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Conceptual Design of an AI-Assisted PCM Thermal Panel for Sustainable Building Applications

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Abstract

The increasing demand for heating and cooling in buildings, driven by rapid urbanization and climate change, has led to higher energy consumption and carbon emissions. Improving thermal energy efficiency has therefore become an important objective in sustainable building design. This paper proposes the conceptual design of an Artificial Intelligence (AI)-assisted Phase Change Material (PCM) thermal panel for residential and commercial buildings. The proposed system combines encapsulated PCMs with embedded temperature sensors and an AI-assisted control framework to improve indoor thermal regulation. During periods of high temperature, the PCM absorbs and stores excess heat, while during cooler conditions it releases the stored heat, thereby maintaining a more stable indoor temperature and reducing dependence on conventional heating, ventilation, and air-conditioning (HVAC) systems. The AI component continuously analyzes environmental parameters such as indoor and outdoor temperature, humidity, occupancy, and weather conditions to support intelligent thermal management and optimize panel operation under different climatic conditions. This paper presents the conceptual architecture, operating principle, and expected performance of the proposed system based on existing research in PCM technology and AI-assisted energy management. The proposed design is expected to enhance thermal comfort, improve building energy efficiency, reduce electricity consumption and carbon emissions, and support the development of sustainable and smart building infrastructure.

Keywords: Phase Change Material (PCM), Artificial Intelligence (AI), Thermal Panel, Thermal Energy Storage, Smart Buildings, Energy Efficiency, Passive Heating, Passive Cooling, Sustainable Construction.

1. Introduction

Buildings account for a significant proportion of global energy consumption, particularly through heating, ventilation, and air-conditioning (HVAC) systems, making energy-efficient thermal management an important challenge in sustainable construction [3], [4]. Rapid urbanization, increasing demand for indoor thermal comfort, and climate change have further intensified the need for innovative solutions that reduce energy consumption and greenhouse gas emissions. Among various thermal energy storage technologies, Phase Change Materials (PCMs) have received considerable attention because they can absorb, store, and release latent heat during phase transitions, thereby stabilizing indoor temperatures and reducing dependence on conventional HVAC systems [1], [2], [3], [5]. Previous studies have demonstrated the successful application of PCMs in building components such as walls, roofs, ceilings, and thermal panels, showing their potential to improve thermal regulation and building energy efficiency [8], [9], [10], [11], [12], [14]. However, conventional PCM systems operate passively and cannot adapt to changing environmental conditions, occupancy patterns, or varying thermal demands, which may limit their overall performance.

Recent advancements in Artificial Intelligence (AI) have enabled intelligent energy management in buildings through environmental monitoring, energy demand prediction, and adaptive control strategies [9], [13], [15]. AI-assisted techniques have been widely applied to optimize HVAC operation and improve building energy efficiency, while recent studies have also explored the potential of AI for predicting and optimizing the thermal performance of PCM-based energy storage systems [13]. Despite these developments, existing research has largely investigated PCM technology and AI-assisted building management separately. A conceptual framework that integrates PCM-based thermal energy storage, environmental sensing, and AI-assisted decision-making into a unified intelligent thermal panel for sustainable building applications remains limited in the current literature.

Therefore, this paper proposes the conceptual design of an Artificial Intelligence (AI)-assisted Phase Change Material (PCM) thermal panel for sustainable residential and commercial buildings. The proposed framework combines encapsulated PCM, environmental sensors, and an AI-assisted monitoring and control approach to support adaptive thermal regulation based on changing indoor and outdoor conditions. Rather than developing or experimentally validating a physical prototype, this study presents the conceptual architecture and operating principle of the proposed system based on existing literature. The proposed concept is intended to provide a foundation for future simulation studies, prototype development, and experimental evaluation of intelligent PCM-based thermal management systems.

2. Literature Review

Previous studies have established Phase Change Materials (PCMs) as one of the most effective latent heat thermal energy storage technologies for improving building energy efficiency. Fundamental studies by Mehling and Cabeza [1], Cabeza [2], and Dincer and Rosen [3] explain that PCMs store and release thermal energy during melting and solidification, enabling buildings to maintain stable indoor temperatures while reducing heating and cooling loads. Comprehensive review studies further classify PCMs into organic, inorganic, and eutectic materials and discuss their thermal properties, selection criteria, and suitability for different applications [5], [8], [11]. These studies identify PCM technology as a promising passive approach for reducing energy consumption and supporting sustainable building development.

