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Next-Generation Bio-Based Phase Change Materials for Integrated Thermal Energy Storage in Net-Zero and Climate-Responsive Buildings: A Comprehensive Review

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Abstract

Introduction: Buildings are rapidly transitioning toward decarbonization, electrification, and climate-adaptive performance, increasing the demand for compact, controllable, and code-compliant thermal energy storage (TES). Latent TES using phase change materials (PCMs) offers high energy density near comfort temperatures, yet widespread adoption remains limited due to low thermal conductivity in organic/bio-based PCMs, reliability challenges in salt hydrates, and insufficient evidence on composite safety, durability, and life-cycle impacts.

Objectives: This review aims to synthesize two decades of progress on next-generation bio-based PCMs and provide an integrated framework that treats PCMs as actively scheduled thermal batteries within building envelopes, air-side/hydronic loops, and dedicated TES tanks. The objective is to map material families, composite/encapsulation strategies, integration pathways, and operational horizons while producing practice-ready guidance for sizing, placement, safety, and supervisory control.

Methods: The review aligns thermophysical operating windows of PCMs with building comfort and system setpoints (≈20–30 °C for envelopes/radiant systems; 5–18 °C for air-side pre-cooling). An impact-by-likelihood assessment is used to prioritize material and system constraints, link them to mitigation strategies, and define acceptance criteria. Comparative evaluation includes latent capacity, thermal conductivity, durability, system-level integration performance, and control effectiveness across experimental, field, and simulation studies.

Results: Bio-based PCMs can achieve latent capacities comparable to petro-organic PCMs while offering improved circularity when conductivity is enhanced through recyclable pathways. Practical performance targets include in-situ latent heat ≥90–120 kJ kg^{-1}, effective thermal conductivity ≥2 W m^{-1} K^{-1}, and <5% degradation after ≥10,000 cycles. When integrated into lightweight building envelopes, PCMs reduce peak sensible loads by ~15–30% and provide 2–4 K swing attenuation. Air-side/hydronic modules and coil-sleeve tank configurations reduce compressor cycling and increase thermal availability when melting points and heat-exchange geometries are properly matched. Forecast-aware supervisory control (e.g., MPC, digital twins) reliably converts latent capacity into peak-shaving and cost savings, given proper commissioning and enforcement of thermal comfort, fire/IAQ, and composite-integrity constraints.

Conclusions: Bio-based PCMs, when specified at the composite level, co-designed with predictive operation, and supported by evidence of durability, safety, and circularity, can deliver measurable energy, carbon, and resilience benefits in grid-interactive and climate-responsive buildings. A structured deployment roadmap—including pre-screening, simulation-aided sizing, composite procurement specifications, commissioning tests, and M&V with LCA/EPD documentation—enables reliable large-scale implementation of next-generation PCM-based TES technologies.

keyword: phase change materials; bio-PCMs; thermal energy storage; envelope/HVAC integration; predictive control; demand response; sustainability

1. Introduction

The built environment is at the nexus of decarbonization, electrification, and climate adaptation, while buildings remain among the largest end-use energy consumers and sources of operational CO_2 emissions, driven primarily by space conditioning and domestic hot water. Rising frequency and intensity of heatwaves and the urban heat island effect amplify peak thermal loads, exacerbate grid stress, and threaten indoor environmental quality [1]. Within this context, thermal energy storage (TES) has re-emerged as a first-order strategy to reconcile temporal mismatches between energy supply and demand, to enable peak shaving and valley filling, and to enhance resilience across new and existing buildings. Latent heat TES using phase change materials (PCMs) is

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especially attractive because it stores and releases large amounts of energy under quasi-isothermal conditions near comfort setpoints, thereby damping indoor temperature swings with limited added volume and mass [2]. Traditional PCM families—paraffin waxes among organics and salt hydrates among inorganics—are well studied but not without limitations: paraffins are chemically stable and non-corrosive, yet fossil-derived and flammable; salt hydrates exhibit higher latent heat and better conductivity at lower cost, but suffer from supercooling[3], phase segregation, and corrosiveness unless carefully stabilized [4]. In recent years, bio-based PCMs (bPCMs) synthesized from renewable feedstocks such as fatty acids and plant-derived oils have gained traction as sustainable alternatives. They combine favorable melting ranges for thermal comfort (≈20–30 °C), competitive latent heats, and improved environmental profiles that align with circular economy principles. Advances in micro/nano-encapsulation, shape stabilization via porous scaffolds (silica gels, biochar, expanded graphite), and conductivity enhancement using graphitic pathways or metallic foams are addressing historical bottlenecks of leakage, low thermal conductivity, and cycling degradation [5].

