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Energy Optimization in Residential Buildings: Evaluating PCM-CLT Wall Systems Across U.S. Climate Zones

Amit Deb Nath [1], Ahmed Abdelaty [1*], Aysegul Demir Dilsiz [1], Mohamed S. Yamany [1, 2]

[1] *Department of Civil and Architectural Engineering and Construction Management, University of Wyoming, Laramie, WY, 82071, USA.*

[2] *Department of Construction Engineering, Faculty of Engineering, Zagazig University, Zagazig 44159, Egypt*.

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Abstract

Buildings consume approximately 43% of their electricity for space heating and cooling, emphasizing the need for energy-efficient solutions. Among the strategies to reduce this demand, phase change materials (PCM) have been recognized for their potential to enhance thermal performance. While PCM has been extensively studied in building envelopes, its integration with cross-laminated timber (CLT) remains unexplored. Additionally, the optimal placement of PCM within wall assemblies lacks consensus, as previous studies have reported inconsistent findings. This study addresses these research gaps by investigating the performance of PCM-integrated CLT (PCM-CLT) wall systems across 17 climate zones in the United States. Using EnergyPlus simulation, five wall configurations were analyzed, including three PCM-CLT configurations with PCM positioned at different locations within the assembly. The results demonstrate that the PCM-CLT system significantly enhances energy efficiency, achieving cooling energy savings of up to 72.48% and heating energy savings of up to 96.94% in certain locations. Moreover, the findings reveal that placing PCM on the interior side of CLT walls consistently outperforms other configurations across all climate zones. Furthermore, PCM-CLT walls help reduce peak energy loads, alleviating stress on power grids. This research contributes to enhancing building energy performance through PCM-CLT integration, providing valuable insights for both retrofitting and new construction, and advancing sustainable building design.

Keywords: Buildings; Energy Efficiency; Space Heating and Cooling; Phase Change Materials; Cross Laminated Timber.

1. Introduction

Energy is fundamental to modern life, powering everything from technological innovation to daily conveniences. Among various sectors, buildings account for significant global energy consumption. Globally, buildings are responsible for 30% of final energy use and 26% of energy-related emissions [1]. In the United States, buildings are responsible for 40% of total energy use, including 75% of all electricity consumption and 35% of the nation's carbon emissions [2]. These figures underscore the environmental and economic implications of energy use in the building sector.

Space heating and cooling represent major end-uses of energy in buildings and are key targets for energy conservation. Globally, heating alone accounts for nearly 50% of total energy consumption, with 46% of that heat used in buildings for space and water heating [3]. Around 40% of households worldwide require space heating during part of the year, making it a significant component of home energy expenditures [4]. Meanwhile, space cooling consumed approximately 2,100 TWh of electricity in 2022, representing nearly 20% of total electricity consumption in buildings worldwide [5]. The demand for space cooling is projected to grow by 45% by 2050 compared to 2016 levels, driven by

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* Corresponding author: aahmed3@uwyo.edu

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rising temperatures and increased air conditioning adoption [6]. In the U.S., heating and cooling systems account for approximately 43% of the average household utility bill [7], and while 32% of commercial building energy use is allocated to space conditioning [8]. These figures underscore the urgent need to reduce energy consumption for space heating and cooling to mitigate environmental impacts and enhance building energy efficiency. The U.S. decarbonization plan for 2050 emphasizes reducing greenhouse gas emissions by reducing operational energy demand and improving energy efficiency [9].

Among various contributors to building energy consumption, space cooling and heating loads play a crucial role in maintaining thermal comfort by regulating air temperature, airflow rates, and relative humidity. With the expected increase in the need for heating and cooling, it is important to develop sustainable techniques to reduce energy consumption in the building sector [10]. Researchers have been exploring various methods to minimize space heating and cooling loads to address the pressing need to reduce energy consumption. Among these approaches, passive buildings aim to reduce energy consumption by optimizing building envelopes, including walls, roofs, doors, and windows. The building envelope is a critical parameter, influencing how heat is retained or dissipated to maintain indoor comfort. Improving the insulation and thermal performance of building envelopes significantly reduces heating and cooling loads [11]. Particularly, as one of the thermal performance enhancement initiatives, integrating phase change materials (PCM) into building assemblies has shown considerable promise in reducing heating and cooling loads. PCMs store and release heat as they melt and solidify within a specific temperature range [12]. This PCM property helps maintain stable indoor temperatures and reduces the need for heating and cooling systems [13]. PCMs have been applied in various building applications, such as free cooling systems that utilize nighttime air to solidify the PCM for daytime cooling, peak load shifting strategies that reduce energy demand during peak hours, and both active systems like radiant floor heating and passive systems where PCMs are embedded directly into building materials to enhance thermal mass and energy efficiency [14].

Within the broad range of PCM applications, passive building systems have been extensively studied, particularly through the integration of PCMs into building envelope components such as walls [15], floors [16], and ceilings [17]. In these systems, PCM has been incorporated into materials like concrete [18], gypsum [19], and oriented strand board (OSB) [20] to improve insulation and energy efficiency. However, the incorporation of PCM in mass timber products, particularly cross-laminated timber (CLT), has not been widely explored in current literature. CLT is increasingly recognized for its cost-effectiveness, environmental sustainability, efficient construction process, and strong structural performance, making it a viable alternative to traditional building materials like concrete and steel [21]. Recent research by Park et al. (2025) [22] demonstrated that integrating PCM and biochar composites into CLT can improve its thermal storage performance by approximately 40% compared with conventional CLT. However, their study was limited to short-term experimental testing under controlled indoor conditions, without examining full-scale wall assemblies or environmental variability. This underscores the need for further investigation into the thermal behavior of PCM-integrated CLT walls, particularly in different climate zones and PCM configurations, to better understand their potential for improving building energy performance.

Additionally, while the integration of PCM has shown benefits in enhancing thermal performance, the optimal placement of PCM within wall systems remains unclear. Studies have explored positioning PCM in the different wall layers, such as exterior, interior, or intermediate, yet results vary across climate zones and wall configurations. For instance, He et al. (2024) demonstrated that placing PCM toward the exterior side ensures efficient melting and greater latent heat utilization in semi-arid climates [23]. Al-Yasiri and Szabó (2021) [20] emphasized exterior placement in hot climates and interior placement in cold climates, whereas Cascone et al. (2018) [24] and Lagou et al. (2019) [25] found interior placement more effective across diverse climates. Meanwhile, Arıcı et al. (2020) [26] and Darvishi et al. (2019) [27] reported mixed results depending on climate severity and wall configuration. These discrepancies highlight the need for further investigation, particularly in the context of PCM integration with CLT.

Therefore, this study aims to investigate the thermal performance of CLT wall systems integrated with PCMs across multiple U.S. climate zones. By evaluating different PCM placements within CLT wall assemblies, the research seeks to identify the most effective configuration for reducing energy consumption and peak heating and cooling loads. This work contributes to advancing sustainable building design by addressing current gaps in PCM-CLT integration and optimizing its application for diverse climatic conditions.

2. Background

2.1. Integration of PCM with Building Envelopes

PCMs play a crucial role in improving building energy efficiency by regulating heat exchange between indoor and outdoor environments. PCMs absorb, store, and release thermal energy through phase transitions, effectively stabilizing indoor temperatures and reducing energy consumption [28]. By restoring and releasing thermal mass in response to temperature fluctuations, PCMs help mitigate peak heating and cooling loads, enhancing overall building performance [18, 29]. Researchers have explored PCM integration in various building envelopes, including walls, ceilings, and floors, to optimize thermal efficiency. Incorporating PCMs into these components enables better energy reallocation, minimizes heat transfer, reduces temperature fluctuations, and leads to significant energy savings [30]. Concrete is among the most commonly studied materials. For instance, Dora et al. (2025) developed a PCM-based foam concrete wall panel, where the integration of PCM enhanced both thermal insulation and mechanical strength [31]. Similarly, Kwon et al. (2024) integrated microencapsulated PCM into concrete and demonstrated improved thermal insulation and mechanical strength, highlighting the potential of PCM-concrete composites for energy-efficient building applications [32]. Lachheb et al. (2024) conducted a comprehensive review on PCM-integrated brick walls and highlighted significant improvements in thermal comfort and energy efficiency [33]. The study concluded that PCM incorporation into brick structures effectively reduces heat flow fluctuations and energy consumption. In addition, Soleiman Dehkordi & Afrand (2022) studied PCM within clay brick walls to assess energy savings in Iran's hot and cold climates [16].

In lightweight constructions, gypsum-based materials are prominent. Shi et al. (2023) developed and applied paraffin/expanded graphite-based PCM-enhanced gypsum boards and demonstrated improvement in thermal conductivity and significant reduction in surface temperature and temperature fluctuations [34]. Similarly, Liu et al. (2021) employed gypsum board in lightweight walls to optimize PCM placement for maximum heat flux reduction [35]. OSB is often used alongside the gypsum board in PCM applications. Al-Yasiri & Szabo et al. (2021) incorporated PCM with OSB and gypsum board to improve energy efficiency across varied climatic conditions [20]. Furthermore, Baylis & Cruickshank (2024) incorporated PCM into wood plates and plaster walls to improve energy efficiency in cold climates [17].

Mass timber is an engineered wood product designed to address the small dimensions, dimensional instability, and variability commonly found in traditional wood. It has become increasingly recognized in construction due to its cost-effectiveness, environmental sustainability, efficient construction process, aesthetic appeal, and adaptability [36]. In the United States, the initiation of new mass timber projects now occurs at a frequency of approximately one every three days [37]. Among these mass timber products, CLT stands out for its unique structure and benefits. CLT is a quasi-rigid composite timber product composed of multiple layers of timber boards arranged at 90° angles [38]. It is manufactured by the most widely used kiln-dried softwood species, such as pine, spruce, larch, and Douglas fir, with thicknesses ranging from 15 mm to 50 mm [39]. CLT has the potential to regulate the indoor climate more efficiently by storing heat, which reduces the need for heating and cooling energy. This makes CLT a highly promising material for sustainable building construction [40].

