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Comprehensive Review of Phase Change Materials for Building Applications: Passive, Active, and Hybrid Systems (2022–2025)

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Abstract

Phase change materials (PCMs) have emerged as a key enabler of high-performance, low-carbon buildings through latent heat-based thermal energy storage. This paper presents a systematic and critical synthesis of advances in PCM technologies for building applications published between 2022 and 2025, analyzing over 300 peer-reviewed studies to evaluate thermal performance, economic viability, environmental impact, and climate adaptability across three integration approaches: passive, active, and hybrid systems. The studies analyzed show that passive envelope integration employing macroencapsulated or form-stable PCMs in walls, roofs, and glazing is reported to deliver 15–45% energy savings with payback periods of 8–15 years, primarily through enhanced thermal inertia and indoor temperature stabilization. Active systems, which couple PCMs with HVAC, heat pumps, or air handling units, are found to achieve 20–40% energy reductions and shorter payback periods (3–8 years) by enabling load shifting, peak shaving, and improved coefficient of performance (COP). Hybrid configurations integrating passive and active strategies with AI-driven control demonstrate, in the literature, the highest potential, with reported energy savings of up to 50%, though they entail greater complexity and capital cost. The review further highlights material-level innovations, including ternary composite PCMs, bio-based alternatives, and nano-enhanced formulations that address intrinsic limitations such as low thermal conductivity (0.1–0.3 W/m·K for organics) and cycling instability. Despite significant progress, critical gaps persist in standardized testing protocols, long-term field validation, comprehensive lifecycle assessments, and real-world scalability, particularly in tropical and cold climates. By bridging material science, building physics, and energy system engineering, this work provides a forward-looking roadmap to accelerate the deployment of PCM-based solutions in the global decarbonization of the built environment.

Keywords: phase change materials; building energy efficiency; thermal energy storage; passive systems; active systems; HVAC integration; thermal comfort

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Academic Editor: Ziad Saghir

Received: 23 November 2025
Revised: 13 February 2026
Accepted: 19 February 2026
Published: 26 February 2026

1. Introduction

Building energy consumption accounts for approximately 40% of global energy consumption and 36% of CO_2 emissions, making building energy efficiency a critical component of climate change mitigation strategies [1–3]. The increasing demand for thermal comfort and extreme weather events due to climate change have intensified the need for innovative building energy technologies to provide efficient heating and cooling while minimizing environmental impact [4,5]. This perspective highlights the role of phase change materials (PCMs) in reducing energy consumption and enhancing indoor thermal comfort in buildings, particularly with regard to climate change challenges.

Phase change materials (PCMs) have emerged as a transformative technology for building applications, offering the unique capability to store and release large amounts of thermal energy during phase transitions at nearly constant temperatures [6,7]. Unlike conventional thermal storage materials that rely solely on sensible heat, PCMs exploit the latent heat of fusion, providing energy storage densities 5–14 times higher than traditional materials such as water, rock, or concrete [8–10]. Integrating PCMs into building designs offers a sustainable solution to meet growing energy demands while addressing climate-related challenges. The potential of PCMs to enhance energy efficiency in buildings is particularly evident in their ability to optimize thermal management during peak temperature periods.

The fundamental principle underlying building PCM applications involves absorbing excess thermal energy during peak heating/cooling periods and its subsequent release during off-peak periods, thereby reducing energy demand and improving thermal comfort [11,12]. This thermal regulation capability is particularly valuable in terms of increasing renewable energy integration, where energy storage systems are essential for managing intermittent energy supplies [13,14]. Integrating PCMs can significantly enhance indoor climate control, particularly in regions experiencing extreme temperature fluctuations due to climate change. This review underscores the transformative potential of PCMs in building applications, emphasizing their role in achieving energy efficiency and improving occupant comfort in response to climate challenges.

The application of PCMs in building systems has evolved significantly over the past two decades. Early research (2000–2010) primarily focused on material characterization and basic integration concepts, with limited practical applications due to technical challenges, including thermal conductivity limitations, phase separation issues, and high costs [15,16]. Recent advancements have led to improved integration techniques and material formulations, facilitating the broader adoption of PCMs in sustainable building practices. As research progresses, understanding the economic feasibility and long-term performance of PCM systems will be crucial for their successful implementation in diverse construction projects.

The years 2010–2015 witnessed significant advances in micro-encapsulation technologies, enabling the better integration of PCMs into building materials while addressing leakage and compatibility issues [17–20]. During this phase, researchers demonstrated the feasibility of PCM-enhanced wallboards, concrete blocks, and insulation materials, with several pilot projects showing promising results [21,22]. The subsequent years (2016–2021) marked a shift towards hybrid systems that combine PCMs with other energy-efficient technologies, further enhancing their effectiveness in building applications. The ongoing research aims to refine PCM formulations and explore innovative integration methods to maximize their benefits in diverse building environments.

The 2016–2021 period marked a transition toward system-level integration, with increasing focus on active PCM systems coupled with HVAC equipment, heat pumps, and renewable energy systems [23,24]. This era also saw the development of advanced nu-

https://doi.org/10.3390/en19051151

merical modeling tools and optimization algorithms for PCM system design [25,26]. The advancements in PCM integration highlight the need for continued research to address challenges such as their compatibility with existing materials and the optimization of control systems for improved performance. Future research should prioritize the exploration of innovative PCM formulations and their integration with emerging building technologies to further enhance energy efficiency and sustainability in construction.

This paper presents a timely and systematic synthesis of advances in phase change materials (PCMs) for building applications from 2022 to 2025, with a focused analysis on their integration into passive, active, and hybrid thermal energy storage systems. By critically evaluating over 300 peer-reviewed studies from high-impact journals, the work aims to clarify the interaction between thermal performance, environmental sustainability, economic feasibility, and climate adaptability across diverse PCM technologies and building contexts. The novelty of this review lies in its integrative, system-level framework that moves beyond material-centric analyses to comparatively assess three strategic deployment approaches, namely passive envelope systems, active HVAC-coupled configurations, and advanced hybrid architectures, while quantifying their climate-specific efficiency across global case studies. It further synthesizes emerging trends such as bio-based and nano-enhanced PCMs, and grid-interactive thermal storage, and critically addresses persistent gaps in lifecycle assessment and scalability. By bridging technical, economic, and environmental dimensions, this work provides a forward-looking roadmap to accelerate the deployment of PCM-based solutions in the decarbonization of the built environment.

The paper is organized as follows. Section 2 presents a comprehensive state-of-the-art review of PCM research from 2022 to 2025, emphasizing emerging trends and technological developments relevant to building applications. Section 3 introduces the bibliometric methodology adopted for the literature selection and analysis. Section 4 provides a concise classification of PCMs, linking their thermophysical characteristics to potential building integration. Sections 5 and 6 examine current applications and integration strategies in passive, active, and hybrid systems, respectively. Finally, Sections 7–9 synthesize the main findings, outline future research perspectives, and discuss remaining challenges associated with the large-scale implementation of PCM technologies in energy-efficient buildings.

2. State-of-the-Art Covering the Period 2022–2025

Contemporary research has shifted toward ternary composite PCMs (CPCMs) that provide enhanced thermal properties and wider phase change temperature ranges. Alrashdan et al. [27]. developed a ternary CPCM system (CA/C18-TD 2.0:8.0) achieving a latent heat capacity of 224.53 J/g with excellent thermal cycling stability over 300 cycles. This significantly improves over single-component systems, typically exhibiting latent heat values of 150–200 J/g [28,29]. Research indicates that multi-component PCM systems can offer superior thermal performance, making them a promising avenue for future developments in energy-efficient building technologies. Recent advancements in PCM technology highlight the potential for multi-component systems to significantly enhance thermal performance and stability for more efficient energy management in buildings.

Liu et al. [30] conducted comprehensive multiscale modeling of polyurethane–PCM composites, demonstrating thermal conductivity improvements of up to 300% through optimized matrix design. These form-stable composites address the critical challenge of PCM leakage while maintaining the structural integrity of building materials. The ongoing research into form-stable PCM composites aims to enhance their thermal performance and stability further, which is essential for effective energy management in building applications. Future research should also focus on integrating bio-based PCMs, which could strengthen sustainability while addressing environmental concerns associated with traditional materials [31].

Sustainable PCM alternatives derived from renewable resources have gained significant attention. Imghoure et al. [32] investigated bio-based PCMs for Moroccan construction applications, showing comparable thermal performance to synthetic alternatives while offering reduced environmental impact and improved cost-effectiveness. Additionally, exploring bio-based PCMs is a crucial step toward facilitating sustainable building practices, potentially reducing reliance on artificial materials and enhancing environmental benefits. The ongoing research into bio-based PCMs reveals their potential to strengthen building materials' sustainability further while addressing environmental concerns associated with conventional options.

Although bio-based PCMs are often highlighted for their low cost and environmental friendliness due to their derivation from abundant natural sources, several studies also report limited their thermal and chemical stability, particularly under repeated phase change cycles or elevated temperatures. This apparent contradiction can be understood in the context of application conditions and material design: while bio-based PCMs are economically attractive, their performance may degrade over time, potentially offsetting initial cost benefits. Several strategies have been proposed to reconcile these issues, including micro- or nano-encapsulation to protect the PCM from oxidation and phase separation, blending with synthetic PCMs to enhance stability, and the use of additives or composite matrices to improve thermal reliability. By adopting these approaches or targeting their moderate-temperature and low-cycle application, it is possible to leverage the cost advantage of bio-based PCMs while mitigating stability limitations, thus providing a more balanced perspective on their practical potential [29–34]

Recent studies have demonstrated substantial improvements in passive PCM integration within building envelopes. Amaral et al. [35] conducted experimental validation of multifunctional façade systems containing PCMs, achieving thermal performance improvements of up to 50% compared to conventional façade systems. The study employed a hot box testing methodology with calibrated numerical models, demonstrating temperature fluctuation reductions of 54.51% during summer conditions and heat flow density reductions of 17.49 W/m^2. These advancements underscore the critical role of PCMs in enhancing thermal performance and energy efficiency in modern building designs and sustainable construction practices. Integrating PCMs into building envelopes improves energy efficiency and occupant comfort by stabilizing indoor temperatures during extreme weather conditions.

Alrashdan et al. [27] conducted comprehensive experimental studies on PCM-enhanced service areas in building envelopes under Saudi Arabian climate conditions. The research demonstrated cooling load reductions of up to 63% with PCM–cement composites containing 20% PCM by mass. Surface temperature reductions of 5.2 °C were observed, corresponding to approximately a 10% improvement in thermal performance. These findings highlight the potential of PCM-enhanced materials to optimize energy efficiency in diverse climatic conditions, promoting sustainable building practices. Integrating PCMs into building envelopes significantly enhances thermal performance, improving energy efficiency and occupant comfort during extreme weather events [36].

Yuk et al. [37] investigated sustainable energy solutions for historic building conservation, implementing hygrothermal control systems with integrated PCMs. The study demonstrated the potential for PCM integration in heritage buildings while maintaining architectural integrity and achieving significant energy savings. Furthermore, the integration of PCMs in roofing systems enhances thermal regulation and contributes to preserving historical architecture, thus supporting sustainable building practices in diverse contexts. The ongoing research into PCM applications reveals innovative solutions for improving energy efficiency and thermal comfort in buildings, particularly in response to climate variability.

Liu et al. [38] developed a two-level optimal scheduling control strategy for air-source heat pump loads with phase change energy storage, demonstrating substantial improvements in system efficiency and peak demand reduction. The study employed optimization of mixed-integer linear programming (MILP) to achieve optimal charge/discharge scheduling based on electricity tariffs and thermal demands. This innovative approach enhances energy efficiency and maintains thermal comfort in residential buildings during peak demand. Integrating PCM with HVAC systems can significantly improve energy management, providing thermal comfort and substantial energy savings in residential applications.

Faramarzi et al. [39] conducted a comprehensive energy and exergy analysis of modified air handling units (AHUs) assisted by PCMs, heat recovery units, and solar energy integration. The research demonstrated annual energy exchange reductions of 687 kWh through optimized PCM integration, with significant improvements in system coefficient of performance (COP). This analysis highlights the importance of integrating phase change materials into HVAC systems, as they can enhance overall energy efficiency and contribute to significant cost savings for building operations. Integrating PCMs into modern building designs is crucial for improving energy efficiency and ensuring occupant comfort amidst climate variability.

Al-Atari et al. [40] investigated the optimization of integrated heat pump and thermal energy storage systems in active buildings for community heat decarbonization. The study demonstrated the potential for large-scale PCM deployment in district heating/cooling applications, which substantially reduced carbon emissions and energy costs. These findings highlight the critical role of PCM integration in advancing sustainable building practices, particularly in addressing energy efficiency challenges linked to climate change. Integrating phase change materials in building applications enhances energy efficiency and plays a pivotal role in mitigating climate change impacts through improved thermal management.

Recent research has emphasized the development of sophisticated control algorithms for hybrid PCM systems. Studies have integrated building energy simulation with optimization algorithms to determine optimal PCM properties, system configurations, and control strategies [27,30]. These advancements improve energy efficiency and enhance occupant comfort, which is increasingly essential in climate change and rising energy demands. The ongoing evolution of PCM technology necessitates focusing on innovative control strategies to optimize performance across diverse building applications. Integrating advanced control algorithms is essential for maximizing the benefits of PCM systems, ensuring optimal performance and energy efficiency in diverse building environments [41–43].

