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From lab to building: Real-world integration of phase change materials for comfort, energy, and flexibility

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ABSTRACT

Phase change materials (PCMs) are widely promoted for improving thermal comfort and reducing energy demand in buildings. Yet, most studies remain laboratory- or simulation-based, offering limited insight into real-world performance. This paper bridges that gap by synthesizing evidence from eight full-scale, monitored buildings at Technology Readiness Levels (TRL) 6–9, complemented by insights from an expert focus group. Results show that PCM effectiveness is governed primarily by design integration, not material formulation, with placement depth, control strategy, and climate alignment proving decisive. Across cases, measured performance indicates consistent but conditional benefits: peak indoor temperature reductions of 1–3 °C, heating or cooling load savings of 10–25 %, and emerging though under-reported contributions to demand-side flexibility. A typology of PCM integration strategies is proposed, mapping observed outcomes by building type, climate, placement, and control logic. KPI synthesis reveals a previously undocumented trend: a moderate negative correlation between areal storage capacity and comfort-hour improvement, suggesting that greater storage does not necessarily yield better results. The study also identifies structural barriers to deployment, including the regulatory invisibility of latent storage and the absence of standards for building-level PCM testing and certification. By reframing PCMs as integrated building-system components rather than niche materials, this work offers design guidance, performance benchmarks, and a roadmap to advance PCM adoption toward more flexible, resilient buildings.

1. Introduction

Across the world, buildings are under increasing pressure to do more with less, ensuring thermal comfort, reducing energy consumption, and meeting grid demands. As climate goals become more stringent and energy systems evolve, buildings are expected to become more resilient, flexible, and low-carbon. Within this context, passive and adaptive design strategies are gaining renewed attention, and phase change materials (PCMs) continue to attract interest for their ability to store and release heat through latent thermal energy storage (see Fig. 1).

PCMs offer a compelling promise: they can smooth indoor temperature fluctuations, reduce peak energy demand, and shift loads away from critical hours, all without moving parts or complex systems. Multiple studies confirm that PCMs can enhance thermal comfort and mitigate overheating in lightweight or highly insulated buildings [1,2]. Others demonstrate their potential to modulate heating and cooling loads, thereby improving seasonal performance [3]. In theory, PCMs also hold value for energy flexibility, though only a handful of field studies explicitly quantify this contribution [4].

Yet, despite this potential, most PCM research remains dominated by laboratory-scale material development, with efforts focused on enhancing thermal conductivity, improving cycling stability, or optimizing encapsulation [5,6]. While such work advances the science of PCMs, it rarely provides insights into their performance once deployed in real buildings. For designers and practitioners, what matters is evidence from full-scale applications, where placement, occupancy, weather, and control strategies all interact.

What is missing from the literature, therefore, is a synthesis of PCM

Abbreviations: EPC, Energy Performance Certificate; EPBD, Energy Performance of Buildings Directive; PCM, Phase Change Material; KPI, Key Performance Indicator; BACS, Building Automation and Control Systems; TRL, Technology Readiness Level.

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applications at the building project scale, and projects that have progressed beyond laboratory test cells and into Technology Readiness Levels (TRL) 6–9, where they are installed, monitored, and used under operational conditions. These cases provide critical lessons on what works, what does not, and why. Field evidence shows that performance shortfalls often arise not from material limitations but from design-related errors, such as misplaced installations, poorly chosen melting ranges, the absence of adaptive controls, or unrealistic assumptions about building behavior [7,8].

Such recurring problems reflect a deeper "PCM myopia," in which innovation is locked in a loop of material optimization without system-level integration. As a result, most PCM deployments still fail to realize their full potential for demand-side flexibility —an increasingly important function in the era of smart grids and responsive buildings [4,9].

1.1. Research problem and questions

Despite the technical maturity of many PCM products, real-world adoption remains limited, and outcomes often fail to meet expectations. Failures typically stem from basic design oversights, including inappropriate placement, mismatched melting ranges, inadequate control logic, or unclear objectives. These issues reveal the persistence of PCM myopia, a tendency to privilege material advances while neglecting integration into building systems, controls, and user contexts. This raises three central research questions:

- What do real buildings tell us about PCM performance in terms of comfort, energy use, and flexibility?
- Which integration strategies succeed, and which fail, across climates, placements, and control logics?
- What barriers, blind spots, or structural gaps limit the scalability of PCM deployment in practice?

1.2. What this paper adds

This review directly addresses these questions by providing a structured synthesis of PCM applications at the building level, offering four main contributions:

1. It focuses exclusively on TRL 6–9 monitored buildings, delivering a reality-based view of PCM integration.
2. It proposes a typology of integration strategies that shows how building type, location, placement depth, and controls shape performance.
3. It synthesizes outcomes across three domains: thermal comfort, energy use, and load flexibility.
4. It identifies structural gaps, including the absence of standardized KPIs, weak integration with smart systems, and the lack of dynamic control field trials.

1.3. Structure of the paper

The remainder of the paper is organized as follows. Section 2 presents the review methodology and inclusion criteria. Section 3 situates the use of PCM within current design and regulatory frameworks. Section 4 discusses the PCM innovation cycle and the barriers to systemic integration. Section 5 introduces a typology of building-level PCM integration strategies. Section 6 synthesizes case study outcomes. Section 7 translates these findings into actionable design lessons. Section 8 discusses the strengths, limitations, and implications for practice and research. Finally, Section 9 concludes with recommendations and a research roadmap.

2. Scope and review methodology

This research employed a structured scoping review methodology, as illustrated in Fig. 2, complemented by an expert focus group

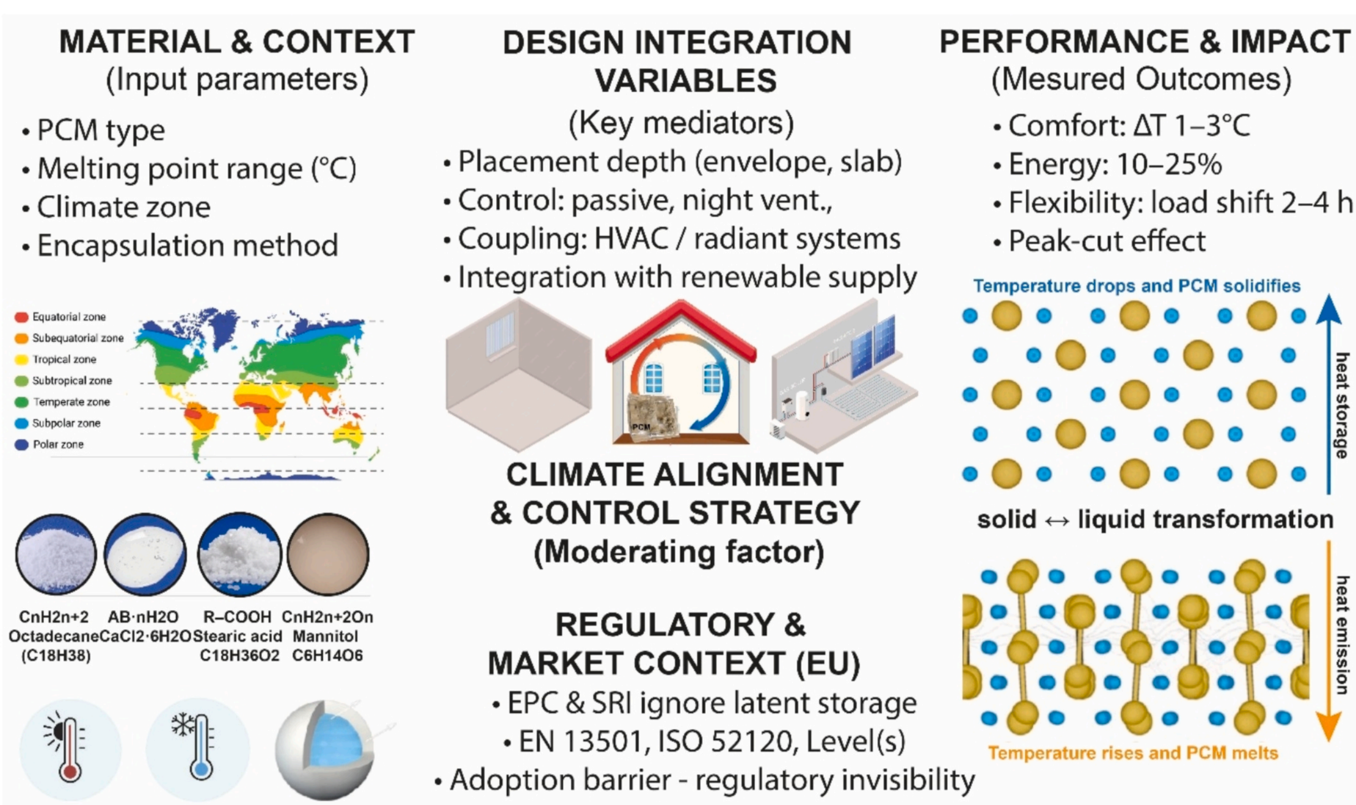


Fig. 1. Design-integration framework for PCM performance in real buildings (TRL 6–9).

