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ICEARC'25 – 4th International Civil Engineering & Architecture Conference
May 17–19, 2025 – Trabzon, Türkiye

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We gratefully acknowledge their presence and contribution to the academic exchange and dialogue during this international event.

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PROCEEDINGS OF THE 4TH INTERNATIONAL

CIVIL ENGINEERING & ARCHITECTURE

CONFERENCE

Volume 2: Architecture

AHMET CAN ALTUNIŞIK
HASAN BASRİ BAŞAĞA
VOLKAN KAHYA
VEDAT TOĞAN



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Editors

Ahmet Can Altunışık

Volkan Kahya

Hasan Basri Başağa

Vedat Toğan

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PREFACE

The 4th International Civil Engineering & Architecture Conference (ICEARC'25) aimed to bring together academics, researchers, and practitioners in the fields of civil engineering and architecture from across the globe. Held in Trabzon, Türkiye on May 17–19, 2025, the conference served as a dynamic platform to review recent achievements, share emerging developments, and address both current and future challenges in these disciplines.

ICEARC'25 has once again demonstrated its truly international character, drawing over **500 participants from 33 countries**. The conference hosted **421 research presentations** delivered in **59 parallel sessions**, and provided participants with excellent networking and collaboration opportunities. In addition to the technical sessions, **four dedicated workshops**—focusing on contemporary themes such as sustainable buildings, hybrid structures, and advanced materials—offered attendees practical insights and knowledge exchange in specialized areas.

The **Proceedings of the 4th International Civil Engineering and Architecture Conference** includes all the accepted and presented papers, compiled in two volumes:

- **Volume 1: Civil Engineering**, comprising 303 papers under major categories such as Structural Mechanics, Earthquake Engineering, Hydraulics & Fluid Mechanics, Geotechnics & Soil Mechanics, Transportation, Structural Materials, Hydrology & Water Resources, Construction Management, and Waste Management.
- **Volume 2: Architecture**, featuring 118 papers grouped under topics such as Architectural Philosophy, Design & Practice, Architecture, Conservation & Restoration, Urban Planning & Landscape, Architectural Engineering, and Interior Design.

We are sincerely grateful to all authors for their valuable contributions. The papers included in these volumes were rigorously reviewed by field experts, and only those that were accepted and presented at the conference have been published. We extend our deepest appreciation to the reviewers for their meticulous evaluations, which significantly contributed to the quality of this publication.

We would also like to express our gratitude for the institutional support provided by **Karadeniz Technical University** and **the Chamber of Civil Engineers (Trabzon Branch)** of the **Union of Chambers of Turkish Engineers and Architects**. We sincerely thank our sponsors:

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Our special thanks go to the **Mayor of Trabzon Metropolitan Municipality**, **Mayor of Ortahisar Municipality**, and **Mayor of Yomra Municipality** for their valuable support.

We also acknowledge the outstanding efforts of the organizing committee, the student volunteers, and all the moderators who chaired our sessions with professionalism and dedication. Their contributions were instrumental in the success of ICEARC'25.

Finally, the conference concluded with a memorable **social tour to the iconic Sümela Monastery and Uzun Göl**, offering participants a taste of the region's rich cultural and natural heritage.

We look forward to welcoming you again at **ICEARC'27**.

Editors

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Enhancing thermal comfort and energy-saving potential of the buildings with multiple-layered phase change material

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Abstract. The increasing population, rising living standards, and growing use of indoor spaces have significantly increased energy demand in the construction sector. This situation highlights the need for innovative building envelope design to reduce energy consumption and promote environmental sustainability. In this context, phase change materials (PCM), known for their high thermal energy storage capacity, emerge as an environmentally friendly solution. Key factors affecting the thermal comfort and energy consumption of buildings include the type, thickness, melting temperature, and number of layers of PCM. Although most of the research is focused on the use of single-layered PCM in exterior wall design, research on multiple-layered PCMs is quite scarce. Thus, the current study aims to assess the use of multiple-layered PCM in the exterior wall design of an educational building located in different climate zones of Türkiye. Simulations were conducted to evaluate the impact of multiple-layered PCM and PCM-thermal insulation (TI) combinations on thermal comfort, energy-savings, and construction costs during both summer and winter periods. Istanbul and Erzurum were chosen to represent temperate-humid and cold climates, respectively. Simulation results revealed that wall sections combining PCM and TI had higher thermal performance and energy-savings compared to those with only PCM. Multiple-layered PCM provided better thermal comfort with lower energy requirements for summer and winter periods, compared to single-layered PCM. Wall sections with multiple-layered PCM (3 PCM layers, each 30 mm) and TI (30 mm) could achieve energy savings of up to 3.93% in heating energy consumption and 2.77% in cooling energy consumption, compared to single-layered PCM.