Evidence from building applications indicates a shift from purely passive envelopes (PCM-gypsum wallboards, PCM-plasters, PCM-enhanced concrete, cool roofs, selective glazing) toward mechanical/HVAC integration: PCM thermal batteries embedded in air-side coils, chilled ceilings, radiant floors, and buffer tanks coupled to heat pumps or solar thermal collectors; modular standalone PCM tanks are also used in grid-interactive efficient buildings to provide flexibility services. Case syntheses repeatedly report reduction of peak loads, extension of useful heat/coolth availability into off-peak hours, and relief of compressor workload when PCMs are properly sized, placed, and controlled [6]. In parallel, digitalization enables predictive operation: IoT sensing, digital twins, and model predictive control (MPC) can schedule PCM charge/discharge against weather and price forecasts as well as on-site PV/PVT availability, converting PCMs from passive dampers into actively managed thermal buffers.

The research record underpinning this trajectory is broad and instructive. Agyenim et al. (2010) synthesize early building-focused PCM literature and clarify heat-transfer bottlenecks—chiefly the low conductivity of organics and supercooling in salt hydrates—while framing design variables such as melting-range selection, capsule size, and charge/discharge strategies that translate laboratory properties into room-scale performance [5]. Mehling and Cabeza (2008) consolidate thermophysical principles—phase equilibrium, enthalpy–temperature characterization, and cycling stability—and propose standardized DSC and cycling protocols that later reviews build upon; their classification of passive envelope versus active storage applications remains a touchstone for method comparison [7]. Farid et al. (2004) offer a seminal survey of PCM materials and uses, emphasizing leakage prevention and compatibility with host matrices as first-order barriers for real buildings [8]. Kenisarin and Mahkamov (2007) review solar TES with PCMs and show that properly encapsulated paraffins and salt hydrates can extend useful solar heat well into nocturnal demand windows, while corrosion control and phase separation remain practical constraints for long-term salt-hydrate operation [9]. Shukla et al. (2009) document that PCM layers in solar water-heating systems increase draw-time availability and stabilize outlet temperatures compared with sensible-only storage, a finding that later motivates hybrid heat-pump/solar + PCM buffers [3]. Zhang et al. (2007) survey building-scale applications and report that microencapsulated PCMs in gypsum/plaster can reduce diurnal indoor temperature swings by several kelvin in lightweight structures, contingent upon capsule loading and placement [10].

Sharma et al. (2009) deliver a widely cited review contrasting organics (paraffins, fatty acids) and inorganics (salt hydrates), recommending composite/encapsulation routes to reconcile trade-offs—stability and non-corrosiveness versus conductivity and cost [11]. Kuznik et al. (2011) introduce an inverse parameter identification approach to estimate in-situ PCM properties from temperature histories in real walls, narrowing the gap between tabulated properties and as-built performance [12]. Nomura et al. (2009) demonstrate impregnation of porous matrices with PCMs for shape stabilization and leakage suppression; this materials strategy underpins today's biochar/expanded-graphite scaffolds that simultaneously improve thermal conductivity and mechanical integrity [13]. Rathore and Shukla (2019) comprehensively evaluate macro-encapsulation (tubes, spheres, panels) in air and water loops, concluding that when melting ranges are tightly matched to system setpoints and units are coupled with heat pumps, compressor cycling can be reduced and seasonal COP improved [14]. Oró et al. (2012) focus on cold TES with PCMs and highlight that sub-comfort melting ranges (≈5–18 °C) enable load shifting for chilled ceilings and ventilation air pre-cooling but require careful management of frosting, subcooling, and control hysteresis [6]. Memon (2014) surveys wall-integrated PCMs and shows that microcapsule loading and board thickness interact nonlinearly with thermal delay; the study stresses co-modeling of hygrothermal and moisture-buffering effects for robust comfort gains

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[15]. Jamekhorshid et al. (2014) compare microencapsulation methods—interfacial/in-situ polymerization and sol–gel—linking shell chemistry to permeability, thermal stability, and compatibility with cementitious or polymeric hosts; they show that shell microstructure governs both cycling durability and VOC/IAQ risk, a key concern for building codes [16]. Medrano et al. (2010) present field-scale evidence of microencapsulated PCM in concrete walls, reporting measurable cooling-energy savings and peak-load reduction and calling for practitioner-friendly design guides and constructability data [17]. Extending this line toward sustainability, Junaid et al. (2022) argue—through a resources and circularity lens—that fatty acids and bio-oils can match the latent heat and comfort-range melting points of petro-organics while improving end-of-life and sourcing sustainability, especially when waste-derived feedstocks are employed [18].

Recent reviews and evaluations sharpen these insights with a bio-based and systems-integration emphasis. Struhala (2022) provides life-cycle assessments (LCAs) for PCM-enhanced components, concluding that operational energy and CO_2 reductions can dominate cradle impacts when service life and cycling durability are adequate, while encapsulation chemistry and filler content are decisive hotspots requiring careful selection [2]. On the operations side, field and lab studies demonstrate that MPC supervising PCM-augmented heat-pump loops can deliver robust peak shaving and cost reductions under time-of-use tariffs, effectively transitioning PCMs from passive dampers to actively scheduled thermal batteries in grid-interactive buildings [19]. Together, these strands motivate a materials-to-systems perspective that maps candidate bPCMs (fatty acids, bio-oils, bio-hybrids) and their composite/encapsulation routes (shape-stabilized scaffolds, polymer/silica microcapsules, graphitic foams) to specific building archetypes (envelope layers, air-side coils, radiant panels, buffer tanks), with feasible melting ranges, effective conductivities, volumetric energy densities, and compliance with safety and indoor-air-quality requirements.