Advanced control systems incorporating machine learning and predictive algorithms have been developed to optimize PCM system performance under varying weather conditions and occupancy patterns [35,36]. These systems can dynamically adjust PCM activation based on real-time data, enhancing energy efficiency and occupant comfort in buildings. This integration of intelligent control systems represents a significant advancement in the management of PCM applications, enabling more responsive and efficient energy use in buildings. Integrating advanced control systems is crucial for maximizing the effectiveness of PCM applications in buildings, ensuring optimal energy efficiency and comfort for occupants. The ongoing research into advanced control systems is vital for optimizing PCM performance, ultimately enhancing energy efficiency and indoor comfort in diverse building environments.

3. Methodology

The bibliometric analysis methodology outlines a systematic process for analyzing bibliographic data, incorporating specific tools and steps, as shown in Figure 1. Data Collection: Relevant data is gathered from academic databases, such as the Scopus database, using a targeted query to retrieve publications that align with the research objectives. Scopus provides comprehensive coverage of peer-reviewed literature, ensuring a robust dataset.

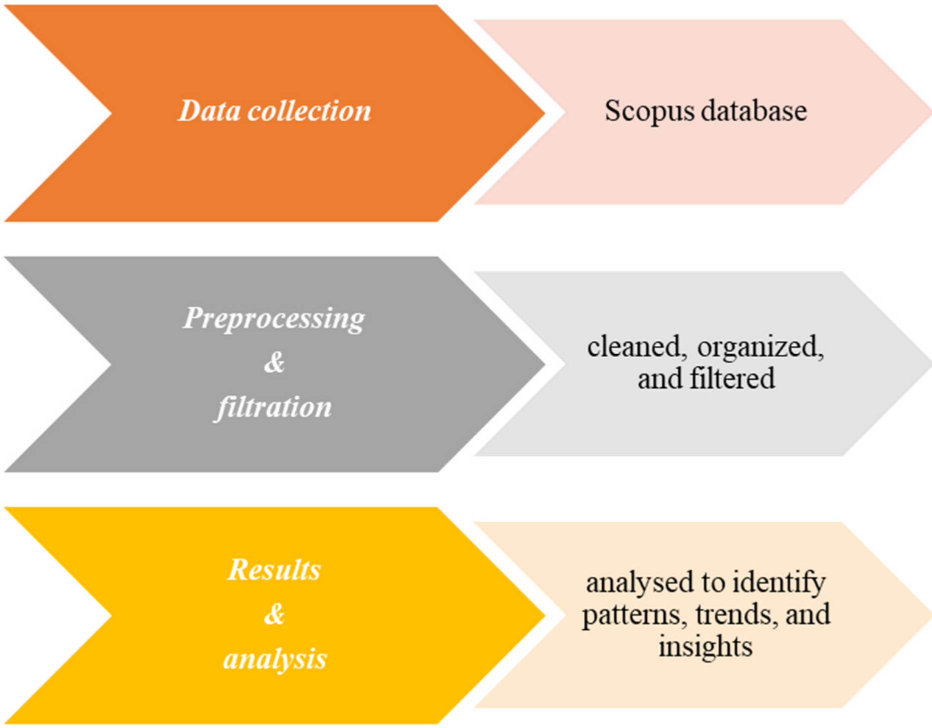

Figure 1. The bibliometric analysis methodology.

Preprocessing and Filtration: The collected data is cleaned, organized, and filtered to ensure quality and relevance. This involves removing duplicates, correcting inconsistencies, and refining the dataset based on criteria like publication type, time frame, or subject area.

Results and Analysis: The pre-processed data is analyzed to identify patterns, trends, and insights, such as citation networks, author collaborations, or keyword co-occurrences. Statistical methods and metrics, like citation counts or h-index, are applied to derive meaningful results.

The query used to retrieve and assess the relevant literature on phase change materials (PCMs) from the Scopus database is as follows: (TITLE-ABS-KEY ("phase change material" OR "phase change materials" OR "PCM in building" OR "PCM integration" OR "hybrid systems with PCM" OR "active systems with PCM") OR "passive systems with PCM") OR "HVAC systems with PCM")) AND (TITLE-ABS-KEY ("Thermal Efficiency Improvement" OR "Environmental Impact Reduction" OR "Economic Viability" OR "Integration Method Effectiveness" OR "Climate Adaptability" OR "classification" OR "perspective" OR "energy efficiency" OR "building cooling" OR "pre-cooling system" OR "civil buildings")) AND (PUBYEAR > 2022 AND PUBYEAR < 2025).

4. Phase Change Materials Classification and Properties

a. Organic PCMs

One classification extensively employed in the development of applications is organic phase change materials (PCMs), encompassing paraffins and fatty acids. These substances are distinguished by their remarkable chemical stability, non-corrosive nature, and diverse melting temperature ranges. These attributes make organic PCMs highly appealing for creating thermal management solutions, particularly within the framework of contemporary sustainable construction methodologies.

Paraffin-based PCMs constitute the most prevalent organic category utilized in building applications. Recent studies have revealed paraffin PCMs with meticulously regulated melting points in the range 18–35 °C, which makes them exceptionally suitable for thermal regulation in building contexts. These materials typically exhibit latent heat capacities ranging from 150 to 250 kJ/kg, thus providing significant thermal energy storage capabilities for construction [33].

The operational characteristics of paraffin PCMs include thermal conductivity values between 0.1 and 0.3 W/m·K, which represents a principal limitation in heat transfer applications. However, this challenge can be mitigated through a variety of enhancement strategies, such as the incorporation of graphite, the integration of metal foams, and the addition of nanoparticles [33]. Furthermore, paraffin PCMs exhibit remarkable thermal cycling stability, exceeding 1000 complete cycles without considerable degradation in performance.

Fatty acid PCMs, such as palmitic acid, stearic acid, and oleic acid, display outstanding thermal properties and are collecting increasing research attention for building applications. These materials offer exceptional thermal cycling stability and are compatible with various advanced encapsulation methodologies. The melting temperature range for fatty acids generally extends from 25 to 65 °C, with latent heat capacities of 120–200 kJ/kg [34,44].

b. Inorganic PCMs

Salt hydrate phase change materials (PCMs) present enhanced latent heat capacities alongside relatively economical material expenses, rendering them particularly appealing for large-scale architectural implementations. These substances generally exhibit latent heat capacities within the 200–300 kJ/kg range, which is markedly superior to their organic counterparts [45]. Consequently, applying salt hydrates facilitates the development of more compact thermal storage solutions in construction.

The thermal conductivity of salt hydrates is within 0.4–0.7 W/m·K, which imparts advantageous thermal transfer properties when contrasted with organic PCMs [46]. This feature supports a more rapid thermal response and increased operational efficiency in building applications. Nonetheless, utilizing salt hydrates introduces specific challenges, including phase separation, supercooling effects, and potentially corrosive properties, necessitating careful consideration through meticulous system engineering.

Notable examples of salt hydrate systems comprise sodium acetate trihydrate, calcium chloride hexahydrate and sodium sulfate decahydrate, with a melting point of 58 °C, 29 °C and 32 °C, respectively, and a latent heat of 264 kJ/kg, 171 kJ/kg and 254 kJ/kg respectively [46]. These materials have been effectively validated in various building applications employing suitable stabilization methodologies.

c. Eutectic Mixtures and Enhanced Systems

Eutectic phase change material (PCM) formulations systematically integrate various phase change substances to attain meticulously optimized thermal characteristics and broadened phase transition temperature intervals [47]. Recent scholarly advancements have illustrated notable enhancements in performance through meticulously designed eutectic formulations. Such systems facilitate the optimization of targeted architectural applications and climatic variables.

Sophisticated eutectic configurations encompass combinations of capric and palmitic acids that achieve distinct melting properties and improved thermal resilience. Salt hydrate eutectics offer prolonged operational temperature ranges appropriate for various climatic zones [48]. Furthermore, organic–inorganic hybrid eutectics amalgamate both material types of benefits while alleviating their drawbacks.

The evolution of these sophisticated systems signifies a pivotal progression in PCM technology pertinent to architectural applications. Through the meticulous optimization of compositions, eutectic blends can attain melting temperatures that are precisely aligned with the specific thermal requirements of buildings. This customization ability allows for enhanced performance when compared to single-component PCM systems.

d. *Thermal Conductivity Enhancement Technologies*

The intrinsically low thermal conductivity of organic phase change materials (PCMs) constitutes a significant limitation for construction applications, severely restricting heat transfer rates and thermal response attributes. Various enhancement methodologies have been devised to mitigate this critical drawback and enhance the overall system efficiency.

Incorporating graphite has enhanced thermal conductivity by as much as 335%, elevating conductivity from 0.17 to 0.74 W/m·K for optimized formulations [49]. This mechanism operates through the high thermal conductivity of graphite particles, which form conductive pathways within the PCM matrix. The optimal loading percentage ranges are 5–15% by weight, which achieve the maximum enhancement while exerting minimal influence on latent heat capacity [49].

The integration of metal foam offers a high surface area and improved thermal conductivity, all while effectively containing the PCM. This method attains 200–500% thermal conductivity enhancements, contingent upon the foam's porosity and thermal conductivity attributes [50]. The technique is especially efficient for applications involving thick PCMs requiring rapid thermal response capabilities.

Enhancement via carbon nanotubes yields 200–400% thermal conductivity improvements with negligible mass addition, generally less than 2% by weight [51]. The remarkable aspect ratio of carbon nanotubes facilitates the formation of efficient thermal pathways within the PCM matrix. Nevertheless, challenges persist regarding the requirements for uniform dispersion and economic considerations for large-scale construction applications.

5. Current State of Knowledge of the Integration of PCMs in Buildings

A critical synthesis of the current state of knowledge on phase change materials (PCMs) in building applications is imperative to define research advancements, and to identify persistent knowledge gaps and useful approaches for future research. PCMs have emerged as a transformative technology for improving building energy performance and sustainability by enabling passive thermal regulation, thereby attenuating indoor temperature fluctuations and diminishing reliance on active heating, ventilation, and air conditioning (HVAC) systems.

The analysis presented in this section assesses the thermal efficiency, environmental impact, and economic viability of diverse PCM integration strategies, encompassing passive, active, hybrid, and retrofit configurations across varying climatic contexts, by consolidating the empirical findings and methodological approaches from recent studies (2022–2025). As illustrated in Figure 2, more than 136 papers published in 2022 were focused on the use of PCMs in buildings compared to 104 papers in 2024.

https://doi.org/10.3390/en19051151

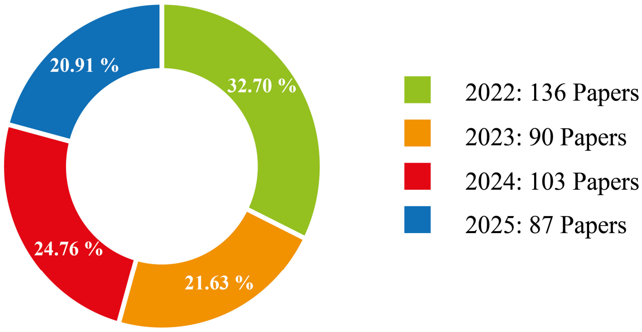

Figure 2. Yearly numbers of papers published in 2022–2025 and focused on the use of PCMs in buildings.

This paper provides evidence-based insights to guide researchers, building designers, and policymakers in the optimal deployment of PCM-enhanced building envelopes and systems. Ultimately, this synthesis contributes to the broader decarbonization agenda by advancing development and energy-efficient building solutions aligned with global climate and sustainability targets. Table 1 reports existing research on the integration of phase change materials in building employing the following criteria: (i) thermal efficiency, (ii) environmental impact, (iii) cost, (iv) integration method, and (v) climate adaptability between 2022 and 2025. Figure 3 shows the distribution of papers published between 2022 and 2025 on the use of PCM in buildings according to the five criteria analyzed in this paper. As presented, more than 26.27% of the elaborated research were focused on enhancing thermal energy efficiency, followed by 21.57% for the integration method.

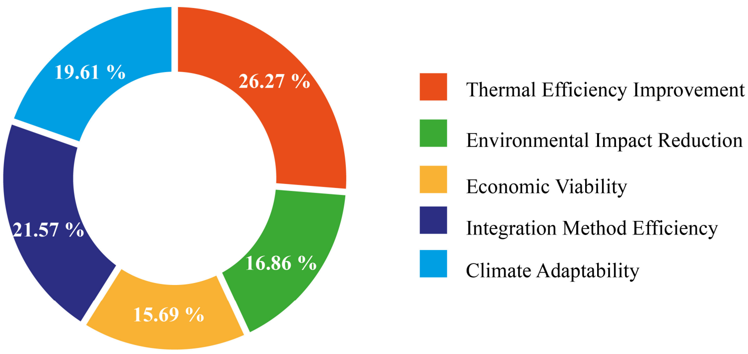

Figure 3. Distribution of the papers published during 2022–2025 on the use of PCMs in buildings according to the five criteria analyzed in the present paper.

5.1. Methodological Influence on Performance Variability

The energy savings associated with phase change materials (PCMs) in building applications are significantly influenced by experimental methodologies and encapsulation techniques. Research indicates that hot box testing yields more consistent results (±5–8%) compared to in situ monitoring, which can vary by ±15–25% due to external factors like weather and occupancy [52].

Furthermore, encapsulation methods play a crucial role in thermal performance, with macro-encapsulation achieving 15–25% savings, micro-encapsulation 25–35%, and nano-enhanced composites reaching up to 45% [53,54].

This analysis highlights that in the design and evaluation of PCM-based systems, it is essential to consider not only material selection and climatic conditions but also the testing methodology and encapsulation strategy, since both substantially influence the measured performance.