Several researchers have investigated the practical integration of PCMs into building envelopes, including walls, roofs, floors, ceilings, and thermal panels [6], [7], [12], [14]. Experimental and review studies consistently report that PCM integration can reduce indoor temperature fluctuations, improve thermal comfort, and decrease HVAC energy demand. Recent developments such as microencapsulation, microencapsulation, composite PCMs, and nano-enhanced PCMs have further improved thermal conductivity, leakage resistance, durability, and long-term thermal storage performance [5], [10], [12], [14]. Despite these advancements, conventional PCM systems remain passive because their charging and discharging processes depend solely on surrounding environmental conditions and cannot adapt intelligently to changing weather patterns or building occupancy.

Recent advances in Artificial Intelligence (AI) have introduced intelligent approaches for building energy management. Ahmad et al. [9] demonstrated the capability of AI and machine learning techniques to forecast building energy demand using methods such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and deep learning algorithms. Similarly, Merabet et al. [15] reviewed AI-assisted intelligent building control systems, highlighting the effectiveness of predictive control, neural networks, and reinforcement learning in improving HVAC operation while maintaining occupant thermal comfort. These studies indicate that AI can analyse environmental data, predict thermal loads, and support adaptive decision-making to improve overall building energy efficiency.

More recently, researchers have begun exploring the integration of AI with PCM-based thermal energy storage systems. Liu et al. [13] reported that AI techniques can predict the thermo-physical behaviour of PCMs, optimize charging and discharging cycles, and improve thermal energy storage performance under varying operating conditions. These findings suggest that combining AI with PCM technology can overcome several limitations of conventional passive PCM systems by enabling intelligent thermal management based on environmental conditions and predicted energy demand. However, current studies primarily focus on material optimization, predictive modelling, or HVAC control individually, while relatively few present a unified conceptual framework that integrates PCM, environmental sensing, and AI-assisted decision-making into a single intelligent thermal panel for building applications. This research gap forms the basis of the proposed conceptual design presented in this study

Table I. Summary of Related Literature

Ref.	Study / Authors	Main Contribution	Limitation	Relevance to Proposed Work
[1]	Mehling & Cabeza (2008)	Introduced the fundamentals of Phase Change Materials (PCMs), including thermal properties, latent heat storage, and building applications.	Focuses on PCM fundamentals without intelligent control strategies.	Provides the theoretical foundation for PCM-based thermal energy storage.
[2]	Cabeza (2015)	Reviewed recent advances in thermal energy storage technologies and PCM applications.	Does not address AI integration.	Supports the selection of PCM as the thermal storage medium.
[3]	Dincer & Rosen (2021)	Discussed thermal energy storage systems, design principles, and energy efficiency.	General coverage of TES without AI-assisted management.	Provides background on thermal energy storage concepts.
[4]	Kalogirou (2014)	Explained solar energy systems and thermal energy storage technologies.	Focuses mainly on solar energy rather than intelligent building thermal management.	Supports the importance of energy-efficient building systems.
[5]	Cabeza et al. (2011)	Reviewed PCM materials, classifications, and thermal properties for buildings.	Limited discussion of intelligent optimization.	Supports PCM material selection for the proposed panel.
[6]	Kuznik et al. (2011)	Reviewed PCM integration into building walls and thermal performance.	Focuses on passive PCM applications.	Supports the structural design of the proposed thermal panel.
[7]	Zhou et al. (2012)	Reviewed PCM applications for improving building thermal comfort and reducing energy consumption.	Does not include AI-assisted control.	Demonstrates the effectiveness of PCM in buildings.
[8]	Sharma et al. (2009)	Reviewed PCM properties, encapsulation methods, and engineering applications.	Limited discussion of intelligent thermal management.	Supports the selection and implementation of PCM technologies.
[9]	Ahmad et al. (2018)	Reviewed AI and machine learning methods for forecasting building energy demand.	Focuses on prediction rather than PCM integration.	Provides the AI basis for predictive thermal management.
[10]	Agyenim et al. (2010)	Discussed heat transfer enhancement and latent heat storage systems.	Concentrates on thermal performance without AI.	Supports heat transfer improvement in PCM systems.
[11]	Zalba et al. (2003)	Comprehensive review of PCM thermal energy storage technologies.	Identifies challenges such as low thermal conductivity and long-term stability.	Highlights limitations addressed by the proposed concept.
[12]	de Gracia & Cabeza (2015)	Reviewed PCM integration into building envelopes to improve energy efficiency.	Focuses on passive PCM applications.	Supports building integration of PCM technology.