A hybrid CLT building had 26.5% lower global warming potential than a comparable concrete building [41]. CLT has significantly lower density than concrete, leading to reduced environmental load despite a slightly higher impact per unit weight. As a bio-based material, CLT has a notably lower cradle-to-gate carbon footprint than concrete, steel, or brick-based structures. It also supports material substitution and resource conservation, which are increasingly important as urbanization escalates the demand for carbon-intensive materials like concrete and steel. Furthermore, CLT’s reduced weight simplifies transportation and construction logistics, resulting in lower emissions during the building phase [42].

Hartig & Haller (2024) explored the integration of PCM into wood elements and demonstrated that such treatment significantly enhances thermal storage capacity up to 600 percent without compromising mechanical strength. They also reported added benefits such as improved surface hardness in the solid PCM state and acceptable fire safety performance when appropriate layering is used. Based on these findings, the authors recommended further investigation of PCM integration into structural wood products like CLT to enhance thermal comfort in lightweight buildings [43].

Limited studies have explored the integration of PCM into mass timber like CLT. A recent study by Park et al. (2025) enhanced the thermal performance of CLT by integrating PCM supported with biochar and reported approximately a 40% improvement in heat storage capacity. These findings indicate the growing potential of PCM-CLT systems for sustainable buildings [22].

While previous studies have demonstrated the benefits of PCM in conventional materials such as concrete, brick, and gypsum board, the unique structure and composition of CLT may influence PCM’s thermal behavior differently. Unlike heavier materials, CLT is a lightweight, layered wood product with natural thermal resistance, potentially interacting with PCM in distinctive ways. This distinction raises questions about whether the integration will amplify or limit thermal storage benefits.

As both PCM and CLT are gaining momentum in sustainable construction, understanding their combined thermal behavior across different climates becomes increasingly important. Evaluating how PCM interacts with CLT, especially in terms of heat transfer, energy savings, and placement within wall assemblies, is essential. This opens up a valuable research direction for optimizing CLT-PCM hybrid systems and exploring their unique contributions to energy-efficient building design.

2.2. Optimal Placement of PCM within Building Envelope

The effectiveness of PCM in enhancing building energy efficiency has been widely explored, highlighting the influence of climatic conditions and PCM placement on their thermal performance. Researchers have reported varying results in their studies depending on the diverse climatic conditions, weather patterns, the integration of PCM in different building envelopes, and the specific locations of the PCM within those envelopes. Al-Yasiri and Szabo (2021) emphasized the impact of regional climate in determining PCM placement. They proposed that it aligns with the dominant heat source. They recommended placing PCM closer to the exterior in hot climates to act as a heat barrier, reduce heat ingress, and utilize night cooling effects. In cold climates, however, PCM should be placed closer to the interior to retain heat indoors and minimize heat loss to the exterior [20]. He et al. (2024) found that placing PCM behind the insulation and closer to the exterior wall surface in hot-arid climates significantly improved energy performance and achieved up to 36% HVAC energy savings compared to conventional walls [23]. In contrast, Arıcı et al. (2020) reached an opposite conclusion regarding PCM placement. They found that in hot summer climates like Diyarbakir and Konya, PCM placement on the interior side of walls resulted in maximum energy savings by effectively utilizing latent heat to stabilize indoor temperatures. Conversely, for regions with severe cold winters, such as Erzurum, PCM placement near the exterior side was more effective in reducing heating energy losses [26].

Cascone et al. (2018) also highlighted the effectiveness of interior PCM placement. Their study demonstrated that retrofitting walls with PCM near the interior side consistently delivered the best energy performance and cost-efficiency in both cooling-dominated and heating-dominated climates, such as Palermo and Turin, respectively [24]. Similarly, Lagou et al. (2019) emphasized that placing PCMs at the interior edge of walls provided maximum energy efficiency and thermal comfort in southern, central, and northern European climates [25].

Darvishi et al. (2019) added another perspective and found that the optimal PCM location depends on thermal performance needs. Their study identified the middle layer, or near the interior layer of walls, as an effective position for reducing both heating and cooling loads in various climates [27]. On the other hand, Li et al. (2019) focused on the role of PCM thermophysical properties, such as thermal conductivity and melting temperature. They result in PCM placement closer to the exterior for optimal heat transfer reduction. These studies reveal that the optimal location of PCM within a wall remains unclear. In addition, climate plays a significant role in determining performance, yet no standardization currently exists to guide it [44].

2.3. Simulation Platform

Experimental studies provide valuable insights into PCM integration with various materials, though their applicability across diverse climates remains limited. To address this, researchers have employed advanced simulation tools to model the thermal behavior of PCM-integrated building envelopes. The simulation platforms commonly used for PCM modeling in buildings include EnergyPlus, TRNSYS, IDA ICE, and ESP-r.

EnergyPlus has been extensively used to simulate PCM integration into building components, including walls, ceilings, and floors [17-19]. Its robust capabilities include the validated Conduction Finite Difference (CondFD) algorithm, which accurately models heat transfer during PCM phase change cycles. This feature allows users to define detailed PCM properties, such as latent heat, melting range, and thermal conductivity, ensuring high-fidelity simulations [45]. The software has enabled PCMs to be integrated into building systems, including walls, roofs, and floors, allowing comprehensive analysis of their impact on energy performance and HVAC operations. EnergyPlus's time-step simulation capabilities, recommended at intervals of three minutes or less, and its sensitivity analysis tools further optimize PCM design and placement for maximum energy efficiency in residential and commercial buildings [46].

TRNSYS has been extensively utilized for PCM simulation in various research studies and applications, including the transient analysis of PCM building walls, PCM tanks, and their integration with specific systems. Notably, it has been widely employed for simulating PCM-enhanced walls, with specific TRNSYS Types developed and validated against experimental data [47]. Mousavi et al. developed a transient simulation model for PCM-embedded radiant chilled ceiling (PCM-RCC) systems using the TRNSYS simulation studio [48]. Xu et al. (2025) developed a dynamic thermal and optical model for PCM-filled multi-glazed windows and implemented it in TRNSYS as a new module [49].

ESP-r has demonstrated flexibility and effectiveness in modeling PCM integration for building energy simulations. Wieprzkowicz & Heim (2020) emphasized the impact of PCM on optical and thermal properties in glazing systems [50]. Meanwhile, Su et al. (2020) highlighted microencapsulated PCM drywalls' energy efficiency and comfort benefits [51]. Similarly, IDA ICE 5.0 has been widely used for evaluating PCM performance in building envelopes through parametric simulations. Its custom PCM layer module allows precise insertion of PCM with varying thicknesses and positions within building components, enabling detailed thermal analysis [52]. Millers et al. (2020) validated IDA ICE's capability in simulating thermally activated PCM cooling panels by comparing its predictions with experimental data from a test chamber [53].

Mazzeo et al. (2020) compared the accuracy and performance of EnergyPlus, IDA ICE, and TRNSYS for simulating the thermal behavior of buildings with and without PCM modules [54]. The study showed that EnergyPlus outperforms other tools because of its more advanced PCM modeling capabilities, allowing for precise heat storage and release predictions during phase transitions, and its ability to account for dynamic thermal interactions within complex building envelopes. Apart from that, its validated CondFD algorithm ensures accurate modeling of PCM performance and is suitable for energy efficiency improvements in wall systems. Due to these benefits, EnergyPlus has been selected for this study.

2.4. EnergyPlus Validations

Among various simulation tools, EnergyPlus has been extensively validated in previous studies by comparing its simulations with experimental data, demonstrating its reliability in modeling building energy performance, including PCM-integrated systems. Tabares-Velasco et al. (2012) conducted two pivotal studies that validated EnergyPlus for PCM applications [46]. The first study demonstrated the model's capability to simulate PCM-enhanced opaque wall assemblies, including insulation, drywall, and thin PCM layers, using a combination of analytical, comparative, and empirical methods. The second study extended this validation to whole-building energy simulations and illustrated EnergyPlus's effectiveness in predicting peak demand reductions and energy savings, thereby optimizing PCM integration for enhanced building performance [55]. Alam et al. (2014) [56] and Baylis & Cruickshank (2024) [17] both validated the PCM module against experimental data from Kuznik & Virgone (2009) [57]. Alam et al. (2014) achieved excellent agreement between simulated and experimental zone temperatures, with an average deviation of approximately 3% for both PCM and non-PCM cases [56]. Additionally, Baylis and Cruickshank (2024) demonstrated close agreement between simulations and experiments and confirmed the model's reliability for analyzing PCM performance under varying seasonal conditions [17]. Wijesuriya et al. (2020) [58] validated the EnergyPlus PCM model using experimental data from hot-box tests conducted by Cao (2010) [59] and field measurements by Biswas et al. (2014) [60]. This study confirmed the model's accuracy in simulating PCM behavior, cementing EnergyPlus as a dependable tool for evaluating the energy performance of PCM-integrated building systems.

2.5. Research objectives

This study aims to bridge existing research gaps by integrating PCM into CLT wall systems with different placement configurations and evaluating their energy efficiency across 17 diverse climatic conditions in the U.S. based on the ASHRAE climate map. Specifically, the research will answer the questions below:

1. How does the interaction between PCM and CLT influence energy consumption for space heating and cooling, and how effective is this integration in improving energy efficiency?
2. How does PCM integration influence energy performance across different climate zones in the United States, particularly in annual energy savings, heating and cooling load reductions, and peak demand mitigation?
3. How do different wall configurations, including a reference wall, a CLT wall without PCM, and three PCM-CLT walls with varying PCM placements (exterior, interior, and intermediate), perform across different climate zones in identifying the most suitable wall envelope for each location?
4. How do PCM-enhanced CLT walls impact energy demand during peak heating and cooling periods, and can they help shift demand to off-peak hours while reducing HVAC load and grid stress?

