packs and grid-scale storage modules [187].

Systems that use PCM + heat pipes or vapor chambers, which effectively absorb cell heat and transfer it to PCM reservoirs where space or airflow is more advantageous, are an especially successful hybrid approach. This hybrid configuration produces extremely

sensitive temperature stabilization by fusing the energy storing capability of PCMs with the quick thermal transmission of heat pipes. Under high C-rate operation, experimental experiments have demonstrated a notable decrease in temperature rise and inter-cell variance [188].

PCM and thermoelectric coolers (TECs) are integrated in another cutting-edge design. To keep the base-line temperature low or to speed up the PCM re-solidification in between cycles, TECs actively remove heat from the PCM blocks in these systems. They represent a promising development for next-generation lithium-ion batteries due to their adaptability and scalability. Although very controlled, this method uses a great deal of power and is, consequently, only used in precision electronics, aerospace, and defense applications where dependability is more important than power efficiency [189].

In another approach, small PCM pockets are positioned close to individual cells in a distributed PCM and central active system to capture localized heat flux, and the PCM network's stored heat is regularly released via a central cooling loop made of liquid or air.

This distributed–central hybrid ensures rapid transient absorption combined with scalable recharge capability [60].

Lastly, PCMs are used in redundant or fail-safe hybrids as a passive safety backup in the event of an active cooling failure, such as a pump failure or power outage. In these situations, the PCM improves system resilience and dependability by absorbing important heat loads and preserving safe operating temperatures until regular cooling returns [190].

In conclusion, hybrid PCM systems offer a clever balance between active efficiency and passive simplicity, guaranteeing dependable, high-performance temperature control (even in the face of challenging operating circumstances). They represent a prospective avenue for the development of next-generation lithium-ion battery thermal management systems due to their adaptability and scalability. Figure 12 presents a schematic overview of the common hybrid integration concepts, such as PCM–air, PCM–liquid, and PCM–heat pipe systems. Table 15 lists the relative performance metrics of these systems.

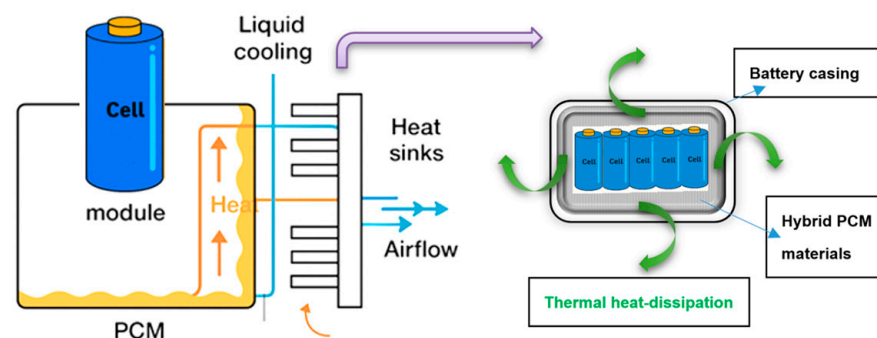


Figure 12. Hybrid integration of PCMs with auxiliary cooling strategies in lithium-ion battery packs.

Table 15. Comparison of hybrid PCM integration performance parameters in lithium-ion battery thermal management.

Hybrid PCM Integration	Peak Temp. Reduction (°C)	Max. Temp. Difference ΔT (°C)	Thermal Response Time	Energy Efficiency
PCM + Air Cooling [66]	5–12	2–5	Moderate	Low–Moderate
PCM + Liquid Cooling [142]	15–25	2–3	Fast	High
PCM + Heat Pipes [188]	12–20	1–3	Very Fast	High
PCM + Fins/Heat Sinks [191]	8–15	2–4	Moderate–Fast	Moderate
PCM + Hybrid (Air + Liquid) [191]	20–30	<2	Very Fast	Very High

4.4. Structural PCM Integration

Structural phase change materials (PCMs) that serve two purposes—regulating temperature and enhancing the battery module’s mechanical strength, safety, or fire resistance—are a developing area of study [192,193]. In many systems, the PCM is an essential component of the battery’s casing or structure rather than just a thermal medium. PCM-filled honeycomb lattices, PCM–aerogel composites, and PCM–polymer hybrid casings are common examples of implementations that provide multifunctional performance.

One intriguing design idea is PCM-filled honeycomb structures, in which PCM-impregnated metallic or polymeric honeycomb lattices offer high latent heat capacity and mechanical reinforcement in a small package. These structures are appropriate for high-stress situations where both mechanical and thermal stability are necessary because of their exceptional vibration tolerance and thermal damping [194].

PCM–aerogel composites are another cutting-edge material class that improves insulation and flame retardancy by utilizing the high porosity and ultra-low thermal conductivity of aerogels [195]. These composites effectively slow the spread of heat and improve fire safety while ensuring consistent phase change behavior and long-term durability. These composites are very helpful in stopping the spread of thermal runaway between adjacent cells because they combine thermal insulation, energy absorption, and structural integrity into a single layer.

In a similar vein, PCM–polymer hybrid systems do away with the requirement for extra packing layers by directly integrating encapsulated PCM with polymer casings or structural shells. In addition to preserving mechanical rigidity, this integration offers inherent thermal buffering and fire suppression capabilities while lowering weight and volume [196]. Apart from controlling heat, these hybrid shells are capable of providing fire suppression and enhanced mechanical protection against shock or puncture, thus improving both safety and reliability at the module level.

All things considered, incorporating PCMs into structural elements is an example of a multipurpose design paradigm that combines mechanical stability, safety improvement, and thermal regulation into a single system. The continuous drive for lightweight, high-energy-density, and intrinsically safer battery systems is supported by such architectures, which enhance space utilization and decrease parasitic mass by directly integrating thermal functioning into load-bearing or protective components. It is anticipated that future PCM-based systems would develop into scalable, lightweight, and multipurpose designs by utilizing cutting-edge composites and efficient integration techniques for high-performance energy storage modules and next-generation electric cars. The potential of these structural PCM integration techniques to reshape the upcoming generation of small, robust, and thermally self-regulating lithium-ion battery modules is demonstrated by the exemplary instances of these tactics, as schematically shown in Figure 13.

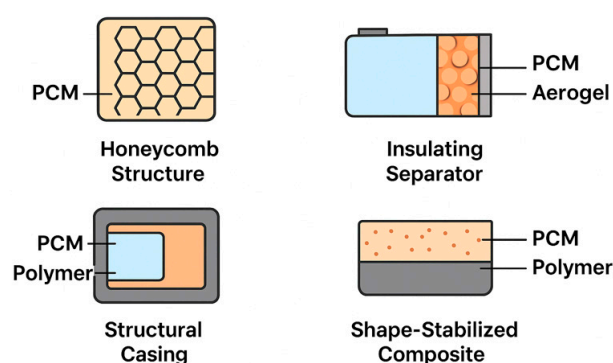


Figure 13. Representative configurations of structural PCM integration in lithium-ion battery packs.

The compact, comparative Table 16 showing the structural PCM vs. the conventional PCM parameter is detailed below.

Table 16. Comparison of conventional vs. structural PCM integration in lithium-ion battery packs.