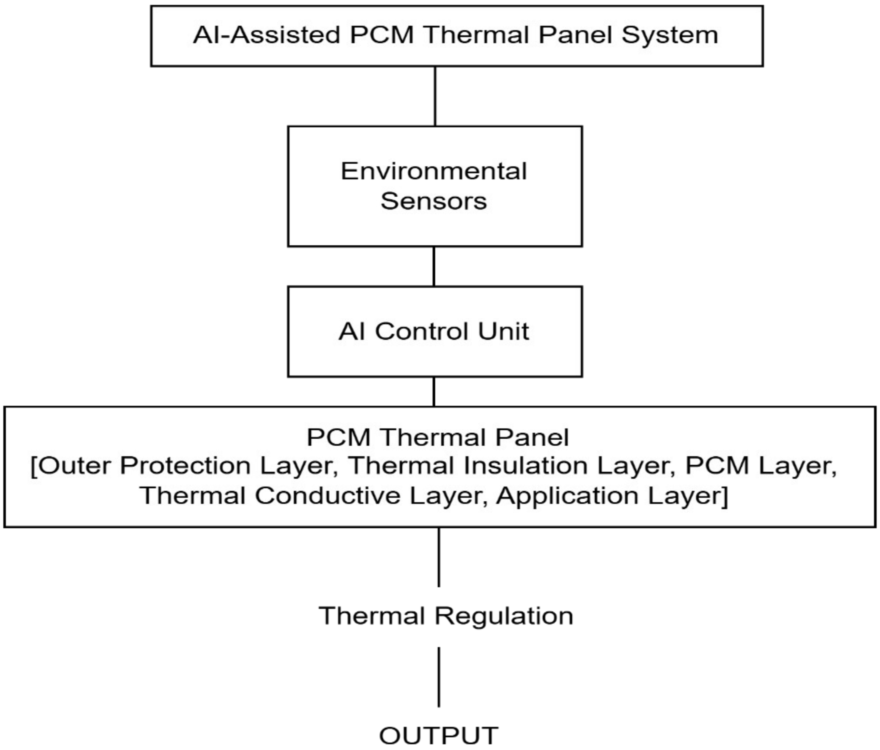
[13]	Liu et al. (2025)	Reviewed AI applications for predicting and optimizing PCM thermal energy storage systems.	Primarily focuses on optimization methods rather than integrated building design.	Forms the primary basis for integrating AI with PCM.
[14]	Teamah & Teamah (2025)	Evaluated PCM integration into building envelopes under different climatic conditions.	Limited emphasis on AI-assisted thermal control.	Supports the proposed building application of the thermal panel.
[15]	Merabet et al.	Reviewed AI-assisted intelligent building control systems for thermal comfort and energy efficiency.	Focuses on AI-based building control without PCM integration.	Provides the intelligent control framework for the proposed system.

3. Methodology

This study adopts a conceptual system design methodology to propose an Artificial Intelligence (AI)-assisted Phase Change Material (PCM) thermal panel for sustainable building applications.The study focuses on developing a conceptual framework that integrates passive thermal energy storage with AI-assisted monitoring and predictive decision-making to improve building thermal management.The proposed system architecture consists of an outer protective layer, a thermal insulation layer, an encapsulated Phase Change Material (PCM) layer, environmental sensors, a microcontroller or embedded processing unit, and an AI-assisted control module. The outer protective layer provides mechanical protection, while the insulation layer minimizes unwanted heat transfer. The encapsulated PCM layer functions as the primary thermal energy storage medium by absorbing and releasing latent heat during phase transitions. Environmental sensors continuously monitor indoor and outdoor temperature, humidity, and other relevant environmental conditions. These data are transmitted to the embedded processing unit, where the AI-assisted controller analyses the thermal conditions and supports intelligent decision-making for thermal regulation.