3. Methodology

3.1. Building Modeling, Wall Configurations, and Material Properties

For this study, a virtual building model measuring 3 m × 3 m × 2.5 m was developed with a south-facing window measuring 1 m × 1 m. The design complies with the 2021 International Residential Code (IRC) to ensure adherence to minimum building standards [61]. Five wall configurations were designed, as illustrated in Figure 1. The reference wall (RW) consists of wood cladding, extruded polystyrene (XPS) insulation, and oriented strand board (OSB). In the CLT0 wall, the OSB layer was replaced with a 48 mm CLT layer [62]. For the CLT1, CLT2, and CLT3 walls, a 10 mm thickness of PCM was integrated into the envelopes at different positions, such as on the exterior, intermediate, and interior sides of the wall. These three positions were selected based on prior research that adopted similar configurations for comparative thermal assessment [20, 23]. A 10 mm PCM thickness was selected based on findings from Liu et al. (2021, 2022) [35, 63], who identified it as the optimal point. Beyond this point, the performance benefits begin to plateau, and any further increases diminish returns while significantly raising material costs. Hasan et al. (2018) [64] also experimentally validated the effectiveness of 10 mm PCM in reducing indoor temperature and cooling load. In addition, Baylis & Cruickshank (2024) [17] and Liu et al. (2022) [65] utilized this thickness in their building models.

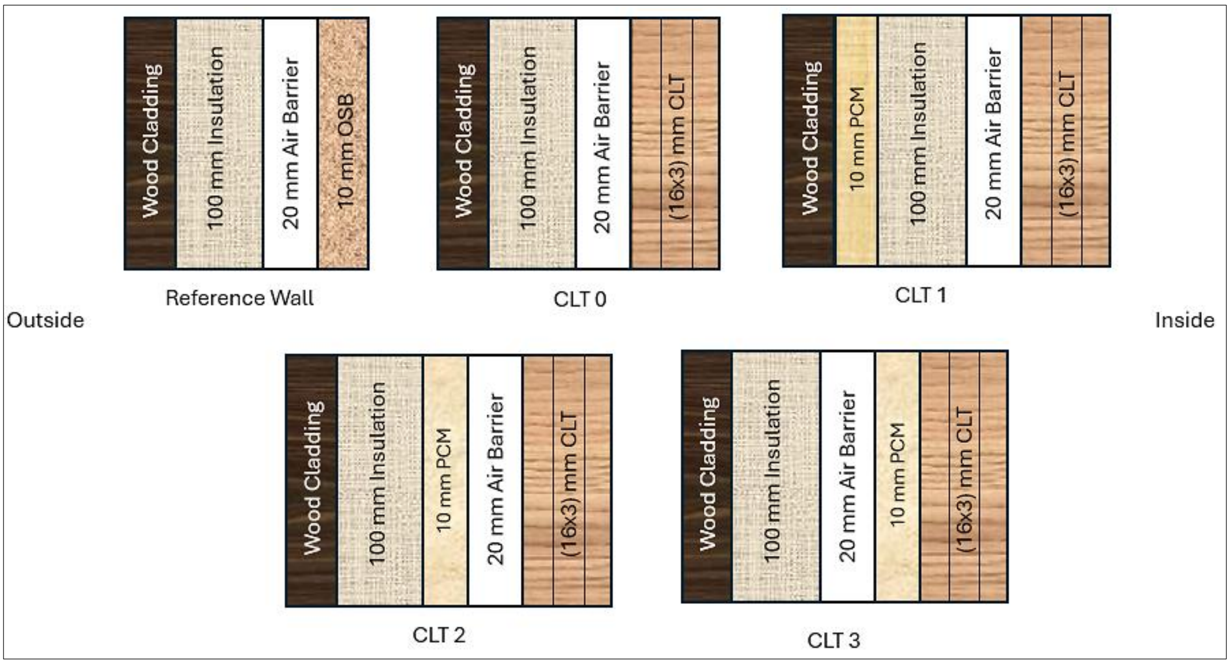

Figure 1. Different Wall Configurations

The melting temperature of the PCM plays a significant role in energy performance [66]. According to Balis and Cruickshank (2024), optimal PCM melting temperatures are 1–2 °C above the heating setpoint or 1–2 °C below the cooling setpoint. These adjustments have been shown to reduce heating loads by 4–18% and cooling loads by 72–94% in four different cities of Canada [17].

This study set the heating and cooling setpoints to 21 °C and 23 °C, respectively, based on the thermal comfort criteria outlined in ASHRAE Standard 55 [67]. To meet these requirements, RT22 HC PCM from the Rubitherm Technologies (RT) line [68] was selected for the wall configurations. The RT22 HC PCM has a solidus and liquidus temperature of 22°C. Its latent heat is 190 kJ/kg, and its specific heat capacity is 2000 J/kg·K. Table 1 details the material properties of the wall materials.

Table 1. Wall materials properties

Material	Thickness (mm)	Thermal Conductivity, λ (W/m.K)	Specific Heat Capacity, Cp (J/Kg.K)	Density, ρ (kg/m^3)	Standard	Source
OSB	10	0.13	1500	650	2021 IRC [69]	[70]
Insulation (XPS)	100	0.0289	1500	28	2021 IECC* [71]	[72]
CLT	48	0.13	1300	490	2024 NDS** [62]	[73]
Wood cladding	10	0.084	1880	350	2021 IRC [61]	[74]
Air layer	20	0.023	1000	1.3	-	-

* Internation Energy Conservation Code (IECC), **National Design Specification (NDS).

3.2. Climate Zones and Weather Data Sources

This study follows the ASHRAE climate zones to identify diverse climatic locations across the United States. The ASHRAE climate zone system, based on the Köppen-Geiger classification and refined by Joseph Lstiburek in the 1990s, categorizes the country into eight temperature-oriented zones, each subdivided into three moisture regimes (A, B, C) [75].

Table 2 presents the climate zones along with their corresponding temperature and moisture conditions, representative cities, and states. Each climate zone is classified based on temperature and humidity levels, following the ANSI/ASHRAE 169-2020 [76]. A representative city was selected for each climate zone based on this standard to accurately reflect the climatic conditions. For instance, Climate Zone 1A, characterized as very hot and humid, is represented by the city of Miami, located in Florida (FL). To conduct the simulations, Typical Meteorological Year 3 (TMY3) weather data files were sourced from climate.onebuilding.org [77].

Table 2. Representative Cities and States for ASHRAE Climate Zones with Temperature and Moisture Characteristics

Climate Zone	Temperature and Moisture	Cities	States
1A	Very Hot Humid	Miami	FL
1B	Very Hot Dry	McAllen	TX
2A	Hot Humid	Tampa	FL
2B	Hot Dry	Tucson	AZ
3A	Warm Humid	Atlanta	GA
3B	Warm Dry	El Paso	TX
3C	Warm Marine	Los Angeles	CA
4A	Mixed Humid	Highlands	VA
4B	Mixed Dry	Albuquerque	NM
4C	Mixed Marine	Seattle	WA
5A	Cool Humid	Buffalo	NY
5B	Cool Dry	Denver	CO
5C	Cool Marine	Port Angeles	WA
6A	Cold Humid	Rochester	MN
6B	Cold Dry	Laramie	WY
7	Very Cold	International Falls	MN
8	Subarctic	Fairbanks	AK

3.3. EnergyPlus Modeling

EnergyPlus (Version 24.1.0) was used to simulate the thermal performance of this study. The CondFD algorithm was selected as the heat balance method to enhance the accuracy of conduction calculations. Simulations were conducted with a three-minute timestep to achieve high temporal resolution [55]. A packaged terminal heat pump (PTHP) system was employed as the HVAC solution, scheduled to operate continuously throughout the year. The system adhered to the performance standards outlined in AHRI 310/380-2017 [78]. A single-zone residential model was used to maintain consistency and simplify comparison among different wall configurations.

Two PCM modeling approaches are utilized in EnergyPlus. The first method, Material Property: Phase Change, uses a temperature-enthalpy function to represent the phase change process and requires detailed temperature-dependent material properties. The second method, Material Property: Phase Change Hysteresis, uses advanced modeling to account for hysteresis effects by defining separate melting and freezing curves. This approach offers a practical and accurate solution, especially when detailed enthalpy data are unavailable [79]. For this study, the Material Property: Phase Change Hysteresis method was selected to enhance accuracy in capturing PCM behavior within CLT walls. The Material section defined the material properties of the building components, including thermal conductivity, density, and specific heat capacity. PCM-specific characteristics, such as solid and liquid-state thermal conductivity, density, specific heat, and peak melting temperature, were input in the Material Property: Phase Change Hysteresis section.

The Building Surface: Detailed section was used to define the assignment of walls, ceilings, and floors by specifying their corresponding surfaces, construction types, zones, and boundary conditions. This section modifies the wall construction type for each simulation to reflect different PCM placements within the envelope. Specifically, the construction section organizes all materials from the inside to the outside layer-by-layer format for walls, floors, and ceilings.

For wall layers without PCM (e.g., OSB, CLT), the algorithm numerically solves the one-dimensional transient heat conduction equation, which governs thermal diffusion [35]:

$$\rho c_{\mathrm{p}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\lambda . \partial T}{\partial x}\right) \tag{1}$$

where ρ is the material density (kg/m³), c_{p} is the specific heat capacity (J/kg·K), T is temperature, λ is thermal conductivity, x is spatial position, and t is time. When PCMs are used, EnergyPlus employs an enthalpy-based formulation to solve the governing energy equation, which accounts for both sensible and latent heat [35, 80, 81]:

$$\rho \frac{\partial h}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \tag{2}$$

The total enthalpy h(T) is defined as:

$$h(T) = \int_{T_0}^{T} c_{\mathrm{p}}(T')dT' + \beta(T)\, L \tag{3}$$

where β(T) is the liquid fraction (phase state), and L is the latent heat of fusion. The liquid fraction function is expressed as:

$$(T) = \begin{cases} 0, T < T_{solidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{Solidus}}, T_{solidus} \leq T \leq T_{liquidus} \\ 1, T > T_{liquidus} \end{cases} \quad (4)$$

During the phase change interval, EnergyPlus calculates an effective heat capacity using enthalpy updates between time steps, where j and $(j-1)$ represent the current and previous time steps, respectively [82].

$$C_{P,eff}(T) = \frac{h^{j} - h^{j-1}}{T^{j} - T^{j-1}} \quad (5)$$

These expressions allow EnergyPlus to internally model the dynamic thermal behavior of PCMs within the wall layers during both melting and freezing cycles.