Table 1. Summary of the existing research on the integration of PCMs in buildings according to the five criteria considered in this paper between 2022 and 2025.

Reference	Thermal Efficiency Improvement	Environmental Impact Reduction	Economic Viability	Integration Method Effectiveness	Climate Adaptability
[55]	Enhanced heat transfer via macro-encapsulation in bricks and wallboards	Promotes sustainability with renewable energy integration	Economic viability linked to novel heat exchanger designs	Macro-encapsulation used; topology optimization improves heat transfer	Suitable for passive and active systems in diverse climates
[56]	Improved indoor climate and energy consumption with passive and active PCMs	Addresses CO_2 reduction potential in building applications	Economic challenges discussed with future prospects	Various integration methods including walls, roofs, and windows	Applicable across multiple building components and climates
[57]	Focus on experimental thermal energy storage applications	Limited studies on environmental impact; LCA scarce	Cost analysis limited; payback periods	Emphasis on thermal energy storage; integration methods varied	Research gaps in tropical and cold climates noted
[58]	Significant thermal performance improvements in walls, roofs, and floors	Environmental benefits through energy demand reduction	Market availability of certified PCM products	Diverse incorporation methods including mortars and bricks	Wide climatic applicability with emphasis on energy savings
[59]	Increased comfort hours and reduced energy consumption	Climate conditions critical for PCM selection	Economic feasibility linked to multi-objective optimization	Incorporation in constructive systems; focus on tropical climates	Emphasis on tropical and humid regions for PCM use
[60]	Thermal regulation in HVAC and passive design	Environmental benefits via reduced energy use	Cost-effectiveness discussed with nano-enhancements	Micro-encapsulation and hybrid solutions explored	Broad climate applicability with tailored PCM types
[61]	Up to 32.2% energy savings in arid climates	CO_2 reduction up to 12,094 kg/year in warm temperate zones	Payback period as low as 7 years	Optimized PCM integration in mid-rise apartments	Performance evaluated across 15 climate zones globally
[62]	Ceiling cooling reduces room temperature by 3.2 °C	Environmental impact reduced by up to 36%	Cost reduction up to 92% compared to mechanical cooling	Passive and active systems combined with fans and coolers	Hot–dry climate focus with ventilation scenarios
[63]	Electrical efficiency increased by up to 13.3% in PVT-PCM hybrid	Carbon emissions reduced by 32%	Payback period of 1.58 years	Water-based PCM capsules in hybrid solar systems	Year-round performance in hot–dry climate (Cairo)
[64]	Peak temperature reductions of 1–9 °C in various components	Energy savings up to 59% in roofs and walls	Economic impacts vary with encapsulation and PCM type	Encapsulation dominant; dopamine-coated capsules improve durability	South-facing walls and roofs optimized for climate

Table 1. *Cont.*

Reference	Thermal Efficiency Improvement	Environmental Impact Reduction	Economic Viability	Integration Method Effectiveness	Climate Adaptability
[65]	PCM integration reduces energy consumption in walls and roofs	Thermal comfort improved in light weight constructions	Economic benefits noted; payback periods vary	Direct incorporation and encapsulation methods compared	Impact of climatic conditions considered in the envelope design
[66]	Energy reductions from 14 to 90% with passive PCM cooling	Environmental benefits through reduced cooling loads	Scalability and cost challenges under investigation	Passive cooling enhanced by solar control and ventilation	Effective in hot climates with nocturnal radiative cooling
[67]	Cooling/heating load reductions and thermal comfort improvements	Environmental impact discussed with energy savings	Economic viability linked to PCM properties and location	Incorporation techniques and modeling approaches reviewed	Emphasis on roof and exterior wall applications
[68]	Increased comfort hours and energy savings in tropical climates	Climate conditions critical for PCM selection	Multi-objective simulations optimize cost and performance	Incorporation and application criteria analyzed	Tropical and humid climates prioritized
[69]	Solar PCM systems improve indoor heating/cooling efficiency	Environmental benefits tied to renewable energy use	Payback periods range from 6 to 30 years	Active heat exchangers preferred over passive systems	Hybrid systems for commercial buildings emphasized
[70]	Heating and cooling energy savings up to 54% and 50%	Reduced CO_2 emissions with radiant systems	Payback periods as low as 3.32 years	Integration with radiant heating/cooling systems	Limited studies on dual-mode systems; future research needed
[71]	Heating load reduced by 24%, and cooling by 12% with PCMs	CO_2 emissions reduced by nearly 50% with PV and PCM	Combined PV and PCM systems maintain energy balance	PCM on walls and ceilings with/without PV panels	Case study in Tehran with mixed climate effects
[32]	Cooling load reduced by 52% using PCM and insulation	GHG emissions decreased by 39% in semiarid climate	Economic analysis not detailed	PCM combined with recycled textile insulation	Semi-arid climate focus with bioclimatic design
[72]	Energy consumption mitigated using PCM and double-skin façades	Climate change scenarios considered for environmental impact	Economic aspects not deeply analyzed	BIM and EnergyPlus used for PCM and façade integration	Office buildings in Iran under future climate scenarios
[73]	Thermal comfort improved in hot climates; limited cold climate data	Limited GHG emission reduction evidence; VOC emissions noted	Economic analysis sparse; health impact studies lacking	PCM integration effects on indoor air quality reviewed	Diverse climates studied; gaps in cold regions identified

Table 1. *Cont.*

Reference	Thermal Efficiency Improvement	Environmental Impact Reduction	Economic Viability	Integration Method Effectiveness	Climate Adaptability
[74]	PCM bricks reduce indoor temperature fluctuations	Energy savings and construction cost analyzed	Lack of high-precision simulation methods	Form stabilization and macro-encapsulation dominant	Ventilation and insulation combined with PCM bricks
[75]	PCM in brick walls reduces energy consumption and temperature swings	CO_2 emissions decreased with PCM brick integration	Economic viability linked to PCM type and quantity	Various integration techniques in brick walls reviewed	Promising for diverse climates with brick construction
[76]	PCM reduces indoor temperature by ~4.5 °C in photovoltaic systems	Thermal load leveling decreased by up to 7%	Economic benefits from improved PV output	PCM integrated with building-integrated photovoltaics	Inclined roofs preferred for cyclic PCM performance
[77]	PCM-incorporated cementitious materials reduce thermal swings	Environmental benefits through energy savings	Negative impacts on mechanical properties noted	Direct incorporation, encapsulation, and admixture compared	Challenges in durability and commercial viability
[78]	Bio-based PCMs reduce conditioning loads in moderate climates	Lifecycle carbon emissions vary; recycled bio-PCMs are promising	Economic barriers and usage limitations discussed	Passive thermal storage with bio-based PCMs	Moderate climates favored; research gaps in lifecycle impacts
[79]	84.3% primary energy reduction with solar PCM geothermal system	Operating costs reduced by 79.7%	Payback period of 8.7 years despite higher installation cost	Innovative self-learning control with PCM storage	Moderate continental climate with renewable integration
[80]	PCM contributes to significant energy savings in buildings	Environmental benefits include reduced carbon footprints	Cost–benefit analyses highlight PCM advantages	PCM among advanced materials for sustainable buildings	Broad applicability across building types and climates
[81]	Cementitious composites with PCM improve thermal regulation	Environmental impact linked to reduced energy use	Mechanical strength and durability challenges	Direct incorporation and encapsulation methods evaluated	Building applications with experimental and modeled studies
[82]	PCM-enhanced insulation materials reduce energy consumption	Environmental focus on sustainable insulation development	Economic aspects of insulation materials discussed	PCM combined with insulation foams and panels	Historical and innovative materials for diverse climates
[83]	PCM applications improve energy efficiency across industries	Environmental benefits include carbon emission reductions	Economic feasibility varies by application sector	Diverse PCM technologies and enhancements reviewed	Building sector among key application areas

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Table 1. *Cont.*

Reference	Thermal Efficiency Improvement	Environmental Impact Reduction	Economic Viability	Integration Method Effectiveness	Climate Adaptability
[84]	PCM integration delays heat peaks and reduces thermal fluctuations	Environmental concerns include fire hazards and toxicity	Higher initial costs balanced by energy savings	Macro-encapsulation and micro/nano-encapsulation compared	Hybrid technologies enhance climate adaptability
[85]	Energy savings up to 85.3% with PCM and controlled ventilation	Carbon emissions reduced by up to 42,004 kg CO_2/year	Payback period as short as 5 years in temperate climates	Controlled natural ventilation enhances PCM effectiveness	Performance evaluated across 45 cities and 15 climate zones
[86]	Energy savings up to 38% with optimized PCM parameters	Economic viability linked to PCM cost thresholds	Orientation and location critical for cost effectiveness	Roof and wall PCM distribution prioritized	China–Japan comparison highlights climate-specific suitability
[87]	Energy consumption and CO_2 emissions reduced up to 48% and 53%	Lifecycle cost savings up to 30%	Optimization balances energy, cost, and emissions	PCM melting temperature, thickness, and location optimized	Tropical climates with diverse wall types analyzed
[88]	Energy savings up to 18.7% with optimal PCM wall boards	CO_2 reductions up to 38% for natural gas	Payback periods vary with PCM properties and climate	PCM melting temperature and transition range critical	U.S. cities with diverse climates studied
[89]	PCM delays peak temperature time in high-temperature envelopes	Energy efficiency improved by reducing cooling demand	Selection of PCM critical for high-temperature climates	Insulation density and thermal conductivity influence	Challenges in extreme heat environments addressed
[31]	PCM moderates indoor temperature fluctuations effectively	Environmental benefits include reduced carbon emissions	Cost–benefit analyses support PCM adoption	Macro-encapsulation prevalent; nano-enhancements explored	Diverse climates and building types considered
[90]	Thermal performance enhanced with BioPCM in moderate climates	GHG emissions reduced significantly with PCM use	Payback period estimated at four years	PCM thickness and placement optimized	Moderate and hot–dry climates compared
[91]	Bio-based and paraffin PCMs reduce cooling energy demand	Energy savings depend on PCM placement and thickness	Optimal PCM thickness varies; economic analysis limited	External envelope integration studied	Case study in Iran with cooling and heating systems
[92]	Indoor temperature reduced by 2–3 °C with PCM composite	Energy consumption reduced by up to 33.4% in summer	Economic and environmental benefits demonstrated	PCM positioned on roof and walls	Small-scale room model with seasonal analysis

Table 1. *Cont.*

Reference	Thermal Efficiency Improvement	Environmental Impact Reduction	Economic Viability	Integration Method Effectiveness	Climate Adaptability
[93]	PCM reduces indoor temperature fluctuations and energy demand	Environmental benefits through load reduction and shifting	Thermal conductivity limitations addressed with fillers	Nano/micro-fillers improve PCM thermal conductivity	Passive cooling focus with thermal energy storage
[94]	R-value increased by 84.9% with PCM-enhanced walls	Indoor discomfort hours reduced by 15.8% annually	Simulation indicates cost effectiveness	Biocomposite PCM with 20 mm thickness used	Hot and humid climate simulation in India
[95]	Macro-encapsulation in facades improves thermal comfort	PCM performance varies with climate and placement	Limitations of PCM types analyzed for Indian climates	Macro-encapsulation is dominant in façade applications	Indian cities with diverse climates compared
[96]	Annual energy savings between 11 and 13.4% with PCM	Cooling and heating loads significantly reduced	PCM selection critical for Mediterranean climates	PCM integrated into building envelopes	Coastal Mediterranean climate case study
[97]	PCM placement reduces temperature and humidity fluctuations	Heat and moisture loads decreased by up to 69.6%	Energy efficiency improved with optimized PCM placement	Bio-based PCM in concrete structures	Performance optimized for summer and winter
[98]	Mortars with form-stable PCMs mitigate indoor temperature swings	Heating and cooling cost reductions demonstrated	Sustainable PCM development using waste materials	PCM incorporated in mortar formulations	Mediterranean climate simulated in climatic chamber
[99]	Heating savings up to 26.6%, cooling up to 17.5% with PCM	Overall energy reductions of 24.1% in retrofitting	PCM thickness and location influence payback	PCM applied to walls, ceilings, and combined	Mediterranean climate retrofit case study
[100]	Dynamic PCM–biomaterial walls reduce temperature fluctuations	Energy savings significant; moisture control improved	Multi-objective optimization balances cost and energy	Dynamic integration method enhances hygrothermal performance	Humid and temperate climates evaluated

5.1.1. Thermal Efficiency Improvement

Numerous studies demonstrate significant improvements in thermal regulation and energy savings through PCM integration in walls, roofs, and façades, with reductions in indoor temperature fluctuations and peak loads validated by both simulations and experiments across various climates [38,39,48,49,67]. Passive PCM systems effectively delay heat transfer and reduce cooling/heating demands, enhancing occupant comfort [49,77]. Hybrid systems combining PCMs with solar or HVAC technologies show promising synergistic effects [46,52,66].

In total, 48 studies found that PCM integration significantly reduces heating and cooling energy demands, with reductions ranging from moderate (11%) to substantial (over 80%) depending on system design and climate [44,62,70].

In total, 12 studies emphasized the importance of PCMs' melting temperature and placement optimization to maximize thermal efficiency across different building components and climates [66,71,77].

In total, seven studies reported that hybrid systems combining PCMs with solar or ventilation technologies further enhance thermal performance beyond passive PCM use alone [38,46,68].

Some studies noted limitations in extreme climates where PCM effectiveness is reduced due to incomplete phase change cycles [56,72].