Parameter	Conventional PCM Integration	Structural PCM Integration
Thermal Regulation [39]	High latent heat storage, good peak shaving	Comparable thermal buffering, dependent on composite matrix
Mechanical Contribution [197]	None (requires external casing/support)	Provides structural support (e.g., honeycomb, polymer-PCM hybrids)
Fire/Impact Protection [198]	Limited (PCM may leak or degrade under fire)	Enhanced (PCM-aerogel composites, flame-retardant matrices)
Weight Penalty [199]	Significant (dedicated PCM mass adds to module weight)	Reduced (PCM contributes dual role, lowering parasitic mass)
Module Compactness [200]	Lower (PCM requires extra volume for encapsulation)	Higher (PCM integrated in casing/separator reduces packaging volume)
Design Complexity [201]	Low-moderate (straightforward encapsulation)	High (requires advanced composites and multifunctional design)
TRL (Technology Readiness Level)	Medium (lab to pilot scale, several demos)	Low-medium (emerging research, limited real-world validation)

4.5. Stability and Safety Enhancements in PCM-Based BTM Systems

Recent developments in phase change material (PCM)-based battery thermal management (BTM) systems have placed a greater emphasis on improving stability, safety, and material compatibility in addition to thermal control. The goal of these advancements is to guarantee that PCM composites continue to function and remain intact throughout harsh circumstances, mechanical pressures, and prolonged cycling [202]. The four main areas of shape stability and leakage avoidance, thermal expansion control, flame retardancy, and chemical compatibility have seen the most advancements.

Shape Stability and Leak Prevention: One of the primary obstacles to real-world use is still the PCM leakage during melting. To address this, researchers have developed shape-stable PCMs designed to retain their form, even in the liquid state. A common strategy involves embedding the PCM within a supporting matrix of polymers, fibers, or porous frameworks that immobilize the liquid phase. For instance, Deng et al. [200] produced a flexible composite PCM by blending paraffin with a styrene-butadiene-styrene (SEBS) elastomer and graphite. The elastomer acted as a containment matrix for the liquid paraffin, thus improving flexibility and preventing leakage during melting. The resulting composite maintained the battery surface temperature near 49 °C under high discharge rates, while exhibiting full shape stability and durability over multiple cycles [39]. Similar immobilization was obtained using porous carbon frameworks or fibrous binder networks [203]. Ensuring such long-term structural and thermal stability is essential for real-world BTM applications.

Thermal Expansion Management: Encapsulation failure and mechanical stress can result from thermal expansion during phase shift [38]. This stress is intended to be absorbed by new PCM structures. In order to counteract this, scientists have created form-stable PCM materials that can internally accommodate expansion and contraction, such as metallic foams or polymer gels. Small amounts of expandable graphite are occasionally included, which provides a counterbalancing expansion that maintains internal pressure when heat-

ing. The significance of strong encapsulation systems that can tolerate these loads without breaking or delaminating was emphasized by Zhang et al. [38]. In order to preserve tight seals across numerous phase change cycles, emerging solutions—like silicone elastomer coatings or flexible polymer shells—are being evaluated.

Thermal Runaway Suppression and Flame Retardancy: Improving fire safety and thermal runaway resistance is crucial since pure paraffin PCMs are flammable. One important feature of PCM-based BTM systems is the ability to remain safe in harsh environments. Non-flammable fillers and flame retardant chemicals have been added to PCM formulations in recent years. For instance, Zhang et al. [38] created a paraffin/expanded graphite composite with additional APP, chitosan, and Al hypophosphite flame retardants. This formulation maintained significant cooling performance (maximum cell temperature $\approx 41\text{ }^{\circ}\text{C}$ at 3C discharge) while self-extinguishing after flame exposure, generating a persistent char layer that resisted further burning. This unequivocally demonstrates that safety may be enhanced without compromising cooling efficiency. Furthermore, inorganic PCMs, including hydrated or molten salts, have been proven to effectively control the propagation of thermal runaway and offer inherent non-flammability. According to Ushak et al. [34], salt-hydrate PCMs greatly decreased the risk of fire and explosion by absorbing substantial amounts of heat during nail penetration tests. All of these findings demonstrate that significant safety improvements are possible without sacrificing the thermal control function.

Chemical Compatibility: Long-term operation depends on chemical inertness and compatibility with battery components, such as cell casings, busbars, seals, and enclosures. Some salt-based or additive-rich PCMs can interact with metallic components and cause corrosion, even though paraffin PCMs are generally inert. The necessity of choosing encapsulating materials carefully was highlighted in the recent Heliyon review [37] since chemical incompatibility might deteriorate the container and result in leaks. It is common practice to use plastic liners for salt-hydrate formulations or to couple paraffin PCMs with aluminum or stainless-steel housings. Güler et al. successfully stopped oxidation and chemical interaction by applying Ni-P alloy plating to metal foam used for PCM encapsulation in 2025 [108]. There is general agreement that PCM systems ought to be housed in inert, chemically resistant containers and that the selected PCMs should be examined for compatibility during the course of the battery's life. Additionally, advanced diagnostic techniques, such as Fourier-transform infrared spectroscopy (FTIR) and storage cycling tests, are becoming more widely used methods for verifying chemical stability over the course of operational lifetimes.

In conclusion, current studies show impressive advancements in enhancing the robustness and safety of PCM-based BTM systems. Shape stabilization, controlled expansion, flame-retardant formulation, and chemical compatibility have all been combined to create PCM composites that are safe from leakage and fire, and they have been able to function dependably throughout a wide range of charge–discharge cycles [204]. These developments are essential for stationary energy storage systems and electric vehicle (EV) systems, where durability and security are just as important as cooling effectiveness.

5. Performance Metrics and Experimental Evaluation

Battery safety, efficiency, and lifespan are intimately correlated with the quantitative performance criteria necessary for a thorough assessment of PCM-based heat management systems. The following metrics, which serve as standards for evaluating the efficacy of conventional, hybrid, and structural PCM integrations, are frequently reported in simulation and experimental investigations.

5.1. Temperature Uniformity: Reduction in Cell-to-Cell Thermal Gradients

Reducing the cell-to-cell temperature gradients within a battery module is one of the main goals of using phase change materials (PCMs) in battery thermal management (BTM) systems. An uneven temperature distribution shortens the lifespan of the system overall, promotes capacity fading, and throws off cell performance. Therefore, one of the most important metrics for evaluating PCM-based designs is the achievement of a consistent temperature field across cells. Dense thermocouple arrays inserted at numerous axial points or attached to individual cell surfaces are used in the majority of experimental validations. For correlation and predictive analysis, these are frequently supplemented by thermal network models, computational fluid dynamics (CFD), or high-resolution infrared thermography [38,205]. To assess sensitivity to ambient conditions and cooling boundary conditions, standard test procedures include step-current or constant-C discharge profiles (1C–4C) and thermal chamber controls.

Depending on thermal conductivity improvement and shape optimization, experimental data from various research consistently demonstrate that PCM integration lowers inter-cell temperature disparities by 30–60% [205]. Recent experiments quantify the impact of PCM (and hybrid/structural designs based on PCM) on inter-cell ΔT , and they have shown which design decisions result in the biggest benefits. Significantly improved uniformity is achieved via non-uniform PCM architectures, such as gradient thickness or selective placement close to hot regions. Intelligent PCM distribution can be just as essential as PCM mass, as evidenced by a recent study that found reductions of approximately 55.6–77.4% for optimum gradient PCM arrangements compared to uniform PCM layouts [206].