Five different simulations were conducted for each climate zone, representing the RW, CLT0, CLT1, CLT2, and CLT3 configurations. This process was repeated across 17 climate zones, resulting in a total of 85 simulations. The simulations were performed using the TMY3 weather file format specific to these locations. Figure 2 presents the climate zone classification across the United States, color-coded for clarity. While the ANSI/ASHRAE Standard 169-2020 defines 19 climate zones (0A–8), only 17 are present in the U.S. Each representative city is pinned on the map for each climate zone. This visualization provides a clear geographic distribution of the selected climate zones and their corresponding cities.

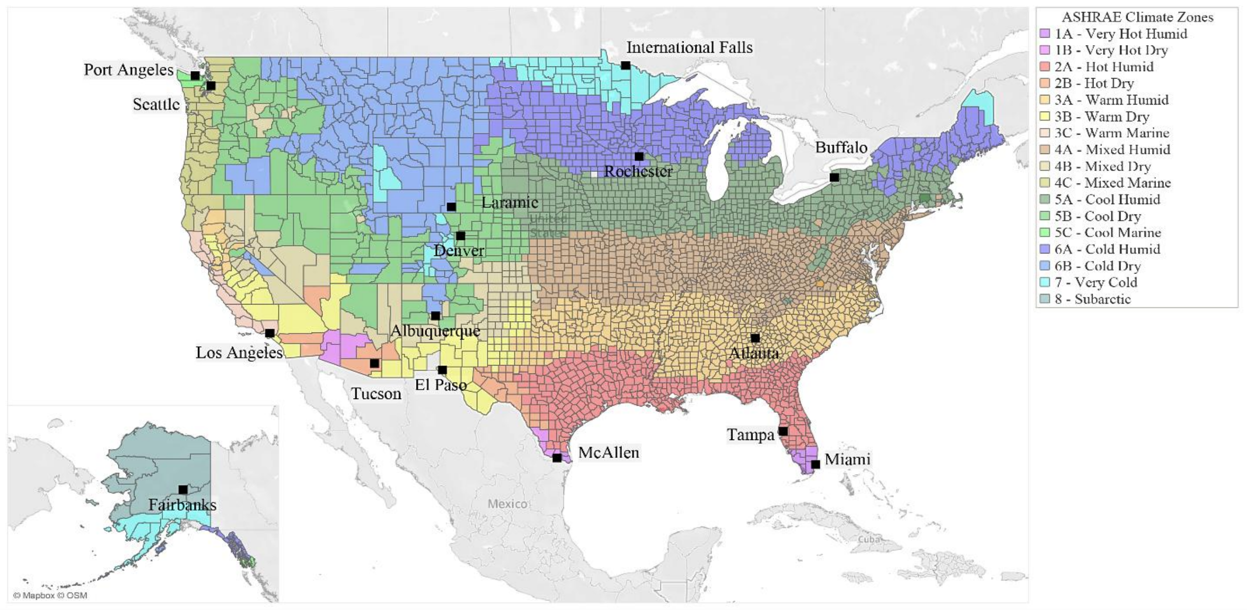

Figure 2. ASHRAE climate zone map (ANSI/ASHRAE Standard 169-2020) [83] and the selected cities

4. Results and Discussion

This section provides a detailed analysis of the energy performance of various wall configurations and focuses on their effectiveness in different climate conditions. Figure 1 presents the five wall configurations, where RW and CLT0 do not include PCM, while the remaining three configurations integrate PCM. In CLT1, PCM is placed on the exterior side of the wall; in CLT2, it is positioned in the intermediate layer and in CLT3, PCM is located on the interior side.

4.1. Performance of CLT Wall

The performance of the CLT0 envelope model, which represents the CLT wall without any PCM, varies significantly across climates. Figure 3 shows the total energy savings percentages by CLT0 for each location compared to the reference wall (RW). It shows that, in the hot and humid climates of Miami, FL (1A), and Tampa, FL (2A), the energy savings are relatively moderate at 7.32% and 15.66%, respectively. This suggests that the CLT0 wall improves thermal performance but struggles to address the high humidity and heat of these regions. In contrast, the performance improves significantly in hot and dry climates such as Tucson, AZ (2B), and El Paso, TX (3B), with energy savings of 19.55% and 22.7%, respectively.

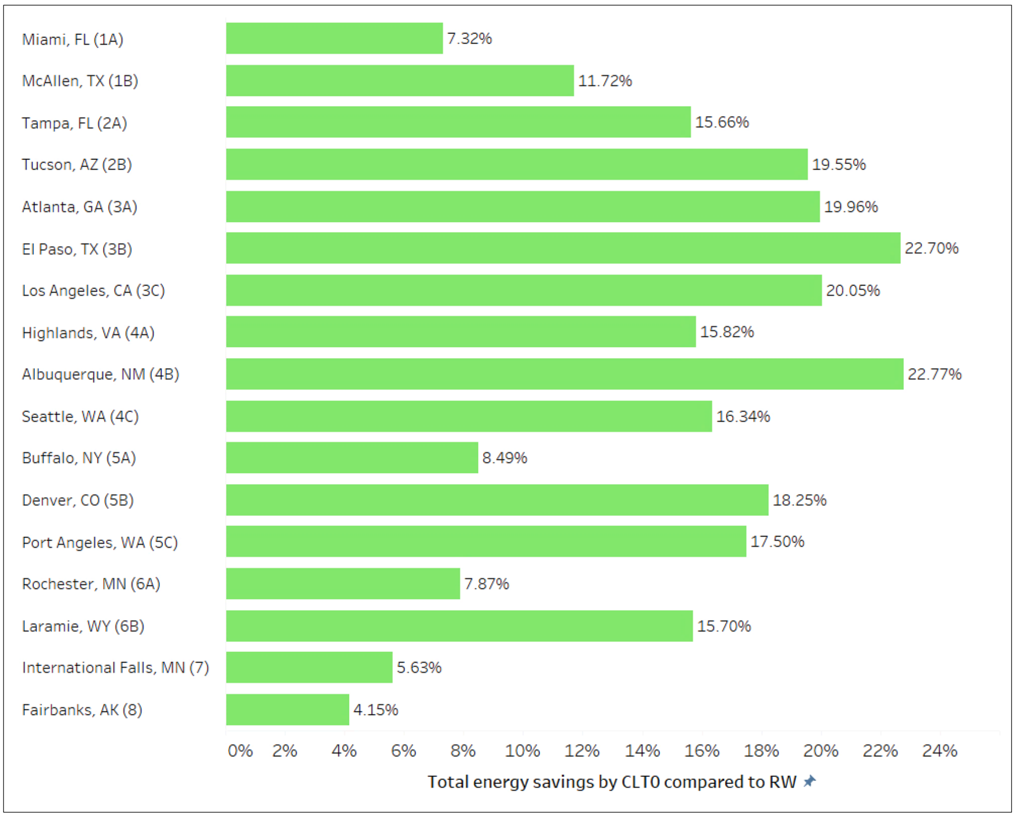

Figure 3. Total energy savings percentages by CLT0 compared to RW

From these results, a common pattern emerges: the energy efficiency of the CLT0 wall is highest in dry climates and decreases in humid climates. This trend remains consistent across very hot (1), hot (2), warm (3), mixed (4), cool (5), and cold (6). Additionally, marine climates exhibit performance levels that are generally intermediate between dry and humid climates, as observed in Zones 3C, 4C, and 5C. The relative stability of marine climates, with moderated temperature swings and reduced solar radiation intensity, may contribute to this improved efficiency over humid regions, despite higher moisture exposure. This stability likely enables the CLT0 wall to maintain better insulation performance and reduce heat exchange in such environments.

The findings suggest that high humidity degrades the performance of CLT walls, likely due to moisture absorption reducing the timber's insulation characteristics and structural integrity. Moisture also accumulates in areas like end grains and connections, leading to slower drying rates and an increased risk of decay, as observed in prior research [84]. Additionally, high moisture levels reduce the airtightness of CLT walls, contributing to greater energy loss in humid climates [85]. Increased moisture content may also lead to dimensional changes in the timber [86], affecting the continuity of insulation and air sealing across joints. These effects are less pronounced in marine climates, as the controlled thermal conditions balance the detrimental impact of moisture to some extent.

In cold climates such as Buffalo, NY (5A), Rochester, MN (6A), and International Falls, MN (7), energy savings declined, with savings of 8.49%, 7.87%, and 5.63%, respectively. The lowest energy efficiency is 4.15%, as observed in the subarctic zone of Fairbanks, AK (8). This drop is likely because cold regions require high levels of continuous insulation to minimize heat loss, and CLT alone may not offer sufficient resistance compared to high R-value assemblies used in colder construction practices. This delineates that the thermal performance of CLT0 walls is less effective in regions requiring higher insulation due to extended periods of low temperatures.

4.2. Improvement of CLT Walls with PCM Integration

This section presents the energy performance of CLT walls (CLT1, CLT2, and CLT3) enhanced with a focus on RT22 PCM integration. In CLT1, PCM is placed on the exterior side of the wall; in CLT2, it is positioned in the intermediate layer; and in CLT3, PCM is located on the interior side. Figures 4 to 8 present comprehensive analyses of energy performance metrics. Each figure illustrates the energy consumption per unit floor area and the corresponding energy savings percentages relative to the RW for heating, cooling, and total energy. The figures are organized by climate zones, with Figure 4 focusing on climate zones 1 and 2, Figure 5 on climate zone 4, and so forth.