Despite positive results, inconsistencies exist in reported thermal performance due to differences in PCM properties, melting temperatures, and integration methods [71,72]. Many studies rely heavily on simulations with limited full-scale experimental validation, reducing confidence in real-world applicability [40,53]. The slow thermal response of PCMs and challenges in optimizing their placement within building envelopes remain unresolved [53,67].

5.1.2. Environmental Impact Reduction

Research highlights the potential of phase change materials (PCMs) to reduce greenhouse gas emissions by lowering energy consumption. Some studies have quantified CO_2 reductions of up to 50% in specific climates [28,44,68,73]. Lifecycle assessments and environmental analyses are emerging that incorporate the carbon intensity of electricity generation and embodied emissions [61,68]. Additionally, bio-based PCMs present opportunities for lower embodied carbon and sustainability benefits [61,80].

In total, 35 studies demonstrated measurable reductions in greenhouse gas emissions and carbon footprints attributable to PCM-enhanced buildings, with CO_2 reductions up to 50% in some cases [44,54,73].

In total, eight studies highlighted the role of PCM integration in lowering peak energy demand, thereby reducing reliance on fossil-fuel-based electricity and associated emissions [62,68,79].

A few studies identified gaps in long-term environmental impact assessments, especially regarding lifecycle emissions and indoor air quality concerns [56,61].

Environmental impact assessments are sparse and often limited to short-term or partial analyses, with few comprehensive lifecycle assessments available [40,56]. Potential indoor air quality issues and the emissions of volatile organic compounds from PCMs are underexplored [73]. The long-term environmental benefits remain uncertain due to limited data on durability and recyclability [56,78].

5.1.3. Economic Viability

Several studies provide economic evaluations indicating payback periods ranging from 3 to 9 years, depending on climate and system configuration [44,46,53,62,68,73]. Cost–

benefit analyses consider installation, operational savings, and maintenance, supporting PCM viability in both retrofit and new construction contexts [62,69]. Hybrid and active systems demonstrate improved economic returns when integrated with renewable energy sources [46,52].

In total, 30 studies reported payback periods ranging from as short as 1.5 years to over 30 years, heavily influenced by PCM type, integration method, and local energy costs [46,52,62].

In total, ten studies emphasized that optimized PCM placement and integration with renewable energy systems [54,68,82] improve economic feasibility.

Several studies noted that initial installation costs and durability concerns remain barriers to widespread adoption despite long-term savings [60,72].

Economic analyses are often simplified and lack comprehensive cost modeling, including lifecycle costs, maintenance, and replacement [40,53]. High initial costs and uncertainties in long-term performance hinder widespread adoption [60,78]. Variability in PCM prices and a lack of standardized cost data complicate economic comparisons [30]. Few studies address economic feasibility in tropical and developing regions with substantial PCM benefits [42,51].

5.1.4. Integration Method Efficiency

The literature covers diverse PCM incorporation techniques such as macro-encapsulation, micro/nano-encapsulation, form stabilization, and direct incorporation into bricks, mortars, and wallboards [38,57,60,66,67]. Studies demonstrate tailored PCM integration in walls, roofs, ceilings, and façades, optimizing thermal performance according to component and climate [58,66,71,79]. Hybrid systems combining PCMs with photovoltaics or ventilation systems show enhanced multifunctionality [46,59,68].

In total, 28 studies found macro-encapsulation to be the most practical and widely used method, offering good thermal performance and ease of installation [38,57,78].

In total, 15 studies discussed micro-encapsulation and nano-enhancements as promising for improving thermal conductivity and mechanical stability, but noted higher costs and complexity [43,67,76].

In total, 12 studies evaluated direct incorporation methods, often highlighting mechanical property degradation and durability challenges [60,64].

Hybrid integration approaches combining PCM with other building technologies showed enhanced performance but require further research [52,67].

Siddesh et al. [81] reported that the encapsulation methods have a significant effect on the thermal conductivity and stability, with no consensus on best practices [38,78]. Many studies focus on laboratory-scale or simulation models, with limited full-scale implementation data [40,67]. The influence of PCM placement and thickness requires further optimization [80,82].

5.1.5. Climate Adaptability

Studies cover various climates, including hot–dry, tropical, Mediterranean, temperate, and cold regions, demonstrating PCM adaptability [28,44,70,73,79]. Research emphasizes the importance of climate-specific PCM selection, melting temperature optimization, and system design [69,71,79], and humid climates are gaining attention, addressing previous research gaps [42,51,70].

In total, 40 studies confirmed that PCM performance is highly climate dependent, with optimal melting temperatures and integration strategies varying significantly between tropical, temperate, arid, and Mediterranean zones [42,70,79].

In total, ten studies stressed the need for climate-specific PCM selection and placement to maximize energy savings and occupant comfort [69,73,82].

Some research identified gaps in PCM application in cold climates and tropical humid regions, indicating areas for future investigation [40,51,56].

Other studies showed that combining PCM with ventilation or solar systems can improve adaptability across diverse climates [46,68].

Despite progress, research remains unevenly distributed geographically, with an underrepresentation of tropical and cold climates in experimental studies [40,56]. Many findings are climate specific, limiting their generalizability [26,70]. The influence of extreme weather events and climate change on PCM performance is insufficiently addressed [55,82]. Table 2 reports the most recommended PCM properties adapted to the climate conditions [94–97].

Table 2. PCM characteristics recommended according to the climate type.

Climate Type	Main Objective	Recommended PCM Melting Temperature	Typical PCM Placement	Recommended Thickness
Hot–dry (desert and arid)	• Reduce overheating • Delay heat flow	28–35 °C	Roof External walls	20–50 mm
Hot–humid	• Limit indoor temperature peaks	26–32 °C	Internal walls ceilings	15–40 mm
Cold (Continental and Nordic)	• Store solar heat • Reduce heating load	18–24 °C	South facing walls floors	10–30 mm
Mediterranean	• Stabilize daily temperature swings	22–28 °C	Walls and ceilings	15–40 mm
Temperate	• Improve thermal inertia	20–26 °C	Internal partitions	10–30 mm

6. Critical Analysis and Synthesis

The reviewed literature on phase change materials (PCMs) in building integration reveals a robust interest in their potential to enhance thermal efficiency, reduce environmental impact, and offer economic benefits. Strengths include comprehensive experimental and simulation studies across diverse climates and building components, and innovative integration techniques such as macro-encapsulation and hybrid systems. However, significant gaps remain in relation to standardizing methodologies, addressing long-term durability, and fully quantifying environmental and economic impacts. The variability in PCM types, climatic conditions, and building applications complicates direct comparisons and generalizations. Moreover, while passive systems show promise, active and hybrid systems require further optimization and cost–benefit validation. Overall, the literature underscores the transformative potential of PCMs but calls for more integrated, multidisciplinary research to overcome current limitations and realize their widespread adoption.

7. Technical Integration of Passive, Active, and Hybrid Systems with PCM in Building

Passive PCM systems are well-documented for their simplicity and energy-saving potential, especially in thermal mass enhancement and passive cooling [49,76,77]. Active systems incorporating PCMs with HVAC or solar thermal technologies demonstrate improved control and efficiency [46,52,53]. Hybrid systems, combining passive and active elements, offer promising pathways for maximizing benefits and adapting to variable climates [38,52,66].

7.1. Passive Integration Systems

Passive phase change material (PCM) systems incorporate thermal storage directly within the components of the building envelope, facilitating continuous thermal management without the need for external energy inputs or intricate control mechanisms [101–103]. This integration method presents the benefit of simplicity while simultaneously enhancing thermal comfort and yielding substantial energy savings. The integration within the building envelope encompasses wall assemblies, roof systems, and enhancements to fenestration.

The fundamental principle of passive integration entails embedding PCMs into construction materials so that these materials undergo phase transitions during the regular thermal cycles experienced by buildings. During warmer periods, PCMs absorb surplus thermal energy via melting, diminishing heat transfer into the building's interior [104]. Conversely, PCMs release the stored thermal energy through solidification in cooler periods, thereby delivering advantageous heating effects.

Recent investigations have indicated that the strategic integration of PCMs in building envelopes can result in annual energy savings ranging from 15% to 45%, contingent upon climatic conditions, building typology, and system design [90]. These energy savings arise from a reduction in HVAC system operation, attributed to the enhanced thermal regulation afforded by the thermal mass effects of PCMs.

7.1.1. Wall System Applications

PCM-enhanced concrete and masonry systems are regarded as one of the most thoroughly researched methodologies for passive integration. Extensive experimental assessments have illustrated remarkable enhancements in performance across diverse climatic conditions. The investigation employs stringent hot box testing protocols alongside calibrated heat flux sensors to measure improvements in thermal performance accurately.

Recent research has reported reductions in cooling loads of up to 63% compared to traditional wall systems. Documented surface temperature reductions of 5.2 °C indicate an approximate 10% enhancement in thermal performance relative to baseline systems [105–107]. The optimal proportion of PCM for concrete applications has been established at 20% by mass to achieve maximal efficiency while preserving structural integrity [106].

These systems exhibit reliable performance across 300 complete thermal cycles without significant deterioration [94,95]. The method of PCM integration involves direct combination with the cement matrix, utilizing phase change temperatures optimized explicitly for the range of 25–28 °C [108]. The resultant composite systems manifest thermal storage capacities of 80–120 J/g while sustaining compressive strengths exceeding 85% of those in traditional concrete [109].

PCM-enhanced wallboard systems present considerable promise for building retrofitting applications due to their ease of installation and remarkable compatibility with current construction practices. These systems achieve an optimal PCM mass loading of 15–25%, resulting in thermal capacity enhancements of 2–3 times compared to conventional gypsum performance [110]. Reduced temperature fluctuations of 40–60% relative to baseline systems have been recorded [110].

Sophisticated formulation techniques encompass micro-encapsulated PCM integration to avert leakage and preserve board integrity. Developing form-stable composites eliminates the need for liquid PCM handling during installation and operational phases. Multi-layer configurations improve thermal performance by strategically placing PCM within the wallboard structure.

7.1.2. Roof and Attic Applications

Comprehensive roof integration presents substantial potential for reducing cooling loads, particularly in hot climates where roofing surfaces are subjected to severe solar heating. Recent investigations highlight remarkable performance outcomes achieved through the deliberate placement of phase change materials (PCM) and the optimization of system configurations.

Quantified performance advantages encompass reductions in surface temperatures reaching up to 23 °C during peak solar exposure. Documented decreases in heat flux range from 13 to 20 W/m^2, contingent upon the distinctive characteristics of the climate zone [111]. Such enhancements lead to delays in cooling system operations, extending approximately 10 days during transitional seasons, resulting in significant energy conservation.

Technical methodologies for implementation encompass the direct integration of PCM within roofing membrane systems to maximize thermal contact. Modular PCM panels yield prefabricated systems that facilitate straightforward installation and maintenance. Hybrid roofing solutions merge PCM integration with reflective surfaces and ventilation systems to bolster overall performance.

Attic PCM systems offer proficient thermal buffering between external environmental conditions and conditioned indoor spaces. Performance evaluations indicate peak temperature reductions around 8–15 °C during severe weather events [62]. Comprehensive monitoring studies have documented cooling load reductions ranging from 20% to 35% of the total cooling demands of the building [62].

Options for system configuration include loose-fill PCM systems designed for direct application within attic environments. Encapsulated PCM modules provide systems that simplify maintenance and replacement; integrated ventilation systems amalgamate PCM thermal storage with natural ventilation to enhance cooling efficiency.

7.1.3. Fenestration and Glazing Integration

PCM-infused glazing assemblies present an exceptional amalgamation of natural illumination facilitation and thermal energy accumulation capabilities. Technological advancements have led to noteworthy improvements in optical and thermal performance attributes. These systems facilitate dynamic thermal management while ensuring visual continuity with the external environment.

The optical and thermal performance attributes encompass a visible light transmittance range of 60–80% in the solid state, exhibiting varying transmission levels during phase transition intervals [112]. The coefficients for solar heat gain reflect dynamic fluctuations corresponding to the PCM phase state, thereby allowing for adaptive solar regulation. Thermal storage abilities of 100–200 kJ/m^2 of the glazing surface area afford significant thermal buffering effects [113].

Cutting-edge technologies incorporate multi-layered glazing arrangements to enhance thermal performance through several PCM layers. Selective optical properties enable transmission characteristics contingent upon wavelength, enhancing natural illumination, and the thermal management integration of dynamic shading merges PCM systems with automated shading solutions for peak efficiency under diverse conditions.

The incorporation of control systems allows for automated functionality based on the intensity of solar radiation and the necessary indoor temperature. These intelligent glazing systems exemplify the potential for responsive building envelope elements that adjust to fluctuating environmental circumstances while ensuring occupant comfort and visual integrity.

In summary, passive PCM integration in walls, roofs, and glazing consistently reduces building energy demand by 15–45%, with payback periods typically between 8 and 15 years. These systems are most effective in hot–dry and Mediterranean climates when the PCM melting temperature is matched to local conditions (26–35 °C). While simple and reliable, their performance is limited by slow thermal response and reduced efficiency in extreme or highly variable climates.

7.2. Active Integration Systems

7.2.1. HVAC System Integration

Active phase change material (PCM) systems combine thermal storage with heating, ventilation, and air conditioning (HVAC) devices to increase performance, enhance energy efficiency, and improve peak demand management functionalities. These systems employ mechanical and control mechanisms to refine PCM charging and discharging cycles in accordance with the thermal requirements of the building and the pricing structures of utilities.

The primary benefit of active integration lies in its ability to meticulously regulate the timing of thermal storage and release, thereby facilitating strategic energy management and interactions with the grid. Active systems can effectively redistribute building energy usage from peak utility demand times to off-peak periods while preserving ideal thermal comfort levels. This functionality yields savings in energy costs and contributes to grid stability support services.