These technologies produce noticeably consistent temperature distributions throughout the module by improving heat absorption and conduction channels at the same time. For example, it has been demonstrated that non-uniform or gradient PCM architectures, where PCM thickness or concentration is strategically changed close to heat hotspots, perform noticeably better than uniform PCM arrangements.

Likewise, exceptional thermal uniformity has been demonstrated by structural PCM topologies, such as those that incorporate honeycomb or metallic skeleton frameworks. In comparison to an unstructured PCM reference, a representative metallic honeycomb–PCM arrangement reduces the peak surface temperature by almost 42% and achieves a maximum temperature gradient below 2 °C at a 3C discharge rate [207]. These results have been further validated experimentally in a prismatic-cell module, where an optimized honeycomb–PCM design maintained a maximum cell temperature of approximately 45.7 °C with a ΔT of only 4.4 °C under severe coolant and thermal conditions. These findings demonstrate that PCM integration can consistently provide the temperature uniformity needed for high-performance energy storage systems, including electric car battery modules, especially when paired with structural or conductive supports [208].

All of these findings demonstrate how sophisticated PCM topologies, particularly hybrid, gradient, and structural architectures, may provide extremely consistent temperature fields and significant thermal protection, demonstrating their great potential for high-power energy storage modules and next-generation EVs. The main design levers and their measured impacts on temperature uniformity in PCM-based BTM systems are compiled in Table 17.

Table 17. Design levers for improving the temperature uniformity in PCM-based BTM systems.

Design Lever	Description	Reported Effect on ΔT
PCM Placement/Distribution	Gradient thickness, selective positioning near hot spots, or inter-cell gaps instead of uniform blanket	ΔT reduction by 55–77% compared to uniform PCM layouts [205]
Thermal Conductivity Enhancers	Addition of expanded graphite, carbon fibers, metallic foams, or graphene sheets to improve lateral spreading	ΔT reduced by 30–50%, faster heat absorption [38]
Structural Integration	Embedding PCM into honeycomb cores, metallic skeletons, or casings to combine latent heat buffering with conduction pathways	ΔT reduced to <2–5 °C under 3C cycling [208]
Hybridization with Active Cooling	PCM coupled with liquid channels, cooling plates, or forced air to remove stored heat after melting	Maintains ΔT at sub-few °C during high C-rates [38]

5.2. Peak Temperature Suppression: Delays Thermal Runaway Onset

For PCM-based battery thermal management (BTM) systems, suppressing peak cell temperature during high-rate discharge and rapid charging events is another crucial performance requirement. High peak temperatures can cause thermal runaway, raise internal resistance, and hasten electrolyte deterioration. PCMs function as effective thermal buffers by leveraging the latent heat absorption that takes place during phase transition, reducing excessive temperature excursions and postponing, or even averting, the emergence of runaway conditions. Therefore, by postponing the onset of thermal runaway, PCMs efficiently decrease the maximum cell temperatures during high C-rate discharges or quick charging. By buffering peak excursions, latent heat absorption keeps cell surface temperatures below the crucial safety threshold, which is normally less than 60 °C for Li-ion cells.

In comparison to traditional air- or liquid-cooled systems without PCM, enhanced or hybrid PCM configurations—which include metallic foams, fins, or honeycomb structures—further improve heat dispersion and encourage faster dissipation, leading to peak temperature reductions of 10–20 °C. Peak temperature suppression is usually measured experimentally using thermocouples placed at the hottest cell surfaces and are confirmed by infrared thermography during high-power pulses or constant-current discharges. The efficiency of PCM in postponing the onset of thermal runaway under abusive conditions is occasionally evaluated using complementary, accelerating rate calorimetric (ARC) studies.

With improved or hybrid PCM designs, the advantages are even more noticeable. When PCMs are combined with fins, honeycomb structures, or metallic foams, the resulting composite better distributes and stores latent heat throughout the module. For example, a metallic honeycomb–PCM configuration reduces the maximum temperature by 24% while also reducing temperature gradients within the pack, maintaining peak cell surface temperatures close to 45.7 °C under a 3C discharge at a 40 °C ambient (as opposed to ~60 °C for a traditional, non-PCM baseline).

Under prolonged high-power cycling, hybrid systems that incorporate active liquid cooling and PCM layers show even more stability. In these configurations, the liquid cool plate continuously removes stored heat to prevent PCM saturation, while the PCM layer absorbs transient thermal spikes. Even under challenging environmental conditions, these combined effects have produced 10–20 °C drops in peak temperature during 3C–4C cycling.

In a similar vein, it has been demonstrated that gradient PCM distributions, in which thicker PCM layers are placed close to hot regions, can lower localized temperature peaks by up to 18 °C when compared to uniformly dispersed PCM arrangements.

Furthering this performance frontier also heavily relies on structural PCM designs. Incorporating metallic skeletons or PCM-filled conductive honeycomb cores improves mechanical stability and thermal conduction, guaranteeing uniform heat distribution and long-term dependability. These methods have maintained inter-cell temperature differentials below 2 °C while achieving peak temperature reductions of over 40% when compared to typical PCM-only encapsulation [207].

All of these experimental findings support the idea that PCM-based BTM systems can serve as a first line of defense against thermal runaway by significantly delaying or suppressing peak thermal occurrences. Modern PCM systems guarantee both high-performance cooling and the long-term safety needed for demanding applications, like electric vehicles, aerospace systems, and stationary energy storage, by combining latent heat absorption with clever structural and hybrid designs. Overall, gradient and structural PCM designs produce stronger mitigation ($\approx 15\text{--}20$ °C), while PCM-only systems offer modest temperature suppression ($\approx 8\text{--}15$ °C decrease). Hybrid PCM–liquid cooling designs provide the best performance, reliably keeping peak temperatures below 50 °C (even in high C-rate situations), guaranteeing thermal safety and prolonging battery life. A comparison of the peak temperature suppression results from different PCM integration strategies, including the absolute $T_{\max}$ values, is shown in Table 18.

Table 18. The peak temperature suppression results in the PCM-based BTM systems.

Design/Method	Test Conditions	Peak Temperature ($T_{\max}$)	Suppression vs. Baseline
Baseline (air cooled) [208]	Prismatic cells, 3C discharge, 40 °C ambient	~ 60 °C	-
PCM-only encapsulation [204]	Cylindrical/prismatic, 2C–3C discharge	45–52 °C	8–15 °C lower than baseline
Gradient PCM placement [206]	Module with optimized PCM thickness, 3C	Hot-spot reduced by ~ 18 °C	$\approx 30\text{--}40\%$ reduction
Honeycomb + PCM [205]	Prismatic module, 3C, 40 °C ambient	45.7 °C	~ 14 °C lower than baseline
Metallic honeycomb PCM core [207]	Module, 3C cycling	Peak reduced by 42% ($\Delta T < 2$ °C)	$\sim 15\text{--}20$ °C lower
Hybrid PCM + liquid cooling plate [66]	18,650 modules, 3C–4C discharge	$T_{\max}$ reduction 10–20 °C	Maintained < 50 °C

5.3. Thermal Response Time: Speed of Heat Absorption and Dissipation

The speed at which a PCM-based BTM system can absorb and release heat produced under high-power discharge or abuse situations is indicated by its thermal reaction time. This parameter establishes whether the PCM is restricted to steady-state buffering under prolonged loads or is capable of efficiently attenuating brief, transient heat spikes. A quick reaction time is essential in electric vehicles (EVs) and other high-power applications to avoid local overheating and to guarantee effective temperature control throughout charge–discharge cycles. Whether the PCM can blunt brief, high-power spikes (transient protection) or just longer-lasting heat loads (stationary buffering) depends on the response time. The thermal conductivity, encapsulation technique, and contact resistance between PCMs and cells can all have an impact.

