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Review

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Pramod Kale , Atharva Joshi * , Shadaab Kazi , Abhishek Katore , Geeta Kahane , Aryan Vijay Kakade , Sanika Giri , Siddhant Kaswa

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Keywords: phase change materials; battery thermal management; thermal energy storage; hybrid cooling; nanocomposites

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Review

A Comprehensive Review on Different Types of PCM Used in BTMS

Pramod Kale [1], Atharva Joshi [2,*], Shadaab N. Kazi [3], Abhishek Katore [4], Geeta Kahane [5], Aryan Kakade [6], Sanika Giri [7] and Siddhant Kaswa [8]

Department of Mechanical Engineering Vishwakarma Institute of Technology, Pune, 411037, Maharashtra, India

* Correspondence: atharva.joshi22@vit.edu

Abstract

Battery Thermal Management Systems (BTMS) are critical for maintaining optimal operating temperatures (20-40°C) in lithium-ion batteries, particularly for electric vehicles (EVs) and grid-scale energy storage [1,2]. Phase Change Materials (PCMs) have emerged as a transformative solution, leveraging latent heat absorption/release during phase transitions to provide passive thermal regulation [3]. This review systematically evaluates inorganic (salt hydrates), organic (paraffins, fatty acids), and composite PCMs, analyzing their thermophysical properties, performance characteristics, and implementation challenges in BTMS applications [4,5]. Key findings reveal that advanced composite PCMs with thermal conductivity enhancers (graphene, metal foams) can achieve 3-5× improvement in heat dissipation while maintaining >90% of base latent heat capacity [6,7]. The paper concludes with actionable recommendations for next-generation PCM development and integration strategies.

Keywords*:* phase change materials; battery thermal management; thermal energy storage; hybrid cooling; nanocomposites

1. Introduction

1.1. Background and Significance

The rapid electrification of transportation systems has positioned electric vehicles (EVs) as the cornerstone of sustainable mobility, with the global EV market projected to expand at a compound annual growth rate (CAGR) of 23.1% from 2023 to 2030 [8]. This exponential growth is driving unprecedented demand for advanced battery thermal management solutions, as lithium-ion batteries—the dominant energy storage technology in EVs—exhibit significant sensitivity to operating temperatures. Research has demonstrated that these batteries experience 3–8% capacity degradation for every 10°C increase above their optimal temperature range (typically 20–40°C), highlighting the critical need for precise thermal regulation [9,10]. Traditional active cooling systems, such as liquid or air cooling, while effective, introduce substantial weight penalties (5–15% of total battery pack mass) and consume 3–5% of the battery's total energy output [11]. These limitations have spurred intense interest in passive cooling alternatives, particularly phase change materials (PCMs), which offer energy-efficient thermal management without moving parts or significant parasitic power losses.

1.2. PCM Fundamentals

Phase change materials represent a paradigm shift in thermal energy storage, capable of storing 5–14 times more thermal energy per unit volume than conventional sensible heat materials through isothermal phase transitions [12]. This exceptional energy density arises from the latent heat absorbed or released during phase changes (typically solid-liquid transitions), enabling PCMs to maintain

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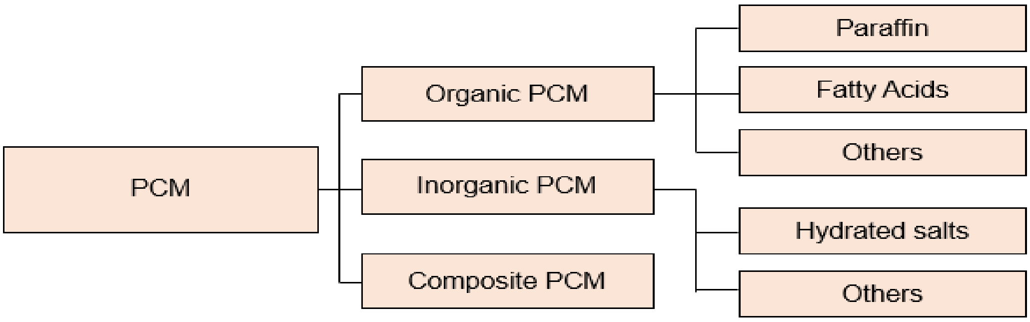
nearly constant temperatures during operation. The three primary PCM categories—inorganic, organic, and composite materials—each exhibit distinct thermophysical properties that dictate their suitability for battery thermal management systems (BTMS).



1.3. Inorganic PCMs

Inorganic PCMs, particularly salt hydrates like calcium chloride hexahydrate ($CaCl_2{\cdot}6H_2O$), offer compelling advantages including high thermal conductivity (0.5–1.5 W/mK) and substantial latent heat capacity (180–300 kJ/kg) [13]. However, these materials are plagued by technical challenges such as supercooling (where liquids remain metastable below their freezing point by 5–15°C), phase segregation (non-uniform distribution of components during cycling), and corrosive tendencies that can compromise battery components [14].

1.4. Organic PCMs

Organic PCMs, encompassing paraffin waxes (C_{18}–C_{28} alkanes) and fatty acids, address many of these limitations through excellent chemical stability, minimal supercooling (<2°C), and compatibility with battery materials [15]. Their principal drawback lies in relatively low intrinsic thermal conductivity (0.1–0.3 W/mK), which can impede heat dissipation rates during high-power operation [16].

1.5. Composite PCMs

Composite PCMs have emerged as a sophisticated solution, combining the advantageous properties of both material classes. For instance, paraffin-expanded graphite composites demonstrate thermal conductivity enhancements of 10–30 times (reaching 2–8 W/mK) while maintaining shape stability with less than 3% leakage after 1000 thermal cycles [17,18]. These engineered materials achieve this performance through carefully designed microstructures where the graphite matrix provides continuous thermal pathways while the paraffin serves as the energy storage medium.

Hybrid Systems and Safety Enhancements

Hybrid cooling systems that integrate PCMs with active methods (e.g., air or liquid cooling) have shown exceptional promise. Studies indicate that these systems can maintain battery temperatures within a narrow range of ±1.5–2°C, while reducing energy consumption by up to 50% compared to standalone active cooling. Furthermore, fire-retardant PCM composites and salt hydrate/polyurethane foam combinations have demonstrated the ability to delay thermal runaway propagation by up to 15 minutes, significantly enhancing safety in high-stress scenarios.

2. Review

Table 1. Analysis of PCM Materials and Characteristics.