Recent investigations have indicated that integrating active PCM with HVAC systems can reduce energy consumption by 20–40% compared to traditional systems [101,102]. Documented peak demand reductions of 40–70% have been observed during periods of maximum load [104]. These enhancements in performance are attributable to the optimized deployment of thermal storage and the capability for load shifting.

7.2.2. Heat Pump Integration Systems

The comprehensive integration of heat pump systems exemplifies one of the most advantageous strategies for active system integration, showcasing significant enhancements in efficiency and capabilities for peak demand management. Recent scholarly investigations have implemented advanced optimization control methodologies, including mixed-integer linear programming, to achieve optimal charge and discharge scheduling [114–117].

These control methodologies leverage the integration of real-time electricity pricing for dynamic optimization aligned with time-of-use tariffs. The inclusion of weather forecasting facilitates predictive horizons spanning 24 to 72 h, thereby aiding in the formulation of optimal scheduling decisions. Building thermal load forecasting employs machine learning techniques to enhance accuracy in demand prediction and system optimization.

Quantifiable performance improvements indicate enhancements in system efficiency ranging from 25% to 35% compared to traditional heat pump systems [114]. The strategic implementation of thermal storage has resulted in peak demand reductions between 40% and 60% [115]. Optimal phase change material (PCM) melting temperatures, identified as being within the range of 35 °C to 45 °C, have been established to optimize heat pump applications across varying operational conditions [116].

Integrating air-source heat pumps reveals remarkable potential for residential and small-scale commercial applications. The technical execution encompasses PCM storage capacity specifications of 0.5 to 2.0 kWh per kW of heat pump capacity [117,118]. The optimization of charge and discharge rates achieves a range of 0.2 to 0.8 kW per kWh of storage capacity, ensuring optimal system functionality [119].

The systems exhibit improvements in the coefficient of performance between 15% and 25% during standard operational phases. Reductions in primary energy consumption are documented at 20% to 30%, resulting in notable annual cost savings [119]. Carbon emission reductions of 25–35% contribute to environmental sustainability objectives while maintaining superior thermal comfort [120].

7.2.3. Air Handling Unit Enhancement

Modified air handling units equipped with integrated phase change material (PCM) thermal storage, heat recovery mechanisms, and solar energy systems significantly enhance energy and exergy performance. Recent studies have performed an exhaustive evaluation, uncovering notable improvements across various performance indicators.

The thorough evaluation reveals annual energy exchange reductions of 687 kWh per unit in contrast to traditional air handling unit (AHU) setups. Enhancements in systems' coefficient of performance (COP) ranging from 20% to 30% have been realized compared to baseline configurations. Additionally, peak cooling load reductions of 35% to 50% during maximum demand yield considerable benefits to infrastructure [121].

The optimization of systems employs advanced energy and exergy analysis techniques to optimize multiple parameters simultaneously. The selection and sizing of PCM quantities and their thermal characteristics are tailored for specific applications. The design and sizing of heat exchangers encompass surface area and configuration parameters aimed at improving overall performance.

The parameter tuning of control strategies incorporates temperature setpoints and operational schedules to achieve maximum efficiency. Integrating solar collectors facilitates the alignment with renewable energy systems, promoting comprehensive sustainability. An assessment of integration complexity indicates a moderate level of complexity involving standard HVAC components, making practical implementation feasible.

7.2.4. Thermal Energy Storage Systems

Implementing extensive thermal energy storage for community-level applications reveals significant performance and economic feasibility enhancements. Recent investigations have explored the thorough optimization of integrated heat pump and thermal energy storage systems, yielding impressive outcomes.

Metrics of community-scale performance indicate that energy conservation is 30–45% in overall community energy use. Additionally, reductions in the peak demand of 50–70% signify a substantial decrease in maximum simultaneous demand on utility infrastructure [122]. Furthermore, carbon emission reductions ranging from 40 to 60% offer considerable environmental advantages in achieving community sustainability goals [123].

The optimization of multi-objective systems utilizes advanced algorithms that simultaneously address various conflicting objectives. Strategies aimed at minimizing energy costs concentrate on reducing operational expenses through optimal scheduling practices. The emphasis on reducing carbon emissions highlights the importance of minimizing environmental impact via integrating renewable energy sources and enhancements in efficiency.

Managing peak demand contributes to providing grid stability support services while ensuring the thermal comfort of the community. Reliability and redundancy in the system design guarantee a resilient framework for uninterrupted operation. An economic viability assessment indicates promising returns when supported by suitable policy frameworks and utility pricing structures.

Overall, active PCM systems coupled with HVAC or heat pumps achieve higher energy savings (20–40%) and shorter payback periods (3–8 years) than passive approaches, primarily through load shifting and improved COP. Their performance depends critically on control strategies and PCM selection (optimal melting range: 35–45 °C). However, increased system complexity and higher upfront costs remain barriers to their widespread adoption.

7.3. Hybrid Integration Systems

7.3.1. Combined Passive–Active Approaches

Hybrid phase change material (PCM) systems strategically combine passive envelope integration with active HVAC coupling to attain enhanced performance metrics in contrast to isolated methodologies. These systems exploit the continuous thermal regulation advantages of passive integration, while simultaneously incorporating the precise control capabilities characteristic of active systems. The outcome is an optimized energy efficiency, improved thermal comfort, and enhanced interaction with the electrical grid.

The primary benefit of hybrid methodologies lies in the synergistic interactions between passive and active elements. Passive integration delivers foundational thermal regulation and mitigates peak load demands through the thermal mass effects inherent in the building envelope. Conversely, active components facilitate the meticulous adjustment of thermal conditions and strategic energy management via regulated charge and discharge cycles.

Recent scholarly investigations have indicated that hybrid PCM systems can realize energy savings of up to 50%, categorizing them within the highest echelons of integration methodologies [123]. These exceptional outcomes arise from the complementary dynamics between passive thermal regulation and the optimization of active thermal storage. Nonetheless, hybrid systems necessitate sophisticated control mechanisms and substantial initial capital outlays.

Configuration strategies for these systems encompass the strategic distribution of PCMs across various building envelope components, complemented by centralized thermal storage systems. Multi-zone coordination fosters comprehensive thermal management at the building level, offering individualized control capabilities. Cutting-edge building automation systems deliver the integrated oversight of all PCM elements to ensure optimal operational performance.

7.3.2. Intelligent Control Systems

High-level control systems crafted for hybrid PCM contexts harness model predictive control (MPC) methodologies recognized for their remarkable prediction functionalities. These platforms merge climate predictions with forecasting windows of 24–72 h to develop superior pre-conditioning techniques [124]. Refreshing thermal models of buildings promote live calibration, elevating accuracy and optimizing performance achievements.

Considering fluctuating energy pricing frameworks, the control mechanisms encompass optimal charge and discharge scheduling for economic efficiency [125]. Multi-zone coordination yields a comprehensive approach to thermal management at the building level, while allowing for personalized comfort regulation [126]. Equipment longevity is enhanced through reduced cycling and the maintenance of optimal operational points during system usage.

The blending of machine learning encourages progressive independent optimization via the utilization of artificial intelligence systems. Neural network applications facilitate PCM state estimation, allowing for real-time solid fraction and temperature distribution predictions. Capabilities of performance forecasting provide long-term maintenance planning and optimization insights for the system's efficiency.

Adaptive tuning of control parameters promotes self-optimizing operations that consistently enhance performance metrics. By leveraging fault detection and diagnostics, we can achieve an automated oversight of system health, facilitating preventive maintenance initiatives [127]. Reinforcement learning frameworks empower self-optimizing control strategies to adjust to different operational scenarios.

7.3.3. Grid Integration and Demand Response

Future hybrid phase change material (PCM) systems will integrate fluidly with innovative grid frameworks, offering distributed thermal storage functionalities that bolster grid resilience and facilitate the assimilation of renewable energy sources. Such systems will enable buildings to engage in demand response initiatives while ensuring optimal thermal comfort for their inhabitants.

The integration of PCM enables buildings to store thermal energy and shift heating and cooling loads away from peak demand periods. This thermal flexibility allows PCM-equipped buildings to reduce electricity consumption during peak hours and better align their energy use with renewable energy availability. Blockchain-facilitated energy trading performance provides a secure and transparent framework to valorize this flexibility by enabling buildings to participate in peer-to-peer (P2P) energy markets and demand–response programs. In this context, PCMs act as physical thermal storage systems, while blockchain technologies enable the economic exchange and management of flexibility services, contributing to grid stability, reduced energy, costs, and improved building energy performance.

Automated energy transactions and system optimization will be facilitated by smart contracts, ensuring adherence to grid stability and building performance standards. These advanced integration capabilities establish hybrid PCM systems as pivotal technologies for the future of intelligent building and grid infrastructures.

With limited standardized integration frameworks, active and hybrid systems face design, control, and cost complexities [38,53]. The slow thermal response of PCM challenges dynamic control in active systems [70]. Scalability and reliability issues remain for hybrid solutions, and their economic viability is less established than passive systems [52,53].

Table 3 summarizes the key factors influencing PCM system efficiency, highlighting their effects on performance, quantitative relationships where available, and practical considerations for design and optimization [38,46,52,53,67,124].

Hybrid systems combining passive and active strategies represent the highest-performing configuration, with reported energy savings of up to 50%. Their strength lies in their synergistic capacity for temperature regulation and adaptive control, especially when integrated with AI-driven algorithms. Nevertheless, economic viability is still case specific, and long-term field data remain scarce compared to passive systems.

Table 3. Key factors influencing PCM system.

Influencing Factor	Effect of PCM Performance	Quantitative Insights/Relationships	Notes/Examples
PCM thickness	Affects heat storage capacity and thermal response time	Thermal response time roughly increases linearly with thickness (doubling PCM thickness can nearly double melting/solidification time)	Optimal thickness balances energy storage vs. responsiveness in building or device applications
Encapsulation method	Enhance thermal stability, reduce leakage, and improve thermal conductivity	Micro/nano-encapsulation can increase effective thermal conductivity by 50–300% depending on shell material and PCM type.	Polymer shells improve stability; metal- or carbon-based shells enhance conductivity
PCM thermal conductivity	Directly impacts charging/discharging rate	Pure organic PCMs: 0.2 W/m·K adding conductive fillers (graphite, Al, and Cu) can increase to 1–5 W/m·K reducing melting/solidification time significantly.	Low conductivity limits efficiency for thicker PCM layers
System control strategy	Control heat input/output to optimize comfort or energy efficiency	Smart control with predictive algorithms can reduce peak temperature overshoot by 10–20% and improve utilization factor.	Integration with HVAC or building automation enhances practical energy savings
PCM Type/phase change Temperature	Determines usable temperature range and effectiveness	Selection based on target environment; mismatch leads to underutilization or incomplete phase change	Fatty acids (25–35 °C) and paraffins (20–60 °C) for building thermal storage
Cycling/stability	Repeated melting/solidification can degrade PCM performance	Degradation typically observed after 500–1000 cycles for unprotected bio-based PCMs; encapsulation extends lifespan > 2000 cycles	Important for assessing lifecycle performance and cost effectiveness

7.4. PV–PCM Integration for Building-Integrated Renewable Energy

A growing frontier in building energy systems is the synergistic integration of photovoltaic (PV) and phase change material (PCM) technologies particularly in photovoltaic–thermal PVT-PCM configurations. These hybrid systems address the dual challenge of electricity generation and thermal management: PV panels convert solar radiation into electricity, while the integrated PCM absorbs excess heat, preventing PV efficiency degradation (typically −0.3% to −0.5%/°C) and simultaneously storing thermal energy for space heating or domestic hot water. Recent studies [59,72] demonstrate that PVT–PCM systems achieve up to a 13.3% higher electrical efficiency and a 30–40% reduction in cooling load compared to standalone PV, with payback periods as short as 1.5–5 years in sunny climates. Crucially, such integration enhances building-level energy autonomy and enables grid-responsive thermal storage, positioning PCM not only as a passive buffer but as an active enabler of renewable flexibility. Future perspectives include scalable facade-integrated PVT–PCM modules, AI-optimized dispatch strategies, and the standardization of performance metrics for multi-energy (electricity + heat) yield assessment.

8. Perspectives

Priority research domains for the forthcoming phase of PCM technology advancement encompass sophisticated material engineering concentrating on organic PCMs with an elevated thermal conductivity aimed at surpassing 1.0 W/m·K. The development of sustainable bio-based alternatives is imperative for ensuring environmental stewardship and realizing potential economic benefits via the utilization of renewable feedstocks.

The advent of innovative adaptive materials provided with integrated sensing functionalities presents transformative prospects for genuinely intelligent building systems. Such materials will be capable of autonomously enhancing thermal efficiency in response to environmental variables and occupants' demands. Innovations in manufacturing are crucial for facilitating cost-effective large-scale production alongside automated installation processes.

The robust validation of long-term PCM performance through extensive field trials is essential for accurately assessing system lifetime and real-world efficiency. To enable reliable performance forecasting, it is imperative to develop standardized accelerated aging protocols and advanced predictive modeling techniques. Concurrently, future advancements in system integration must prioritize AI-driven control strategies and the establishment of universally accepted methodologies for performance evaluation.