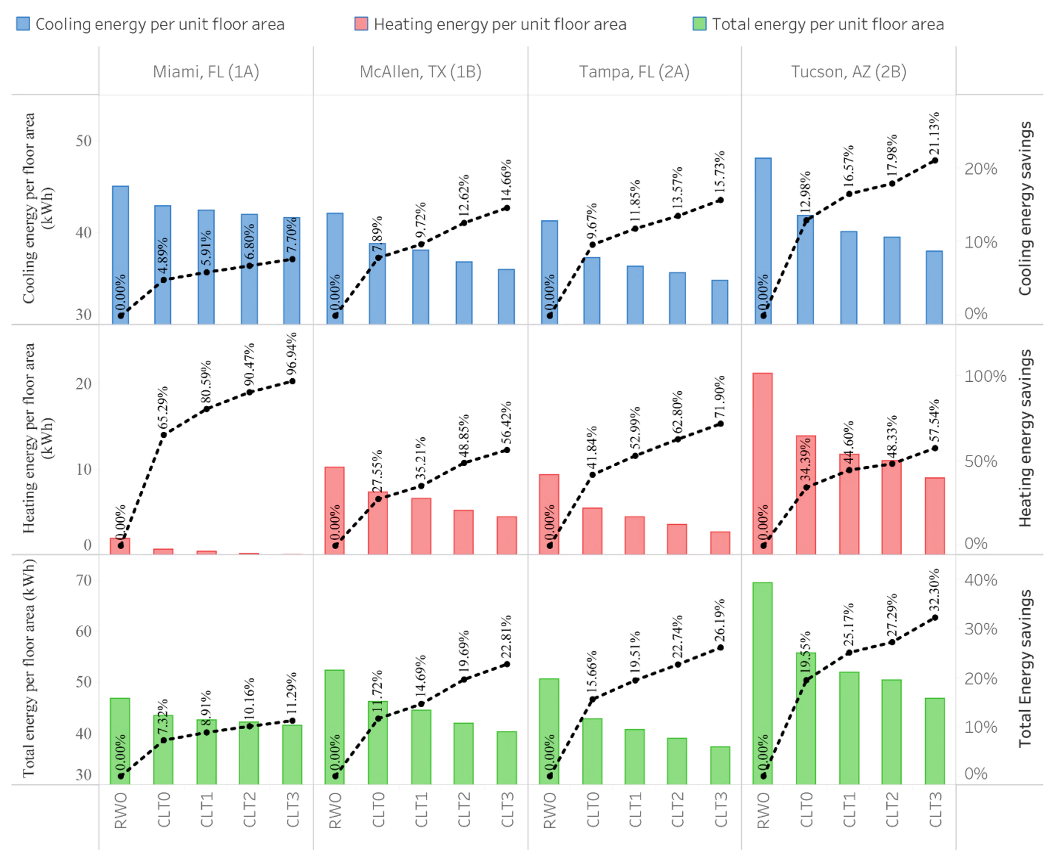

Figure 4. Energy consumption per floor area and energy savings percentage for heating, cooling, and total energy in Climate Zones 1 and 2

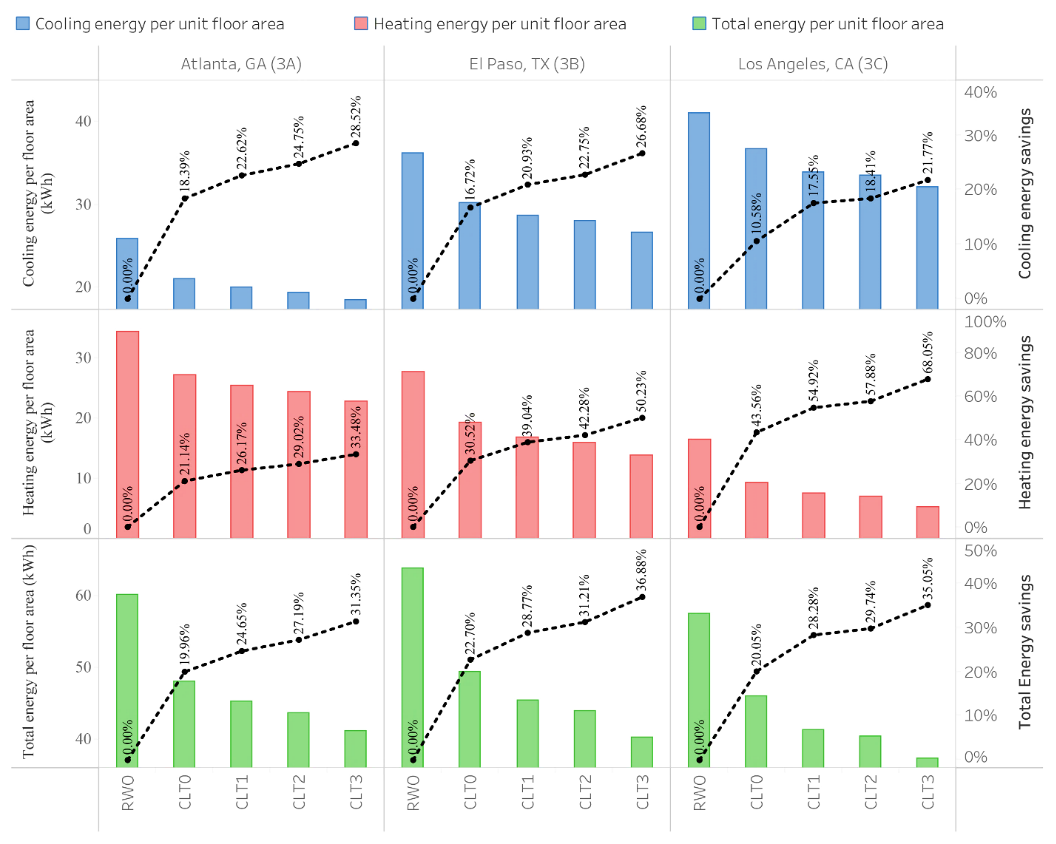

Figure 5. Energy consumption per floor area and energy savings percentage for heating, cooling, and total energy in Climate Zone 3

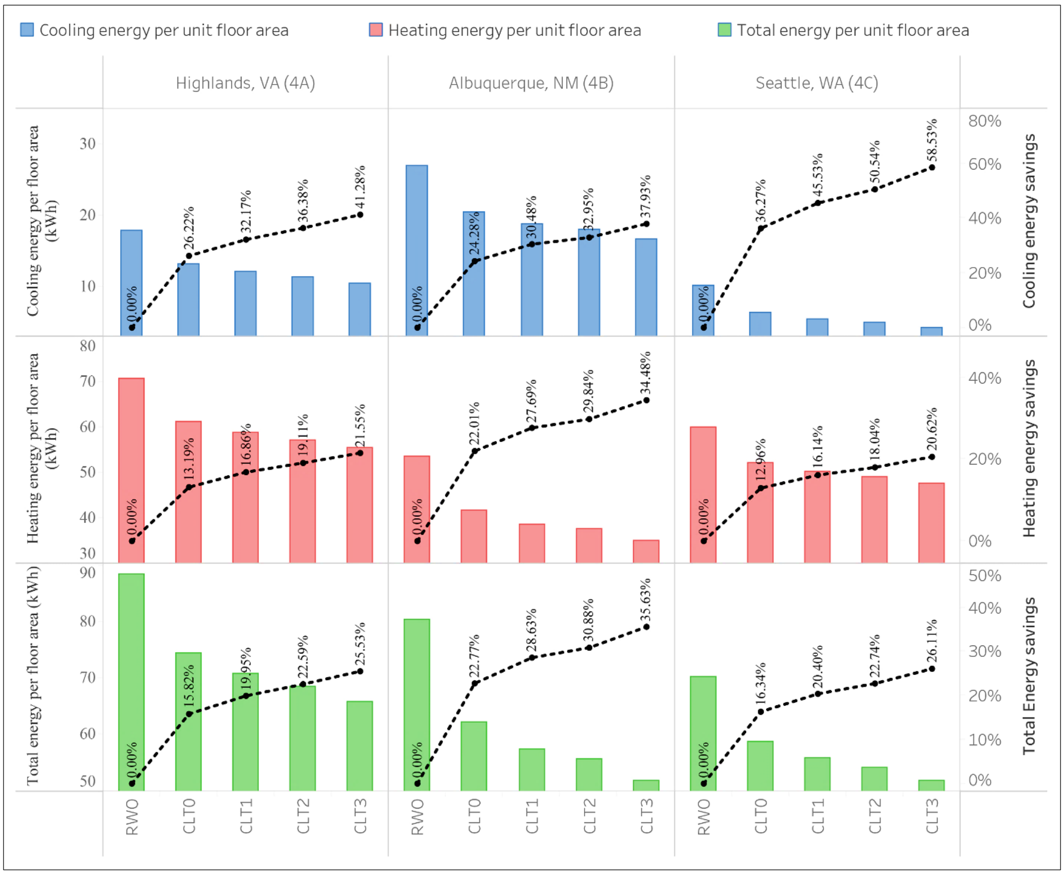

Figure 6. Energy consumption per floor area and energy savings percentage for heating, cooling, and total energy in Climate Zones 4