While graphite-enhanced, metallic foam–PCM, or aerogel–PCM composites offer faster transient cooling, pure PCMs may show delayed reactions because of their limited conductivity. By positioning the PCM closer to heat sources, structural PCMs incorporated into casings or separators lessen thermal lag. The total response behavior is governed by multiple mechanisms [209]. Furthermore, the PCM’s intrinsic properties also influence

how it reacts to heat. Materials with a high latent heat capacity may require a longer melting time under a given heat flux, despite having a greater ability to store thermal energy. This could lead to a delayed overall response, even though they absorb more heat overall. Conversely, materials with lower latent heat and better conductivity react faster but offer less long-term buffering.

Thermal-contact resistance is another important component that frequently controls the initial stage of heat transmission from the cell case into the PCM. Even in cases when the bulk material is very conductive, insulating obstacles caused by small air gaps, surface roughness, or poor mechanical contact might postpone the PCM's engagement. Researchers employ pressure-assisted encapsulation techniques or thermal interface fillers to reduce contact resistance and enhance heat flux continuity in order to lessen this.

The heat-removal pathway controls the PCM's ability to recover from melting and become ready for more thermal events at the macroscopic level. By accelerating post-melting heat extraction through the use of metallic fins, heat pipes, or liquid-cooling channels, hybrid PCM systems avoid local saturation and allow for repeated thermal cycling without sacrificing performance.

These mechanisms are reliably validated by numerical and experimental studies. The response of unmodified paraffin or PEG-based PCMs to short-duration power spikes is limited because they usually need tens to hundreds of seconds (>100 s) to absorb large heat fluxes and to reach full melting during simulated discharge events [210]. On the other hand, because of their higher effective thermal conductivity (which is frequently an order of magnitude better than that of pure PCMs), expanded graphite (EG) or boron-nitride-enhanced CPCMs exhibit 30–60% faster response times. For instance, Xiong et al. [211] found faster transient cooling and improved cycle stability using BN+EG-filled CPCMs, while Ranjbaran et al. [212] demonstrated that increasing the EG content significantly decreased the storage/release times in CPCMs utilized for battery modules.

In a similar vein, PCMs coated with metal foam (using copper or aluminum skeletons) offer continuous conductive networks that speed up lateral heat dispersion and melting. Numerical parametric calculations and experiments reveal an ideal foam volume fraction of approx. ~4–6 vol%, decreasing the time to generate a given liquid fraction and offering the best transient response for battery-scale heat pulses [213]. When compared to no-foam scenarios, the use of metal foam can significantly shorten the time required to obtain a specific melt fraction [214]. Such metal-foam PCMs can, in practice, cut response times to less than 30 s, with intra-pack ΔT falling below 2 °C and corresponding surface temperature drops of 15–20 °C.

Aerogel-PCM composites have also been emphasized in recent studies for their short-term protection against heat spikes. When compared to simple PCM encapsulations, experiments reveal that aerogel-wrapped cells have thermal-runaway delays of up to ~97 s [214]. The aerogel structure provides temporary thermal shielding by functioning as a dispersed local heat sink and an insulating barrier. Additionally, they have low conductivity to block heat sources from the outside, but when paired with PCM, they improve temporary protection by acting as a local heat sink and insulator [214].

Lastly, the latent material is brought into direct thermal contact with the heat source using structural PCM integrations, such as embedding PCM into separator layers, cell casings, or honeycomb cores. These designs reduce the initial temperature rise and increase the efficiency of lateral spreading by achieving considerably faster and more consistent responses. In comparison to bulk PCM blankets, experimental honeycomb-PCM systems consistently exhibit smaller temperature peaks and faster stabilization [215]. Table 19 provides a comparative overview of the thermal response properties for various PCM designs.

Table 19. The thermal response characteristics of different PCM configurations in the Li-ion BTM systems.

PCM Type/ Configuration	Effective Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Thermal Response Time (s)	T_{max} Reduction vs. Baseline
Neat PCM (Paraffin, RT waxes) [205]	~0.2–0.3	>70–100	~8–10 °C at 2C–3C discharge
EG-Enhanced CPCM (5–15 wt%) [38]	5–15	40–60	~12–15 °C reduction; ~30–40% faster response
Metal-Foam PCM (Al/Cu skeletons) [213]	20–40	<30	~15–20 °C reduction; $\Delta T < 2$ °C
Aerogel–PCM Composites [214]	1–5	35–50	~10–14 °C reduction
Structural PCM (Honeycomb integration) [215]	5–10 (distributed pathways)	30–50	~14 °C reduction; improved hot-spot suppression

Due to their limited conductivity, the pure PCMs responded the slowest, as shown in Table 19, whereas the composites reinforced with graphite and aerogel achieved noticeably faster transient cooling. While structural PCM integration reduces thermal lag by placing the latent medium directly at the cell surface, metal-foam composites—an increasingly favored approach for next-generation high-power Li-ion battery modules—offer the best overall performance, with sub-30 s response times and extremely uniform temperature fields.

5.4. Durability and Aging: Long-Term Performance Under Cycling

Even though PCMs may effectively regulate peak temperatures and improve thermal uniformity, their long-term durability is still a critical factor for real-world applications. While paraffin-based PCMs typically exhibit just ~2–3% latent heat loss after ~1000 cycles, some salt-hydrate PCMs have been shown to be durable, according to published research, up to 10,000 cycles in a lab setting. Even though most studies cover fewer cycles than those expected in real-world applications, degradation mechanisms, such as phase-segregation, super cooling, leakage, and container corrosion, are still important considerations [216,217]. Unlike active cooling components, whose performance may be maintained by operational control, PCMs are passive components whose thermal buffering ability may deteriorate with repeated thermal cycling due to leakage, phase segregation, fatigue, or deterioration of thermal conductivity boosters. Maintaining functionality across thousands of charge–discharge cycles requires an understanding of and attention to these systems.

The stability of latent heat storage and the structural integrity of the composite are the two main factors affecting the long-term viability of PCM-based battery thermal management (BTM) systems. Traditional paraffin-based PCMs frequently lose some of their energy storage over time due to leakage during melting and super cooling during solidification. Phase segregation and incongruent melting are also observed in salt-hydrate PCMs, which lower latent heat and dependability. On the other hand, micro/nano encapsulated PCMs and shape-stabilized composite PCMs (CPCMs) have been shown to successfully contain the phase transition within a supporting matrix, reducing leakage and preserving consistent performance during high heat cycling.