The effectiveness of phase change materials (PCMs) in buildings is strongly influenced by local climate conditions. Recent studies confirm that PCMs deliver the highest energy savings (10–30%) and carbon reductions (up to 204 kg CO_2/year) in moderate and hot–dry climates, where daily temperature swings align well with PCM melting ranges [128]. In contrast, performance diminishes in consistently cold or highly humid regions due to incomplete phase cycling or limited thermal driving forces. Despite this variability, PCM integration supports key global sustainability goals, particularly the UN's SDG 7 (affordable clean energy), SDG 11 (Sustainable Cities and Communities) and SDG 13 (climate action), by reducing peak electricity demand and operational emissions. However, fragmented building codes, a lack of climate-specific design guidelines, and insufficient field validation in extreme climates like North America and Southeast Asia remain barriers to equitable global deployment [128,129].

9. Challenges

a. *Technical Limitations and Solutions*

One of the most substantial technical obstacles in implementing phase change materials (PCMs) is organic substances' intrinsically low thermal conductivity, which limits heat transfer rates and the system's levels. This constraint adversely impacts the capability of PCM systems to adapt to fluctuating thermal demands swiftly and diminishes the system's overall efficiency. Contemporary research concentrates on sophisticated enhancement methodologies, including incorporating nanoparticles and developing composite materials.

Thermal cycling stability is another pivotal challenge, particularly for salt hydrate PCMs undergoing supercooling phenomena and phase segregation during prolonged operational durations. Although micro-encapsulation technologies have resolved numerous stability concerns, specific formulations persist in demonstrating performance deterioration following extensive cycling. Long-term field validation studies are critical for establishing dependable performance forecasts.

The fire safety implications for organic PCM systems necessitate thorough assessment and mitigation strategies. Current investigations focus on the formulation of inherently fire-resistant compounds and the establishment of advanced safety testing methodologies. Furthermore, issues regarding the chemical compatibility between PCMs and construction materials require meticulous material selection and system design to ensure sustained performance.

Managing phase separation and crystallization in salt hydrate PCMs demands an ongoing fundamental research focus. The effects of supercooling can diminish practical thermal storage efficiency by 20–40% in actual applications. Advanced nucleation enhancement strategies employing nanoparticles and organic additives exhibit a potential to overcome these challenges.

b. *Economic and Market Barriers*

The significant initial capital expenditures persist as the predominant economic obstacle to the extensive adoption of phase change materials (PCM), with system costs generally ranging from 15% to 30% greater than traditional alternatives. Although lifecycle economic assessments indicate favorable returns, the necessity of substantial upfront investment constrains adoption rates, particularly within price-sensitive market segments.

Market fragmentation and inadequate large-scale production capacity exacerbate price instability and supply chain limitations. The PCM sector is primarily characterized by specialized manufacturers who lack the economies of scale required for competitively priced production. Thus, investment in scaling up manufacturing operations is crucial for realizing desired cost reductions.

Regulatory challenges and compliance with building codes substantially hinder commercial adoption across various jurisdictions. Many regional building codes do not include specific provisions for PCM systems, necessitating costly custom approval procedures. Furthermore, professional training and workforce development pose significant challenges, as construction professionals have a limited comprehension of PCM technology.

The standardization of testing methodologies remains inadequately addressed among research institutions and commercial laboratories. Disparities in testing conditions, measurement methods, and performance evaluation metrics complicate systematic comparisons. Establishing industry standards is vital for facilitating technology transfer and fostering market confidence.

Despite their benefits, there are several practical drawbacks to PCM applications. For example, long-term field data is limited, which raises concerns about durability over a building's lifetime. Some organic PCMs may release volatile compounds that affect indoor air quality. End-of-life management is also problematic, as most PCMs cannot easily be separated from construction materials, which limits their recyclability. Furthermore, the real-world costs of factors such as structural reinforcement or system integration are often underestimated, resulting in longer payback periods than those reported in laboratory studies.

10. Conclusions

This comprehensive analysis of phase change materials' (PCMs') integration within building systems illuminates a technology that has reached significant maturity, offering considerable prospects for widespread commercial adoption. The evaluation indicates that PCM systems yield measurable energy efficiency, improved thermal comfort, and economic feasibility across various building applications and climatic contexts.

Passive integration systems have achieved commercial maturity, demonstrating recorded energy savings ranging from 15% to 45% and favorable payback durations of 8 to 15 years across most applications. These systems are characterized by simplicity and dependability, delivering ongoing thermal regulation advantages. Their successful evolution, reaching market availability through numerous manufacturers indicates their great potential for large-scale implementation.

Active integration systems exhibit enhanced performance capabilities with energy savings between 20% and 40% and expedited payback periods of 3 to 8 years, facilitated by strategic thermal storage and peak demand management techniques. Incorporating advanced control systems and optimization algorithms significantly augments their efficiency, positioning these systems for swift market proliferation in commercial sectors.

Hybrid systems embody the highest performance level, achieving up to 50% energy savings through a synergistic combination of passive and active methodologies. While necessitating sophisticated control systems and elevated initial expenditures, hybrid systems provide exceptional thermal comfort and comprehensive building performance optimization for premium applications.

The economic evaluation indicates progressively advantageous investment returns across all integration methodologies, with market growth forecasts suggesting considerable commercial prospects. Regional market expansion shows the most robust growth in Europe, North America, and Asia Pacific, where supportive policy frameworks and building energy regulations serve as principal catalysts.

Technical obstacles, including limitations in thermal conductivity, cycling stability, and fire safety, warrant ongoing research focus. Nevertheless, substantial advancements through enhanced technologies, innovative materials, and thorough testing offer clear pathways for resolution within the forthcoming 3-to-5-year period.

In light of these factors, PCM technology is balanced to assume a pivotal role in the building sector's decarbonization initiatives, which align with international climate accords. The considerable potential for energy savings, in conjunction with improving economic viability and environmental advantages, positions PCM systems as integral components of sustainable building strategies for the 21st century.

Author Contributions: A.L.: Conceptualization, investigation, methodology, writing—original draft, and writing—review and editing. T.H.: Investigation and writing—review and editing. A.H.: Conceptualization, methodology, and writing—review and editing. M.B.: Conceptualization, methodology, supervision, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data sharing does not apply to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HVAC	Heating, Ventilation, and Air Conditioning
PCMs	Phase Change Materials
CPCMs	Composite Phase Change Materials
MILP	Mixed-Integer Linear Programming
AHUs	Air Handling Units
COP	Coefficient of Performance
BioPCM	Biocomposite Phase Change Materials
MPC	Model Predictive Control
SDG	Sustainable Development Goal
UN SDGs	United Nations' Sustainable Development Goals
SDG 7	Affordable and Clean Energy
SDG 11	Sustainable Cities and Communities
SDG 13	Climate Action

References

1. Tellache, A.; Lazri, Y.; Laafer, A.; Attia, S. Development of a Benchmark Model for Residential Buildings with a Mediterranean Climate: The Aero-Habitat in Algiers City. *Sustainability* **2025**, *17*, 831. [CrossRef]
2. International Energy Agence (IEA). Buildings. 2025. Available online: https://www.iea.org/energy-system/buildings (accessed on 24 June 2025).
3. UNEP. *2022 Global Status Report for Buildings and Construction*; United Nations Environment Programme: Nairobi, Kenya, 2022.
4. IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability*; IPCC: Cambridge, MA, USA, 2022.
5. Gassar, A.A.A.; Cha, S.H. Energy prediction techniques for large-scale buildings towards a sustainable built environment: A review. *Energy Build.* **2020**, *224*, 110238. [CrossRef]
6. Sharma, A.; Tyagi, V.V.; Chen, C.R.; Buddhi, D. Review on thermal energy storage with phase change materials and applications. *Renew. Sustain. Energy Rev.* **2009**, *13*, 318–345. [CrossRef]
7. Farid, M.; Auckaili, A.; Gholamibozanjani, G. *Thermal Energy Storage with Phase Change Materials: Research Contributions of Professor Mohammed Mehdi Farid in Four Decades*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2021; ISBN 978-0-367-56769-9.
8. Cabeza, L.F.; Castell, A.; Barreneche, C.; De Gracia, A.; Fernández, A.I. Materials used as PCM in thermal energy storage in buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1675–1695. [CrossRef]
9. Tyagi, V.V.; Buddhi, D. PCM thermal storage in buildings: A state of art. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1146–1166. [CrossRef]
10. Foual, M.; Sad Chemloul, N.-E.; Chaib, K.; Abdellatif, H.E.; Fellague Chebra, A.; Belaadi, A.; Becheffar, Y.; Laafer, A. Comparative analysis of tube designs in heat exchangers: A numerical simulation study for enhanced thermal-flow efficiency, "optimizing wavy tubes bundle geometries for enhanced heat transfer in underwater applications". *Numer. Heat Transf. Part Appl.* **2026**, *87*, 2369943. [CrossRef]
11. Zhou, D.; Zhao, C.Y.; Tian, Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. *Appl. Energy* **2012**, *92*, 593–605. [CrossRef]
12. De Gracia, A.; Cabeza, L.F. Phase change materials and thermal energy storage for buildings. *Energy Build.* **2015**, *103*, 414–419. [CrossRef]
13. Mehling, H.; Cabeza, L.F. *Heat and Cold Storage with PCM: An Up to Date Introduction into Basics and Applications*; Heat and Mass Transfer; Springer: Berlin/Heidelberg, Germany, 2008; ISBN 978-3-540-68556-2.
14. Husainy, A.; Sawant, S.; Kale, S.; Amouri, A.; Pathan, H. Nano-Enhanced Phase Change Materials: A Novel Approach to Sustainable Refrigeration and Thermal Energy Storage. *ES Gen.* **2025**, *7*, 1408. [CrossRef]
15. Zalba, B.; Marín, J.M.; Cabeza, L.F.; Mehling, H. Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications. *Appl. Therm. Eng.* **2003**, *23*, 251–283. [CrossRef]
16. Pasupathy, A.; Velraj, R.; Seeniraj, R.V. Phase change material-based building architecture for thermal management in residential and commercial establishments. *Renew. Sustain. Energy Rev.* **2008**, *12*, 39–64. [CrossRef]
17. Lauermannová, A.-M.; Lojka, M.; Záleská, M.; Pavlíková, M.; Pivák, A.; Pavlík, Z.; Růžička, K.; Jankovský, O. Magnesium oxychloride cement-based composites for latent heat storage: The effect of the introduction of multi-walled carbon nanotubes. *J. Build. Eng.* **2023**, *72*, 106604. [CrossRef]
18. Kurdi, A.; Almoatham, N.; Mirza, M.; Ballweg, T.; Alkahlan, B. Potential Phase Change Materials in Building Wall Construction—A Review. *Materials* **2021**, *14*, 5328. [CrossRef]
19. Ryms, M.; Haustein, E.; Januszewicz, K.; Lewandowski, W.S.M. Impact of Phase Change Material with Postpyrolytic Char from Recycled Tires as a Carrier on the Properties of Cement Composites. *J. Mater. Civ. Eng.* **2025**, *37*, 04025252. [CrossRef]
20. Ryms, M.; Januszewicz, K.; Haustein, E.; Kazimierski, P.; Lewandowski, W.M. Thermal properties of a cement composite containing phase change materials (PCMs) with post-pyrolytic char obtained from spent tyres as a carrier. *Energy* **2022**, *239*, 121936. [CrossRef]
21. Darkwa, K.; O'Callaghan, P.W. Simulation of phase change drywalls in a passive solar building. *Appl. Therm. Eng.* **2006**, *26*, 853–858. [CrossRef]
22. Castell, A.; Martorell, I.; Medrano, M.; Pérez, G.; Cabeza, L.F. Experimental study of using PCM in brick constructive solutions for passive cooling. *Energy Build.* **2010**, *42*, 534–540. [CrossRef]
23. Kuznik, F.; David, D.; Johannes, K.; Roux, J.-J. A review on phase change materials integrated in building walls. *Renew. Sustain. Energy Rev.* **2011**, *15*, 379–391. [CrossRef]
24. Tyagi, V.V.; Kaushik, S.C.; Tyagi, S.K.; Akiyama, T. Development of phase change materials based microencapsulated technology for buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1373–1391. [CrossRef]
25. Evola, G.; Marletta, L.; Sicurella, F. A methodology for investigating the effectiveness of PCM wallboards for summer thermal comfort in buildings. *Build. Environ.* **2013**, *59*, 517–527. [CrossRef]
26. De Gracia, A.; Navarro, L.; Castell, A.; Ruiz-Pardo, Á.; Álvarez, S.; Cabeza, L.F. Thermal analysis of a ventilated facade with PCM for cooling applications. *Energy Build.* **2013**, *65*, 508–515. [CrossRef]