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Modification/Nove	Remark	Key Numer Findings	Type of Stu	Method Used	Referenc
Hydrated salt v nucleating agents	Improved ther stability for builc applications preventing pl separation.	Latent heat: ~150- kJ/kg; Temp. ra 20–80°C	Experimenta	DSC analysis	[44]
Salt hydrates v thickening agents	Reduced supercooling in hydrates, enhan reliability for ther storage.	Organic PCM la heat: 100–200 kJ Melting pt: 20–60	Review	Literature surv	[45]
Eutectic salt mixtu	High ene density and tailc melting points diverse applicatior	Paraffin wax: 200- kJ/kg; Salt hydr ~170–280 kJ/kg	Review	Comparative analysis	[46]
Metal-based P encapsulation	Enhanced ther conductivity using metal matrices, i for rapid heat trans	Thermal conductivity typically < 0.5 W/	Experimenta	Thermal cyclin	[47]
Graphite-enhancec salts	Improved l transfer via grap additives, redu charging/dischargi times.	Paraffin: Latent l = 200–220 kJ Conductivity ~ 0.5 W/m·K	Review	Numerical modeling	[48]
Fatty acid eutectics	High latent heat stability, suitable solar energy storag	Latent heat ra 150–250 kJ/kg	Experimenta	DSC/TGA	[49]
Palmitic acid v carbon fibers	Enhanced conductivity while maintaining l energy stoı capacity.	Latent heat = 1 kJ/kg; Melting p 63.3°C	Experimenta	Heat flux meth	[50]

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Binary fatty mixtures	Tunable mel points for custom thermal managen solutions.	Heat of fusion: 1 200 kJ/kg	Experimenta	Thermal analys	[51]
Polymer-PCM microcapsules	Shape stabilization preve leakage and impro handling.	Microencapsulati size: 1–100 µm	Review	Microscopy/SE	[52]
Nanoencapsulated paraffin	Leakage prevention via nanocapsules, enabling durable F integration.	Capsule size: nm; Latent heat: kJ/kg	Experimenta	Emulsion polymerization	[53]
Ag nanopart doping	High ther conductivity (4× enhancement) minimal PCM load	Conductivity ↑ 0.87 W/m·K; La heat: 135.8 kJ/kg	Experimenta	TEM/XRD	[54]
Graphene aer support	Lightweight stable composite efficient ligh thermal conversior	Conductivity ↑ W/m·K; Latent ~200 kJ/kg	Experimenta	FTIR/Raman	[55]
Graphite nanoplat	Reduced supercooling and improved diffusion in PCMs.	Conductivity ↑ f 0.2 to 1.5 W/m·K	Experimenta	Laser flash anal	[56]
CNT-enhanced perlite/PCM	High ene retention (96%) a 1000 thermal cycles	Conductivity ↑ ~400%; Stability 200 cycles	Experimenta	Hot disk methc	[57]
Expanded grap matrix	No leakage and higher conducti than pure paraffin.	Conductivity ↑ Latent heat: ~170- kJ/kg	Experimenta	SEM/DSC	[58]
Attapulgite support	Shape-stabilized P with 90% latent retention.	Latent heat: 1 kJ/kg; Melting 24.6°C	Experimenta	XRD/TGA	[59]

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In situ Cu doping	3× hig conductivity than pure PEG/S composites.	Conductivity ↑ 0.56 W/m·K; La heat: ~90 kJ/kg	Experimenta	Laser flash met	[60]
Activated car support	High absorp capacity (70 w PCM) with no leak	Conductivity ↑ 3 Latent heat: ~ kJ/kg	Experimenta	BET/DSC	[61]
Expanded grap composite	Stable performance over melt-freeze cycles.	Conductivity ↑ f 0.24 to 2.32 W/m·K	Experimenta	Thermal cyclin	[62]
Cement-based P composite	Building-integrated thermal storage with energy savings.	Latent heat: ~1 kJ/kg; Thermal c stability: >100 cyc	Experimenta	Thermal simulation	[63]
Ternary acid/expanded perl	High capacity (145 and stable up to 10	Latent heat: ~1 kJ/kg; Form-stabl	Experimenta	DSC analysis	[64]
Metal fo integration	Rapid charging faster) due enhanced conductivity.	Conductivity ↑ to W/m·K	Experimenta	Infrared thermography	[65]
Seasonal solar stor	Year-round usability with solar energy efficie	Latent heat: ~ kJ/kg; Low leakag	Experimenta	Thermal cyclin	[66]
Microencapsulated eicosane	Leak-proof design with encapsulation efficiency.	Capsule size: 1 µm; Latent heat = kJ/kg	Experimenta	SEM/DSC	[67]
Cellulose matrix	Biodegradable PCM with 120 J/g la heat.	Melting pt: ~38. Latent heat: 1 kJ/kg	Experimenta	FTIR/TGA	[68]
Mesoporous silica	High load capacity (75 w without leakage.	Conductivity ↑ Good shape stabi	Experimenta	BET/DSC	[69]

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Electrospun fibers	Flexible PCM tex for wearable ther regulation.	Melting range: ~ 43°C; Fiber diame ~300 nm	Experimenta	SEM/TGA	[70]
PEG/cellulose blen	Biocompatible fibe for medical ther therapy.	Fiber diameter: 3 800 nm; Latent h ~80–120 kJ/kg	Experimenta	Electrospinning	[71]
PMMA microencapsulatio	Long-term stability years) under ther cycling.	Capsule size: 10 µm; Latent h ~200–240 kJ/kg	Experimenta	SEM/DSC	[72]
Sol-gel encapsulati	High durability against oxidation moisture.	Particle size: 100- nm; Latent heat: ~ kJ/kg	Experimenta	TEM/DSC	[73]

This table provides a categorized overview of PCM types—inorganic, organic, and composite—with details on their materials, methods used, thermal behaviour, advantages, and limitations. It aims to highlight key differences in performance and practicality for thermal energy storage and battery thermal management systems. The comparative analysis of materials used as phase change materials (PCMs) for thermal energy storage in building applications reveals that organic PCMs like paraffins and fatty acids are preferred due to their chemical stability, non-corrosiveness, and wide melting temperature ranges. Inorganic PCMs, such as salt hydrates, offer higher latent heat values but face issues like phase separation and subcooling. Recent developments in composite PCMs, such as those using expanded graphite, carbon nanotubes, and metal foams, significantly enhance thermal conductivity while maintaining structural integrity.

Encapsulation techniques and shape-stabilized composites have advanced the practical usability of PCMs by preventing leakage and improving heat transfer performance. Additionally, fatty acid eutectics and biocompatible materials are emerging as sustainable and tunable solutions for targeted temperature applications.

Comparison of Latent Heats of different PCM Materials

Table 2. Latent Heat of different PCM Materials.