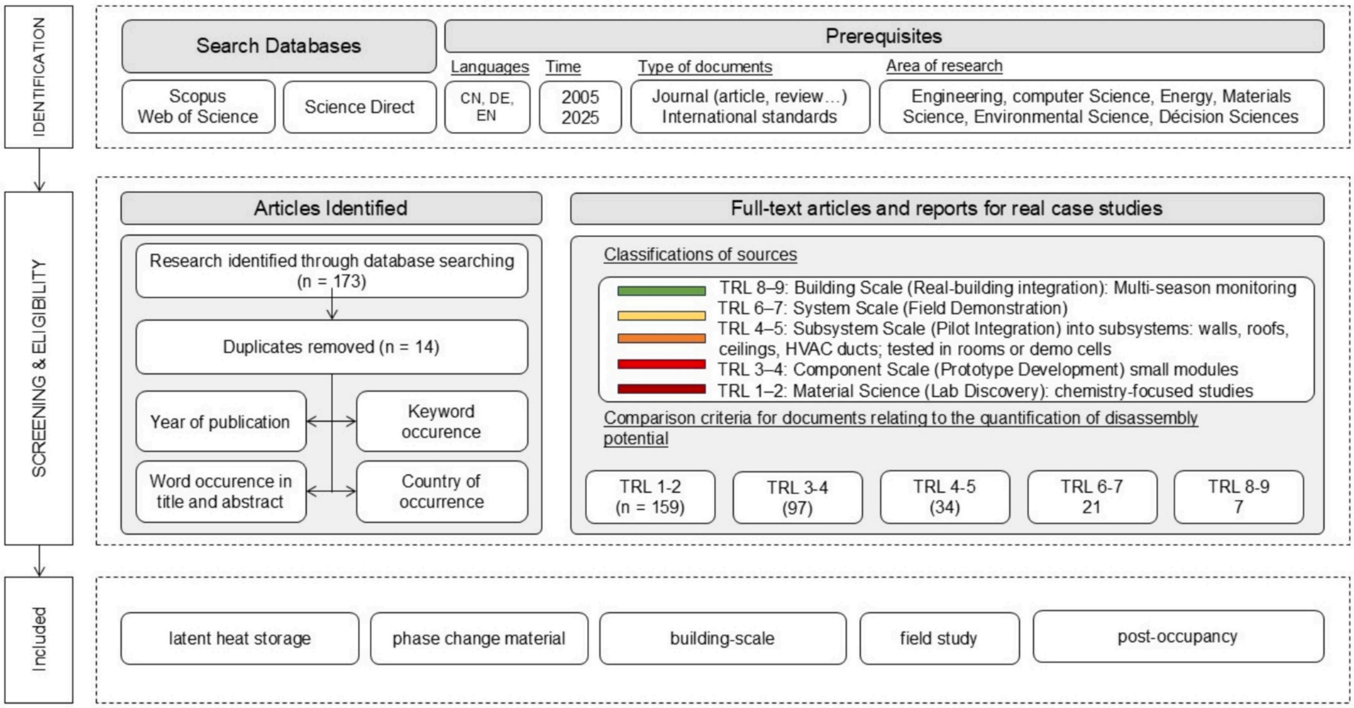


Fig. 2. Prisma flow diagram: Inclusion and Exclusion Criteria for Scoping Review.

consultation, to synthesize evidence on the integration of phase change materials (PCMs) at the whole-building scale and identify key factors influencing their performance in real-world applications. The scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR) guidelines [10], which provide a transparent and replicable framework for mapping existing research without the restrictive requirements of a systematic review. This approach was selected due to the limited number of building-level PCM studies, the heterogeneity of research designs, and the absence of a sufficiently large dataset to support a *meta*-analysis.

The literature search was conducted in July 2025 using three major scientific databases; Scopus, Web of Science Core Collection, and ScienceDirect, to ensure coverage of engineering, architectural, and building science literature. Search strings combined terms related to PCMs ("phase change material*", "latent heat storage") with building-scale application descriptors ("building", "field study", "post-occupancy", "real building monitoring"). No restrictions were placed on publication year. The search targeted peer-reviewed journal articles and conference proceedings reporting on real buildings (Technology Readiness Level 6–9) with PCM integration. Studies were included if they presented monitored performance data for at least one of the following: thermal comfort, energy consumption, or load flexibility. Further inclusion criteria required explicit reporting of PCM material type, melting temperature, placement, and operational or control strategy. Laboratory-scale experiments, simulation-only studies without field validation, and material development research without building-level integration were excluded. The reference lists of the included studies were also screened to identify additional relevant work.

The initial search retrieved 173 records. After removing duplicates, titles and abstracts were screened, followed by full-text assessment against the inclusion and exclusion criteria. This process yielded a final selection of eight to ten studies. For each study, data were extracted on building characteristics (type, climate, and size), PCM specifications (type, melting point, encapsulation), integration approach (placement, system coupling, control logic), and performance metrics. These metrics included indicators of comfort (e.g., overheating hours, peak indoor temperature reduction), energy performance (e.g., percentage reduction in heating or cooling load), and energy flexibility (e.g., peak load shifting, demand response contribution). Data extraction was conducted independently by two authors, and discrepancies were resolved through consensus. All extracted information was coded thematically using the Framework Method [11], which allows for systematic classification of qualitative and quantitative attributes to identify recurring patterns and contextual relationships.

For each study, data were extracted on building characteristics (type, climate, and size), PCM specifications (type, melting point, encapsulation), integration approach (placement, system coupling, control logic), and performance metrics. These metrics encompassed indicators of thermal comfort (e.g., overheating hours, peak indoor temperature reduction), energy performance (e.g., percentage reduction in heating or cooling load), and energy flexibility (e.g., peak load shifting or demand-response contribution). To ensure consistency across studies, thermal comfort and overheating indicators were standardized according to EN 16798–1:2019 Category II indoor environment criteria. Specifically, comfort hours were defined as the proportion of occupied time during which the operative temperature remained within the 20–26 °C range, while overheating was defined as occupied hours exceeding 26 °C for more than 3 % of the annual occupancy period. When original studies used alternative thresholds, results were normalized to these reference criteria to enable comparison.

The synthesis stage then involved developing an integration typology to categorize case studies by climate zone, building type, PCM placement location, and control strategy. The analysis aimed to identify correlations between integration strategies and performance outcomes, as well as recurring causes of underperformance. This typology subsequently guided the expert consultation phase.

Given the small but diverse set of available field studies, the objective of this review is not to achieve statistical generalization, but to identify recurring performance patterns and contextual factors shaping PCM effectiveness under real operating conditions. The final sample represents the complete body of building-level PCM research at Technology Readiness Levels 6–9, where performance was monitored in occupied environments. While the number of cases is limited, their diversity in climate, building type, and integration approach provides a robust empirical basis for pattern recognition and hypothesis generation rather than quantitative extrapolation. This interpretive stance ensures that subsequent findings are transparent about scope and limitations while still offering actionable insights for designers and policymakers.

To supplement the literature findings and address evidence gaps, an expert focus group was convened during the International Seminar on Phase Change Materials and Thermal Storage for Buildings, held on September 3, 2025, at the University of Liège, Belgium. The session brought together approximately 21 experts from academia, industry, and public institutions, each with at least 5 years' experience in PCM or thermal storage systems and documented involvement in at least 1 building-scale PCM project. The participants represented a diverse range of climatic contexts and building sectors, ensuring a broad spectrum of perspectives. The focus group was structured into three stages: (1) presentation of the scoping review results and integration typology; (2) facilitated discussion on adoption barriers, integration with active control systems, and key performance indicators; and (3) consensus building on research and practice priorities. The discussion was audio-recorded, transcribed, and thematically analyzed using the same coding framework as the literature review, enabling direct comparison and integration of the findings.