After 500–1000 thermal cycles, experimental research has shown that advanced CPCMs maintain about 90–95% of their initial latent heat capacity with just slight compositional deterioration. Due to stable porous frameworks that stop PCM depletion, graphite-enhanced CPCMs and metal-foam-embedded PCMs, for instance, display remarkable longevity, exhibiting less than 5% capacity loss after 1000 cycles. With 85–90% latent heat retention after several hundred cycles, aerogel–PCM composites have also shown good cycling stability, demonstrating the mechanical robustness of aerogel scaffolds during repeated expansion–contraction cycles. However, additional testing under mechanical vibration, impact, and fire exposure is necessary for structural PCM integrations, like honeycomb or

polymer–PCM hybrids, especially in EV situations where shock loads and structural stress are substantial. An ongoing engineering difficulty is making sure that PCM-integrated casings or cores maintain adhesion, integrity, and thermal coupling over the course of the vehicle’s lifetime. The endurance traits and modes of degradation observed in different PCM setups during repeated heat cycling are compiled in Table 20.

Table 20. The durability of the PCM configurations under thermal cycling.

PCM Type	Latent Heat Retention	Cycles Tested	Degradation Mode
Paraffin PCM	~70–85% after 300 cycles	100–300	Leakage, supercooling [38]
Salt-hydrate PCM	~65–70% after 200 cycles	200	Phase segregation, incongruent melting [66]
EG-enhanced CPCM	>90% after 500 cycles	300–500	Minor PCM depletion, stable overall (metallic honeycomb PCM study) [38]
Metal-foam PCM [170]	>90% after 500–1000 cycles	500–1000	Pore saturation, slight PCM loss [208]
Aerogel–PCM composites	~85–90% after 200–300 cycles	200–300	Limited leakage, stable [208]

Table 21 summarizes the important performance measures, experimental procedures, and benchmark results spanning temperature uniformity, peak suppression, transient responsiveness, and durability in order to translate these findings into useful design insights. The operational reliability of PCM-based BTM system solutions is defined by these factors taken together.

Table 21. The performance metrics, evaluation methods, and benchmark results of the PCM-based battery cooling systems.

Metric	Evaluation Methods	Benchmark Results (Literature)
Temperature Uniformity	Thermocouples placed across cells; infrared (IR) thermography; CFD simulations	PCM integration reduces the ΔT between cells by 40–59% compared to air cooling. Hybrid PCM–fin systems achieve $\Delta T < 3\text{--}5\text{ }^{\circ}\text{C}$ at 3C discharge [218]
Peak Temperature Suppression	In situ cycling at different C-rates; thermal chamber testing; calorimetry	Maximum cell temperature reduced by 10–20 $^{\circ}\text{C}$ vs. baseline. Critical safety threshold ($<60\text{ }^{\circ}\text{C}$) maintained up to 3–4C discharge [219]
Thermal Response Time	Transient heating experiments; step-current load tests; high-resolution IR imaging	Pure PCM: slow response ($>100\text{ s}$). Graphite/foam-enhanced PCM: 30–60% faster heat absorption. Structural PCM near casing reduces lag significantly [220]
Durability and Aging	Accelerated thermal cycling (hundreds–thousands of cycles); DSC for latent heat retention; mechanical/vibration tests (EV conditions)	Advanced composites retain $>95\%$ latent heat capacity after 500–1000 cycles. Leakage and segregation minimized in encapsulated or polymer-stabilized PCMs [37,38]

The interdependence of temperature uniformity, peak suppression, transient response, and long-term durability in PCM-based battery thermal management systems is shown in Figure 14 (which provides a graphical representation of these four critical performance indicators).

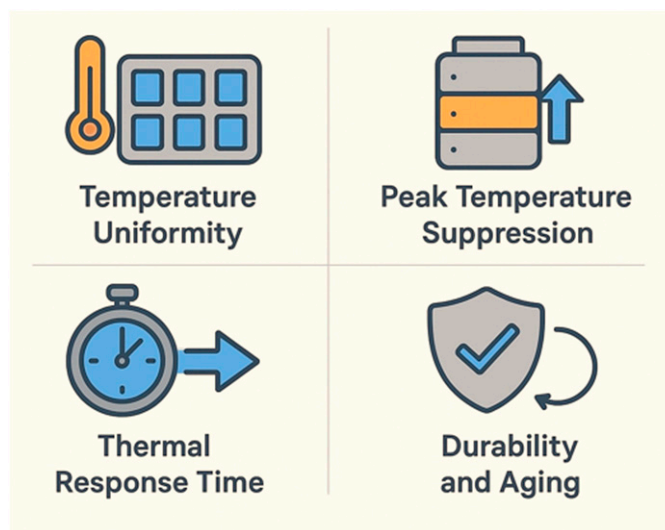


Figure 14. Performance metrics of the PCM-based battery cooling systems.

6. Integration and Application in Battery Systems

How these materials are included into battery packs and coupled with complementary cooling techniques is a critical component of PCM-based thermal management. In addition to enhancing PCM formulations, recent developments have concentrated on designing efficient structural and functional integration into workable battery topologies.

Encapsulated PCM modules are one noteworthy method. Many studies now support modular encapsulation approaches rather than dumping PCM into the battery pack in a free-flowing manner. Discrete PCM panels or cylindrical “jackets” that can be installed or inserted straight around battery cells have been created by researchers. For instance, graphite-foam/PCM composites were enclosed in a 3D-printed shell that slides around each battery cell in the hollow cylindrical Battery Cooling Pack (BCP) idea by Nishad et al. (2025) [35]. When compared to a cell that merely had air cooling, these PCM “jackets” lowered the peak cell temperature during testing by about 11 °C. Simple customization is made possible by these modular designs; paraffin waxes with varying melting points can be blended or stacked to target particular temperature ranges. Additionally, these plug-and-play PCM modules make scaling and retrofitting in commercial battery systems possible, guarantee consistent contact, and simplify construction.

The development of hybrid cooling systems, which integrate PCMs with active cooling techniques like liquid or air loops, is another new trend. PCMs can become saturated once completely melted, even though they passively absorb brief heat spikes. Conversely, active cooling constantly dissipates heat; however, it might not keep up with sudden changes in temperature.

In hybrid BTM systems, the active subsystem progressively eliminates accumulated heat (re-solidifying the PCM for following cycles), while the PCM buffers short-term surges, such as those during high acceleration or fast charging. According to recent evaluations, integrating PCMs with heat pipes or liquid cooling can enhance temperature uniformity and lessen the strain on active cooling [99]. For example, when a PCM-based passive unit and a conventional liquid cooling loop were integrated in this study, peak temperatures reduced and coolant power consumption decreased overall. Another integrated PCM with

air-cooled fins has achieved more consistent cell temperatures than air cooling alone by encircling cells with a phase-changing substance in addition to fins and air cooling [38].

One of the most promising routes to highly effective, secure, and portable thermal management solutions is through hybrid BTM systems, which combine latent heat absorption and convective heat removal. However, combining active and passive techniques is thought to be a future path for BTM systems in order to strike a compromise between dependability and efficiency.

The mitigation of thermal runaway is considered another challenge. In addition to controlling temperature, PCM integration provides built-in safety benefits in harsh or abusive operation environments. PCMs inhibit the spread of thermal runaway in specific configurations by acting as thermal buffers or flame-retardant barriers. PCMs augmented with salt hydrate or metal foam have shown promise in absorbing significant amounts of heat and, in certain situations, initiating endothermic reactions that postpone ignition [99].