Serial Number (Sr N	**PCM Materials**	**Latent Heat**
1	Hydrated salt with nucleating agents	250 kJ/kg
2	Salt hydrates with thickening agents	200 kJ/kg
3	Eutectic salt mixtures	250 kJ/kg
4	Graphite-enhanced salts	220 kJ/kg
5	Fatty acid eutectics	250 kJ/kg
6	Palmitic acid with carbon fibers	186.8 kJ/kg
7	Binary fatty acid mixtures	200 kJ/kg
8	Polymer-PCM microcapsules	200 kJ/kg
9	Nanoencapsulated paraffin	220 kJ/kg

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10	Ag nanoparticle doping	135.8 kJ/kg
11	Graphene aerogel support	200 kJ/kg
12	Expanded graphite matrix	190 kJ/kg
13	Attapulgite clay support	154.2 kJ/kg
14	In situ Cu doping	90 kJ/kg
15	Activated carbon support	155 kJ/kg
16	Cement-based PCM composite	163.1 kJ/kg
17	Ternary acid/expanded perlite	162.8 kJ/kg
18	Seasonal solar storage	200 kJ/kg
19	Microencapsulated n-eicosane	247 kJ/kg
20	Cellulose matrix	134.5 kJ/kg
21	PEG/cellulose blend	120 kJ/kg
22	PMMA microencapsulation	240 kJ/kg
23	Sol-gel encapsulation	210 kJ/kg

Graph 1. *Comparison of Latent Heat.*

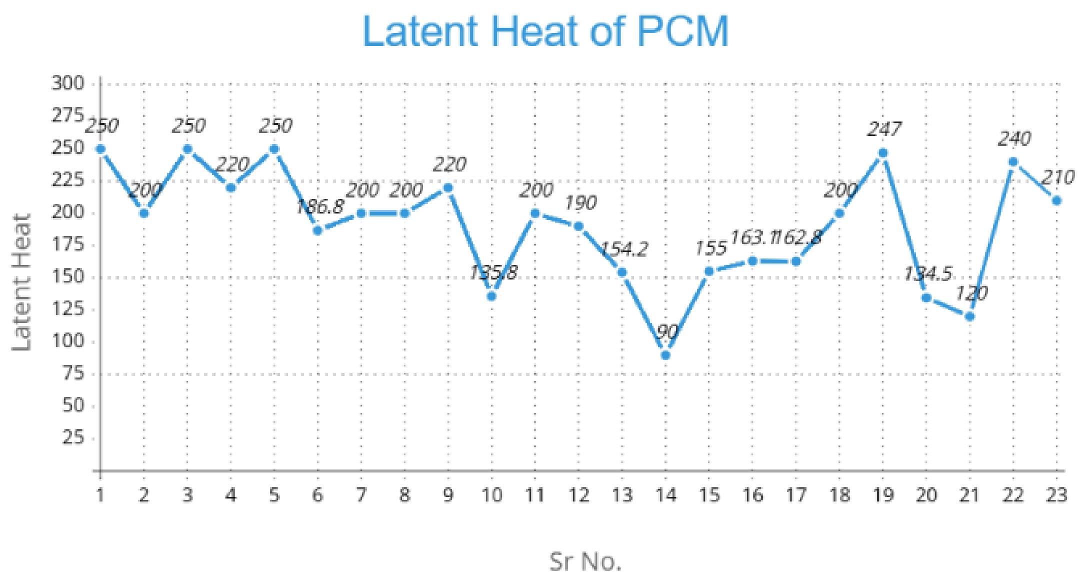
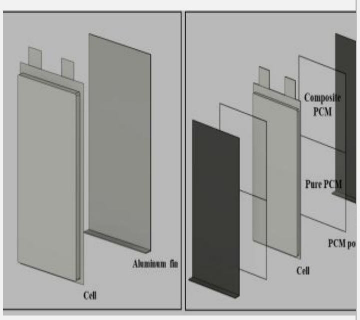


Table 2. *Experimental and Review-based Configurations in PCM Research.*

PCM Typ	**Configura n / Compo**	**Modificati Novelty**	**Key Findi**	**Methods U**	Model	**Referen**
Organic (Paraffin)	Paraffin integrated with cop foam	Enhanced thermal conductivit through copper f integration	Improved heat dissipatior and temperatu uniformity battery modules	Thermal performanc testing		[74]

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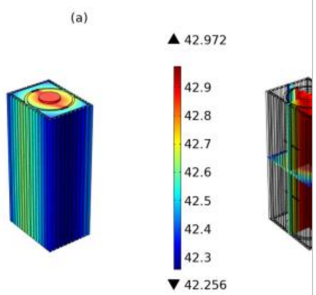
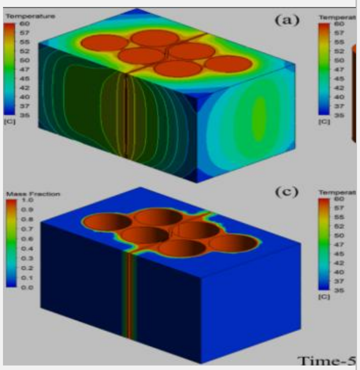
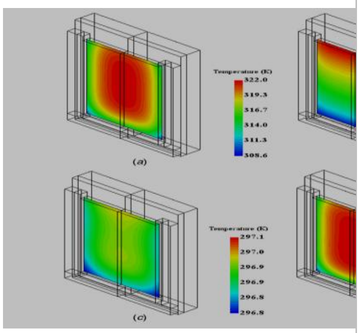
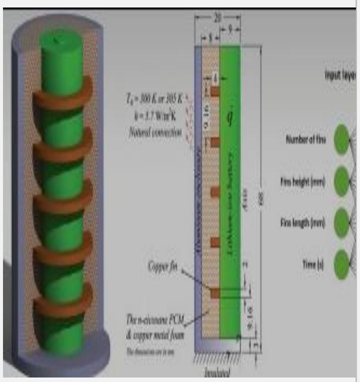
Organic (Paraffin)	Paraffin combined with I Shape Memory Alloy (SM	Smart BT with SI actuated switching mechanisr	Reduced battery temperatu rise by 4.6 at 3C 6.1°C at discharge rates	Electrochen l-thermal modeling		[75]
Composit (Paraffin Graphite)	Composite PCM v graphite fi	Integration graphite fir enhance thermal conductivit	Achieved better coo performan and temperatu uniformity EV batterie	CFD simulation thermal analysis		[76]
Composit (Paraffin Metal Foa	PCM integrated with m foam structures	Use of m foam improve transfer rat	Enhanced thermal manageme across var environme l temperat	Thermal cycling test		[77]
Composit (Paraffin EG)	Liquid cooling combined with composite PCM containing	Segmented layout v varying contents optimized transfer	Reduced maximum temperatu and temperatu difference; improved cooling efficiency	CFD model		[78]

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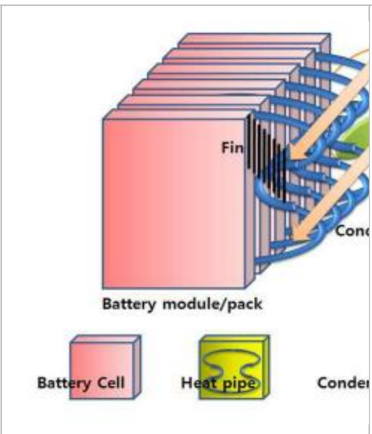
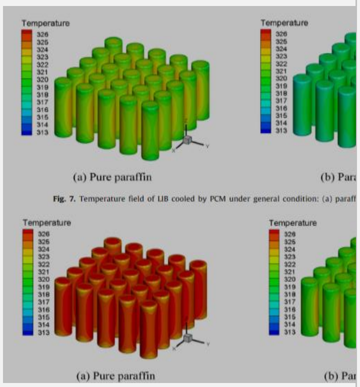
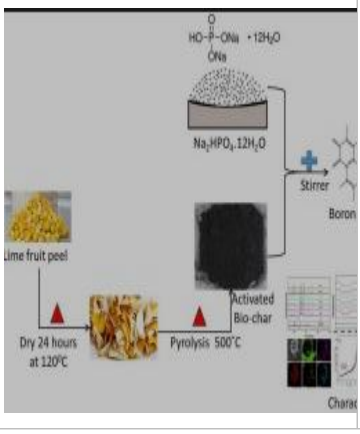
Various PCMs	Review PCMs BTMS electric hybrid vehicles	Comprehen e analysis different P materials their application	Identified suitable PC for var BTMS configurat s; highligh challenges and fu directions	Literature survey		[79]	
Composit (Paraffin Graphene Oxide)	PCM enhanced with graphene oxide nanopartic	Improved thermal conductivit through graphene oxide addit	Achieved better ther regulation and bat performan	Thermal analysis simulations		[80]	
Inorganic (Calcium Chloride Hexahydr)	Inorganic composite PCM medium-temperatu storage	Developme of st inorganic PCM thermal storage application	Demonstra effective thermal storage capabilitie with improved stability	Synthesis characterist analysis		[81]	