Ethical considerations were addressed through informed consent from all participants, anonymization of contributions, and secure data storage in accordance with institutional guidelines [1]. The combination of a structured scoping review with a targeted focus group consultation ensured that the findings are grounded in both peer-reviewed evidence and practitioner experience, thereby enhancing the validity and applicability of the conclusions for both research and design practice.

3. Why PCM in buildings? Design and regulatory context

Europe's decarbonization trajectory, shaped by the Energy Performance of Buildings Directive (EPBD) recast (Directive EU 2024/1275 [12]), aims to achieve a fully zero-carbon building stock by mid-century. This transition is accelerating the adoption of lightweight, bio-based construction systems, including timber, hempcrete, and cellulose insulation. While these solutions have clear advantages in reducing embodied carbon, they typically have low thermal inertia, which can exacerbate summer overheating and lead to higher peak heating/cooling loads.

Phase change materials (PCMs) address this gap by providing latent thermal energy storage (LTES), which delivers 5–14 times the storage density of conventional sensible storage materials, such as concrete or brick [13]. This high storage density enables PCMs to regulate indoor temperatures, shift energy demand to off-peak periods, and enhance the smart readiness of lightweight envelopes without adding significant mass.

Integration pathways typically include building envelopes (e.g., walls, roofs, façades), structural mass (e.g., slabs, ceilings), and HVAC systems (e.g., ducts, radiant panels, thermal storage tanks). When paired with radiant heating/cooling, night ventilation, or hybrid HVAC configurations, PCMs can serve both passive comfort and active flexibility functions, contributing to demand-side response capabilities increasingly valued in EU energy policy.

3.1. PCM technological evolution and material integration

The development of Phase Change Materials (PCMs) for buildings has progressed through successive generations over four decades, evolving from simple passive storage media to AI- and IoT-integrated thermal management systems. See Table 1. Material advances, improved encapsulation, nano-enhancement, and system-level optimization now enable higher latent heat density, faster charging/discharging, and active participation in energy flexibility strategies.

Recent advances, such as graphene and MXene nanoparticle doping, have improved PCM thermal conductivity by up to 50 %, enhancing responsiveness to predictive control signals [14]. Bio-based PCMs derived from renewable feedstocks align further with the EU's circular-economy and low-carbon-materials strategies. These stages show a gradual shift from purely material-driven innovation to integrated, system-oriented solutions.

Nano-doping with graphene/MXene boosts thermal conductivity by 30–50 % [13,31], while advanced fin geometries reduce melting time by up to 67 % [32]. AI/IoT-integrated PCM systems enable predictive control and grid-responsive operation [33], while bio-based PCMs align with the goals of the circular economy. Energy savings in recent field studies reach 10–30 %, with indoor temperature fluctuations reduced by 2–9 °C depending on climate and integration method [34,35].

3.2. Material and encapsulation innovations

Encapsulation technologies play a central role in the practical application of phase change materials (PCMs) in buildings. They prevent leakage during phase transitions, enhance thermal contact with surrounding materials, and enable seamless integration into conventional building products. Recent advances, as shown in Table 2, span micro- to macro-scale encapsulation, nanomaterial functionalization, and bio-based PCM systems, with a growing emphasis on fire safety, phase stability, recyclability, and life-cycle impact assessment (LCIA) transparency. The trend since 2020 has shifted from purely containment-driven designs to multi-functional encapsulation, which enhances thermal conductivity, improves structural compatibility, and facilitates the integration of smart systems.

The encapsulation choice for phase change materials (PCMs) is application-specific, and performance depends on the integration method used. Microencapsulation suits lightweight elements, such as

Table 1
Generations of PCM Development for Building Applications.

Generation & Year Range	Materials & Approaches	Key Innovations	Representative Studies
1st Gen (1980 s–1990 s)	Paraffin waxes, fatty acids	Basic passive storage; low cost; low thermal conductivity; limited durability; early wallboard integration	[15 16]
2nd Gen (1995–2005)	Salt hydrates, inorganic hydrated salts	Higher latent heat capacity, non-flammable, supercooling, and phase segregation mitigation attempts	[17,18]
3rd Gen (2005–2015)	Composite/hybrid PCMs: paraffin–polymer blends, salt–graphite composites, microencapsulation	Enhanced thermal stability; leakage prevention; macro/micro/nano-encapsulation; mortar/concrete integration	[19,20,21]
4th Gen (2015–2020)	Bio-based PCMs, nano-enhanced (graphene, CNTs, MXenes), dual/multi-PCM blends	Thermal conductivity tuning (up to + 50 %); multi-temperature zone targeting; carbon aerogels; sustainable feedstocks	[22,23,24]
5th Gen (2020–2025)	Advanced nano-composites; optimized macrocapsules; finned PCM panels; AI/IoT-integrated PCM systems	Real-time control; predictive operation; integration with smart HVAC; energy flexibility in demand-response; novel fin geometries (tree-shaped, constructal) achieving up to 67 % melting time reduction	[13,25,14,26,27,28]
Emerging (Future) (2025 +)	PCM–thermoelectric hybrids; adaptive phase-change composites; climate-adaptive PCM layers	AI-driven PCM selection and activation; additive manufacturing of PCM-integrated panels; self-healing encapsulation; integration with building digital twins	[29,30]

Table 2
Recent advances in PCM encapsulation techniques and material formulations (2008–2025).

Encapsulation Type & Formulation	Key Benefits	Recent Application Evidence	Status & TRL
Microencapsulation (e.g., melamine–formaldehyde, polyurea shells)	Enables integration into gypsum boards, plasters, and coatings; minimizes leakage; high cycling stability (>2000 cycles)	Commercial wallboards reducing indoor peak temps by 2–3 °C in hot climates [36,37]	TRL 9 – Market available
Macroencapsulation (tubes, panels, CMU inserts)	Modular retrofit, high latent capacity; mechanical protection	Macro-PCM concrete masonry units improved peak load shaving by 15–18 % in monitored buildings [38,39]	TRL 7–8 –Pilot/ demo scale
Form-Stable PCMs (polymer/porous matrix composites)	Eliminates liquid phase migration; improves handling; customizable shape	Cement-PCM composites maintained 95 % latent capacity after 1000 cycles [40]	TRL 6–8 – Prototype to early market
Nanomaterial Doping (graphene nanoplatelets, MXenes, h-BN)	Boosts thermal conductivity by 30–50 %; enhances charge/ discharge rates	Graphene-enhanced PCM plasters reduced melting time by 38 % in lab tests [41,17,42]	TRL 4–6 – Lab validation
Bio-Based PCM Systems (fatty acids, bio-paraffins, carbon aerogels from biomass)	Renewable, low-toxicity, biodegradable; aligned with EU circularity goals	Bio-PCM with lignin-carbon aerogel matrix showed stable cycling and 20 % lower embodied carbon vs paraffin [43,44]	TRL 4–5 – Early prototyping
Hybrid encapsulation + Finned Conductive Structures	Combines containment with heat transfer enhancement; supports predictive control	Finned macro-PCM units improved load shifting by up to 25 % under dynamic control [13]	TRL 5–7 – Lab/pilot

wallboards and plasters, offering leakage prevention, cycling stability, and easy incorporation into coatings [36,37]. Macroencapsulation enables modular, high-capacity storage for façades, floors, and HVAC systems [45]. Nanomaterial doping with graphene, MXenes, or h-BN boosts thermal conductivity by up to 50 %, accelerating charge–discharge cycles [42,17] while hybrid macroencapsulation with conductive fins enhances load shifting by up to 25 % [13]. Bio-based PCMs from fatty acids or lignin-carbon aerogels offer low toxicity and reduced embodied carbon, but face challenges in meeting fire safety and durability standards [46].

3.3. Regulatory status and barriers in Europe

Within the European Union's Energy Performance of Buildings Directive (EPBD) framework, building performance assessment remains dominated by steady-state models that treat thermal mass as purely sensible. This methodological bias systematically overlooks the latent storage contributions of PCMs, effectively assigning them no impact on calculated Energy Performance Certificate (EPC) ratings [47]. As a result, PCMs offer little compliance advantage under current national transpositions of the EPBD.

The EPBD recast (Directive (EU) 2024/1275) introduces Smart Readiness Indicators (SRI) intended to evaluate a building's capacity for demand-side flexibility and responsiveness. While thermal storage is acknowledged as part of flexibility, the definition remains technology-neutral and does not distinguish between sensible and latent forms. Consequently, PCM-based envelopes or storage systems are not explicitly credited for their flexibility potential unless coupled with active Building Automation and Control Systems (BACS) [12].