Keywords: Multiple-layered phase change material; Thermal insulation; Heating and cooling; Thermal comfort; Energy-saving

1. Introduction

In Türkiye, approximately 33% of the total energy consumption occurs in the residential sector. Therefore, the development of technologies that enhance energy efficiency in residential buildings is of great importance (Terhan, 2021). Energy efficiency refers to the reduction of energy consumption without compromising the level of comfort. Considering the correlation between energy consumption and the level of development, energy efficiency is not only a key component of environmental sustainability but also a critical factor in economic development (Terhan et al., 2023).

The building envelope, which consists of external components such as walls, roofs, and windows, is one of the primary sources of thermal energy losses. Among these, walls play a critical role in energy efficiency by accounting for approximately 25% to 30% of the total thermal energy loss (Abanda & Byers, 2016). A thermally optimized building envelope design contributes significantly to the reduction of both heating and cooling loads. In this context, one of the innovative and increasingly applied solutions in building envelope design is the integration of "thermal energy storage systems."

Phase change materials (PCM) are innovative substances employed in the thermal energy storage systems of buildings (Beltran & Martinez-Gomez, 2019). These materials transfer the stored thermal energy to the indoor environment in a controlled manner, thereby enhancing indoor thermal comfort. Consequently, they offer significant potential for reducing the heating and cooling energy demands of a building (Sivanathan et al., 2020).

Conventional thermal insulation materials (TI) enhance the thermal resistance of the building envelope by limiting heat transfer between the interior and the external environment (Al-Homoud, 2005). The combination of PCM-TI improves the overall thermal performance of buildings and enables more stable indoor thermal comfort levels (Alizadeh & Sadrameli, 2019). A review of the existing literature reveals that the majority of studies have focused on single-layered PCM applications. These studies often assess performance based on PCM with a fixed

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thickness and a single melting temperature. However, multiple-layered PCM applications offer the potential to regulate heat flow across the building envelope more effectively, significantly reducing thermal loads. Various studies have demonstrated that, depending on the thermophysical properties of the building envelope and the type, thickness, and melting temperature of the multiple-layered PCM and TI used under different climatic conditions, energy savings in heating loads of approximately 2.26–27% and in cooling loads of approximately 8.54–38% can be achieved (Arıcı et al., 2022; İlgar & Terhan, 2024; Asghari et al., 2024; Refahi et al., 2024; Rehman et al., 2021; Dardouri et al., 2023). To fill the current knowledge gap in the literature, the aim of this study is to comprehensively examine the effects of using multiple-layered PCM in the external wall design of an educational building located in two different climate region of Türkiye, in terms of energy efficiency, indoor thermal comfort, and construction cost during both summer and winter periods. Istanbul and Erzurum were selected to represent temperate-humid and cold climate zones, respectively. It is anticipated that the use of multiple-layered PCM could significantly contribute to environmental sustainability by reducing building energy consumption.

2. Methodology

2.1. Description of the Simulated Building

A basic single-story education building model (500 cm x 400 cm x 300 cm) was designed for the simulation (Fig. 1). Because the building model consisted of a single zone, there were no inner walls, and all of the exterior walls were modelled identically. The building has a terrace roof. The west wall was equipped with a wooden door measuring 90 cm wide and 220 cm high. In the current study, the south wall of the building was equipped with a window 400 cm in length and 150 cm in height. The distance between the window bottom and floor was 80 cm. The glass was an air-filled double glass with an overall heat transfer coefficient (U) of 2.8 W/m^{2}K, solar heat gain coefficient of 0.7, and visible transmittance of 0.8.