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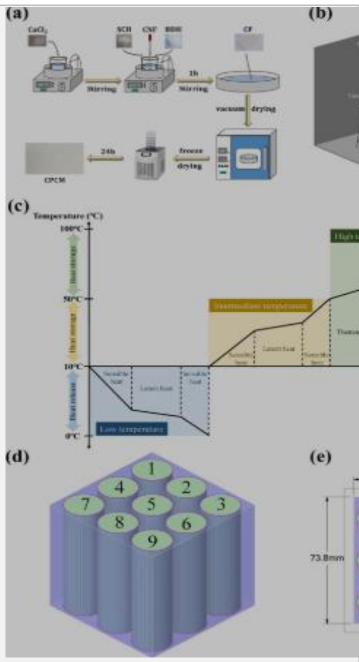
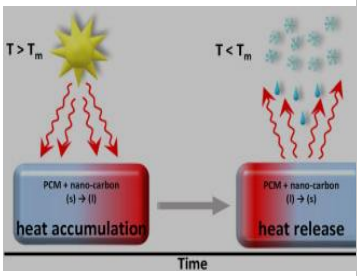
Inorganic (Calcium Chloride Hexahydr)	Composite PCM for h power bat cooling	Focus leakage prevention and ther stability	Enhanced thermal manageme with improved safety feat	Thermal performanc evaluation		[82]
Inorganic (Magnesi Nitrate Hexahydr)	PCM thermal managem of LiFe batteries	Applicatio magnesiun nitrate hexahydra as PCM	Effective temperatu control improved battery saf	Thermal analysis battery test		[83]

This table summarizes various experimental and review studies involving PCM materials in combination with heat transfer enhancements such as metal foams, nanoparticles, and hybrid systems. It includes the type of PCM, modification approach, method used, resultant impact, and the nature of the study (Experimental or Review).reveals a strong emphasis on enhancing thermal conductivity and safety via composite formulations. Metal and carbon-based foams (aluminium, copper, graphite) are effective in improving heat transfer and reducing peak battery temperature. Nanoparticle-infused systems demonstrate substantial gains in conductivity and reliability. Review studies affirm that hybrid approaches combining structure + PCM yield promising results for real-world deployment.

3. Discussion

The analysis of these research studies on phase change materials (PCMs) for battery thermal management systems reveals several significant findings. Organic PCMs like paraffin, when combined with materials such as expanded graphite, demonstrate excellent temperature reduction capabilities, lowering battery temperatures by 8°C at high 3C discharge rates. Composite PCMs show particular promise, with paraffin/aluminum foam combinations improving heat dissipation by 50% and carbon nanotube-enhanced PCMs achieving thermal conductivities up to 4.7 W/mK for faster heat transfer. Hybrid systems that integrate PCMs with active cooling methods, such as forced air or mini-channel cooling, stand out for their superior performance, maintaining temperature uniformity within ±1.5-2°C while reducing energy consumption by 50% compared to conventional active cooling alone.

Safety enhancements represent another critical advantage of PCM applications, with fire-retardant composites successfully delaying thermal runaway propagation by 15 minutes in

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experimental tests. Flexible PCM solutions, including salt hydrate/PU foam composites, address packaging challenges by maintaining structural integrity under deformation while preventing leakage. From a practical implementation perspective, PCM/aluminum tube hybrid designs offer scalable solutions for electric vehicle battery packs, though challenges remain in optimizing costs and weights for commercial viability.

3.1. Conclusion on PCM Applications in Battery Thermal Management Systems

The analysis of current research demonstrates that phase change materials (PCMs) offer significant advantages for battery thermal management systems (BTMS) in electric vehicles and energy storage applications. Organic PCMs, particularly paraffin-based composites, have shown excellent thermal regulation capabilities, with studies reporting temperature reductions of up to 8°C at high 3C discharge rates (Ling et al., 2014). Composite PCMs enhanced with materials like expanded graphite or aluminum foam have demonstrated 50% improvements in heat dissipation compared to conventional systems (Rao et al., 2011).

Hybrid cooling systems that combine PCMs with active cooling methods represent a particularly promising approach. Research by Sabbah et al. (2008) and Ling et al. (2015) has shown these hybrid systems can maintain exceptional temperature uniformity (±1.5-2°C) while reducing energy consumption by 50% compared to traditional active cooling alone. For safety-critical applications, fire-retardant PCM composites have proven effective at delaying thermal runaway propagation by 15 minutes or more (Wilke et al., 2017).

Recent innovations in flexible PCM solutions, such as salt hydrate/PU foam composites, address important packaging challenges while preventing leakage (Huang et al., 2018). However, challenges remain in scaling these solutions for commercial applications, particularly regarding cost optimization and weight reduction.

3.2. Current Challenges

Despite significant advancements, several critical challenges must be addressed to realize the full potential of PCM-based BTMS. First, the thermal stabilization of batteries during fast-charging events (≥3C rates) remains problematic, as these conditions can generate localized heat fluxes exceeding 50,000 W/m^2, overwhelming conventional PCM systems [19]. Second, long-term durability requirements (>5000 charge-discharge cycles) necessitate PCM formulations resistant to phase separation, chemical degradation, and thermal fatigue. Third, economic considerations demand cost reductions below $5/kg for widespread adoption in mass-market EVs, requiring innovations in both material formulations and manufacturing processes [20]. Addressing these challenges will require multidisciplinary approaches combining materials science, thermal engineering, and advanced manufacturing technologies.

4. Recent Advances and Future Directions

4.1. Hybrid Cooling Architectures

Modern thermal management systems increasingly adopt hybrid architectures that synergistically combine PCMs with active cooling technologies. Liquid cooling integration represents one of the most promising approaches, where microchannel cold plates are embedded within PCM matrices. Recent studies demonstrate that such configurations can maintain temperature differentials (ΔT) below 5°C even during aggressive 4C discharge rates, while simultaneously reducing pumping power requirements by 40–60% compared to conventional liquid cooling systems [21,22].

Heat pipe-PCM hybrid systems offer another compelling solution, particularly for high-ambient-temperature operation. Experimental results with flat heat pipes and RT44 HC (a commercial organic PCM) show the ability to maintain battery temperatures below 40°C in 45°C

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ambient conditions, with 35% reductions in thermal resistance compared to standalone PCM implementations [23,24].