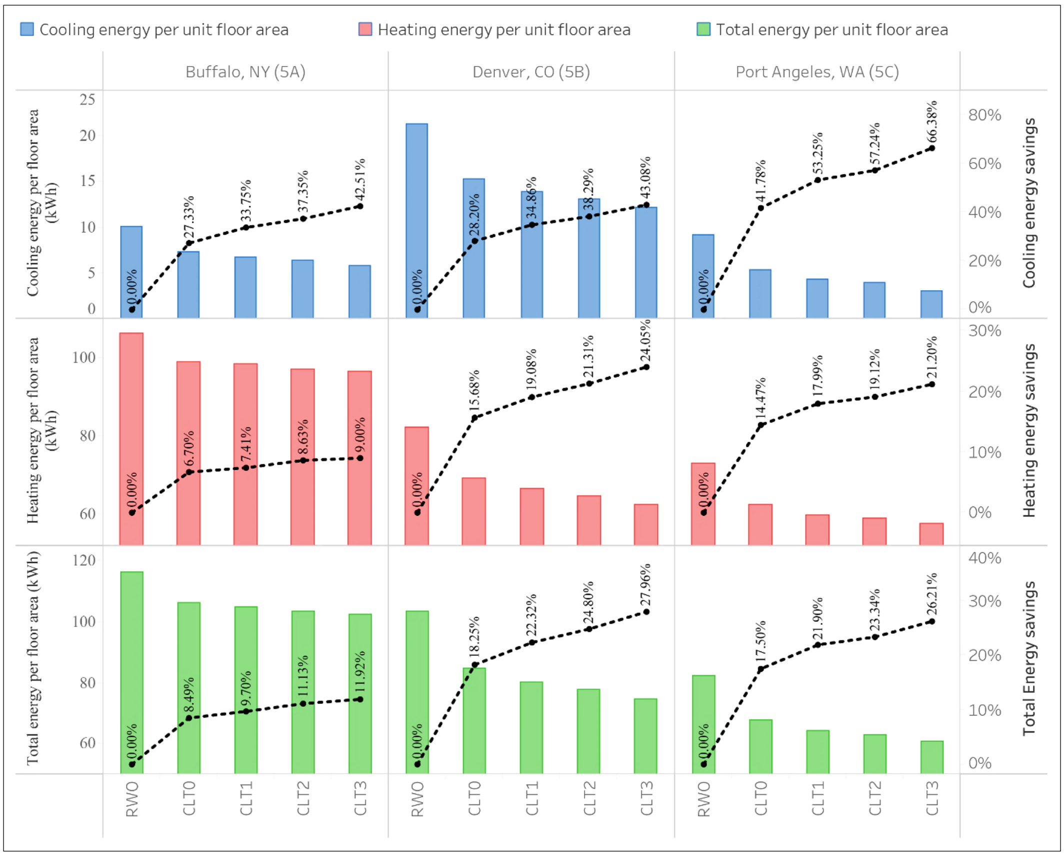

Figure 7. Energy consumption per floor area and energy savings percentage for heating, cooling, and total energy in Climate Zone 5

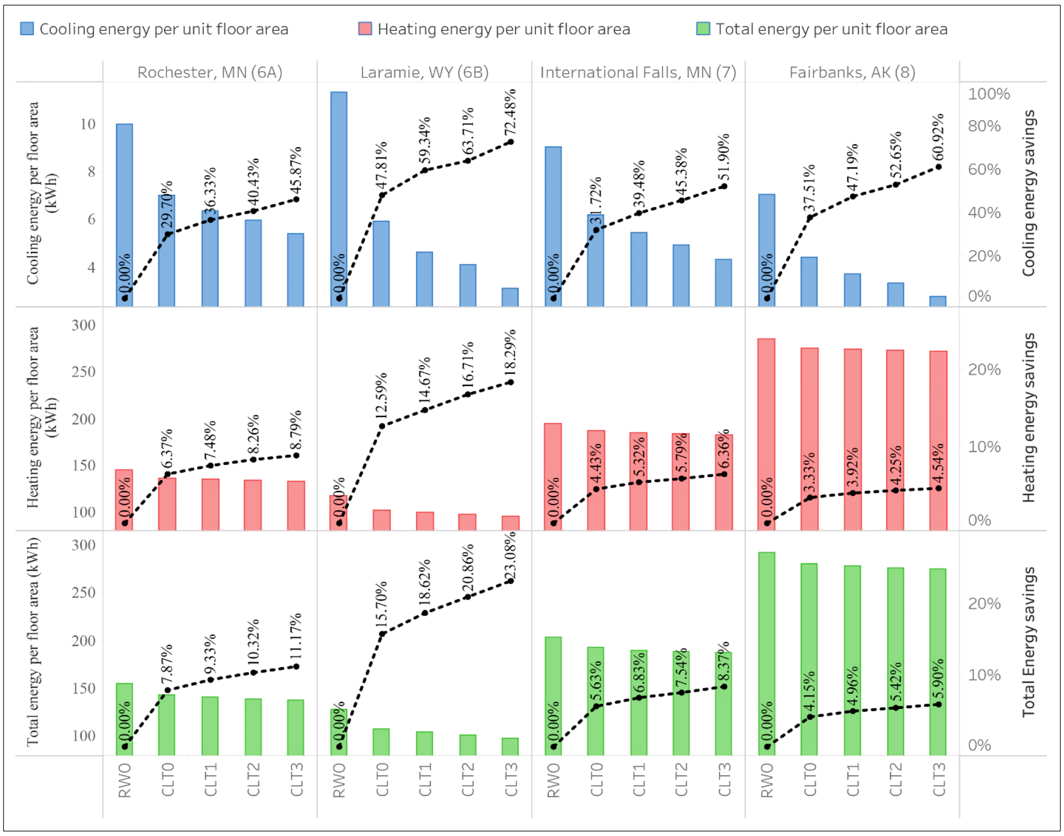

Figure 8. Energy consumption per floor area and energy savings percentage for heating, cooling, and total energy in Climate Zone 6, 7 and 8

4.2.1. Climate Zones 1, 2 and 3: Extreme Hot, Hot and Warm Conditions

Integrating PCM into CLT walls significantly improved the thermal performance of CLT walls in these climate zones (Figures 4 and 5). These regions are characterized by high temperatures, with cooling loads dominating energy demand. In terms of cooling energy demand, PCM-integrated CLT walls performed substantially better compared to CLT0. For instance, in warm climate zones, cooling energy savings reached up to 21.77% in Los Angeles (3C), which is 11.19% higher than the savings achieved with CLT0. In hot zones such as Tampa (2A) and Tucson (2B), PCM-integrated walls achieved cooling energy savings of 15.73% and 21.13%, respectively, which are significantly higher than the 9.67% and 12.98% savings achieved with CLT0. Even in very hot climates (1), PCM-integrated walls provided notable cooling energy savings, reaching up to 7.7% in Miami (1A) and 14.66% in McAllen (1B). This enhanced performance can be attributed to the PCM's ability to respond to diurnal temperature fluctuations by absorbing heat during the peak daytime period and releasing it during cooler nights. Soleiman Dehkordi & Afrand (2022) [16] emphasized that effective PCMs require discharging stored thermal energy to engage in the following day's phase change cycle. In this context, nighttime conditions serve as a natural discharge phase and allow the PCM to reset.

In these regions, PCM walls also demonstrated remarkable performance during transitional seasons or nighttime, when temperatures dropped below the daytime peaks. PCM-integrated CLT walls achieved significant heating energy savings, ranging from 33.48% in Atlanta (3A) to 96.94% in Miami (1A). The high heating energy savings in cities like Miami result from the PCM's ability to retain heat during a short cool period and gradually release it when indoor temperatures fall below comfort thresholds. These results highlight that integrating PCM into the walls reduces dependency on HVAC systems for heating, making buildings more energy efficient.

The energy savings achieved with PCM-enhanced walls significantly impact the total annual energy demand in these locations. In very hot climate zones, the CLT3 wall system reduced total energy demand by 11.29% (1A) and 22.81% (1B). In other hot zones, such as Tampa (2A) and Tucson (2B), total energy savings reached 26.19% and 32.3%, respectively. In warm zones like Los Angeles (3C), the savings were even higher, with up to 35.05% of total space heating and cooling energy demand reduced by utilizing PCM-enhanced walls.

4.2.2. Climate Zones 4 and 5: Mixed and Cool Conditions

In mixed and cool climate zones, where heating loads dominate and cooling demands are comparatively lower, PCM-integrated CLT walls also demonstrated significant performance improvements. In mixed climate zones, heating energy savings with the CLT3 configuration ranged from 20.62% in Seattle (4C) to 34.48% in Albuquerque (4B), providing at least 7.66% higher savings compared to the CLT0 configuration, as illustrated in Figure 6. For cooling loads, the savings were even more pronounced, with CLT3 achieving 58.53% cooling energy savings in Seattle (4C), significantly outperforming the 36.27% savings observed with CLT0. These improvements are largely due to the PCM's ability to store daytime solar gains or internal heat and release it during cooler nighttime periods. These savings trends are also reflected in the total energy performance, where CLT3 delivered a minimum total energy savings of 25.53% in Highlands (4A), which is 9.71% higher than that achieved with CLT0.

In cool climate zones, despite being heating-dominated regions, the heating load savings range from 9% to 24.05% in Buffalo (5A) and Denver (5B), indicating a notable reduction (Figure 7). The cooling energy savings are even more substantial, reaching up to 66.38% in Port Angeles (5C). The total energy savings across these locations range from 11.92% to 27.96%, demonstrating the effectiveness of the PCM-enhanced wall envelopes in improving overall energy performance in these climates.

4.2.3. Climate Zones 6, 7 and 8: Cold, Very Cold and Subarctic

In cold, very cold, and subarctic climate zones, where temperatures are significantly lower than in other regions, heating loads dominate the energy demand. For heating load reductions, PCM-enhanced walls consistently outperformed non-PCM configurations. Figure 8 demonstrates that, in Rochester (6A) and Laramie (6B), the CLT3 configuration achieved heating energy savings of 8.79% and 18.29%, respectively, which represent improvements of 2.41% and 5.71% over the CLT0 configuration. In International Falls (7), the savings reached 6.36%, approximately 2% higher than CLT0, while in Fairbanks (8), a heating load reduction of 4.54% was observed.

The relatively lower savings in climate zones 7 and 8 may be attributed to insufficient thermal activation of PCM under persistently low temperatures. It can limit the material's ability to undergo complete phase transitions and utilize its latent heat capacity. As noted by Al-Yasiri & Szabó (2021), solar radiation is poor in cold locations and may not reach the PCM layer naturally, thereby limiting its charging potential during the day and reducing the PCM's effectiveness [20].