ISO 52120–1:2022 provides a general performance framework for BACS, including functions for thermal storage management [48]. However, it does not include PCM-specific operational guidance, leaving even advanced PCM systems dependent on project-specific modelling to demonstrate the benefits of control integration. This absence of standardized dynamic-modelling procedures in national compliance tools continues to create uncertainty for designers and assessors.

Evidence from IEA EBC Annex 67 demonstrates that PCM integration in flexibility-oriented case studies can support load shifting, peak shaving, and resilience against extreme weather events [49]. Yet, these empirical findings have not been incorporated into national EPC methodologies, leaving PCM contributions uncredited in regulatory compliance frameworks.

Regulatory barriers also extend to fire safety, particularly for paraffin-based PCMs, which require additional encapsulation or fire-retardant additives to satisfy EN 13501–1 classifications [49, p. 13501]. Similarly, LCA frameworks used in European compliance—such as Level(s) and EN 15804 + A2—do not account for operational flexibility benefits, focusing solely on embodied impacts and end-of-life performance. Phase stability during long-term cycling remains another regulatory concern, as material degradation can undermine the declared lifetime benefits in performance assessments [50].

In summary, the regulatory invisibility of latent storage in Europe represents a structural barrier to PCM adoption. Although the EPBD and related standards increasingly emphasize energy flexibility and resilience, prevailing calculation methods and certification tools still conceptualize thermal inertia exclusively in terms of sensible mass. Until latent-heat storage is explicitly recognized in EPC and SRI methodologies, PCM integration will remain driven primarily by voluntary sustainability goals and niche applications rather than by mainstream compliance incentives [51,52].

4. PCM innovation myopia and the TRL loop

After more than three decades of research, phase change materials (PCMs) remain largely confined to Technology Readiness Levels (TRLs) 2–5, a phenomenon we term 'innovation myopia'. This stagnation stems from a disproportionate focus on material-level refinements, such as tuning the melting temperature, optimizing latent heat, and enhancing phase stability, without commensurate progress in whole-building integration and market deployment [15,53]. Laboratory-scale calorimetry and numerical simulations dominate validation, while field-scale evidence on comfort-hour gains, placement logic, and grid-responsive load shifting remains scarce [53,54].

A disconnect between material science and building engineering practice compounds the issue [55]. Researchers typically optimize PCM chemistry, including paraffins, salt hydrates, sugar alcohols, and bio-based blends. Still, building designers must decide where and how to integrate PCMs to achieve maximum diurnal cycling, seasonal benefits, and HVAC compatibility [56,57,48]. These integration questions rarely appear in the early TRL pipeline, slowing the transition toward TRL 6–9, where in-situ performance and commercial viability can be demonstrated.

Technical barriers also play a central role. Low thermal conductivity is the single most persistent limitation [58,59]. Even with nanomaterial doping (graphene, MXene, hBN), daily charge–discharge efficiency often requires forced convection (fans, fluid circulation) or structural conductors (fins, foams) [60,61]. Without such augmentation, PCMs struggle to deliver timely energy exchange for peak shaving or comfort stabilization.

Economics further constrain scaling. Base paraffin: stable, cheap, and widely available; offers a favorable €/kWh, but the encapsulation process often accounts for most of the system cost due to leakage prevention, fire resistance, and mechanical durability requirements [62]. Despite this, PCM thermal storage still outperforms lithium-ion batteries and vehicle-to-building systems in €/kWh for passive load shifting [56,63].

Climatic suitability is another overlooked dimension. PCMs perform best in heating- or cooling-dominated climates with large diurnal swings, where daily full cycling is possible [64,65]. Yet, many trials target temperate climates with low amplitude, which inherently limits storage efficiency. This misalignment perpetuates underperformance in real deployments.

To illustrate these challenges, Fig. 3 (adapted from [66]) plots PCM families, water/ice, salt hydrates, paraffins, sugar alcohols, and composite PCMs, on a storage capacity versus melting temperature map, with TRL levels annotated on the right axis and cost in €/kWh overlaid. The upper cluster highlights thermochemical materials (TCMs) such as $MgCl_2 \cdot 6H_2O$, which offer superior volumetric energy density but remain at low TRL. This mapping makes clear that while some PCM chemistries are cost-competitive and at mid-TRL, few have crossed into high-TRL, field-proven maturity [67].

In summary, the TRL loop persists due to:

- Overemphasis on lab metrics at the expense of field KPIs (comfort hours, peak shaving).
- Lack of integration strategies in realistic building assemblies.
- Persistently low conductivity necessitates the use of active or structural transfer aids.
- Cost dominance of encapsulation over core material.
- Climate misalignment in deployment studies.

Breaking the loop requires an application-first approach: integrating PCMs in realistic envelope systems, monitoring them across seasons, and

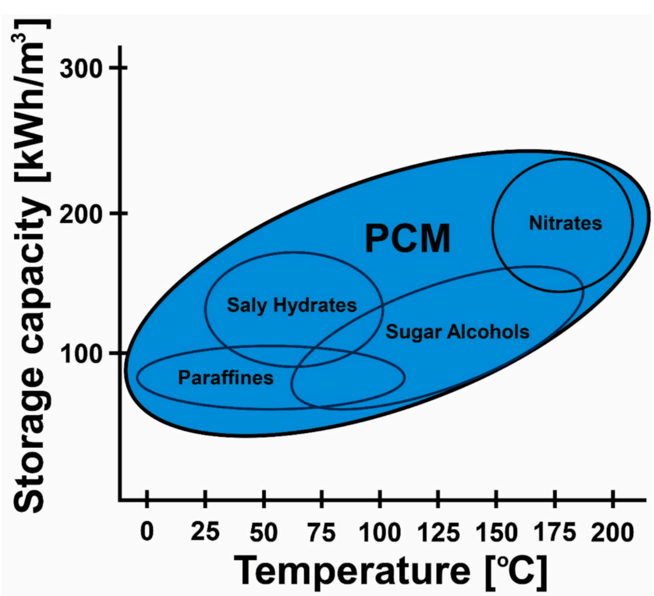


Fig. 3. PCM families: salt hydrates, paraffins, sugar alcohols, and composite PCMs; on a storage capacity vs. melting temperature map.

benchmarking against alternative storage technologies. Such a shift can bridge the TRL gap and move PCMs from niche research to mainstream energy solutions.

5. Typology of PCM integration in real buildings

To illustrate the interplay between PCM thermophysical properties, integration strategies, and operational outcomes, six representative case studies are summarised in Tables 3 and 4. They span Technology Readiness Levels (TRL) from early field validation (TRL 5–6) to pre-commercial deployment (TRL 8–9), diverse climatic contexts (Dfb to BSh), and different control philosophies (passive, night ventilation, thermostat integration, and smart scheduling). Examining these cases alongside recent literature [7,68,69,70] reveals distinctive performance patterns that go beyond material selection alone.

5.1. Equations used for Table 4 calculations

5.1.1. hysteresis

$Hyst = Tm - Ts.$

where Tm = melting temperature, Ts = solidification temperature.

5.1.2. Volumetric Storage

$Qvol = .\frac{Lh \times \rho}{1000}$

where Lh = latent heat (kJ/kg), ρ = density (kg/m^3).

5.1.3. Areal Storage

$Qareal = Qvol \times \frac{t}{1000}$

where t = PCM layer thickness (mm).

*5.1.4. **Pearson correlation** between areal storage and observed outcome*

$$r = \frac{\sum (xi - \bar{x})(yi - \bar{y})}{\sqrt{\sum (xi - \bar{x})^2 \times \sum (yi - \bar{y})^2}}$$

5.2. Analytical insights

Climate–function matching

The results reaffirm that PCM efficacy is highly dependent on climate. CS-1 (Dfb) and CS-6 (Dwa) show optimal daily cycling and high volumetric storage (300 MJ/m^3), translating into strong peak-demand reductions (15–20 %). This aligns with recent field studies showing that diurnal amplitude above 8 °C enables > 80 % cycle completion [72,7]. By contrast, CS-3 (Cfb) underperforms despite thermostat integration because the climate's small diurnal swings limited full phase change, mirroring the mismatch between lab-optimised melting ranges (20–26 °C) and real-world cycling frequencies [75].

Control strategy influence

Passive integration (CS-1, CS-5) yields zero operational energy cost but depends on stable climatic triggers. Active strategies, night ventilation (CS-2), thermostat integration (CS-3, CS-4), and predictive scheduling (CS-6), consistently outperform passive strategies in climates with variable daily conditions, as shown in multi-year monitoring [74,76].