27. Alrashdan, A.; Ghaleb, A.M.; Ahmad, K.H.; Daoud, A.N. Integration of Phase Change Materials in Service Areas of Building Envelopes for Improved Thermal Performance: An Experimental Study in Saudi Arabia. *Buildings* **2024**, *14*, 904. [CrossRef]
28. Zotova, I.; Gendelis, S.; Kirilovs, E.; Štefanec, D. Thermal Performance of Lignocellulose's By-Product Wallboards with Bio-Based Microencapsulated Phase Change Materials. *Energies* **2024**, *17*, 257. [CrossRef]
29. Kong, X.; Fu, Y.; Yuan, J. Room-temperature flexible phase change material with high emissivity and high enthalpy for building energy saving. *Renew. Energy* **2024**, *235*, 121253. [CrossRef]
30. Liu, B.; Lu, W.; Hu, X.; Zhang, C.; Wang, C.; Qu, Y.; Olofsson, T. Multiscale modeling of thermal properties in Polyurethane incorporated with phase change materials composites: A case study. *arXiv* **2023**, arXiv:2308.13123. [CrossRef]
31. Jha, S.K.; Sankar, A.; Zhou, Y.; Ghosh, A. Incorporation of Phase Change Materials in Buildings. *Constr. Mater.* **2024**, *4*, 676–703. [CrossRef]
32. Imghoure, O.; Belouaggadia, N.; Zaite, A.; Ezzine, M.; Lbibb, R.; Sebaibi, N. Enhancing Energy Efficiency in Moroccan Construction through Innovative Materials: A Case Study in a Semiarid Climate. *Buildings* **2024**, *14*, 3087. [CrossRef]
33. Hmida, A.; Erchiqui, F.; Laafer, A.; Bourouis, M. Energy Efficiency in Buildings Through the Application of Phase Change Materials: An In-Depth Analysis of the Integration of Spent Coffee Grounds (SCGs). *Energies* **2025**, *18*, 3629. [CrossRef]
34. Attia, S.; Hammouma, T.; Galeone, D.; Zhang, Z.; Zhang, N.; Corrado, V.; Yuan, Y. From lab to building: Real-world integration of phase change materials for comfort, energy, and flexibility. *Energy Build.* **2026**, *352*, 116813. [CrossRef]
35. Laafer, A.; Yahiou, A.; Hammouma, T. Optimising the integration of phase change materials in construction in South Mediterranean regions: A case study from Algiers, Algeria. *J. Inf. Syst. Eng. Manag.* **2025**, *10*, 180–193. [CrossRef]
36. Amaral, C.; Gomez, F.; Moreira, M.; Silva, T.; Vicente, R. Thermal Performance of Multifunctional Facade Solution Containing Phase Change Materials: Experimental and Numerical Analysis. *Polymers* **2023**, *15*, 2971. [CrossRef] [PubMed]
37. Said, Z.; Pandey, A.K.; Tiwari, A.K.; Kalidasan, B.; Jamil, F.; Thakur, A.K.; Tyagi, V.V.; Sarı, A.; Ali, H.M. Nano-enhanced phase change materials: Fundamentals and applications. *Prog. Energy Combust. Sci.* **2024**, *104*, 101162. [CrossRef]
38. Yuk, H.; Choi, J.Y.; Suh, W.D.; Jin, D.; Kim, S. Sustainable energy synergy for historic building: Conservation retrofit solution of hygrothermal control. *Energy Build.* **2024**, *317*, 114392. [CrossRef]
39. Liu, M.; Xie, X.; Yang, W.; Xu, F.; Gao, S.; Ding, L.; Liang, H. A two-level optimal scheduling control strategy for air source heat pump loads with phase change energy storage. *IET Gener. Transm. Distrib.* **2025**, *19*, e70004. [CrossRef]
40. Faramarzi, S.; Mohammad Mehdi Asadzadeh, S.; Reza Mohammad Hassani, M.; Abdollahi, S.A.; Zarehzadeh, R.; Mafi, M. Energy and exergy analysis of a modified air handling unit assisted by phase change material, heat recovery unit, and solar energy. *Sci. Rep.* **2024**, *14*, 31952. [CrossRef]
41. Al-Atari, Z.; Shipman, R.; Gillott, M. Optimisation of Integrated Heat Pump and Thermal Energy Storage Systems in Active Buildings for Community Heat Decarbonisation. *Energies* **2024**, *17*, 5310. [CrossRef]
42. Pielichowska, K.; Paprota, N.; Pielichowski, K. Fire Retardant Phase Change Materials—Recent Developments and Future Perspectives. *Materials* **2023**, *16*, 4391. [CrossRef]
43. Ovadiuc, E.-P.; Calotă, R.; Năstase, I.; Bode, F. Integration of Phase-Change Materials in Ventilated Façades: A Review Regarding Fire Safety and Future Challenges. *Fire* **2024**, *7*, 244. [CrossRef]
44. Zeng, C.; Yuan, Y.; Cao, H.; Panchabikesan, K.; Haghighat, F. Stability and durability of microencapsulated phase change materials (MePCMs) in building applications: A state of the review. *J. Energy Storage* **2024**, *80*, 110249. [CrossRef]
45. Man, X.; Lu, H.; Xu, Q.; Wang, C.; Ling, Z. Review on the thermal property enhancement of inorganic salt hydrate phase change materials. *J. Energy Storage* **2023**, *72*, 108699. [CrossRef]
46. Uttam, A.; Purohit, B.K.; Le, M.T.; Sistlais, V.S. Disodium Phosphate Dodecahydrate Salt Hydrate-Based Approach for Thermal Energy Storage Systems. *J. Tech. Educ. Sci.* **2023**, *18*, 1–7. [CrossRef]
47. Proca, A. Advancing Phase Change Materials (PCM) Technology: Research, Development, and Optimization. *Res. Sq.* **2024**, *preprint*. [CrossRef]
48. Wu, W.; Li, W.; Han, H.; Xu, M.; Lu, E.; Wang, Z.; Zhai, C. Advanced thermal energy storage made of a ternary CPCM with two phase change temperatures in building walls. *Energy Build.* **2024**, *318*, 114445. [CrossRef]
49. Li, M.; Wang, X.; Shen, J.; Zhao, D.; Lian, J. Phase change-related thermal property characterization and enhancement in carbon-based organic phase change composites. *Appl. Phys. Rev.* **2024**, *11*, 021322. [CrossRef]
50. Alhusseny, A.; Al-Zurfi, N.; Al-Aabidy, Q.; Nasser, A.; Al-Madhhachi, H. Response to the design conditions of a tube-bundle thermal energy storage unit with paraffin-copper foam composite as a storage medium. *Int. J. Heat Mass Transf.* **2024**, *228*, 125679. [CrossRef]
51. Feng, D.; Zhao, Z.; Li, P.; Li, Y.; Zha, J.; Hu, J.; Zhang, Y.; Feng, Y. Multifunctional performance of carbon nanotubes in thermal energy storage materials. *Mater. Today* **2024**, *75*, 285–308. [CrossRef]
52. Mancin, S.; Calati, M.; Guarda, D. Experimental Techniques and Challenges in Evaluating the Performance of PCMs. In *Solid–Liquid Thermal Energy Storage*; CRC Press: Boca Raton, FL, USA, 2022; pp. 37–70; ISBN 978-1-003-21326-0.

53. Biswas, K.; Childs, P.; Atchley, J. *Field Testing of Nano-PCM Enhanced Building Envelope Components*; ORNL/TM-2013/207, 1093088, 600301010; U.S. Department of Energy Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2013.
54. Zetola Vargas, V.A. Morteros Acumuladores con Parafinas Microencapsuladas para el Aprovechamiento de la Energía Solar en Suelos Radiantes. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2013.
55. Ait Laasri, I.; Es-sakali, N.; Charai, M.; Mghazli, M.O.; Outzourhit, A. Recent progress, limitations, and future directions of macro-encapsulated phase change materials for building applications. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114481. [CrossRef]
56. Lin, W.; Yao, X.; Zhao, W.; Pu, Y.; Wang, S. Pathways to carbon neutrality in the built environment: Phase change materials. *Green Carbon* **2024**, *2*, 197–204. [CrossRef]
57. Vega, M.; Marín, P.E.; Ushak, S.; Shire, S. Research trends and gaps in experimental applications of phase change materials integrated in buildings. *J. Energy Storage* **2024**, *75*, 109746. [CrossRef]
58. Ismail, K.A.R.; Lino, F.A.M.; Teggar, M.; Arıcı, M.; Machado, P.L.O.; Alves, T.A. A Comprehensive Review on Phase Change Materials and Applications in Buildings and Components. *ASME Open J. Eng.* **2022**, *1*, 011049.
59. Togun, H.; Basem, A.; Jweeg, M.J.; Mohammed, H.I.; Abed, A.M.; Anqi, A.E.; Rashid, F.L.; Shelare, S.; Slimi, K.; Barmavatu, P. A review of Phase-Change materials for building Applications: Innovations, Assessments, and design Implications. *Energy Build.* **2025**, *349*, 116573. [CrossRef]
60. Barbhuiya, S.; Das, B.; Adak, D. Phase Change Materials in Buildings: Fundamentals, Applications, and Future Perspectives. In *Advances in Chemical and Materials Engineering*; González-Lezcano, R.A., Ed.; IGI Global: Hershey, PA, USA, 2024; pp. 207–262; ISBN 979-8-3693-3398-3.
61. Abilkhassenova, Z.; Memon, S.A.; Ahmad, A.; Saurbayeva, A.; Kim, J. Utilizing the Fanger thermal comfort model to evaluate the thermal, energy, economic, and environmental performance of PCM-integrated buildings in various climate zones worldwide. *Energy Build.* **2023**, *297*, 113479. [CrossRef]
62. Rabani, M.; Alafzadeh, M.; Rabani, M. Performance Evaluation of Ceiling Cooling with PCM in the Hot-Dry Climate of Yazd, Iran: An Experimental Analysis of Energy, Environmental, and Economic Impacts. *Buildings* **2025**, *15*, 198. [CrossRef]
63. Emam, M.; Hamada, A.; Refaey, H.A.; Moawed, M.; Abdelrahman, M.A.; Rashed, M.R. Year-round experimental analysis of a water-based PVT-PCM hybrid system: Comprehensive 4E assessments. *Renew. Energy* **2024**, *226*, 120354. [CrossRef]
64. Reddy, V.J.; Ghazali, M.F.; Kumarasamy, S. Innovations in phase change materials for diverse industrial applications: A comprehensive review. *Results Chem.* **2024**, *8*, 101552. [CrossRef]
65. Tripathi, B.M.; Shukla, S.K. A comprehensive review of the thermal performance in energy efficient building envelope incorporated with phase change materials. *J. Energy Storage* **2024**, *79*, 110128. [CrossRef]
66. Ghamari, M.; See, C.H.; Hughes, D.; Mallick, T.; Reddy, K.S.; Patchigolla, K.; Sundaram, S. Advancing sustainable building through passive cooling with phase change materials, a comprehensive literature review. *Energy Build.* **2024**, *312*, 114164. [CrossRef]
67. Saliby, A.; Kovács, B. Minimization of Annual Energy Consumption by Incorporating Phase Change Materials into Building Components: A Comprehensive Review. *Heat Transf. Res.* **2023**, *54*, 65–91. [CrossRef]
68. Oliveira, M.M.; Lucarelli, C.D.C.; Carlo, J.C. Phase change materials in building systems: An integrative literature review. *Ambiente Construído* **2022**, *22*, 67–111. [CrossRef]
69. Aziz, S.; Talha, T.; Mazhar, A.R.; Ali, J.; Jung, D.-W. A Review of Solar-Coupled Phase Change Materials in Buildings. *Materials* **2023**, *16*, 5979. [CrossRef]
70. Abdel-Mawla, M.A.; Hassan, M.A.; Khalil, A. Phase change materials in thermally activated building systems: A comprehensive review. *Int. J. Energy Res.* **2022**, *46*, 11676–11717. [CrossRef]
71. Sedaghat, M.; Heydari, A.H.; Santos, P. The Use of PCMs and PV Solar Panels in Higher Education Buildings towards Energy Savings and Decarbonization: A Case Study. *Buildings* **2024**, *14*, 2691. [CrossRef]
72. Moradinia, S.F.; Hussein, A.R.; Chan, M.; Bagherifam, N.; Baghalzadeh Shishehgarkhaneh, M. Evaluating the Impact of Phase Change Materials and Double-Skin Façades on Energy Performance in Office Buildings Under Climate Change Scenarios: A Case Study in Iran. *Eng* **2024**, *5*, 3049–3079. [CrossRef]
73. Amoatey, P.; Al-Jabri, K.; Al-Saadi, S. Influence of phase change materials on thermal comfort, greenhouse gas emissions, and potential indoor air quality issues across different climatic regions: A critical review. *Int. J. Energy Res.* **2022**, *46*, 22386–22420. [CrossRef]
74. Gao, Y.; Meng, X. A comprehensive review of integrating phase change materials in building bricks: Methods, performance and applications. *J. Energy Storage* **2023**, *62*, 106913. [CrossRef]
75. Lachheb, M.; Younsi, Z.; Youssef, N.; Bouadila, S. Enhancing building energy efficiency and thermal performance with PCM-Integrated brick walls: A comprehensive review. *Build. Environ.* **2024**, *256*, 111476. [CrossRef]
76. Nouira, M.; Sammouda, H.; Azimi, N. Impact of building integrated photovoltaic-phase change material panels on building energy efficiency improvement: A case study. *Energy Sources Part Recovery Util. Environ. Eff.* **2022**, *44*, 7453–7482. [CrossRef]