Additionally, in these regions, indoor and outdoor temperature differences are high, which accelerates heat loss. PCM-enhanced walls help slow this heat loss by acting as a thermal buffer and delaying heat transfer. However, the extremely high heating demand in such climates may limit the relative impact of thermal storage materials. Still, even modest percentage savings indicate substantial energy reductions due to the high baseline consumption in these regions.

Regarding cooling load performance during summer, PCM-integrated walls exhibited remarkable efficiency even in these predominantly heating-oriented climates. For instance, in Laramie (6B), cooling energy savings reached 72.48% with PCM-enhanced walls. This significant reduction underscores the capability of PCM to mitigate cooling demands during warmer periods. The total energy savings achieved with PCM-integrated walls in these colder climate zones were equally promising. From Fairbanks (8) to Laramie (6B), total energy savings ranged from 5.9% to 23.08%, significantly surpassing the performance of CLT0. These results demonstrate that PCM integration reduces space heating and cooling energy demands and delivers consistent energy efficiency improvements in colder regions, similar to the trends observed in other climates.

These findings align with Baylis & Cruickshank (2024) [17], who concluded similar results in cold Canadian cities like Winnipeg and Yellowknife, where PCM integration led to modest heating savings but notable cooling reductions due to low baseline cooling loads and short summer peaks.

4.3. Comparison of Wall Envelopes

The placement of PCM within CLT walls significantly impacts their thermal performance and energy savings. This research demonstrates that CLT3 consistently outperforms CLT2 and CLT1 across all climate zones.

In Albuquerque (4B), total energy savings with CLT3 reached 35.63%, significantly outperforming CLT2 at 28.63% and CLT1 at 19.95%. Similarly, in Los Angeles, CA (3C), CLT3 achieved 35.05% total savings, which exceeds the 29.74% recorded for CLT2 and the 28.28% for CLT1. In Tucson, AZ, (2B) total energy savings with CLT3 reached 32.30%, compared to 27.29% for CLT2 and 25.17% for CLT1. In addition, in McAllen (1B), total energy savings with CLT3 were 22.81%, compared to 19.69% for CLT2 and 14.69% for CLT1. On the other hand, in regions like Highlands, VA (4A), Seattle, WA (4C), Denver, CO (5B), and Atlanta, GA (3A), the differences between CLT3 and CLT2 narrowed slightly but still remained consistent. For example, in Seattle, total energy savings with CLT3 reached 26.11%, compared to 22.74% with CLT2.

In some colder climates where heating dominates, such as Fairbanks, AK (8), and Rochester, MN (6A), the differences between configurations narrow. For example, in Fairbanks, total energy savings with CLT3 reached 5.90%, compared to 5.42% with CLT2 and 4.96% with CLT1. A similar pattern was observed in Rochester, where CLT3 achieved 11.17% savings, while CLT2 followed closely at 10.32%. These smaller margins reflect the reduced influence of PCM placement in specific climates and highlight that the overall insulation of the wall assembly plays a more significant role in these conditions.

The consistent superiority of CLT3 can be explained by its ability to maximize the PCM's latent heat storage capacity by placing it closest to the indoor environment. This strategic placement introduces thermal lag, which delays heat transfer from the outdoor environment while stabilizing indoor temperatures [87]. The performance can also be attributed to its placement near the interior surface, where it directly responds to indoor air temperature fluctuations. This proximity enables the PCM to operate more efficiently in stabilizing indoor thermal conditions, compared to CLT1 or CLT2.

By contrast, exterior placement in CLT1 is less effective, as much of the PCM's thermal storage potential is lost to the outdoor environment before benefiting indoor conditions. Middle placement in CLT2 provides a balance but lacks direct interaction with indoor air, which makes CLT3 superior. In colder climates, the smaller differences between configurations can be attributed to the dominant heat transfer mechanism being conduction through the wall assembly, which is influenced more by the insulation properties of the wall layers rather than the specific PCM placement.

While CLT3 is the most effective configuration, CLT2 emerges as a viable alternative if constructability or cost constraints make interior PCM placement challenging. For instance, in Fairbanks, AK, and Rochester, MN, the total energy saving difference between CLT2 and CLT3 is less than 1%, which is very minimal. In such cases, CLT2 provides nearly comparable energy performance while simplifying construction processes.

4.4. Impact on Peak Loads

Figures 9 and 10 illustrate sensible cooling loads on an extreme temperature day (July 27) for Climate Zones 1A and 1B and sensible heating loads on December 24 for Climate Zone 7 and February 23 for Climate Zone 8, respectively, consumed by the RW, CLT0, and the best-performing CLT3 wall envelope. The figures also depict the outdoor dry-bulb temperature.

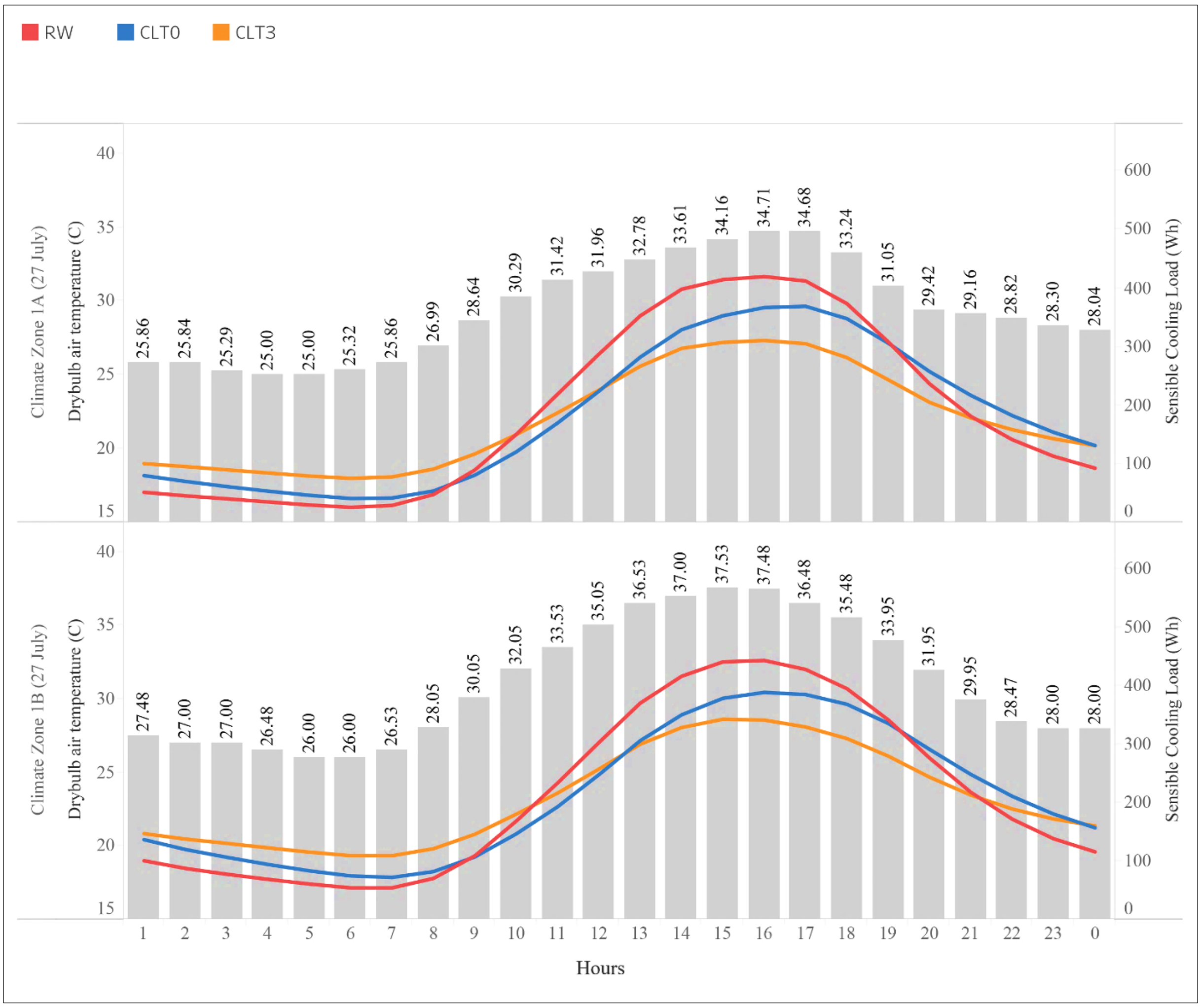

Figure 9. Sensible Cooling Load with Outdoor Dry-Bulb Temperature for Selected Extreme Temperature Day Across Climate Zones 1A and 1B