Despite substantial progress, important gaps remain. Reported thermophysical properties are still difficult to compare across studies due to heterogeneous DSC protocols and cycling regimens; harmonized testing—including long-cycle stability beyond 5,000–10,000 cycles together with flammability and IAQ screens—remains incomplete for many bPCMs. Multi-year field evidence on durability and safety, particularly for bio-polymer encapsulants and high-filler composites, is limited; techno-economic clarity across climates and retrofit constraints also remains case-specific [5], [11] These limitations have implications for codes, certifications, and environmental product declarations. Addressing them will require co-design of materials (melting-point distributions, hysteresis), geometry (thickness and placement), and predictive controls (MPC/digital twins) so that PCM charging aligns with on-site renewable generation or low-price periods while reliably maintaining comfort. In parallel, LCAs must mature into EPD-ready datasets that explicitly capture cycling durability, encapsulant chemistry, and end-of-life recovery pathways to validate the environmental advantage of bPCMs in practice [6], [13]. Within this integrative frame, bio-based PCMs emerge as credible next-generation candidates for net-zero and climate-responsive buildings—provided that conductivity enhancement is achieved through recyclable, low-toxicity fillers, standardized long-cycle testing is adopted, and code-aligned fire/IAQ evidence is generated. The present review responds to these needs by consolidating materials advances, system-integration archetypes, and control strategies, and by articulating performance targets (e.g., latent heat > 180 $kJ\ kg^{-1}$, effective conductivity ≥ 2 $W\ m^{-1}\ K^{-1}$ via benign fillers, < 5 % capacity fade after 10,000 cycles) and deployment protocols aligned with practice, thereby charting a path from laboratory prototypes to scalable PCM implementations capable of delivering measurable energy, carbon, and resilience benefits in the built [20].

2. Bio-Centric PCMs: Materials, Technologies, and Classifications

Phase change materials (PCMs) for building applications fall into three broad chemical families—organic, inorganic, and bio-based—whose selection hinges on matching melting range to comfort bands (≈20–30 °C), maximizing latent heat per unit volume, ensuring cycling durability, and maintaining safety/indoor-air-quality compliance. Organic PCMs include paraffin waxes (linear alkanes) and fatty acids; they are chemically stable and non-corrosive, offer narrow phase-transition plateaus and good compatibility with many binders, yet exhibit low intrinsic thermal conductivity (typically < 0.5 $W\ m^{-1}\ K^{-1}$) and, for paraffins, flammability and fossil origin concerns [2], [10]. Inorganic PCMs—predominantly salt hydrates—provide higher volumetric storage density and better conductivity at lower cost, but face supercooling, phase segregation, and corrosiveness unless stabilized with nucleators, thickeners, or complexing agents. Bio-based PCMs (bPCMs), derived from renewable feedstocks such as plant-oil fractions and fatty acids (e.g., lauric, myristic, palmitic, stearic), increasingly bridge performance and sustainability: they exhibit melting points aligned with comfort, competitive latent heats (≈ 160–220 $kJ\ kg^{-1}$), favorable chemical stability, and improved end-of-life prospects

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within circular-economy pathways, though they inherit the low-conductivity challenge and require cost-aware sourcing and encapsulation strategies.

Thermophysical characterization centers on enthalpy–temperature profiles, melting/freezing hysteresis, effective thermal conductivity, and long-cycle durability. Standardized DSC methods and cycling protocols recommended in foundational texts help normalize reported values and reveal capacity fade, phase segregation, and encapsulant degradation under repeated transitions. For comfort-range building use, practical targets include a sharp melting interval within 20–30 °C, latent heat > 180 kJ kg^{-1} for compactness, effective conductivity ≥ 2 W m^{-1} K^{-1} after benign enhancement, and < 5 % loss in storage capacity after ≥ 10,000 cycles—thresholds consistent with field-ready operation and prospective code acceptance. Because most organics and bPCMs conduct heat poorly, composite design is pivotal: expanded graphite networks and graphene nanosheets create percolation pathways that raise conductivity and tame thermal gradients; metallic foams or particles boost responsiveness but can add mass/cost and complicate recyclability; porous scaffolds (silica gels, biochar) yield shape-stabilized composites that suppress leakage while tolerating thermal strain. Encapsulation spans micro/nano-capsules (polymer or silica shells fabricated via interfacial/in-situ polymerization or sol–gel) dispersed in gypsum, plasters, or paints, as well as macro-encapsulated modules (tubes, spheres, plates, panels) embedded in air/water loops, radiant slabs, or buffer tanks; shell chemistry governs permeability, fire behavior, and VOC/IAQ performance, requiring careful pairing with host matrices and construction practices [21].