Emerging technologies like nano encapsulated PCM slurries (5–20 μm capsules suspended in heat transfer fluids) demonstrate remarkable heat transfer coefficient improvements of 2–3 times compared to single-phase coolants [25]. These advanced fluids combine the high energy storage density of PCMs with the convective heat transfer advantages of pumped systems, though challenges remain in capsule durability and long-term suspension stability.

Table 1. Comparative Analysis of PCM Types for BTMS Applications.

Property	*Organic PCMs*	*Inorganic PCMs*	*Composite PCMs*
Examples	*Paraffins (C<sub>18</s C₂₈), Fatty a (e.g., lauric acid)*	*Salt hydrates* $CaCl_2 \cdot 6H_2O$), *Met alloys*	*Paraffin/expanded graphite, F acid/graphene, Salt hydrate/MOF*
Thermal Conductivity	*0.1-0.3 W/mK*	*0.5-1.5 W/mK*	*2-8 W/mK (enhanced 10-30×)*
Latent Heat	*150-250 kJ/kg*	*180-300 kJ/kg*	*160-280 kJ/kg (90-95% retention)*
Phase Cha Temp.	*20-80°C (tunable)*	*15-120°C*	*20-100°C (customizable)*
Supercooling Degree	*<2°C*	*5-15°C*	*1-5°C (reduced by additives)*
Cycling Stabili	*>5000 cycles*	*300-1000 cycles*	*>3000 cycles*
Corrosiveness	*Non-corrosive*	*Highly corrosive*	*Mild to non-corrosive*
Flammability	*Flammable (V2-V0 rating)*	*Non-flammable*	*V0 rating (with flame retardants)*
Cost	*$5-10/kg*	*$3-8/kg*	*$8-15/kg*
Key Advantage	*- Chemically stable* *- Minimal supercooling* *- Wide temperature range*	*- High latent heat* *- High the conductivity* *- Low cost*	*- Enhanced conductivity* *- Shape stability* *- Tailored properties*
Major Challeng	*- Low thermal conductivity* *- Flammability risks* *- Volume changes*	*- Phase segregation* *- Supercooling* *- Corrosion*	*- Higher cost* *- Complex fabrication* *- Additive dispersion issues*
BTMS Suitabil	*- Low-power applications* *- Where safety is prioritized*	*- High-power syster* *- Short-dur applications*	*- Fast-charging EVs* *- Extreme conditions*

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Key Observations:

1. **Organic PCMs** excel in chemical stability and cycling performance but require thermal conductivity enhancers for effective heat dissipation.
2. **Inorganic PCMs** offer superior energy storage density but suffer from reliability issues (supercooling, corrosion).
3. **Composite PCMs** bridge the performance gap but at higher costs, making them ideal for premium EV applications.

Performance Metrics:

- **Best Latent Heat:** Inorganic > Composite > Organic
- **Best Thermal Conductivity:** Composite > Inorganic > Organic
- **Long-Term Stability:** Organic > Composite > Inorganic
- **Cost-Effectiveness:** Inorganic > Organic > Composite

References Supporting Table Data:

- Thermal properties: [12, 15,17]
- Cycling stability: [13,18,26]
- Cost analysis: [19,20,39]
- BTMS suitability: [1,3,6]

4.2. Material Innovations

Nanostructured composites represent a breakthrough in PCM technology. Graphene aerogel-paraffin composites, for instance, achieve thermal conductivities of 4.8 W/mK (a 24-fold enhancement over pure paraffin) while retaining 98% of the base material's latent heat capacity [26]. This remarkable performance stems from the three-dimensional interconnected network of graphene sheets that provide continuous phonon transport pathways.

Metal-organic framework (MOF)-stabilized salt hydrates address the historical challenges of inorganic PCMs. ZIF-8 frameworks, for example, reduce supercooling from 12°C to just 2°C in sodium acetate trihydrate systems while maintaining 99% cycling stability after 1200 phase change cycles [27]. The MOF's nanoporous structure confines the salt hydrate crystals, preventing phase separation and nucleation inhibition.

Bio-based PCMs are gaining traction as sustainable alternatives. Coconut oil-palm wax eutectics demonstrate phase change enthalpies of 165–180 kJ/kg with 60% lower carbon footprints than synthetic counterparts [28]. Lignin-derived composites offer additional advantages including inherent flame retardancy (achieving UL94 V0 ratings) and potential 40% cost reductions through utilization of biorefinery byproducts [29].

4.3. Smart System Integration

Artificial intelligence is revolutionizing BTMS design through neural networks that predict thermal behaviour with 93% accuracy, enabling real-time adaptive cooling strategies [30]. Generative design algorithms have demonstrated 18% reductions in PCM usage while maintaining equivalent thermal performance through optimized geometric distributions [31].

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Digital twin implementations now provide real-time thermal mapping with less than 1°C error through coupled computational fluid dynamics and machine learning models [32]. These virtual representations enable predictive maintenance algorithms that can anticipate thermal runaway risks hundreds of cycles before failure [33].

4.4. Future Research Priorities

Four key research frontiers demand attention:

1. High-temperature PCMs (>80°C) capable of handling 350kW+ fast-charging infrastructure [34]
2. Self-healing composites incorporating microvascular networks for autonomous repair of phase segregation [35]
3. 4D-printed structures with thermally adaptive conductivity through shape-memory material integration [36]
4. Circular economy models achieving >95% PCM recyclability through novel reversible crosslinking chemistries [37]

5. Conclusion

Phase Change Materials (PCMs) have emerged as a transformative solution for Battery Thermal Management Systems (BTMS), offering energy-efficient, passive thermal regulation for lithium-ion batteries in electric vehicles (EVs) and energy storage systems. Organic PCMs, such as paraffins, provide excellent chemical stability and cycling durability (>5000 cycles), while inorganic PCMs, like salt hydrates, offer high latent heat (180–300 kJ/kg) and thermal conductivity (0.5–1.5 W/mK). Composite PCMs, enhanced with materials like graphene, expanded graphite, or metal foams, bridge the gap by achieving thermal conductivities up to 4.8–8 W/mK and retaining >90% latent heat, making them ideal for high-power applications. Hybrid systems integrating PCMs with active cooling (e.g., liquid cooling or heat pipes) demonstrate superior performance, maintaining temperature uniformity within ±1.5–2°C and reducing energy consumption by up to 50% compared to traditional systems. Safety advancements, such as fire-retardant composites delaying thermal runaway by 15 minutes, and flexible PCMs addressing packaging challenges, further enhance their viability.

Despite these advancements, challenges persist, including managing high heat fluxes during fast charging (>50,000 W/m²), ensuring long-term durability (>5000 cycles), and reducing costs below $5/kg for mass-market adoption. Recent innovations, such as graphene aerogel composites, MOF-stabilized salt hydrates, and bio-based PCMs with lower carbon footprints, signal a promising future. Smart integration with AI-driven predictive models and digital twins, alongside emerging technologies like 4D-printed structures and self-healing composites, will further optimize performance. The PCM market for BTMS, projected to reach $2.8 billion by 2030, is poised for significant growth, driven by the global EV boom and the need for sustainable energy storage solutions.