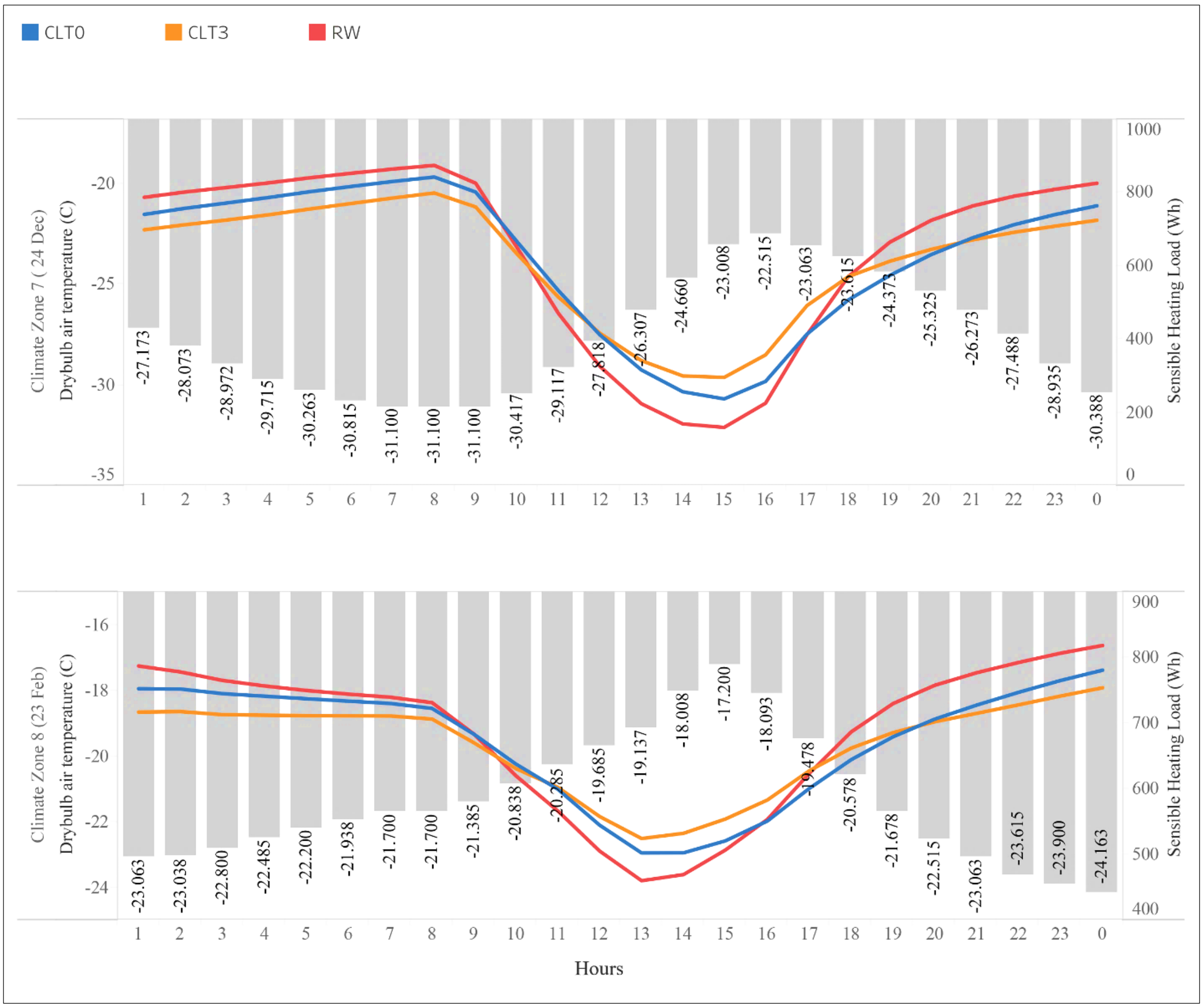

Figure 10. Sensible heating Load with Outdoor Dry-Bulb Temperature for Selected Extreme Temperature Day Across Climate Zones 7 and 8

The results from Figure 9 reveal an interesting correlation with PCM's thermal behavior. During its phase transition, PCM absorbs and releases thermal energy by changing its state (e.g., from solid to liquid or vice versa). Unlike other materials, this phase transition process occurs gradually, which influences energy consumption patterns. During peak cooling hours, typically around noon when outdoor temperatures are at their highest, the RW exhibits the highest energy consumption among the wall systems. In contrast, CLT3 consistently shows the lowest energy consumption during these peak periods. This performance is attributed to the PCM's ability to release stored heat and reduce the cooling load. Conversely, during non-peak hours when temperatures are lower, CLT3-RT22 consumes slightly more energy as the PCM absorbs heat and stores it as latent energy. This stored heat is later released during peak periods, thereby reducing overall energy demands and improving energy efficiency. This trend is consistent with findings by Gholamibozanjani and Farid (2021), who demonstrated that PCM-enhanced systems stored free cooling during off-peak hours and released it during peak cooling demand, thereby reducing load and improving comfort [88].

Similarly, during the lowest outdoor temperatures, typically observed before sunrise, the energy consumption patterns of RW, CLT0, and CLT3 exhibit similar trends in colder regions (Figure 10). At these peak times, the RW consumes the highest heating load compared to the other wall systems. However, during periods when the temperature rises slightly, such as around noon, CLT3 shows higher heating energy consumption than the other two non-PCM wall systems. This behavior reflects the same principle as in cooling scenarios. When heating demand is lower than during the peak periods, PCM-integrated walls absorb energy and store it as latent heat. This stored energy is later released when temperatures drop significantly, allowing PCM walls to consume less energy during extreme low-temperature conditions. Gholamibozanjani and Farid (2021) similarly found that PCMs were effective in meeting heating demands during morning peaks by releasing latent heat from overnight storage, shifting peak loads by several hours [88].

As a result, PCM walls effectively reduce peak heating demand by storing energy during non-peak hours and utilizing it during peak periods, thereby enhancing overall energy efficiency and alleviating stress on the national energy grid. This aligns with the observations of Saffari et al. (2022), who noted that PCM retrofitting in building envelopes not only minimized indoor temperature fluctuations but also reduced heating and cooling demands while offering demand response benefits in grid-constrained systems [89].

5. Conclusions

Phase change materials (PCM) have been widely used in building materials to enhance thermal performance, but their integration with cross-laminated Timber (CLT) has not been studied. Previous research also shows conflicting results about the best placement of PCM within wall cross-sections. This study explored five wall configurations to address these gaps, including a reference wall (RW) and four CLT walls. PCM was placed in the CLT walls, exterior (CLT1), middle (CLT2), and interior (CLT3), while one wall had no PCM (CLT0). Recognizing that PCM performance strongly depends on geographical and climatic conditions, simulations were carried out across 17 climate zones, as defined by the ASHRAE climate map, using EnergyPlus software.

The findings demonstrate that CLT0 walls consistently outperformed the reference wall in energy efficiency, achieving up to 22.77% total energy savings in locations like Albuquerque. A clear trend emerged, indicating that the highest energy savings were achieved in dry climates, followed by marine and humid regions. The integration of PCM with CLT walls further enhanced energy efficiency. Among the three PCM-integrated configurations, the CLT3 wall, where PCM was positioned on the interior side, showed the most significant performance gains across all climate zones, from very hot and humid to subarctic conditions. This wall configuration effectively reduced both cooling and heating loads. For example, in hot climates such as Miami, CLT3 reduced cooling energy consumption by at least 7.70%, while in moderate and cold climates like Laramie, Wyoming, cooling load reductions reached 72.48%. Similarly, heating load reductions with CLT3 ranged from 56.42% in hot climates to 96.94% in mixed and cold regions. Even in extreme subarctic zones, 6.36% and 4.54% reductions were achieved in climate zones 7 and 8, respectively. When accounting for both heating and cooling energy savings, the PCM-integrated CLT3 wall delivered significant total annual energy reductions, ranging from 5.90% in subarctic zones to 36.88% in El Paso.

A key observation in this study is the role of PCM in moderating peak energy demand. PCM absorbed excess heat during non-peak hours in hot climates, acting as a thermal buffer and reducing peak cooling loads when demand was highest. Conversely, in extreme cold conditions, PCM stored heat during relatively warmer periods and released it during the coldest hours, minimizing heating energy demand. This thermal behavior resulted in a more balanced energy consumption pattern throughout the day and reduced peak load stress on the grid.

5.1. Research Contributions, Limitations, and Future Work

This study introduces a new dimension in the integration of PCM within CLT wall systems, expanding its potential as an energy-efficient building material. While previous research has explored PCM applications in conventional materials such as concrete, gypsum board, and brick walls, the integration of PCM into CLT structures remains largely unexplored. By addressing this gap, the study provides critical insights into PCM placement strategies across diverse climatic conditions, contributing to the ongoing discourse on optimal thermal storage and energy performance in residential buildings.

Furthermore, this research establishes a foundation for future investigations into PCM-CLT systems by systematically analyzing their impact through energy simulations. The findings offer a framework for designers and engineers to incorporate PCM-integrated CLT panels into new construction and retrofitting applications, ultimately enhancing the thermal efficiency of buildings.

Despite its contributions, this study has certain limitations. The simulations were conducted on a single-zone residential building model, which does not fully capture the complexity of multizone structures, varying occupancy patterns, and diverse building geometries. Additionally, the study relied solely on simulation-based assessments using predefined climate conditions, which may not fully represent real-world variations. In particular, the use of TMY3 weather files may exclude extreme weather events and lack microclimatic accuracy, potentially limiting the precision of energy performance estimates in diverse or non-typical climate scenarios. While EnergyPlus has been extensively validated for PCM modeling, experimental validation of PCM-integrated CLT walls in actual building environments is necessary to further verify simulation results and assess long-term performance. Additionally, this study used a single PCM type for consistency; however, PCM performance can vary based on properties like melting temperature, which can potentially influence energy savings across climates.

To build upon these findings, future research should focus on PCM impregnation within CLT layers, which could offer a more uniform and durable thermal storage solution. This approach will be compared against the optimum PCM placement strategies identified in this study to propose an ultimate design for energy-efficient buildings.

Another key direction for future research is the optimization of PCM melting temperatures for different climate zones. This study assumed a fixed PCM type; however, selecting location-specific PCM thermal properties based on regional climatic variations could enhance energy savings and peak load reductions. Future work will involve parametric analyses of different PCM melting temperatures to determine the most effective thermal characteristics for diverse climatic conditions. Diverse building typologies, zoning configurations, and occupancy patterns should also be considered to evaluate the broader applicability in real-world settings. In addition, experimental integration and validation should also be explored to assess the practical efficacy of PCM-CLT systems in terms of adaptability, cost, and retrofitting challenges.

6. Declarations

6.1. Author Contributions

Conceptualization, A.A., A.D., and A.N.; methodology, A.N., A.A., A.D., and M.Y.; software, A.D. and A.N.; validation, A.A., A.D., and A.N.; formal analysis, A.N., A.A., and A.D.; investigation, A.N., A.A., and A.D.; resources, A.D. and A.N.; data curation, A.N.; writing—original draft preparation, A.N., A.A., A.D., and M.Y.; writing—review and editing, A.N., A.A., A.D., and M.Y.; visualization, A.N., A.D., and A.A.; supervision, A.A. and A.D.; project administration, A.A. and A.D.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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