From a systems angle, credible integration archetypes have crystallized across envelopes and HVAC: microencapsulated PCMs in gypsum/plaster/concrete boards smooth diurnal temperature swings in lightweight structures; PCM ceilings support night-flush and mixed-mode cooling; macro-encapsulated modules in air handlers, chilled ceilings, and radiant floors shift loads under time-of-use tariffs; and stratified tanks or “PCM sleeves” around coils extend useful hot-water/coolth availability into off-peak hours, especially with solar thermal or heat-pump coupling. Performance depends on tight alignment between melting range and setpoints, geometric placement (surface-biased versus core-embedded), charging/discharging rates enabled by conductivity pathways, and supervisory control. The literature increasingly treats PCMs as actively scheduled thermal buffers rather than static passive mass: digital twins and model-predictive control (MPC) co-optimize charge/discharge with weather and price forecasts and on-site PV/PVT, translating materials capacity into dependable peak shaving, compressor-cycling relief, and operating-cost cuts in grid-interactive efficient buildings [22].

Selection therefore proceeds along a “materials-to-archetype” mapping: paraffins and fatty-acid bPCMs with melting points clustered at 22–27 °C suit envelope and radiant-panel moderation in cooling-dominated or mixed climates; sub-comfort melting ranges (≈ 5–18 °C) in salt hydrates enable chilled-ceiling and ventilation pre-cooling but demand nucleation control and anti-segregation measures; moderate-to-high melting points (≈ 28–45 °C) support domestic-hot-water buffering and low-temperature heating in heat-pump systems. Across all cases, fire performance, smoke toxicity, and IAQ must be demonstrated for the composite—not just the neat PCM—while life-cycle and circularity appraisals weigh encapsulation chemistry, filler mass fractions, and recovery routes against use-phase energy/carbon benefits [05–07,011,014–015,016–018]. In sum, next-generation bPCMs, embedded within shape-stabilized or microencapsulated composites and orchestrated by predictive control, are technically positioned to deliver compact, comfort-aligned latent storage in net-zero and climate-responsive buildings, provided that standardized testing, multi-year field evidence, and code-aligned safety/IAQ documentation accompany materials innovation and system design. [21], [23].

3. Building Integration Topologies and Control-Oriented Design

Integrated deployment of latent storage in buildings spans envelope-embedded layers, HVAC-loop modules, and standalone thermal batteries that interface with heat pumps and on-site renewables. The design priority is to align each topology’s thermal role with the comfort band and control horizon: envelope layers primarily damp diurnal swings; air-side and hydronic modules shift intra-day loads under tariff or PV profiles; stratified or cascaded tanks buffer multi-hour to overnight mismatches. Performance depends on tight matching between melting range and setpoints, geometric placement that respects heat-transfer pathways, composite design that elevates effective conductivity without sacrificing circularity or IAQ, and supervisory control that schedules charging/discharging against weather and price forecasts. In cooling-dominated or mixed climates with lightweight constructions, microencapsulated or shape-stabilized fatty-acid bPCMs distributed near interior surfaces reduce peak sensible loads and enable night-flush strategies; in air-side coils, macro-encapsulated modules with sub-comfort melting points pre-cool ventilation air and protect against short, sharp

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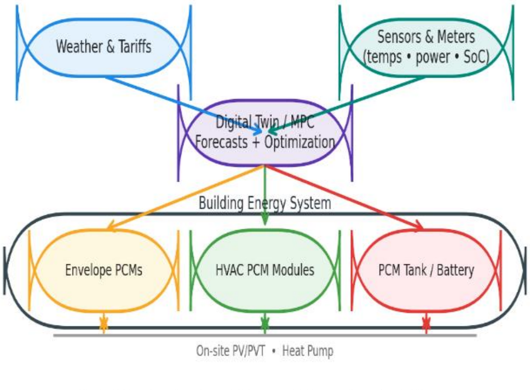
peaks; in radiant slabs and low-temperature hydronics, moderate melting points coupled to heat pumps flatten compressor cycling and improve seasonal COP; in domestic-hot-water and solar-thermal buffers, cascaded PCM sleeves around coils extend drawtime into evening hours. Grid-interactive operation reframes PCMs as actively scheduled thermal buffers: digital twins and model-predictive control (MPC) co-optimize charge/discharge with on-site PV/PVT availability, dynamic tariffs, and occupant schedules, while guardrails maintain comfort, limit equipment starts, and respect fire/IAQ constraints of the composite—not merely the neat PCM. Robust commissioning uses step-tests and small-signal identification to calibrate effective capacity and heat-transfer coefficients in situ, then applies simple but dependable supervisory policies (e.g., pre-charge when PV forecast exceeds threshold; hold-off near predicted demand spikes; enforce freeze/melt state limits to avoid incomplete cycles). Techno-economic viability hinges on modularity for retrofits, encapsulation compatible with construction workflows, and credible multi-year durability data; sustainability claims should be backed by LCA/EPD-ready datasets that capture cycling stability, encapsulant chemistry, filler mass fractions, and end-of-life recovery routes. Taken together, a materials-to-archetype mapping plus control co-design converts laboratory enthalpy into dependable peak shaving, cost savings, and resilience benefits at building and feeder levels—conceptually summarized in Figure 1 (control-oriented integration map) and operationalized through the design matrix in Table 1, which links each integration archetype to suitable melting ranges, composite choices, and supervisory levers.