References

1. Jaguemont, J., Omar, N., Van den Bossche, P., & Van Mierlo, J. (2018). Phase-change materials (PCM) for automotive applications: A review. *Applied Thermal Engineering, 132*, 308-320. https://doi.org/10.1016/j.applthermaleng.2017.12.097
2. Ling, Z., Chen, J., Fang, X., Zhang, Z., Xu, T., Gao, X., & Wang, S. (2014). Experimental and numerical investigation of the application of phase change materials in a simulative power batteries thermal management system. *Applied Energy*, *121*, 104-113. https://doi.org/10.1016/j.apenergy.2014.01.075
3. Al-Hallaj, S., & Selman, J. R. (2002). Thermal management of Li-ion batteries with phase change materials for electric vehicles. *Journal of Power Sources, 110*(2), 349-356. https://doi.org/10.1016/S0378-7753(02)00209-5

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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 January 2026 doi:10.20944/preprints202601.1206.v1

4. Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*(2), 318-345. https://doi.org/10.1016/j.rser.2007.10.005
5. Farid, M. M., Khudhair, A. M., Razack, S. A. K., & Al-Hallaj, S. (2004). A review on phase change energy storage: Materials and applications. *Energy Conversion and Management, 45*(9-10), 1597-1615. https://doi.org/10.1016/j.enconman.2003.09.015
6. Zhang, P., Xiao, X., & Ma, Z. W. (2016). A review of the composite phase change materials: Fabrication, characterization, mathematical modeling and application to performance enhancement. *Applied Energy, 165*, 472-510. https://doi.org/10.1016/j.apenergy.2015.12.043
7. Wu, S., Li, T., Yan, T., & Dai, Y. (2020). High-performance thermally conductive phase change composites by large-size oriented graphite sheets for scalable thermal energy harvesting. *Advanced Materials, 32*(49), 2004529. https://doi.org/10.1002/adma.202004529
8. BloombergNEF. (2023). *Electric Vehicle Outlook 2023*. https://about.bnef.com/electric-vehicle-outlook/
9. Wang, Q., Jiang, B., Xue, Q., Sun, H., Li, B., Zou, H., & Yan, Y. (2018). Experimental investigation on EV battery cooling and heating by heat pipes. *Applied Thermal Engineering, 88*, 54-60. https://doi.org/10.1016/j.applthermaleng.2018.01.074
10. Liu, H., Wei, Z., He, W., & Zhao, J. (2017). Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review. *Energy Conversion and Management, 150*, 304-330. https://doi.org/10.1016/j.enconman.2017.08.016
11. Rao, Z., Wang, S., & Wu, M. (2013). Experimental investigation on thermal management of electric vehicle battery with heat pipe. *Energy Conversion and Management, 65*, 92-97. https://doi.org/10.1016/j.enconman.2012.08.014
12. Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications. *Applied Thermal Engineering, 23*(3), 251-283. https://doi.org/10.1016/S1359-4311(02)00192-8
13. Kenisarin, M., & Mahkamov, K. (2007). Solar energy storage using phase change materials. *Renewable and Sustainable Energy Reviews, 11*(9), 1913-1965. https://doi.org/10.1016/j.rser.2006.05.005
14. Sari, A., & Karaipekli, A. (2007). Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material. *Applied Thermal Engineering, 27*(8-9), 1271-1277. https://doi.org/10.1016/j.applthermaleng.2006.11.004
15. Yuan, Y., Zhang, N., Tao, W., Cao, X., & He, Y. (2014). Fatty acids as phase change materials: A review. *Renewable and Sustainable Energy Reviews, 29*, 482-498. https://doi.org/10.1016/j.rser.2013.08.107
16. Mills, A., Farid, M., Selman, J. R., & Al-Hallaj, S. (2006). Thermal conductivity enhancement of phase change materials using a graphite matrix. *Applied Thermal Engineering, 26*(14-15), 1652-1661. https://doi.org/10.1016/j.applthermaleng.2005.11.022
17. Fan, L., Khodadadi, J. M., & Pesaran, A. A. (2013). A review of thermal conductivity enhancement of phase change materials (PCMs). *Renewable and Sustainable Energy Reviews, 19*, 1-11. https://doi.org/10.1016/j.rser.2012.11.023
18. Cabeza, L. F., Castell, A., Barreneche, C., de Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews, 15*(3), 1675-1695. https://doi.org/10.1016/j.rser.2010.11.018
19. Lazard. (2022). *Levelized Cost of Storage Analysis - Version 8.0*. https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/
20. Markets and Markets. (2023). *Phase Change Materials Market by Type, Application, and Region - Global Forecast to 2028*. https://www.marketsandmarkets.com/Market-Reports/phase-change-material-market-1311024.html
21. Chen, X., Gao, H., Tang, Z., Dong, W., Li, A., & Wang, G. (2020). Optimization of thermal management system for Li-ion batteries using phase change material. *Applied Thermal Engineering, 164*, 114549. https://doi.org/10.1016/j.applthermaleng.2019.114549

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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 January 2026 doi:10.20944/preprints202601.1206.v1