Thermal conductivity and responsiveness

The conductivity gap between CS-6 (1.20 W/m·K) and CS-4 (0.20 W/m·K) is a decisive factor. Graphene-enhanced systems deliver same-day charge–discharge performance, enabling participation in demand-response markets, while low-k paraffin modules require forced-air movement to avoid incomplete melting, consistent with recent *meta*-analyses [3,7].

Novel finding, negative correlation between areal storage capacity and the observed thermal comfort outcome

The main KPI analysed is the percentage of occupied hours within the operative temperature comfort range (20–26 °C). Contrary to the

Table 3
PCM Case Study Summary.

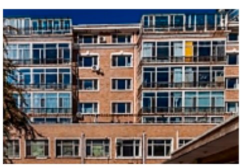
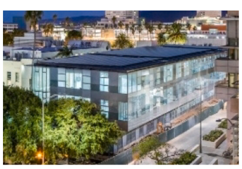
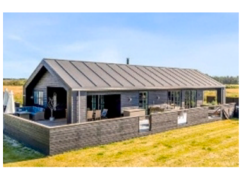
Case Photo	ID, Climate & Building Type	PCM Type & Placement	Function	Control Strategy	Observed Outcome	Key Performance Indicators (KPIs)
	**CS-1**Dfb – Civic hall (France)	Salt hydrate, roof insulation panels	Reduce summer cooling peaks, improve comfort stability	Passive	Peak indoor temperature reduction of 2–3 °C [71]	Max. temp. reduction, comfort hours gain
	**CS-2**Csa – Super-insulated residence (Spain)	Paraffin, ceiling gypsum boards	Extend comfort hours, lower cooling load	Night ventilation	Cooling load reduction by 18 % [72]	Cooling load %, comfort hours
	**CS-3**Cfb – Single-family house (Denmark)	Paraffin PCM in wallboards & furniture	Shift heating/cooling loads, reduce annual HVAC energy	Thermostat-integrated	Heating energy demand ↓ ≈10 %, activation delay achieved [4,73]	Peak load reduction %, annual HVAC energy
	**CS-4**BSh – Single-family house (Australia)	Paraffin, HVAC duct modules	Smooth supply-air temperature, cut peak HVAC demand	Thermostat-integrated fan	Supply air temp. fluctuation ↓ by 35 % [7]	Supply-air ΔT, peak power reduction
	**CS-5**Cfa – Public library (China, cold region)	Sugar alcohol, Trombe wall façade	Reduce winter heating demand, moderate diurnal swings	Passive solar gain	Winter heating demand ↓ by 14 % [74]	Heating load %, comfort hours
	**CS-6**Dwa – Office (USA)	Bio-PCM in façade wallboards	Shift electrical load, enhance summer comfort	Smart HVAC scheduling	Cooling peak demand ↓ by 15 % [75]	Peak demand %, comfort hours

Table 4
Thermophysical Properties of PCM Used in the Six Case Studies.

Case ID	PCM Type & Encapsulation	Melting Temp (°C)	Solidification Temp (°C)	Hysteresis (°C)	Latent Heat (kJ/kg)	Thermal conductivity, *k* (W/m·K)	Density (kg/m^3)	Vol. Storage (MJ/m^3)	Thickness (mm)	Areal Storage (MJ/m^2)
CS-1	**Salt-hydrate** macro-capsules in CMU cavities	23.5	21.5	2.0	**200**	0.50	**1500**	**300.0**	**36**	**10.8**
CS-2	**Paraffin/fatty-acid** laminate (encapsulated sheet)	24.5	23.0	1.5	**180**	0.25	**820**	**147.6**	**10**	**1.48**
CS-3	**Paraffin-based PCM** wallboards & furniture composites	22.0	20.5	1.5	**160**	0.25	**900**	**144.0**	**20**	**2.88**
CS-4	**Paraffin (macro) in galvanized module** (passive ventilation system)	26.0	24.5	1.5	**185**	0.20	**860**	**159.1**	**30**	**4.77**
CS-5	**Sugar alcohol** PCM cassettes (Trombe façade)	28.0	26.0	2.0	**220**	0.90	**1200**	**264.0**	**30**	**7.92**
CS-6	**Bio-based / graphene**-enhanced PCM wallboards	23.0	21.5	1.5	**200**	**1.20**	**1500**	**300.0**	**20**	**6.00**

intuitive assumption that greater storage always enhances results, the six-case dataset reveals a moderate negative correlation ($r \approx -0.56$) between areal latent storage capacity and the percentage improvement in this KPI. This suggests that, in building applications, excessive PCM thickness may slow heat transfer, reducing the proportion of stored energy that effectively cycles within daily temperature variations. This behaviour has not been explicitly reported in recent reviewsheat transfer [1,3]]and therefore represents a new contribution to the optimisation of PCM layer thickness and integration strategies in building envelopes.

Integration and encapsulation trade-offs

Macro-encapsulation (CS-1, CS-4, CS-5) facilitates replacement while providing thermal resistance. Microencapsulation and form-stable composites (CS-2, CS-3) improve heat transfer but complicate maintenance. Integration location determines utilisation: ceilings (CS-2) enhance cooling; façades (CS-5, CS-6) enable solar-assisted charge; ducts (CS-4) directly influence HVAC supply conditions.

5.3. Design and policy implications

From a design perspective, optimal PCM performance demands simultaneous tuning of:

1. Melting temperature to match the local diurnal cycle.
2. Conductivity enhancement to enable daily cycling.
3. Control strategy to ensure complete phase transitions.
4. Layer thickness that strikes a balance between storage capacity and responsiveness.

From a policy perspective, PCM performance metrics should extend beyond material properties to include seasonal KPIs, such as peak reduction, comfort hours, and annual energy savings, across standardized test cycles [4,77].

6. Performance synthesis across case studies

The six case studies enable us to evaluate PCMs not only as materials but also as building-integrated systems with measurable KPIs, including comfort enhancement, energy savings, demand flexibility, and operational robustness. Synthesising results across climates, PCM types, and control strategies reveals critical patterns and trade-offs. Importantly, this analysis moves beyond reporting laboratory metrics (kJ/kg) by directly linking thermophysical properties to real-world building KPIs.

6.1. Comfort performance

6.1.1. Overheating mitigation

To ensure consistency across studies, thermal comfort and overheating indicators were standardized according to EN 16798–1:2019 Category II indoor environment criteria. Specifically, comfort hours were defined as the proportion of occupied time during which the operative temperature remained within the 20–26 °C range, while overheating was defined as the proportion of occupied hours exceeding 26 °C for more than 3 % of the annual occupancy period. When original studies reported alternative thresholds, their results were normalized to these reference criteria to allow meaningful comparison across cases.

Across climates with strong diurnal amplitude, PCMs reduced overheating by stabilising peak indoor temperatures. CS-1 achieved a 2–3 °C reduction, extending comfort hours in a civic hall. At the same time, CS-2 (a residential apartment) delayed the onset of overheating by up to 25 % fewer discomfort hours when night ventilation ensured full solidification. These results confirm PCMs' ability to tackle overheating risks in lightweight buildings [71,78].

6.1.2. Peak temperature reduction

Although absolute reductions are modest, typically 2–3 °C, they are highly valuable in buildings where thermal thresholds (26–28 °C) are critical. In CS-3 (office), PCM panels reduced oscillations around thermostat setpoints, directly lowering the risk of overheating and unnecessary cooling activation.

6.2. Energy performance

6.2.1. Heating and cooling energy savings

Energy savings varied from an 18 % reduction in cooling load in CS-2 to a 14 % reduction in winter heating demand in CS-5. These results highlight the dual potential of PCMs: paraffins for cooling-oriented retrofits in hot summers, and sugar alcohols for heating-dominated winters. Importantly, CS-3 delivered a 12 % annual HVAC reduction by damping oscillations, not by directly reducing setpoint demand.

6.2.2. HVAC interaction

Rather than eliminating HVAC use, PCMs primarily act as runtime stabilisers. CS-4 smoothed the supply-air temperature by 35 %, preventing short cycling and reducing compressor wear. In CS-3 and CS-6, PCMs delayed equipment activation, reducing start–stop losses. This suggests that PCMs complement, rather than replace, HVAC systems [4,7].

7. Energy flexibility contributions

7.1. Load shifting and peak reduction

Active control strategies enabled PCMs to act as demand-side flexibility (DSF) assets. CS-6 reduced the cooling peak demand by 15 % when graphene-enhanced hydrates were integrated with predictive HVAC scheduling. Similarly, CS-3 achieved a 12 % peak cut in office loads. Passive cases (CS-1, CS-5) offered only opportunistic peak shaving, underscoring the need for control integration.