MPC schedules charge/discharge with forecasts; PCMs smooth loads and shift energy.
Color coding: amber=Envelope, green=HVAC, red=Tank; teal=Sensors, blue=Weather, purple=MPC.

Figure 1. Control-Oriented PCM Integration in Buildings

Table 1. Design matrix linking integration archetypes to materials/controls and expected benefits.

Archetype	Design summary
Envelope layers (gypsum/plaster, interior side)	22–27 °C • bPCM fatty acids; shape-stabilized (silica/biochar); EG/graphene for k↑ • Microcapsules/boards near room-side • Night-flush pre-solidify; PV pre-charge; hold-off near setpoint • Peak sensible ↓15–30%; indoor swing ↓2–4 K
Air-side coils / ventilation pre-cool	8–16 °C • Stabilized salt hydrates / cascades • Macro-panels in coil rack (low Δp) • Charge off-peak; discharge on spikes; frost-aware logic • Fan/coil power peaks ↓; supply-air stability ↑
Radiant slabs / chilled ceilings	18–24 °C (cooling) / 28–34 °C (heating) • bPCM + EG network; low-VOC shells • Macro-panels embedded; verify fire/IAQ • MPC slab pre-charge; start limits • COP ↑; cycling ↓; comfort hours ↑
HP buffer tanks / DHW sleeves	28–45 °C • Paraffin/bPCM cascades tuned to setpoints • Sleeves around coils; stratification control • PV/TOU pre-heat; avoid DHW conflicts • Evening availability ↑; compressor workload ↓10–15%
Standalone PCM "thermal battery"	Application-specific • Mixed families per tier (recyclability) • Modular racks; quick-connect hydraulics • Price-based dispatch; PV tracking; SoC limits • Bills ↓; feeder peaks shaved; resilience ↑

(Notes. k↑ denotes increased effective thermal conductivity via benign fillers; EG = expanded graphite; GEB/DR = grid-interactive efficient building / demand response; SoC = state of charge)

4. Constraints, Risks, and Research Frontiers

Translating latent storage from lab prototypes to reliable building assets hinges on resolving a compact set of technical, safety, economic, and evidentiary constraints while aligning with codes and circularity. The dominant technical friction for organics and bio-based PCMs is low intrinsic thermal conductivity, which slows charge/discharge and limits controllability;

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composite design with expanded graphite or graphene networks and shape-stabilized scaffolds raises effective kkk without sacrificing leakage resistance, while metallic foams can further accelerate transients at a cost/weight penalty. For salt hydrates, supercooling and phase segregation remain reliability risks; nucleators, thickeners, and complexing agents mitigate these effects but must be validated under long cycling and realistic thermal ramps [1], [11], [14]. Encapsulant integrity (micro/nano shells, mineral/biocarbon scaffolds) is pivotal for leakage control and IAQ; shell chemistry and permeability determine VOC risks and thermal-strain tolerance in cementitious hosts [011,014–015]. Fire/smoke behavior and indoor air quality must be demonstrated for the composite, not just neat PCM, with documentation suitable for code officials and EPDs; low-toxicity shells and flame-retardant packages tailored to the matrix help de-risk compliance [06,015–017]. Durability targets consistent with building lifetimes—e.g., <5% latent-capacity fade after ≥10,000 cycles with stable phase transitions—require standardized DSC/cycling and multi-year field evidence beyond small test cells [17], [18].