Furthermore, some researchers have included expanding fire-retardant materials inside PCM layers; in the event of a fire, the PCM melts and the retardant expands, physically dividing adjacent cells. In next-generation battery modules, this dual-function technique helps with safety-by-design and fire containment.

Battery module placement and packaging have also drawn a great deal of attention. Recent engineering research has focused on the effective positioning and packaging of PCMs within modules. Options range from filling gaps between cells with PCM slurry or pads, including PCM sheets within module walls or cooling plates, to embedding PCM directly inside large-format cell housings. Circulating microencapsulated PCM slurries, in which small PCM capsules embedded in a carrier fluid provide both convective cooling and latent heat absorption, is one example of a recent breakthrough [38]. The simplicity and compactness of passive solutions, like form-stable PCM sheets or pads wrapped around cells, continue to be appealing.

To avoid mechanical stress or leakage, it is crucial to make sure that PCM and cells have adequate thermal contact and that PCMs can expand via voids or elastic containment. The advantages of these tactics are supported by experimental findings. For example, Zhang et al. found that PCM-integrated modules significantly reduced the temperature variations between cells, enhancing overall pack uniformity [11]. When compared to natural air cooling, another experimental investigation found a 34 °C drop in cell temperature at 3C discharge. As temperature homogeneity reduces localized degradation, such improvements directly result in longer battery life and improved safety [11].

However, significant developments in PCM materials and system-level integration for lithium-ion battery heat management have been reflected in studies in the literature. By developing composite and nano-enhanced PCMs with increased thermal conductivity, strong cycle stability, and enhanced safety (lower flammability), researchers have addressed the conventional shortcomings of PCMs and created innovative integration techniques that increase the viability of PCM-based BTM systems in energy storage and electric cars, such as macro-encapsulated PCM modules and hybrid cooling systems. These peer-reviewed research studies generally agree that PCM incorporation can improve cycle life, improve safety, and efficiently buffer thermal loads without significant design penalties. Scalable packaging solutions for large-format packs are being investigated, as is the optimization of composite formulations (such as MOF-based PCMs and improved flame retardants). The developments seen between 2022 and 2025 suggest that composite PCMs will most likely be essential parts of the thermal management architectures of next-generation battery systems. Figure 15 shows a graphical review of the important PCM integration techniques and performance results.

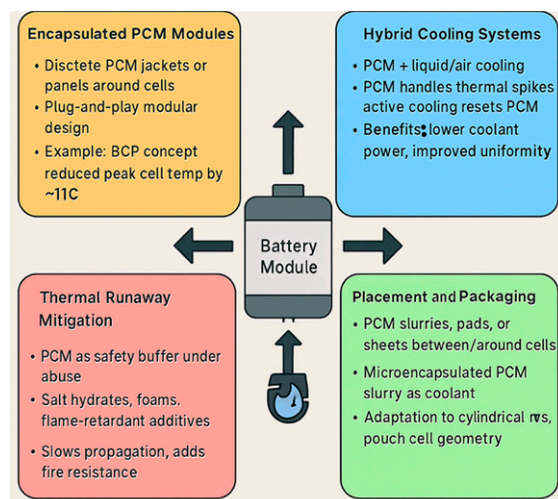


Figure 15. Key PCM integration strategies.

7. Challenges and Research Gaps

7.1. Low Thermal Conductivity: Composite Materials Need Optimization

The intrinsic low heat conductivity of phase change materials (PCMs), which typically ranges from 0.2 to $0.4 \text{ W m}^{-1} \cdot \text{K}^{-1}$ for organic PCMs like paraffin, is one of the most persistent limitations of PCMs in battery thermal management (BTM) systems [38]. During high C-rate charging and discharging, this limits heat transfer rates and produces uneven temperature fields. Thermally enhanced PCM composites, which incorporate high-conductivity additives, including carbon-based materials (graphene, carbon nanotubes, and expanded graphite), metal foams (Al and Cu), and ceramic fillers, have been extensively studied in order to address this problem [82,148,153]. These composites retain a significant amount of latent heat while increasing effective thermal conductivity by an order of magnitude. For instance, graphene-coated nickel foam improved paraffin conductivity by about $23\times$, but uncoated foam only improved it by $6\times$ [73]. Despite these encouraging outcomes, increasing thermal conductivity presents a number of trade-offs and real-world difficulties that scientists are now working to resolve.

The balance between latent heat capacity and filler loading is a key concern. Increasing filler content lowers the total latent heat storage capacity while simultaneously increasing conductivity and decreasing the PCM fraction. For instance, one study found that latent heat capacity is considerably reduced when fillers (expanded graphite, h-BN, etc.) are added. When fillers are added, paraffin's latent heat decreases from 235 kJ/kg to 191 kJ/kg , according to one review [73]. One unsolved design difficulty is striking the ideal balance between conductivity enhancement and energy storage capacity. According to recent research, hybrid and hierarchical filler systems (such as 3D porous or linked scaffolds) may be able to provide continuous heat conduction pathways while preserving high latent heat [73,82,153].

Interfacial compatibility is another important factor. Interfacial thermal resistance can be introduced by poor filler–PCM bonding, greatly reducing the anticipated conductivity improvements. During temperature cycling, nano-fillers frequently clump together or separate. Therefore, to maintain homogenous dispersion and stabilize the filler–matrix interface, strong surface functionalization and chemical anchoring techniques are required [212]. Leakage and structural stability present further difficulties. Through mechanical stress, micro-cracking, and leakage, many PCM composites distort or leak with time. While shape-stabilized PCMs, such as aerogels and PEG-silica gels, reduce leakage, they also frequently lower the active PCM content and, as a result, the total latent heat capacity [38].

To preserve mechanical integrity while retaining thermal performance, future research on multi-scale encapsulation or durable, recyclable matrices is required [154].

Practical and financial factors are also crucial. Commercialization of advanced fillers, especially high-purity graphene, CNTs, and metallic foams, is still hampered by their cost and scalability. As previously shown, producing homogeneous composites using 3D scaffolds or metal matrices can be “considerably more expensive” than using more straightforward nanoparticle additions [73]. Mass production is further complicated by high filler loading. Ball milling, ultrasonication, and 3D foaming are only a few examples of laboratory-scale dispersion processes that are currently unfeasible for industrial-scale production [38,147,155].

In order to enhance scalability, future research should concentrate on creating hierarchical/hybrid composites that strike a compromise between conductivity and latent storage while investigating affordable, sustainable fillers (such as recycled graphite and bio-derived carbons). Although they require optimized designs, novel 3D architectures (porous aerogels, carbon foams, and polymer frameworks) can offer continuous heat routes [38]. Standardized long-term cycling experiments under practical operating conditions are also urgently needed to assess mechanical and thermal stability over thousands of cycles [148,153,155].

7.2. Material Cost and Scalability: Economic Feasibility for EV-Scale Deployment

When applied to large-scale electric vehicle (EV) battery packs, PCM-based BTM systems encounter substantial obstacles in terms of economic viability and scalability, despite notable advancements in material performance and safety. Advanced composites, particularly those including graphene, carbon nanotubes, expanded graphite, or metal foams, significantly raise material and processing costs, whereas traditional paraffin-based PCMs are reasonably priced and easily accessible [147,155,161].