77. Das, R.; Gandhi, I.S.R.; Palanisamy, M. A Critical Review on Properties of PCM-Incorporated Cementitious Building Materials. *Adv. Civ. Eng. Mater.* **2023**, *12*, 271–294. [CrossRef]
78. Baylis, C.; Cruickshank, C.A. Review of bio-based phase change materials as passive thermal storage in buildings. *Renew. Sustain. Energy Rev.* **2023**, *186*, 113690. [CrossRef]
79. Coelho, L.; Koukou, M.K.; Konstantaras, J.; Vrachopoulos, M.G.; Rebola, A.; Benou, A.; Karytsas, C.; Tourou, P.; Sourkounis, C.; Gaich, H.; et al. Assessing the Effectiveness of an Innovative Thermal Energy Storage System Installed in a Building in a Moderate Continental Climatic Zone. *Energies* **2024**, *17*, 763. [CrossRef]
80. Alassaf, Y. Comprehensive Review of the Advancements, Benefits, Challenges, and Design Integration of Energy-Efficient Materials for Sustainable Buildings. *Buildings* **2024**, *14*, 2994. [CrossRef]
81. Siddesh, J.S.; Shivaprasad, K.N.; Yang, H.M. Enhancing the thermal performance of cementitious composites: A comprehensive review of phase change material integration. *Appl. Therm. Eng.* **2025**, *268*, 125849. [CrossRef]
82. Klemczak, B.; Kucharczyk-Brus, B.; Sulimowska, A.; Radziewicz-Winnicki, R. Historical Evolution and Current Developments in Building Thermal Insulation Materials—A Review. *Energies* **2024**, *17*, 5535. [CrossRef]
83. Reddy, V.J.; Ghazali, M.F.; Kumarasamy, S. Advancements in phase change materials for energy-efficient building construction: A comprehensive review. *J. Energy Storage* **2024**, *81*, 110494. [CrossRef]
84. Jiao, K.; Lu, L.; Zhao, L.; Wang, G. Towards Passive Building Thermal Regulation: A State-of-the-Art Review on Recent Progress of PCM-Integrated Building Envelopes. *Sustainability* **2024**, *16*, 6482. [CrossRef]
85. Ahmad, A.; Memon, S.A. A novel method to evaluate phase change materials' impact on buildings' energy, economic, and environmental performance via controlled natural ventilation. *Appl. Energy* **2024**, *353*, 122033. [CrossRef]
86. Liu, Z.-A.; Hou, J.; Mo, W.; Liu, Z.; Wang, D. Parameters/configurations adaptability and economic evaluation of PCM for reducing energy demands with lightweight buildings under different climates/cities based on orthogonal experiment and EnergyPlus: China-Japan comparison. *Therm. Sci. Eng. Prog.* **2023**, *45*, 102143. [CrossRef]
87. Elenga, R.G.; Zhu, L.; Defilla, S. Performance evaluation of different building envelopes integrated with phase change materials in tropical climates. *Energy Built Environ.* **2025**, *6*, 332–346. [CrossRef]
88. Al Jebaei, H.; Aryal, A.; Jeon, I.K.; Azzam, A.; Kim, Y.-R.; Baltazar, J.-C. Evaluating the potential of optimized PCM-wallboards for reducing energy consumption and CO_2 emission in buildings. *Energy Build.* **2024**, *315*, 114320. [CrossRef]
89. Rashid, F.L.; Dulaimi, A.; Hatem, W.A.; Al-Obaidi, M.A.; Ameen, A.; Eleiwi, M.A.; Jawad, S.A.; Bernardo, L.F.A.; Hu, J.W. Recent Advances and Developments in Phase Change Materials in High-Temperature Building Envelopes: A Review of Solutions and Challenges. *Buildings* **2024**, *14*, 1582. [CrossRef]
90. Jaradat, M.; Al Majali, H.; Bendea, C.; Bungau, C.C.; Bungau, T. Enhancing Energy Efficiency in Buildings through PCM Integration: A Study across Different Climatic Regions. *Buildings* **2023**, *14*, 40. [CrossRef]
91. Jahangir, M.H.; Alimohamadi, R. A comparative evaluation on energy consumption of a building using bio-based and paraffin-based phase change materials integrated to external building envelope. *Energy Rep.* **2024**, *11*, 3914–3930. [CrossRef]
92. Yousefi, A.; Tang, W.C.; Alghamdi, S. Computer Simulation for Energy-Efficient Buildings Integrated with Developed Phase Change Material (PCM). *Key Eng. Mater.* **2023**, *951*, 161–165. [CrossRef]
93. Jacob, J.; Paul, J.; Selvaraj, J.; Vaka, M. Phase change materials integrated buildings: A short review. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1281*, 012008. [CrossRef]
94. Bordoloi, U.; Das, B. Enhancing thermal comfort in buildings through the integration of phase change material on the building envelope: A simulation study. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1372*, 012089. [CrossRef]
95. Sloka, P.Y.; Kaushik, S.A.S. Phase Changing Material (PCM) based envelope materials for energy efficient buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1326*, 012067. [CrossRef]
96. Lahoud, C.; Chahwan, A.; Rishmany, J.; Yehia, C.; Daaboul, M. Enhancing Energy Efficiency in Mediterranean Coastal Buildings Through PCM Integration. *Buildings* **2024**, *14*, 4023. [CrossRef]
97. Wu, D.X.; Yao, Z.N.; Shi, Y. Hygrothermal and Energy Performance Optimization on Bio-Based Envelope Integrated with PCM. *Key Eng. Mater.* **2024**, *1006*, 45–52. [CrossRef]
98. Sarcinella, A.; Cunha, S.; Aguiar, J.; Frigione, M. Enhancing energy efficiency of buildings located in the Mediterranean area using Phase Change Materials (PCMs) integrated into mortar formulations. *J. Phys. Conf. Ser.* **2024**, *2893*, 012047. [CrossRef]
99. Stasi, R.; Ruggiero, F.; Berardi, U. Assessing the Potential of Phase-Change Materials in Energy Retrofitting of Existing Buildings in a Mediterranean Climate. *Energies* **2024**, *17*, 4839. [CrossRef]
100. Li, W.; Rahim, M.; Wang, B.; El Ganaoui, M.; Bennacer, R. Optimizing Hygrothermal and Energy Performance of Building Envelopes with Dynamic PCM-Biomaterial Concrete Configurations. 2025. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5093832 (accessed on 2 March 2025).
101. Mettrick, A.J.; Ma, Z. Integrating phase change materials in buildings for heating and cooling demand reduction—A global study. *Case Stud. Therm. Eng.* **2024**, *63*, 105337. [CrossRef]

102. Yang, T.; Ding, Y.; Li, B.; Athienitis, A.K. A review of climate adaptation of phase change material incorporated in building envelopes for passive energy conservation. *Build. Environ.* **2023**, *244*, 110711. [CrossRef]
103. Kamel, J.A.; Mina, E.M.; Elsabbagh, A.M. Implementation of phase change material for cooling load reduction: A case study for Cairo, Egypt. *Int. J. Air Cond. Refrig.* **2022**, *30*, 13. [CrossRef]
104. Brozzesi, Z.; Li, D.D.; Lee, A. Exploring the Potential of Phase Change Material for Thermal Energy Storage in Building Envelopes. *J. Energy Power Technol.* **2023**, *5*, 27. [CrossRef]
105. Thongtha, A.; Khongthon, A.; Boonsri, T.; Hoy-Yen, C. Thermal Effectiveness Enhancement of Autoclaved Aerated Concrete Wall with PCM-Contained Conical Holes to Reduce the Cooling Load. *Materials* **2019**, *12*, 2170. [CrossRef]
106. Huang, X.; Guo, J.; He, J.; Gong, Y.; Wang, D.; Song, Z. Novel phase change materials based on fatty acid eutectics and triallyl isocyanurate composites for thermal energy storage. *J. Appl. Polym. Sci.* **2017**, *134*, 44866. [CrossRef]
107. Jiang, J.; Ju, S.; Wang, F.; Wang, L.; Shi, J.; Liu, Z.; Xin, Z. Cement-based materials incorporated with polyethylene glycol/sepiolite composite phase change materials: Hydration, mechanical, and thermal properties. *J. Sustain. Cem. Based Mater.* **2024**, *13*, 311–323. [CrossRef]
108. Rmili, Y.; Ndiaye, K.; Plancher, L.; Tahar, Z.E.A.; Cousture, A.; Melinge, Y. Properties and Durability of Cementitious Composites Incorporating Solid-Solid Phase Change Materials. *Appl. Sci.* **2024**, *14*, 2040. [CrossRef]
109. Marín, P.E.; Ushak, S.; De Gracia, A.; Cabeza, L.F. Characterisation of the COMFORTBOARD gypsum board for thermal energy storage in buildings. *J. Energy Storage* **2024**, *77*, 109850. [CrossRef]
110. Kwon, T.K.; Zoh, H.D.; Ahn, W.; Lee, S.; Kim, T.H. Analysis of Indoor Thermal Environment Improvement in Apartment Buildings through the Application of Heat-Reflective Paint. *Buildings* **2024**, *14*, 3834. [CrossRef]
111. Komerska, A.; Ksionek, D.; Rosiński, M. Determination of the solar transmittance for the translucent shutter with PCM in liquid and solid state. *E3S Web Conf.* **2017**, *22*, 00084. [CrossRef]
112. Shaik, S.; Priya, V.; Ramana, M.V.; Rahaman, S.A.; Arıcı, M.; Kontoleon, K.J.; Li, D. PCM-Based Glazing Systems: Solar-Optical Properties, Energy Savings, and Carbon Emission Abatement. In *Proceedings of the 2023 8th International Conference on Smart and Sustainable Technologies (SpliTech), Split/Bol, Croatia, 20–23 June 2023*; IEEE: New York, NY, USA, 2023; pp. 1–6.
113. Sultan, S.; Hirschey, J.; Kumar, N.; Cui, B.; Liu, X.; LaClair, T.J.; Gluesenkamp, K.R. Techno-Economic Assessment of Residential Heat Pump Integrated with Thermal Energy Storage. *Energies* **2023**, *16*, 4087. [CrossRef]
114. Khayyaminnejad, A.; Fartaj, A. Efficient Cooling Approach with Integrated PCM Rooftops for Sustainable Load Reduction in Buildings with Natural Ventilation Systems. *J. Fluid Flow Heat Mass Transf.* **2024**, *11*, 9. [CrossRef]
115. Lee, S.H.; Liu, M.; Saman, W.; Bostrom, M. Smoothing cooling demand of buildings with PCM thermal batteries. *Renew. Energy Environ. Sustain.* **2024**, *9*, 6. [CrossRef]
116. Eze, V.H.U.; Robert, O.; Sarah, N.I.; Tamball, J.S.; Uzoma, O.F.; Okafor, W.O. Transformative Potential of Thermal Storage Applications in Advancing Energy Efficiency and Sustainability. *IDOSR J. Appl. Sci.* **2024**, *9*, 51–64. [CrossRef]
117. Zhang, Y.; He, Z.; Guo, W.; Zhang, P. Data-driven optimization of packed bed thermal energy storage heating system with encapsulated phase change material. *J. Energy Storage* **2024**, *79*, 110017. [CrossRef]
118. Di Prima, P.; Santovito, M.; Papurello, D. CFD Analysis of a Latent Thermal Storage System (PCM) for Integration with an Air-Water Heat Pump. *Int. J. Energy Res.* **2024**, *2024*, 6632582. [CrossRef]
119. Robadey, J.; Richard, R. A new heat and cold storage system to enhance the thermal autonomy of residential buildings. *J. Phys. Conf. Ser.* **2023**, *2600*, 022004. [CrossRef]
120. Dimchev, I.; Terziev, A.; Ivanov, M.; Vassilev, M. Climate change impact on the energy performance of an air handling unit with two-stage heat recovery. *E3S Web Conf.* **2025**, *608*, 01009. [CrossRef]
121. Zhu, Y.; Wu, S.; Li, J.; Jia, Q.; Zhang, T.; Zhang, X.; Han, D.; Tan, Y. Towards a carbon-neutral community: Integrated renewable energy systems (IRES)–sources, storage, optimization, challenges, strategies and opportunities. *J. Energy Storage* **2024**, *83*, 110663. [CrossRef]
122. Arévalo, P.; Ochoa-Correa, D.; Villa-Ávila, E. Advances in Thermal Energy Storage Systems for Renewable Energy: A Review of Recent Developments. *Processes* **2024**, *12*, 1844. [CrossRef]
123. Woo, H.; Park, S.; Joo, Y.; Kwon, K. MPC-Based HVAC Control System for Energy Efficiency and User Comfort. In *Proceedings of the 2024 15th International Conference on Information and Communication Technology Convergence (ICTC), Jeju Island, Republic of Korea, 16–18 October 2024*; IEEE: New York, NY, USA, 2024; pp. 1960–1961.
124. Xiong, R.; Jing, H.; Li, M.; Shi, Y.; Miki, T.; Hatanaka, T.; Nakahira, Y.; Tang, P. Optimizing HVAC Systems for Energy Efficiency and Comfort: A Scalable and Robust Multi-Zone Control Approach with Uncertainty Considerations. In *Proceedings of the Computing in Civil Engineering 2023, Corvallis, OR, USA, 25–28 June 2024*; American Society of Civil Engineers: Reston, VA, USA, 2024; pp. 987–995.
125. Jeon, B.-K.; Kim, E.-J. White-Model Predictive Control for Balancing Energy Savings and Thermal Comfort. *Energies* **2022**, *15*, 2345. [CrossRef]

126. Zohuri, B. Artificial Intelligence and Machine Learning Driven Adaptive Control Applications. *J. Mater. Sci. Eng. Technol.* **2024**, *2*, 1–4. [CrossRef]
127. Kulumkanov, N.; Memon, S.A.; Khawaja, S.A. Evaluating future building energy efficiency and environmental sustainability with PCM integration in building envelope. *J. Build. Eng.* **2024**, *93*, 109413. [CrossRef]
128. Ayalew, B.S.; Andrzejczyk, R. Recent Advancements in Latent Thermal Energy Storage and Their Applications for HVAC Systems in Commercial and Residential Buildings in Europe—Analysis of Different EU Countries' Scenarios. *Energies* **2025**, *18*, 4000. [CrossRef]
129. Teamah, H.M.; Teamah, M. Phase Change Materials Integration in Building Envelopes Under Different Climatic Conditions: State of the Art, Opportunities, and Challenges. *Energy Storage* **2025**, *7*, e70250. [CrossRef]