The operational framework begins with real-time environmental sensing. Sensor data are continuously collected and forwarded to the AI-assisted control module for analysis. Based on the observed thermal conditions, the controller predicts the appropriate charging or discharging behaviour of the PCM layer. During periods of high ambient temperature, the PCM absorbs excess thermal energy and stores it as latent heat through the melting process, thereby reducing heat transfer into the building. When the surrounding temperature decreases, the PCM gradually solidifies and releases the stored thermal energy, helping to maintain a stable indoor temperature and reducing dependence on conventional heating and cooling systems. This sensing, analysis, decision-making, and thermal regulation cycle operates continuously to provide adaptive thermal management.

Rather than implementing a specific machine learning algorithm, the proposed AI module is designed as an intelligent decision-support system. It processes environmental data, identifies thermal trends, predicts temperature variations, and determines the most appropriate thermal response of the PCM layer. This predictive control strategy is intended to improve the efficiency of thermal energy storage while enhancing indoor thermal comfort and minimizing unnecessary HVAC operation



4. Expected Results

he proposed Artificial Intelligence (AI)-assisted Phase Change Material (PCM) thermal panel is expected to improve the thermal performance and energy efficiency of sustainable buildings by integrating passive thermal energy storage with intelligent monitoring and predictive control. The conceptual framework combines an encapsulated PCM layer, environmental sensors, and an AI-assisted control unit to provide adaptive thermal regulation under varying environmental conditions. During periods of high ambient temperature, the PCM is expected to absorb excess heat and store it as latent heat through melting. As the surrounding temperature decreases, the stored heat is anticipated to be gradually released during solidification, helping to maintain stable indoor temperatures and reduce thermal fluctuations. This passive thermal storage mechanism is expected to decrease the heating and cooling load on conventional heating, ventilation, and air-conditioning (HVAC) systems, thereby improving indoor thermal comfort and overall building energy efficiency.

The AI-assisted control unit is expected to further enhance system performance by continuously analysing indoor temperature, outdoor temperature, humidity, occupancy, and weather conditions to predict thermal demand and optimize the charging and discharging cycles of the PCM layer. Through intelligent control, the proposed system is anticipated to reduce peak heating and cooling loads, improve energy utilization, and support sustainable building operation. As this study presents a conceptual proposal, the expected outcomes are theoretical and have not yet been experimentally validated. Future work should include numerical simulations using building energy analysis software, followed by prototype development and experimental testing to evaluate thermal performance, energy savings, control accuracy, and long-term reliability under real operating conditions.

5. Conclusion

The paper presents the conceptual design of an Artificial Intelligence (AI)-assisted Phase Change Material (PCM) thermal panel for sustainable building applications by integrating encapsulated PCM, environmental sensors, and an AI-assisted control unit to enable intelligent thermal management through passive thermal energy storage and predictive monitoring. The proposed framework is intended to improve indoor thermal comfort, enhance building energy efficiency, and reduce dependence on conventional heating, ventilation, and air-conditioning (HVAC) systems. As this study is purely conceptual, no prototype fabrication, simulation, or experimental validation was conducted; instead, it establishes a system architecture and operational framework that demonstrates the potential feasibility of integrating AI with PCM technology for sustainable buildings. The proposed concept provides a foundation for future intelligent thermal management systems capable of adapting to changing environmental conditions while supporting energy-efficient and climate-resilient building design. Future work should focus on numerical simulations using building energy modelling software, prototype development, and experimental validation under different climatic conditions to evaluate thermal performance, energy-saving potential, control effectiveness, economic feasibility, and the long-term durability of PCM materials for practical implementation in next-generation smart buildings

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

This study is a conceptual research work and does not involve the generation or analysis of primary experimental data. All information supporting this study is derived from published journal articles, books, and other publicly available scientific literature cited in the References section.

AI Usage Disclosure

The authors used ChatGPT (GPT-5.5, OpenAI) for language editing and improving the clarity of the manuscript. All content was reviewed, verified, and approved by the authors.

Author Contributions

Conceptualization, A. Niranjana V and B. Asna P V; methodology, C. Krishnapriya C S; analysis, D. Raniya DT.; writing original draft, E. Jewel Johnson; writing, review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

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