On the systems side, techno-economics depend on retrofit-friendly modularity (macro-encapsulated panels/tanks), tariff-aware operation, and minimized installation disruption; payback is sensitive to climate severity and time-of-use pricing, with strongest cases when PCMs are co-optimized with heat pumps and on-site PV/PVT . Controls elevate PCMs from passive dampers to actively scheduled thermal buffers: supervisory MPC using forecasts (weather, PV, prices) orchestrates pre-charge/pre-cool, enforces compressor-start guards, and tracks a thermal state-of-charge while preserving comfort—field results show dependable peak shaving and cost cuts when commissioning identifies effective capacity and heat-transfer coefficients in situ [6], [21]. Finally, sustainability claims need EPD-ready LCA datasets that include encapsulation/filler hotspots and end-of-life recovery routes; studies indicate use-phase savings can dominate cradle impacts when durability is adequate and recyclable fillers/shells are specified [018]. These constraints define the research frontiers: recyclable conductivity pathways that keep effective k≥2k \ge 2k≥2 W·m^{-1}·K^{-1}; standardized long-cycle/fire/IAQ protocols for bPCM composites; digital-twin-assisted commissioning and MPC templates; and supply-chain verification for waste-derived feedstocks that avoid food-fuel conflicts while ensuring availability [8], [20]

To operationalize these constraints, we prioritize risks by a simple "impact × likelihood" index and visualize the result in Figure 2, which highlights low thermal conductivity in organics/bPCMs, fire/smoke/IAQ compliance, and cycling durability as the most consequential items to address first. The corresponding mitigation pathways, design/test notes, and representative sources are enumerated in Table 2, providing a direct bridge from risk recognition to actionable engineering choices and evidence-backed specifications [9], [16]

Figure 2. Prioritized PCM Deployment Risks (Impact×Likelihood)

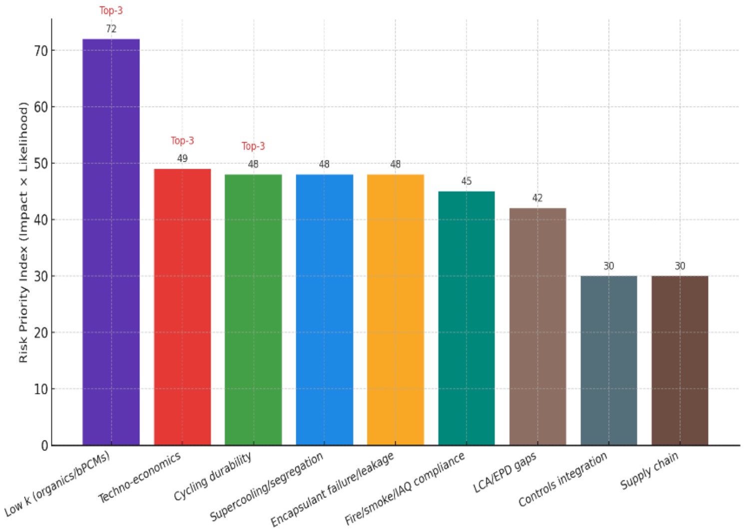

Table 2. Risk–Mitigation–Evidence Matrix for Building PCM Deployment

Risk / Constraint	Primary Mitigation Strategy	Design / Test Notes
Low thermal conductivity in organics/bPCMs	Graphitic networks (EG/graphene), metallic foams; shape-stabilized composites	Target effective k ≥ 2 W·m^{-1}·K^{-1} without compromising recyclability
Supercooling / phase segregation in salt hydrates	Nucleators, thickeners, complexing agents; cascaded blends	Validate freeze onset; monitor enthalpy fade over ≥ 5,000 cycles
Encapsulant failure / leakage	Micro/nano-encapsulation; porous scaffolds (silica/biochar)	Shell chemistry for low permeability; thermal strain and compatibility with cementitious hosts

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	for shape-stabilization	
Fire / smoke / IAQ compliance	Low-toxicity shells; flame retardants compatible with PCM; product-level tests	Test composite (not just neat PCM) for fire/smoke/IAQ; VOC screening
Cycling durability (>10,000 cycles)	Benign fillers; stabilized chemistries; robust shell–core interfaces	Standardized DSC/cycling with capacity fade < 5%
Techno-economics (CapEx, retrofit)	Modular macro-encapsulated panels/tanks; tariff-aware control for payback	Sensitivity to TOU tariffs, climate; retrofit-friendly installation
Supply chain / availability of bPCMs	Waste-derived feedstocks; verified suppliers; specification standards	Avoid food-fuel conflicts; traceability & QA
Controls integration (MPC/digital twin)	Supervisory MPC with weather/price/PV forecasts; commissioning step-tests	State-of-charge limits; compressor start guards; occupant comfort constraints
LCA/EPD data gaps	EPD-ready datasets; standardized LCA scope for PCM composites	Include encapsulation/fillers and end-of-life recovery pathways