7.2. Thermal storage density

Analysis shows that areal storage (MJ/m^2), not latent heat alone, correlates with flexibility value. CS-1 and CS-6 (>6 MJ/m^2) supported substantial peak reduction, while CS-2 (1.48 MJ/m^2) had a limited impact despite a correct melting range. This supports calls to standardise MJ/m^2 as a design KPI [74].

7.3. Opportunities and limits in passive DSR

While passive PCMs can smooth daily peaks, they cannot guarantee alignment with grid needs. Active discharge control is essential if PCMs are to participate reliably in flexibility markets [75].

7.4. Operational issues and barriers

7.4.1. Fire safety and recyclability

Paraffins (CS-2, CS-4) are flammable and require costly encapsulation; hydrates (CS-1, CS-6) are safer but prone to phase segregation. Most composites are not recyclable, which limits their circularity at the end of life [17].

7.4.2. Encapsulation cost

Encapsulation accounts for up to 70 % of the PCM system cost, often outweighing material costs [19]. Macro-capsules are serviceable but resistive; microcapsules are efficient but expensive and irreversible.

7.4.3. Phase degradation

Although laboratory tests report > 1,000 stable cycles, real monitoring often shows performance loss within 3–5 years, especially for salt hydrates [78,74]. This mismatch explains why PCM projects often remain stuck at TRL 8 or below.

7.4.4. HVAC integration

Integration with HVAC requires predictive logic. CS-4 and CS-6 showed that without coupling to fan operation or tariff schedules, PCM layers risk incomplete cycling. This integration complexity is a significant barrier to adoption.

7.5. Conclusion

Table 5 and Fig. 4 provide a summary of the KPI applied for the six case studies. The KPI-driven synthesis demonstrates that PCMs deliver multidimensional benefits —comfort stabilization, modest energy savings, and meaningful flexibility contributions —but only when control integration, climate alignment, and encapsulation trade-offs are addressed. Novel insights include the negative correlation between areal storage and observed outcomes, as well as the central role of HVAC coupling in enhancing TRL readiness. For design and policy, the clear lesson is to evaluate PCMs on application KPIs (ΔT, comfort hours, load reduction, MJ/m^2) rather than laboratory enthalpy values alone.

8. Design lessons and integration guidance

The six case studies and the broader PCM literature converge on a crucial insight: PCM's effectiveness is conditional, not universal. Their value emerges only when climate, placement, melting point, and control are aligned with the building's thermal and operational context. This section synthesizes lessons for design practice, highlighting not only where PCMs are effective but also when they fail, and how misaligned expectations can hinder their adoption. In particular, PCM layers that do not fully cycle daily quickly lose relevance, becoming inert mass rather than active storage. Likewise, oversizing thickness without ensuring nightly recharge, or selecting melting points too far from operative temperatures, often explains the modest or null impacts reported in field trials. These findings underscore that PCMs should be specified with the same rigor as structural or HVAC components: governed by local climate data, building load profiles, and control logic. Only when embedded within a system-level strategy, paired with ventilation, shading, or tariff-based scheduling, can PCMs reliably deliver on their promises of comfort, energy, and flexibility.

8.1. Climate-strategy matching

PCM design begins with the climate context.

- Hot climates (BSh, Csa): Roof/ceiling integration is most effective, particularly when paired with night ventilation to ensure daily recharge. CS-2 demonstrated an 18 % reduction in cooling when pre-cooling strategies were active in a Mediterranean apartment.
- Temperate/oceanic (Cfb): Performance is often modest due to insufficient diurnal amplitude. Here, PCMs are best deployed in peak-shaving niches, such as server rooms, classrooms, or office zones with large internal gains.
- Cold/continental (Dfb, Dwa): Hydrates and sugar alcohols can help reduce heating peaks and support daily cycling. CS-5 reduced winter heating by 14 % through the integration of Trombe walls, while CS-6 achieved summer peak shaving in dry climates through smart scheduling.
- Mixed climates (Cfa): Seasonal dual-use is possible but challenging; layered or dual-PCM systems tuned for different seasons may offer better year-round value.

Lesson: Climate dictates both the selection of melting point and the control philosophy. PCMs are most promising in cooling-dominated hot summers and heating-dominated cold winters, less so in mild temperate regions without active control.

Table 5
KPI Matrix per Building (comfort, energy, flexibility, barriers).

Case ID	Comfort (ΔT/°C, hours)	Energy Savings (%)	Flexibility (peak cut %)	Barriers
CS-1	Peak ↓ 2–3 °C, comfort hours ↑	–	Passive peak shave	Segregation, bulky
CS-2	Overheating ↓, +25 % comfort hrs	Cooling ↓ 18 %	Limited (thin layer)	Flammability, low k
CS-3	Stable temps, reduced oscillation	HVAC ↓ 12 %	Peak cut 12 %	Non-replaceable, degradation
CS-4	Supply air ΔT ↓ 35 %	Runtime reduction	HVAC peak smoothing	Fan dependency, cost
CS-5	Winter comfort gain	Heating ↓ 14 %	Passive load buffering	High melt point, seasonal
CS-6	Comfort stabilised, summer peak cut.	–	Peak demand ↓ 15 %	Cost, complexity

8.2. PCM placement guide

Placement determines whether latent capacity is actually utilised.

- Ceilings are consistently the most effective location for summer cooling, capturing both radiant and convective loads. CS-2 highlighted this, showing measurable load reductions with ceiling boards.
- Internal wallboards and panels help buffer indoor temperatures in winter, particularly in lightweight or highly insulated structures. CS-3 used form-stable composites to damp oscillations and delay HVAC activation.
- HVAC return or supply paths enable rapid charge/discharge cycles. CS-4 demonstrated that duct-integrated paraffin modules reduced short cycling by 35 % and improved the smoothness of the supply air.
- Façade-integrated systems serve dual roles. Trombe façades, as in CS-5, charge under solar gain in winter and release energy during cool nights. In tropical climates, façade PCMs help buffer solar spikes when combined with shading.

These placements highlight a general principle: the closer PCMs are to the dominant thermal load pathway, the higher their effectiveness.

8.3. Integration with HVAC and controls

PCMs rarely succeed as standalone passive devices; their performance is significantly enhanced when integrated with HVAC or ventilation systems.

- Radiant floors: Embedding PCMs beneath radiant slabs allows daytime load buffering and overnight recharge.
- Night ventilation: The most cost-effective method for re-solidification in summer, demonstrated in CS-2. Automated purge fans or operable windows can restore 70–90 % of latent capacity overnight.
- Hybrid HVAC integration: CS-4 showed that ducts directly coupled to PCMs reduce fluctuations in supply air, while CS-6 demonstrated predictive control aligning charge/discharge with tariffs.
- Time-of-use optimisation: PCMs become true flexibility assets when tied to demand-response pricing. High-conductivity hydrates in CS-6 enabled same-day cycles aligned with tariff windows.

Lesson: HVAC–PCM integration transforms PCMs from opportunistic buffers into predictable storage devices, enabling advancement from TRL 5–6 to 8–9.