Another bottleneck is scalability. Numerous potential laboratory-scale PCM composites rely on nano-filler dispersion techniques (such as chemical functionalization, ultrasonication, and ball milling), which are not yet commercially scalable. Additionally, while encapsulation and stabilization techniques—like microencapsulation, polymer shell creation, or aerogel supports—improve safety and stability, they significantly increase the number of manufacturing stages and decrease the active PCM fraction [155,161]. PCM systems that concurrently accomplish low cost, dependable supply chains, and manufacturing scalability without sacrificing safety and effective thermal control are necessary for the EV sector. Reaching this equilibrium raises a number of unresolved issues and potential lines of inquiry: (i) inexpensive, plentiful fillers (bio-carbons, recycled graphite, or waste-derived conductive additives) with verified supply chains and consistent properties; (ii) energy-efficient, scalable manufacturing (switching from batch to continuous processes, like extrusion, roll-to-roll lamination, and foaming) compatible with large-scale module production; (iii) early integration of techno-economic and life-cycle analysis (TEA/LCA) to benchmark against conventional cooling; and (iv) design-for-manufacture guidelines by the establishment of mechanical anchoring, expansion tolerance, and recyclability [66,147,150,155,160].

7.3. Integration Complexity: Custom Pack Design Required for Efficient Implementation

Although PCMs provide a passive and energy-efficient way to manage the temperature of lithium-ion batteries, integrating them successfully into EV battery packs is still a significant engineering problem. PCM-based systems need specialized module designs to provide optimal contact between the cells and PCM medium—in contrast to liquid or air-cooling systems, which are frequently retrofitted. Uneven temperature fields, ther-

mal hotspots, and ineffective use of latent heat capacity can result from poorly planned architectures [66,142,190].

Geometric design is one of the main integration issues. Cell configurations need to optimize the PCM's contact area. This lowers the total volumetric energy density and frequently necessitates more space and special containers. This can lower the battery pack's total volumetric energy density, even as it increases heat uniformity. The heat channels of PCM modules present another significant problem. Thermal gradients and decreased efficiency might come from uneven melting and solidification rates caused by poor architectural design (as outside PCM layers may transition more quickly than inner areas).

Moreover, PCM layers and encapsulated composites have weight and volume penalties that make integration more difficult since they add mass and take up valuable space, which may conflict with EV design requirements that emphasize high energy density and compactness. Compatibility with auxiliary systems is another crucial factor. Fins, heat pipes, or liquid loops are frequently used in hybrid PCM systems to improve heat dissipation; however, adding these auxiliary components raises design complexity, manufacturing costs, and assembly challenges.

Ongoing research is concentrating on a number of important avenues to address these issues: (i) establishing standard PCM module "form factors" for cylindrical, prismatic, and pouch cells; (ii) creating coupled electro-thermal-CFD tools to co-optimize PCM placement, thickness, and hybrid interfaces; (iii) developing structural PCMs (honeycomb, laminboard, and aerogel skins) that provide fire barriers or carry loads to offset weight/volume penalties; and (iv) developing scalable assembly techniques (e.g., in situ casting, vacuum filling, or insert-molding of composite PCMs) [58,66,143,150,208]. PCM-based battery thermal management (BTM) systems encounter a number of cross-cutting problems that restrict their widespread implementation, in addition to the well-known difficulties of low heat conductivity, high material cost, and integration complexity.

Leakage during phase transition is a recurring issue. Organic PCMs expand and become fluid when they melt, which can lead to contamination, leakage, and a decline in cycle stability. A number of techniques have shown promise in reducing leakage, including microencapsulation, shape-stabilized composites, and the use of porous supporting matrices (expanded graphite, aerogels, and polymer frameworks). Future research should focus on creating long-lasting, recyclable supporting matrices and multi-scale encapsulation methods that maintain latent heat while guaranteeing form stability [154,155,184,197].

Latent heat capacity and energy density are two more constraints. The latent heat values of PCMs ($150\text{--}250\text{ kJ kg}^{-1}$) are generally insufficient for long-duration heat absorption in EV battery packs, despite their ability to buffer thermal variations. Additionally, adding conductive fillers that enhance heat transfer typically reduces latent heat capacity, resulting in a trade-off between energy storage and conductivity. When compared to solid–solid thermal storage systems, PCMs' relatively low density also limits their volumetric energy density. Developing nano-enhanced PCMs that preserve latent heat while enhancing conductivity, eutectic mixtures with adjustable melting points, and solid–solid PCMs (like salt hydrate or polyethylene glycol-based systems) that reduce leakage while raising volumetric energy density are all promising avenues [148,151,153,198].

Equally important are mechanical stability and battery system compatibility. Frequent phase shifts cause expansion and contraction, which can lead to encapsulating material degradation, leakage, or mechanical stress. Additionally, prolonged contact between PCMs and battery components may cause problems with corrosion, chemical reactivity, or protective coating deterioration. Chemically inert supports, polymeric stabilizers, and robust encapsulation designs are some partial answers; nevertheless, reliable mechanical

fatigue and chemical compatibility studies under real battery conditions are still lacking [197,198,208,209]. Finally, cycling durability and long-term reliability are critical for real-world EV applications, where PCM-based BTM systems must endure thousands of temperature cycles without losing functionality.

Unfortunately, over time, a great deal of PCMs experience phase segregation, sub-cooling, or thermal deterioration. For example, paraffin's can undergo structural degradation at prolonged high temperatures, while salt hydrates may show incongruent melting. Current research has focused on developing thermally stable eutectic systems, using anti-aging additives to stop degradation, and developing accelerated testing procedures that can forecast long-term dependability in order to address these problems [55,58,151]. Developments in encapsulation, form stabilization, and nanostructured fillers are increasing durability and making it possible for PCM-based BTM systems to be reliably and widely used in next-generation electric vehicles.

8. Future Outlook

Closing current research gaps through scalable, sustainable, and intelligent innovations is essential to the ongoing development of PCM-integrated lithium-ion batteries. The creation of intelligent PCMs with adjustable characteristics is one of the most promising areas. Due to their fixed melting points and thermal conductivities, conventional PCMs are only useful in specific temperature ranges. On the other hand, emerging materials are being designed to respond dynamically. Researchers are developing composites whose phase transition temperatures and heat transfer behavior may be adjusted to suit various battery operating circumstances by combining nanoparticles, graphene, or metal–organic frameworks (MOFs). Packs may be able to self-regulate their temperature in response to shifting loads, ambient conditions, or charging profiles because of this adaptability. Active or controlled PCMs, in which additions like magnetic or electrically conductive particles enable real-time modulation of heat transport by external fields, are even more promising [153,184,212]. The most significant paths for PCM-based battery thermal management (BTM) systems are schematically shown in Figure 16.