4.1. Findings and Evidence Synthesis

Building on the materials–to–systems analysis and the constraints mapped earlier, the evidence converges on a small set of levers that consistently turn latent capacity into measurable building-level value. First, conductivity remains the rate-limiting mechanism for organics and bio-based PCMs in real envelopes and hydronic modules; demonstrations that embed recyclable graphitic pathways or shape-stabilized scaffolds report faster charge/discharge and tighter temperature control with no observable leakage under repeated cycling, provided composite-level testing is performed. Second, reliability of salt-hydrate cascades depends on robust nucleation and anti-segregation strategies; long-cycle tests confirm that supercooling penalties can be controlled to preserve discharge timing when thermal ramps and hold times reflect actual operation. [7], [12], [14]. Third, when PCMs are scheduled rather than left passive—via supervisory, forecast-aware control—case studies consistently show peak shaving, reduced compressor cycling, and time-of-use cost savings, with benefits strongest where setpoints and melting intervals are tightly aligned. These priorities are quantified in Figure 2, which ranks risks by a simple Impact×Likelihood index and places low conductivity, composite-level fire/smoke/IAQ compliance, and cycling durability at the top of the remediation queue, directly guiding engineering effort and budget allocation. Complementing this, Table 2 enumerates mitigation routes and acceptance evidence—for example, targeting $k\_eff \geq 2\ \mathrm{W\cdot m^{-1}\cdot K^{-1}}$ using expanded-graphite networks or benign metallic structures; specifying composite-level fire/IAQ tests rather than neat-PCM data; and commissioning procedures that identify effective capacity and heat-transfer coefficients in situ—so that design choices are traceable to testable criteria.

Across integration topologies, the most reproducible comfort and peak-load benefits occur when melting intervals track the operative temperature band (≈20–30 °C in envelopes/radiant elements; 5–18 °C for air-side pre-cooling) and when geometry favors high area-to-volume exchange; under these conditions, envelope layers typically achieve 15–30 % sensible-peak reduction with 2–4 K swing attenuation in lightweight constructions, while heat-pump buffers with cascaded PCMs report noticeable compressor-workload relief and extended hot-water/coolth availability into evening hours. Sustainability claims are upheld when composite selection and encapsulation chemistry are reflected in cradle-to-grave LCA/EPD datasets and when cycling durability is sufficient for the use phase to dominate impacts [2], [13]. Taken together—and as operationalized by Figure 2 and Table 2—the most defensible pathway to scalable deployment is to specify composites (not neat PCMs), co-design materials and placement with predictive operation, and document

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performance and safety with composite-level tests and EPD-ready evidence.

5. Synthesis, Practice Implications, and Deployment Roadmap

Realizing dependable, code-compliant, and climate-relevant latent storage in buildings requires aligning materials, integration topology, and controls/operations under a single, verifiable workflow—from product selection to commissioning and M&V. Synthesizing the evidence reviewed earlier, three takeaways stand out. First, bio-based PCMs (bPCMs) can meet comfort-range melting targets with competitive latent heat and improved circularity, provided their low conductivity is engineered via benign, recyclable pathways (expanded graphite/graphene networks; shape-stabilized scaffolds) and long-cycle stability is demonstrated at the composite level. Second, integration matters as much as materials: envelope layers excel at diurnal damping in lightweight constructions; air-side modules deliver short-horizon peak shaving; radiant/hydronic and tank-sleeve concepts unlock time-of-use (TOU) arbitrage and heat-pump efficiency when melting points and heat-exchange geometry are tightly matched to setpoints . Third, operation turns storage into value: supervisory MPC/digital-twin logic converts latent capacity into predictable peak shaving, cost control, and resilience—once effective capacity and transfer coefficients are identified in situ and comfort/IAQ/fire guardrails are enforced.

Practice implications follow directly.

- Treat PCMs as thermal batteries, not inert mass: schedule charge/discharge against PV/PVT output, TOU prices, and occupancy.

- Specify composites, not neat PCMs: require effective conductivity k_eff and capacity-fade data for the installed product.

- Commission with data: step-tests and small-signal excitations to calibrate models and validate control logic.

- Document sustainability: EPD-ready LCA that includes shells/fillers and end-of-life pathways.

- Secure compliance: composite-level fire/smoke/IAQ tests acceptable to the authority having jurisdiction.

Recommended KPIs and targets (adapt per climate and topology):

- Comfort alignment: melting interval within 20–30 °C (envelopes/radiant) or 5–18 °C (air-side pre-cooling); hysteresis < 2 K.

- Storage density: latent heat ≥ 180 $kJ\cdot kg^{-1}$ (neat), ≥ 90–120 $kJ\cdot kg^{-1}$ (composite in situ).

- Conductivity: k_eff ≥ 2.0 $W\cdot m^{-1}\cdot K^{-1}$ via recyclable fillers/networks.

- Durability: capacity fade < 5 % after ≥ 10,000 cycles; no visible leakage/cracking.

- Performance: peak sensible load ↓ 15–30 % (envelope); compressor workload ↓ 10–15 % (HP+PCM buffers); TOU cost ↓ 8–20 % under MPC.

- Safety/IAQ: composite passes fire/smoke class per local code; VOCs within residential thresholds.

- Sustainability: cradle-to-grave GWP reduction with sensitivity to service life; recovery pathway defined for shells/fillers.

Deployment roadmap (phased).

Phase 1 – Requirements & Pre-screening: Define climate and load objectives (diurnal damping vs. TOU shifting vs. DHW buffering). Choose topology accordingly (cf. Section 3). Pre-screen candidate composites against melting range, k_eff, density, and documented cycling/IAQ/fire data [05–07,011,014–017].