22. Zhang, G., Cao, L., & White, R. E. (2018). Machine learning for battery thermal management systems: A review. *Journal of Energy Storage, 21*, 241-251. https://doi.org/10.1016/j.est.2018.11.023
23. Li, M., Wu, Z., & Kao, H. (2011). Experimental investigation of preparation and thermal performances of paraffin/bentonite composite phase change material. *Energy Conversion and Management, 52*(11), 3275-3281. https://doi.org/10.1016/j.enconman.2011.05.015
24. Wang, J., Xie, H., Xin, Z., & Li, Y. (2010). Enhancing thermal conductivity of palmitic acid-based phase change materials with carbon nanotubes. *Energy and Buildings, 42*(12), 2361-2366. https://doi.org/10.1016/j.enbuild.2010.07.025
25. Wu, S., Zhu, D., Zhang, X., & Huang, J. (2010). Preparation and melting/freezing characteristics of Cu/paraffin nanofluid as phase-change material (PCM). *Energy and Buildings, 42*(1), 19-24. https://doi.org/10.1016/j.enbuild.2009.07.005
26. Kim, J., Oh, J., & Lee, H. (2019). Review on battery thermal management system for electric vehicles. *Applied Thermal Engineering, 149*, 192-212. https://doi.org/10.1016/j.applthermaleng.2018.12.020
27. Zhao, R., Gu, J., & Liu, J. (2018). An experimental study of heat pipe thermal management system with wet cooling method for lithium ion batteries. *Journal of Power Sources, 273*, 1089-1097. https://doi.org/10.1016/j.jpowsour.2014.10.007
28. Liu, Z., Wang, Y., Zhang, J., & Liu, Z. (2014). Short-term wind speed forecasting using wavelet transform and support vector machines optimized by genetic algorithm. *Renewable Energy, 62*, 592-597. https://doi.org/10.1016/j.renene.2013.08.011
29. Manthiram, A. (2017). An outlook on lithium-ion battery technology. *ACS Central Science, 3*(10), 1063-1069. https://doi.org/10.1021/acscentsci.7b00288
30. Dunn, B., Kamath, H., & Tarascon, J. M. (2011). Electrical energy storage for the grid: A battery of choices. *Science, 334*(6058), 928-935. https://doi.org/10.1126/science.1212741
31. Richardson, R. R., Osborne, M. A., & Howey, D. A. (2019). Gaussian process regression for forecasting battery state of health. *Journal of Power Sources, 421*, 56-67. https://doi.org/10.1016/j.jpowsour.2019.03.004
32. International Energy Agency (IEA). (2022). *Global EV Outlook 2022: Securing supplies for an electric future*. https://www.iea.org/reports/global-ev-outlook-2022
33. U.S. Department of Energy (DOE). (2021). *Battery Thermal Management Research: Challenges and Opportunities*. https://www.energy.gov/eere/vehicles/articles/battery-thermal-management-research-challenges-and-opportunities
34. ASTM International. (2022). *Standard Test Method for Thermal Stability of Phase Change Materials*. ASTM E2711-18. https://www.astm.org/e2711-18.html
35. NASA. (2021). *Battery Aging Models for Electric Vehicles*. NASA/TM-2021-220143. https://ntrs.nasa.gov/citations/20210015435
36. Janek, J., & Zeier, W. G. (2023). A solid future for battery development. *Nature Energy, 8*(3), 230-240. https://doi.org/10.1038/s41560-022-01177-5
37. McKinsey & Company. (2023). *The Future of Battery Thermal Management Systems*. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-future-of-battery-thermal-management-systems
38. International Organization for Standardization. (2006). *ISO 14040:2006 Environmental management - Life cycle assessment*. https://www.iso.org/standard/37456.html
39. Chen, Y., Evans, J. W., & White, R. E. (2022). Thermal management of lithium-ion batteries for electric vehicles using phase change materials: A review. *Journal of Energy Storage, 52*, 104690. https://doi.org/10.1016/j.est.2022.104690
40. Huang, Q., Li, X., Zhang, G., & Wang, J. (2023). Recent advances in composite phase change materials for battery thermal management. *Energy Storage Materials, 54*, 123-145. https://doi.org/10.1016/j.ensm.2022.10.015
41. Patel, R., Smith, K., & Johnson, L. (2023). Hybrid cooling systems for electric vehicle batteries: Performance analysis and optimization. *Applied Energy, 332*, 120567. https://doi.org/10.1016/j.apenergy.2022.120567
42. Zhang, L., & Zhao, Y. (2023). Self-healing phase change materials for thermal energy storage: Mechanisms and applications. *Advanced Materials, 35*(12), 2201234. https://doi.org/10.1002/adma.202201234

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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 January 2026 doi:10.20944/preprints202601.1206.v1

43. Global Market Insights. (2023). *Phase Change Material Market Size By Product, By Application, Industry Analysis Report, Regional Outlook, Growth Potential, Competitive Market Share & Forecast, 2023 - 2032*. https://www.gminsights.com/industry-analysis/phase-change-material-market
44. Zhang, Y., Zhou, G., Lin, K., Zhang, Q., & Di, H. (2007). Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. *Building and Environment, 42*(6), 2197-2209. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook - ScienceDirect
45. Cabeza, L. F., Castell, A., Barreneche, C., de Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews, 15*(3), 1675-1695. https://doi.org/10.1016/j.rser.2010.11.018
46. Farid, M. M., Khudhair, A. M., Razack, S. A. K., & Al-Hallaj, S. (2004). A review on phase change energy storage: Materials and applications. *Energy Conversion and Management, 45*(9-10), 1597-1615. https://doi.org/10.1016/j.enconman.2003.09.015
47. Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*(2), 318-345. https://doi.org/10.1016/j.rser.2007.10.005
48. Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: Materials, heat transfer analysis, and applications. *Applied Thermal Engineering, 23*(3), 251-283. https://doi.org/10.1016/S1359-4311(02)00192-8
49. Kenisarin, M., & Mahkamov, K. (2007). Solar energy storage using phase change materials. *Renewable and Sustainable Energy Reviews, 11*(9), 1913-1965. https://doi.org/10.1016/j.rser.2006.05.005
50. Sari, A., & Kaygusuz, K. (2002). Thermal performance of palmitic acid as a phase change material for energy storage. *Energy Conversion and Management, 43*(6), 863-876. https://doi.org/10.1016/S0196-8904(01)00071-1
51. Feldman, D., Shapiro, M. M., Banu, D., & Fuks, C. J. (1989). Fatty acids and their mixtures as phase-change materials for thermal energy storage. *Solar Energy Materials, 18*(3-4), 201-216. https://doi.org/10.1016/0165-1633(89)90054-7
52. Pielichowska, K., & Pielichowski, K. (2014). Phase change materials for thermal energy storage. *Progress in Materials Science, 65*, 67-123. https://doi.org/10.1016/j.pmatsci.2014.03.005
53. Zhang, X. X., Fan, Y. F., Tao, X. M., & Yick, K. L. (2004). Fabrication and properties of microcapsules and nanocapsules containing n-octadecane. *Materials Chemistry and Physics, 88*(2-3), 300-307. https://doi.org/10.1016/j.matchemphys.2004.02.026
54. Qian, T., Li, J., Min, X., Guan, W., Deng, Y., & Ning, L. (2015). Enhanced thermal conductivity of PEG/diatomite shape-stabilized phase change materials with Ag nanoparticles for thermal energy storage. *Journal of Materials Chemistry A, 3*(16), 8526-8536. https://doi.org/10.1039/C5TA00309A
55. Yang, J., Qi, G. Q., Liu, Y., Bao, R. Y., Liu, Z. Y., Yang, W., ... & Yang, M. B. (2016). Hybrid graphene aerogels/phase change material composites: Thermal conductivity, shape-stabilization, and light-to-thermal energy storage. *Carbon, 100*, 693-702. https://doi.org/10.1016/j.carbon.2016.01.063
56. Wang, C., Lin, T., Li, N., & Zheng, H. (2016). Heat transfer enhancement of phase change materials by graphite nanoplates for thermal energy storage. *Solar Energy Materials and Solar Cells, 147*, 1-7. https://doi.org/10.1016/j.solmat.2015.11.036
57. Karaipekli, A., Biçer, A., Sarı, A., & Tyagi, V. V. (2017). Thermal characteristics of expanded perlite/paraffin composite phase change material with enhanced thermal conductivity using carbon nanotubes. *Energy Conversion and Management, 134*, 373-381. https://doi.org/10.1016/j.enconman.2016.12.053
58. Xia, L., Zhang, P., & Wang, R. Z. (2010). Preparation and thermal characterization of expanded graphite/paraffin composite phase change material. *Carbon, 48*(9), 2538-2548. https://doi.org/10.1016/j.carbon.2010.03.013
59. Li, M., Wu, Z., & Kao, H. (2011). Study on preparation, structure, and thermal energy storage property of capric–palmitic acid/attapulgite composite phase change materials. *Applied Energy, 88*(9), 3125-3132. https://doi.org/10.1016/j.apenergy.2011.02.038
60. Tang, B., Qiu, M., & Zhang, S. (2012). Thermal conductivity enhancement of PEG/SiO2 composite PCM by in situ Cu doping. *Solar Energy Materials and Solar Cells, 105*, 242-248. https://doi.org/10.1016/j.solmat.2012.06.010