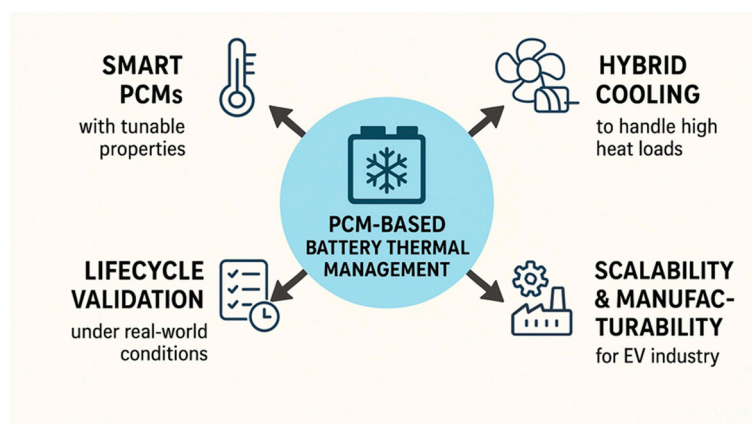


Figure 16. Future research directions for PCM-based BTM systems.

The terrain is also changing due to sustainability concerns. Even though PCMs based on paraffin and salt hydrate predominate in contemporary systems, recycling and end-of-life management are difficult with them. Bio-based and biodegradable PCMs, like those made from fatty acids or plant-based waxes, are becoming feasible substitutes as battery industries transition to circular manufacturing models. These materials offer quicker recovery, less toxicity, and less environmental effects, in addition to performing similarly in terms of latent heat capacity. PCM-based BTM systems can be further aligned with

sustainability and life-cycle efficiency goals by adding recyclable skeletons or biodegradable polymer matrices [147,155,198].

The creation of combined thermal–electrical modeling tools is another important avenue. As heat generation in batteries is closely related to electrochemical reactions and mechanical forces, thermal management cannot be improved in a vacuum. However, the majority of models that are now in use handle these domains independently. Heat transport, phase transitions, electrochemical kinetics, and structural behavior can all be simultaneously simulated thanks to recent developments in physics modeling. These predictive frameworks can help with pack-level design, expedite material screening, and could potentially facilitate predictive maintenance in electric cars [55,66,150].

Additionally, multifunctional PCM composites that operate as structural and safety elements in addition to thermal buffers are becoming more popular among material scientists. For instance, flame-retardant additives can prevent thermal runaway propagation, and porous carbon or polymer scaffolds can offer mechanical strength while preserving the PCM's structure. These multipurpose materials have the potential to convert PCM layers into integrated modules that combine fire resistance, load bearing, and heat absorption, all crucial characteristics for small, high-performance EV battery topologies [58,143,150,191,208].

PCMs are increasingly being hybridized with active cooling systems to increase their operational envelope. Although PCMs effectively absorb brief heat surges, prolonged high-power operation eventually causes them to achieve saturation. Hybrid BTM systems can maintain steady performance over extended periods of time by connecting PCMs with liquid channels, heat pipes, or forced-air circuits. Coordinating the two cooling methods is crucial to ensuring that the PCM can withstand sudden temperature spikes while active systems eliminate stored heat and return the PCM to its solid state. To achieve this equilibrium, clever control algorithms and optimized geometries will be essential [55,66,143].

However, thorough life-cycle validation under practical circumstances is necessary to guarantee the long-term dependability of PCM-based systems. The intricate mechanical, thermal, and chemical stressors found in automobiles are rarely taken into consideration in laboratory cycling testing. To discover degradation pathways, such as phase segregation, encapsulant fatigue, or chemical incompatibility, advanced validation techniques (such as vibration, shock, abuse, and aging simulations) are crucial. PCM systems may only gain the trust necessary for widespread adoption through such thorough testing [58].

Scalability and manufacturability are equally important issues. Due to complicated synthesis processes or the usage of expensive nanofillers, many promising PCM composites are still only available in lab settings. PCM materials must be manufactured with careful consideration for cost, safety, and environmental performance using scalable processes like extrusion, injection molding, or roll-to-roll encapsulation in order to be industrially relevant. Developers can quantify the trade-offs between performance and sustainability by incorporating life-cycle analysis (LCA) and techno-economic assessment (TEA) early on in the design process. A more seamless transition from lab-scale prototypes to industrial production can also be achieved by establishing explicit design-for-manufacture standards [58].

Lastly, uniformity is necessary for the commercialization process. There are currently no standardized testing and certification procedures for PCM-based BTM systems, despite the quick advancement of science. Important criteria, including conductivity thresholds, leakage tolerance, ideal melting temperature ranges, and long-term cycling behavior, are still inconsistently assessed across research. Interoperability, safety, and broader mar-

ket adoption will be made possible by establishing industry standards and integrating environmental indicators into certification frameworks [58,161].

9. Conclusions

One of the most promising approaches to improving the performance, safety, and lifespan of LIBs is PCM-based temperature management. PCMs offer a passive yet extremely effective way to regulate cell temperature by making use of the latent heat of phase transition, especially during the quick charging or high-rate discharges that traditional cooling systems frequently find difficult to keep up. Organic materials, like paraffins and polyethylene glycols (PEG), continue to be appealing among the several types of PCMs because of their ease of production, tunable melting points, and chemical stability. However, their shortcomings, particularly their flammability and low intrinsic heat conductivity, continue to restrict their stand-alone applicability.

Conversely, inorganic PCMs, particularly salt hydrates, offer greater heat storage density and non-flammable behavior, but they continue to have problems with phase segregation, supercooling, and battery component compatibility. Composite and hybrid PCM systems, which combine organic or inorganic matrices with high-conductivity additions, like expanded graphite, carbon nanotubes, or metallic foams, have produced the most encouraging findings yet. Rapid heat dissipation and latent heat storage are practically balanced by these designed materials. Shape-stabilized and encapsulated composites, such as aerogel-supported or polymer-bound PCMs (which reduce leakage and enhance durability under heat cycling), have made further strides. When taken as a whole, these developments are progressively transforming PCMs from experimental oddities into useful parts for practical battery thermal management (BTM) systems.

However, despite their potential, a number of obstacles continue to prevent widespread industrial deployment. One major limitation of PCMs is their limited ability to maintain extended high-power operation; once the material fully melts, its buffering function reduces. Furthermore, increasing thermal conductivity frequently lowers latent heat capacity, resulting in a fundamental trade-off between total energy absorption and quick response. Significant obstacles also arise during integration: in order to guarantee consistent contact and reduce dead zones, PCM modules must be customized to each battery pack's geometry. This frequently raises the cost, mass, and complexity of the design. Furthermore, because high-performance fillers and encapsulation techniques are still costly and challenging to scale, the economic viability of nanocomposite PCMs is unknown.

Future research must concentrate on sustainable, multifunctional PCM composites that serve as fire-retardant barriers, structural reinforcements, and thermal buffers all at once in order to transition from the lab to manufacturing. The next generation of PCMs should contain recyclable or bio-derived components to suit the circular economy's objectives while maintaining high energy density and cycling stability. In order to balance transient and continuous heat management at the system level, hybrid cooling architectures that combine PCMs with active techniques, like liquid circulation, air channels, or heat pipes, will be essential. Equally important will be the development of scalable manufacturing techniques that include roll-to-roll encapsulation, in situ molding, and the extrusion that can yield consistent quality and cost effectiveness.

For PCM-based BTM systems, there are currently no unified standards for thermal conductivity, cycling durability, leakage resistance, and safety under abuse conditions. By guaranteeing dependability and regulatory compliance, consensus standards will not only speed up industry adoption, but they will also enable direct comparison between research studies.

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