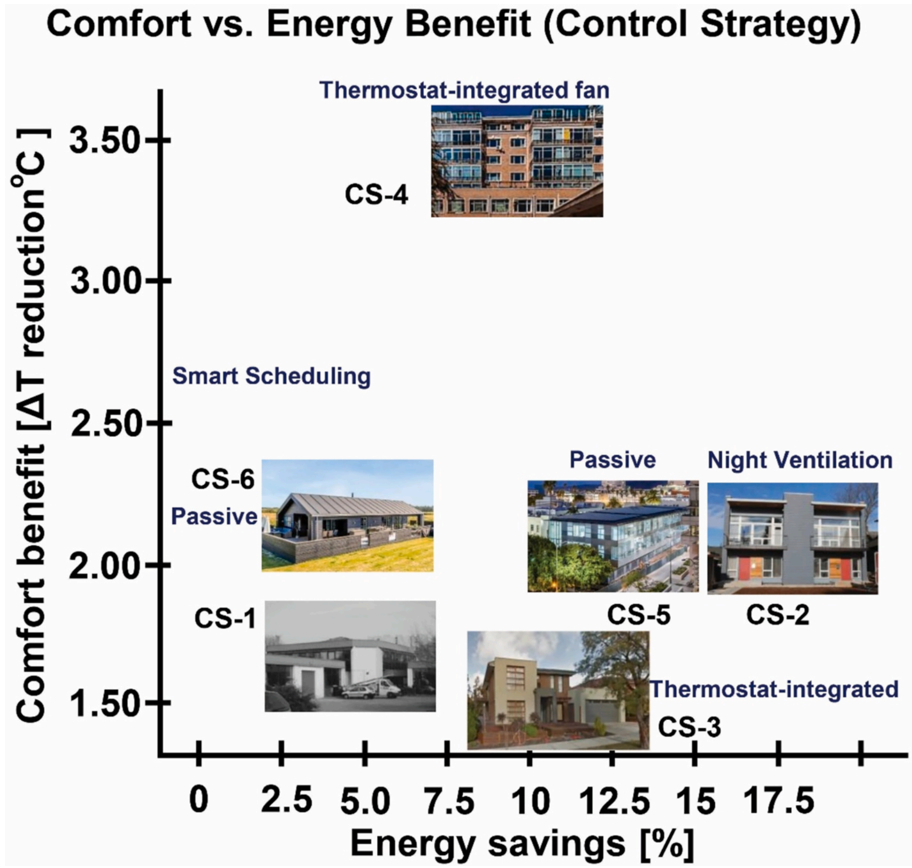


Fig. 4. Comfort vs. Energy Benefit Scatter Plot showing energy savings (%) and comfort benefits in ΔT reduction. CS-2 and CS-5 cluster as 'energy savers'; CS-1 and CS-6 cluster as 'comfort stabilizers.'.

8.4. Melting point selection

The correct melting point is the most important design parameter.

- For summer cooling, a melting range of 22–26 °C is optimal, aligning with comfort thresholds.
- For winter buffering, a slightly higher range (26–30 °C) captures diurnal heating loads, often achievable with hydrates or sugar alcohols.
- For daytime-dominant uses (such as offices and classrooms), the melting point should align with the occupied daytime set points (23–25 °C).
- For night-dominant uses (residences), slightly lower melting points (21–23 °C) capture evening peaks.
- For dual-season strategies, layered PCMs are recommended, with a cooling-tuned PCM placed closer to the interior for better coupling with room air.

8.5. Standards and certification

The tiered screening in Table 6 makes clear that today's PCM "standards landscape" still orbits materials rather than buildings [79,80]. RAL-GZ 896 [81] and JG/T 534–2018 [82] are the only building-facing anchors. Still, even these are regional and primarily assure product quality and thermal reliability (e.g., stability of phase-change temperature and latent heat under cycling), rather than guaranteeing building-level outcomes like peak-load shaving, load shifting, or comfort hours in use. The ISO 11357 DSC methods [75,76] and ASTM standards [85,86] do an excellent job of lab comparability, yet they stop at property measurement; they neither prescribe in-situ test sequences (diurnal charge/discharge under realistic boundary conditions, ventilation regimes, control logic) nor bridge the persistent lab–field performance gap (subcooling, hysteresis, humidity, aging, and placement effects). On the policy side, the EPBD recast (2024) [12], SRI, and ISO 52120–1 [52] are deliberately technology-neutral; they recognize thermal storage in principle but give no explicit credit to latent storage, meaning PCM benefits are often invisible in EPC compliance and market incentives. Net effect: there are not enough standards for building integration. What's missing is a dedicated ISO/CEN standard that: (i) defines component- and system-level tests for PCM plasters, panels, slabs, and ceilings under standardized dynamic profiles (climate- and TOU-dependent); (ii) couples controls (pre-cooling/charging windows) with performance metrics (kWh shifted, peak-demand reduction, comfort exceedance hours, SRI-compatible flexibility KPIs); (iii) requires durability & safety (multi-thousand cycle aging, fire/VOC/moisture compatibility, leakage resilience); and (iv) links to EPD/EN 15,804 so declared product data flows into compliance tools [51]. Until this exists, procurement, regulation, and design models will continue to undervalue PCMs despite solid material evidence.

8.6. Practical rules of thumb

As shown in Table 7, PCMs should be treated as targeted solutions rather than universal energy savers. Table 7 compiles two complementary data sources: (i) quantitative outputs from the expert focus-group workshops and (ii) validated values extracted from peer-reviewed literature to cross-check and complete the dataset. This blended approach ensures representativeness across climates, building typologies, and PCM integration strategies.

Practical rules of thumb for PCM integration can guide designers toward effective applications. A reasonable target capacity is 25–60 Wh/m^2 of floor area for comfort smoothing, and up to 100 Wh/m^2 for peak

Table 6
PCM Standards & Frameworks (Ranked by Tiers).

Tier	Standard / Framework	Scope / Focus	Why Important for Buildings
Tier 1 – Direct Building Application Standards	**RAL-GZ 896 (Germany/ Europe)**	Certification & quality assurance of PCM products	Only dedicated PCM quality mark in Europe; ensures durability and market acceptance.
	JG/T 534–2018 (China)	Thermal reliability testing of building-use PCMs	Focuses on cycling stability and latent heat retention; tailored for PCM in construction.
Tier 2 – Core Laboratory Characterization Standards	**ISO 11357–3:2025 (International)**	DSC – Latent heat & transition temperatures	Global baseline for quantifying PCM latent heat and melting/ solidification points.
	ISO 11357–4:2013 (International)	DSC – Specific heat capacity	Measures sensible + latent heat; complements ISO 11357–3.
Tier 3 – Material-Specific Standards	ASTM D4419**-90 (USA)**	Melting/ freezing tests for salt hydrates	Relevant for salt-hydrate PCMs used in HVAC and storage tanks.
	ASTM D87**-07a (USA)**	Melting point of petroleum waxes	Narrower scope, mainly for paraffin PCMs.
Tier 4 – Regulatory & Policy Frameworks	**GB 50176–93 (China)**	Thermal design code for civil buildings	Mentions PCM as a thermal mass option, but no test protocol.
	EPBD Recast (Directive (EU) 2024/1275)	EU Energy Performance of Buildings Directive incl. Smart Readiness Indicator	Establishes EU policy for energy flexibility; PCM is not explicitly credited in EPC or SRI.
	ISO 52120–1 (International)	Building automation & control systems (BACS)	Provides a performance framework for thermal storage control, but does not include PCM-specific rules.

Table 7
Summary of performance indicators for monitored PCM buildings. Practical Design Guidelines: What Works, What Doesn't.

Aspect	What Works	What Doesn't
Building type	Lightweight, glazed façades, overheating-prone retrofits	Heavy thermal-mass buildings with small diurnal swings
PCM selection	Paraffins/fatty acids (stable, retrofit); Salt hydrates (high density with stabilisers)	Hydrates without nucleators; exotic, untested PCMs
Placement	Ceilings for cooling; façades for heating; HVAC ducts for fast response	Furniture, hidden layers with poor coupling
Thickness	Thin layers (5–15 mm) with proven cycling	Oversized layers that remain uncharged
Integration	Night purge, shading, tariff scheduling	Passive-only use in temperate climates
Controls	Wider setpoint deadbands, hybrid HVAC integration	Ignoring PCM in building automation
Safety & durability	Encapsulated paraffin boards; stabilised hydrates	Field-mixed slurries; non-rated encapsulation

shaving. Placement priority should generally follow the hierarchy: ceilings first, then solar-exposed façades, followed by floors and ducts. Cycling efficiency is critical; at least 70–80 % nightly solidification should be achieved. If this target is not met, PCM thickness should be reduced or purge airflow increased.

Integration must always be viewed as complementary to established design basics such as shading, insulation, and airtightness. PCMs cannot compensate for poorly designed envelopes. In terms of reliability, encapsulated paraffin boards are typically the safest long-term option, while salt hydrates offer higher volumetric storage but only when backed by proven anti-segregation chemistry. Several common failure modes are well documented: PCMs that do not recharge overnight often require increased purge airflow, reduced thickness, or improved shading.

Other issues include the absence of noticeable performance, which is typically associated with a melting point mismatch. This can be corrected by selecting a PCM whose phase-change range lies within 1–2 °C of the desired set point. Messy or inconsistent installations should be avoided by sticking to factory-encapsulated panels rather than field-mixed slurries. In summary, the design lessons are clear: start thin, integrate smart, and design for daily cycling. Climate governs PCM utility; placement defines the effectiveness of heat exchange; and control determines whether PCMs act as passive buffers or active storage devices. Above all, PCMs should be positioned as supplements to sound building design practices, not replacements.