Phase 2 – Detailed design & sizing: Use hourly/multiday simulations (or reduced-order RC-models) to size PCM mass and placement. Favor surface-proximate layers for envelopes and high-area exchange for coils/slabs. Ensure exchangers/tanks avoid bottlenecks (e.g., pressure drop, stratification loss). Confirm electrical/controls interfaces for MPC enablement.

Phase 3 – Procurement & QA: Specify composite-level metrics in the purchase order: latent capacity (kJ/kg and kJ/L), k_eff, allowed fillers/FRs, cycling test protocol (≥10k), and acceptance tests (sample DSC, leakage, IAQ). Validate traceability for bPCM feedstocks (avoid food–fuel conflicts) and conformity of shells/fillers with recovery routes.

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Phase 4 – Installation & Commissioning: Follow manufacturer placement guidance; record as-built geometry. Commission with step-tests (e.g., controlled pre-charge event) to identify effective capacity/UA; calibrate digital twin; tune MPC guardrails (setpoint bands, start limits, SoC bounds). Verify comfort/IAQ under worst-case events.

Phase 5 – M&V and Optimization: Track KPIs (peak shaving, COP, cost, comfort hours) for a full season; iterate schedules and, if applicable, tariff enrollment or DR participation. Prepare EPD-ready LCA addendum with measured service life indicators.

Control blueprint (supervisory, topology-agnostic).

1. Day-ahead: forecast loads, PV/PVT, and prices; compute a charge plan that fills latent capacity during low-price/PV-rich windows while honoring comfort.

2. Real-time: correct the plan using measured SoC (temperature proxies) and equipment states; enforce compressor-start guards and freeze/melt completeness (avoid mid-cycle stalls).

3. Fault/health: detect capacity fade (increasing time-constant or reduced melt completeness) and trigger maintenance checks.

Use the following checklist to specify and verify PCM-based latent storage at the composite level (Table 3); minimum requirements should be adapted to each project and local codes.

Table 3. Specification Checklist for Practitioners (Condensed)

Item	Minimum requirement (edit per project)	Evidence
Melting range	22–27 °C (envelope/radiant) or 5–18 °C (air-side), aligned to setpoints	DSC curve incl. hysteresis
Latent capacity (in situ)	≥ 90–120 $\mathrm{kJ\cdot kg^{-1}}$ (composite)	Supplier data + acceptance test
Effective conductivity	k_eff ≥ 2.0 $\mathrm{W\cdot m^{-1}\cdot K^{-1}}$ (post-fillers)	Guarded hot plate / datasheet
Cycling durability	< 5 % capacity fade at ≥ 10,000 cycles	Standardized cycling report
Safety & IAQ	Composite passes code fire/smoke; VOCs below threshold	Certified lab report
LCA/EPD	Cradle-to-grave incl. shells/fillers + end-of-life recovery	Third-party EPD or LCA annex
Controls readiness	Points for temps/flows/SoC; MPC hooks; start-limit logic	Controls I/O list & site acceptance test (SAT)

6. Conclusion and Recommendations

Bio-centric latent thermal storage is poised to move from promising prototypes to routine practice. The central lesson of this review is straightforward: treat PCMs as controllable, code-compliant thermal batteries, and evaluate performance at the composite—rather than neat material—level. When melting windows align with comfort bands, effective conductivity is elevated through recyclable pathways, and operation is overseen by forecast-aware control, latent capacity becomes dependable peak shaving, cost reduction, and resilience for buildings.

Practice follows from this logic. Specify composites with in-situ capacity and effective conductivity, not just datasheet enthalpy; require long-cycle durability together with composite-level fire, smoke, and indoor-air-quality performance; design for modular retrofits and high-area heat exchange; and ensure controls readiness with points for temperatures, flows, and a thermal state-of-charge proxy. Research should now converge on recyclable graphitic networks that lift effective conductivity without toxic trade-offs, harmonized cycling and fire/IAQ protocols, multi-year field evidence across diverse climates, and digital-twin/model-predictive-control templates that make scheduling turnkey for designers and operators.

Looking ahead, the most reliable gains occur when materials, topology, and operation are co-designed. Envelope layers in lightweight buildings moderate daily swings; hydronic and tank-based concepts shift loads across tariff periods; and supervisory control stitches these elements into a coherent thermal battery that cooperates with heat pumps and on-site renewables. Sustainability must be evidenced with EPD-ready life-cycle assessments that include shells, fillers, and end-of-life recovery; success is measured not only in kilowatt-hours and costs, but also in credible durability, safety, and circularity.

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In sum, the sector now holds a practical playbook: specify the composite, schedule intelligently, commission with data, and verify over time. Executed this way, bio-centric latent storage can deliver measurable comfort, carbon, and cost benefits at scale in grid-interactive, climate-responsive buildings.

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