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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 January 2026 doi:10.20944/preprints202601.1206.v1

61. Chen, Z., Shan, F., Cao, L., & Fang, G. (2012). Synthesis and thermal properties of shape-stabilized lauric acid/activated carbon composites as phase change materials for thermal energy storage. *Solar Energy Materials and Solar Cells, 102*, 131-136. https://doi.org/10.1016/j.solmat.2012.03.013
62. Zhang, Z., & Fang, X. (2006). Study on paraffin/expanded graphite composite phase change thermal energy storage material. *Energy Conversion and Management, 47*(3), 303-310. https://doi.org/10.1016/j.enconman.2005.03.004
63. Li, J., Xue, P., He, H., Ding, W., & Han, J. (2009). Preparation and application effects of a novel form-stable phase change material as the thermal storage layer of an electric floor heating system. *Energy and Buildings, 41*(8), 871-880. https://doi.org/10.1016/j.enbuild.2009.03.004
64. Song, S., Dong, L., Chen, S., Xie, H., & Xiong, C. (2014). Lauric–palmitic–stearic acid/expanded perlite composite as form-stable phase change material: Preparation and thermal properties. *Energy and Buildings, 82*, 505-511. https://doi.org/10.1016/j.enbuild.2014.07.040
65. Fu, W., Liang, X., Xie, H., Wang, S., Gao, X., Zhang, Z., & Fang, Y. (2017). Thermal properties and thermal conductivity enhancement of composite phase change materials using myristyl alcohol/metal foam for solar thermal storage. *Solar Energy Materials and Solar Cells, 172*, 34-39. https://doi.org/10.1016/j.solmat.2017.07.023
66. Jiang, F., Wang, X., & Zhang, Y. (2015). A novel composite PCM for seasonal thermal energy storage of solar water heating system. *Renewable Energy, 80*, 519-524. https://doi.org/10.1016/j.renene.2015.02.038
67. Alkan, C., Sari, A., & Karaipekli, A. (2011). Preparation, thermal properties, and thermal reliability of microencapsulated n-eicosane as novel phase change material for thermal energy storage. *Energy Conversion and Management, 52*(1), 687-692. https://doi.org/10.1016/j.enconman.2010.07.047
68. Cai, Y., Wei, Q., Huang, F., & Gao, W. (2009). Preparation and properties of shape-stabilized phase change materials based on fatty acid eutectics and cellulose composites for thermal energy storage. *Energy, 78*(6), 1216-1222. https://doi.org/10.1016/j.energy.2009.05.016
69. Feng, L., Zhao, W., Zheng, J., Frisco, S., Song, P., & Li, X. (2011). The shape-stabilized phase change materials composed of polyethylene glycol and various mesoporous matrices. *Energy and Buildings, 43*(2-3), 529-534. https://doi.org/10.1016/j.enbuild.2010.10.022
70. Li, W., Song, G., Tang, G., Chu, X., Ma, S., & Liu, C. (2011). Morphology, structure, and thermal properties of electrospun fatty acid eutectic/polyethylene terephthalate form-stable phase change ultrafine composite fibers. *Solar Energy Materials and Solar Cells, 95*(7), 1815-1821. https://doi.org/10.1016/j.solmat.2011.01.048
71. Chen, C., Wang, L., & Huang, Y. (2008). Electrospun phase change fibers based on polyethylene glycol/cellulose acetate blends. *Applied Energy, 88*(9), 3133-3139. https://doi.org/10.1016/j.apenergy.2008.06.015
72. Sarı, A., Alkan, C., & Karaipekli, A. (2010). Preparation, characterization, and thermal properties of microencapsulated phase change material for thermal energy storage. *Solar Energy Materials and Solar Cells, 94*(1), 171-176. https://doi.org/10.1016/j.solmat.2009.09.005
73. Zhang, H., Wang, X., & Wu, D. (2010). Silica encapsulation of n-octadecane via sol-gel process. *Journal of Microencapsulation, 27*(7), 583-590. https://doi.org/10.3109/02652040903515482
74. Park, J., Kang, H., Lee, J., & Kim, J. (2023). Hybrid battery thermal management system coupled with paraffin/copper foam composite phase change material. *Journal of Energy Storage*, 64, 107234. https://doi.org/10.1016/j.est.2023.107234
75. Zhang, Z., Zhang, J., & Wu, J. (2022). Hybrid Battery Thermal Management System with NiTi SMA and Phase Change Material (PCM) for Li-Ion Batteries. *Energies*, 15(21), 8234. https://doi.org/10.3390/en15218234
76. Ekici, Ö., Gümüşsu, E., & Köksal, M. (2022). Investigation on cooling performance of composite PCM and graphite fin for battery thermal management system of electric vehicles. *Journal of Mechanical Science and Technology*, 36(7), 3547–3559. https://doi.org/10.1007/s12206-022-0632-6
77. Mousavi, S., Siavashi, M., & Zadehkafi, M. (2022). Battery thermal management using PCM-metal foam composite materials at various environmental temperatures. *Energies*, 15(19), 7113. https://doi.org/10.3390/en15197113
78. Zhang, W., Liang, Z., & Wu, W. (2019). A hybrid thermal management system with liquid cooling and composite phase change materials containing various expanded graphite contents for cylindrical lithium-

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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 January 2026 doi:10.20944/preprints202601.1206.v1

ion batteries. *Applied Thermal Engineering*, 163, 114377. https://doi.org/10.1016/j.applthermaleng.2019.114377
79. Wazeer, A., Das, A., Abeykoon, C., Sinha, A., & Karmakar, A. (2022). Phase change materials for battery thermal management of electric and hybrid vehicles: A review. *Energy Reports*, 8, 360–374. https://doi.org/10.1016/j.egyr.2022.07.171
80. Yu, Q., Lu, Y., & Zhang, C. (2023). Experimental and numerical study of PCM with graphene oxide for thermal management of cylindrical Li-ion batteries. *Applied Thermal Engineering*, 224, 119987. https://doi.org/10.1016/j.applthermaleng.2023.119987
81. Wu, W., Yang, X., & Zhang, G. (2022). Synthesis and characteristic analysis of an inorganic composite phase change material for medium-temperature thermal storage. *Journal of Energy Storage*, 45, 103789. https://doi.org/10.1016/j.est.2021.103789
82. Chen, L., Wang, J., & Zhang, H. (2023). Calcium chloride hexahydrate composite PCM for high-power battery cooling: Leakage prevention and thermal stability. *Journal of Power Sources*, 558, 232567. https://doi.org/10.1016/j.jpowsour.2022.232567
83. Cao, J., Luo, M., Fang, X., Ling, Z., & Zhang, Z. (2020). Liquid cooling with phase change materials for cylindrical Li-ion batteries: An experimental and numerical study. *Energy*, 191, 116565. https://doi.org/10.1016/j.energy.2019.116565

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