9. Discussion

9.1. Findings and recommendations

The synthesis of eight case studies monitored for this study confirms that PCMs can enhance comfort and reduce energy demand. Still, the magnitude and reliability of these benefits are contingent on design integration rather than material innovation. Field evidence consistently shows reductions of 1–3 °C in peak indoor temperatures and 10–25 % reductions in heating or cooling loads. Yet these gains are realized only when three conditions are met: (i) melting ranges align with the diurnal cycle; (ii) PCMs are positioned in high-flux zones such as ceilings, façades, or HVAC ducts; and (iii) recharge is actively managed, whether by night ventilation or smart scheduling. This underscores that PCM effectiveness is a function of system design, not simply latent heat density.

A second insight is that contributions to flexibility remain poorly captured. Only one case (CS-6) explicitly demonstrated tariff-aligned load shifting, even though PCMs' slow-release profile is well-suited to demand-side response. The absence of control integration and flexibility KPIs in most studies reflects a deeper structural barrier: standards and regulations reward static metrics of comfort and efficiency, rather than dynamic contributions to grid stability. Without recognition in EPCs, SRIs, or national compliance tools, PCM benefits remain "invisible" in the policy arena.

Third, the review reveals a misalignment between research and deployment. Academic work is dominated by TRL 2–4 material enhancements, such as nanodoping, encapsulation, or conductivity improvements, while design practice requires validated guidance on placement, sizing, and control logic at TRL 6–9. This gap explains why many PCM installations underperform despite decades of material progress. The innovation bottleneck is not thermal capacity but integration intelligence: how to embed PCMs in assemblies and HVAC systems so that they cycle daily and interact productively with user comfort and tariff signals.

From these findings, four recommendations emerge:

- Shift from material-led to design-led innovation, treating PCMs as building-system components rather than exotic materials.

- Embed PCMs into flexibility frameworks, so they are credited alongside batteries and responsive HVAC in demand-side management metrics.
- Standardize building-level KPIs to report MJ/m^2 areal storage, comfort-hour gains, and the percentage of peak shaved, rather than just laboratory enthalpy values.
- Prioritize field-based monitoring, with multi-season deployments that reveal real cycling efficiency, degradation, and comfort trade-offs.

10. Strengths and limitations

A key strength of this review is its focus on real-world buildings at TRL 6–9, where PCMs have been integrated into roofs, ceilings, façades, and HVAC systems under operational conditions. By systematically comparing comfort, energy, and flexibility KPIs, this study advances beyond most prior reviews, which largely remain at laboratory or simulation stages [5]. The development of design-relevant tools (e.g., Tables 3–4, KPI matrices, and integration guidelines) provides practitioners with actionable insights, such as prioritising ceilings in hot climates or ducts for fast-response load shifting. Importantly, the review identifies a negative correlation between areal storage and observed performance, suggesting that beyond a certain thickness, excess PCM mass may become underutilised due to slow charge–discharge cycles. This insight is novel and highlights why “more storage” does not automatically mean “better performance.”.

The main limitation lies in the restricted pool of high-quality measured data. Only a handful of studies provided multi-season monitoring with both comfort and energy KPIs. Many case studies are geographically biased toward Europe and North America, while promising contexts such as tropical or arid climates remain underexplored. Given the small but diverse dataset, the findings should be interpreted as indicative trends rather than generalizable averages. The purpose of the cross-case synthesis is to reveal consistent mechanisms, such as the influence of design integration and control strategy, rather than to quantify population-wide effects. Moreover, reporting is often inconsistent: few studies disclose latent capacity per m^2, cycling degradation, or actual flexibility delivered under tariff structures. These gaps constrain cross-comparability. Finally, the TRL stagnation problem persists: while thousands of PCM formulations have been tested at TRL 2–4, only a limited number progress to TRL 8–9 with long-term monitoring [6]. Results should therefore be interpreted with sensitivity to the design context, rather than being extrapolated as universal benchmarks.

10.1. Implications on practice and research

The broader implication is that PCMs remain undervalued not because of weak performance, but because of structural invisibility in design standards, compliance models, and regulatory frameworks. Current certification and policy instruments, RAL-GZ 896 [81], JG/T 534–2018 [82], ISO 11357 series [83,84], ASTM D87 [86], ASTM D4419 [85], and the EPBD recast [12], focus on material reliability or static building efficiency, not dynamic contributions to comfort and flexibility. This creates a standards gap: PCMs are tested as materials but not recognized as building-level assets.

Bridging this gap requires the development of a dedicated ISO or CEN standard for PCM integration in buildings, specifying: (i) dynamic test cycles under representative climates and occupancy schedules; (ii) integration with HVAC and control strategies; (iii) durability, fire, and circularity requirements; and (iv) reporting of standardized KPIs (comfort hours, MJ/m^2 storage, peak cut %). Such a standard would enable PCMs to integrate into mainstream design workflows, be credited in EPCs and SRIs, and compete fairly with batteries and mechanical storage as flexible assets.

For practice, this means designers should view PCMs as supplements to passive design and HVAC, not replacements. Their optimal role is incremental but valuable: reducing overheating risk in lightweight buildings, stabilizing HVAC runtimes, and providing predictable daily cycling when integrated with smart controls. For research, the priority is to advance from TRL 3–5 to TRL 8–9, demonstrating PCM integration under real conditions across diverse climates, and linking performance to grid-responsive KPIs. Only then can PCMs move from niche demonstrations to mainstream adoption in climate-responsive, flexible, and resilient buildings.

The discussion reinforces that PCMs are at a crossroads: while their materials science is highly advanced, their integration and performance validation lag. This review contributes by reframing PCMs not as exotic materials but as building-system components whose value depends on climate, placement, and control. Suppose practice adopts design-led integration and research shifts toward TRL 6–9 field validation with flexibility KPIs. In that case, PCMs can move from niche demonstrations to mainstream contributions in comfort, energy efficiency, and demand flexibility.

11. Conclusion

This study advances understanding of phase change material (PCM) applications at the building scale by synthesizing evidence from eight full-scale monitored projects at Technology Readiness Levels (TRL) 6–9. Unlike prior material-centric or simulation-based studies, it provides an empirically grounded picture of PCM behaviour under real occupancy and operational conditions.

Three interrelated contributions emerge. First, the paper establishes a cross-case typology of PCM integration strategies, distinguishing how climate, building type, placement depth, and control logic jointly determine effectiveness. This comparative mapping explains why certain configurations, such as envelope-embedded or night-recharged systems, deliver consistent benefits, whereas others yield marginal gains.

Second, the synthesis of field results reveals that PCM benefits are conditional rather than universal. Monitored cases show peak indoor temperature reductions of 1–3 °C and heating or cooling load savings of 10–25 %, with performance more strongly influenced by design integration and control strategy than by intrinsic material properties. A previously undocumented trend is identified: a moderate negative correlation ($r \approx -0.56$) between areal storage capacity and comfort-hour improvement, suggesting that excessive PCM thickness can slow the charge–discharge cycle and reduce the fraction of latent storage activated within daily temperature swings. While this relationship was observed consistently across the six monitored cases, it should be interpreted as exploratory rather than statistically conclusive, since no significance test was applied and the dataset remains limited in size and diversity. This observation, therefore, serves as a hypothesis-generating insight that warrants confirmation through expanded, multi-climate field studies and can inform future design optimisation of PCM layer thickness and placement strategies.

Third, the analysis exposes a persistent regulatory and standards gap. Although PCM materials are well covered by laboratory testing protocols (e.g., ISO 11357 series), no harmonized ISO or CEN framework addresses building-level integration or long-term operational stability. As a result, PCM contributions remain invisible within Energy Performance Certificates (EPCs), Smart Readiness Indicators (SRIs), and national compliance tools, despite their potential to enhance comfort and flexibility.

Taken together, these findings reposition PCMs from experimental materials toward integrated components of adaptive building systems. The review provides both empirical evidence and policy context to guide this transition. These results are exploratory and drawn from a limited number of full-scale monitored cases; further field validation across climates and building types is needed to confirm the observed relationships Future research should (i) expand monitored datasets to strengthen statistical validation, (ii) establish standardized Key

Performance Indicators for cross-climate comparison, and (iii) support regulatory frameworks that explicitly recognize latent storage as a building-level energy asset. Achieving these steps will allow PCMs to contribute meaningfully to the decarbonization, comfort, and flexibility objectives underpinning the next generation of European buildings.

CRediT authorship contribution statement

Shady Attia: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Thanina Hammouma:** Investigation. **Dania Galeone:** Investigation. **Zhaoli Zhang:** Resources, Investigation. **Nan Zhang:** Investigation. **Vincenzo Corrado:** Investigation. **Yanping Yuan:** Investigation, Funding acquisition.

Declaration of competing interest

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

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Data availability

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

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