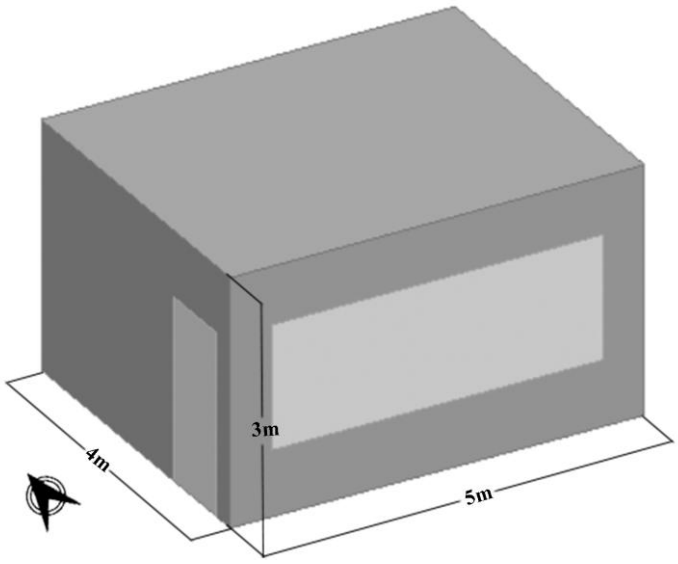


Fig. 1. Geometrical model of the education building analysed

The type and thickness of the materials in the building envelope have been designed in accordance with the thermal conductivity coefficients specified in TS 825 (2013). The details of the building envelope are provided in Table 1, and the thermophysical properties of the materials used are given in Table 2.

Table 1. Details of the building envelope layers

Building Envelope	Layers (from inside to outside)
Roof	20 mm cement-based plaster, 120 mm reinforced concrete slab, 30 mm cement screed, 50 mm thermal insulation, waterproofing, and gravel roofing
Reference wall	20 mm plaster, 30 mm PCM, 240 mm aerated autoclaved concrete and 20 mm plaster
Exterior wall with integrated thermal insulation	20 mm plaster, 30 mm PCM (up to three layers), 240 mm aerated autoclaved concrete, 30 mm TI, 20 mm plaster

Table 2. Thermophysical properties of the selected materials

Material	Density (kg/m³)	Thermal conductivity (W/mK)	Water vapor diffusion resistance (μ)
Cement-based plaster	2000	1.6	15/35
Aerated autoclaved concrete	500	0.15	5/10
Thermal insulation (Glasswool)	32	0.04	1

In this study, the PCM used was directly selected from the database of the DesignBuilder® software (BioPCM® M27/Q21). The thermophysical properties of the PCM are summarized in Table 3. Based on findings from a previous study, the optimal melting temperature of the PCM was determined to be 21 °C for winter, as lower outdoor temperatures allow for more efficient phase transition between melting and solidification, and 27 °C for summer conditions. The lowest heating and cooling energy demands were achieved when the PCM layer was placed on the interior side of the wall section and the TI layer on the exterior. The most effective configuration in terms of maintaining indoor thermal comfort and maximizing energy savings was identified as using 30 mm thick PCM and 30 mm thick TI (Yemenici & Barış, 2024). Therefore, to evaluate the effects of PCM layering on indoor thermal comfort, total energy savings, and construction costs, 30 mm thick PCM was applied on the inner side of the wall section, and 30 mm thick TI was positioned on the outer side in PCM-TI integrated wall configurations.

Table 3. Thermophysical properties of the PCM

Thermophysical properties		Values
Density (kg/m³)	Solid form	880
	Liquid form	760
Thermal conductivity (W/mK)	Solid form	0.2
	Liquid form	0.15
Specific heat (J/kgK)		2000

In this study, two different combinations of material layering have been developed. The wall containing a single-layered PCM (Fig. 2Ref) is defined as the reference wall, and its details are provided in Table 1. To determine the optimal number of PCM layers, the following approach was used:

- The PCM (up to three layers) was placed in the innermost layer of the walls
- The PCM (up to three layers) was placed in the innermost layer, and TI was placed in the outermost layer

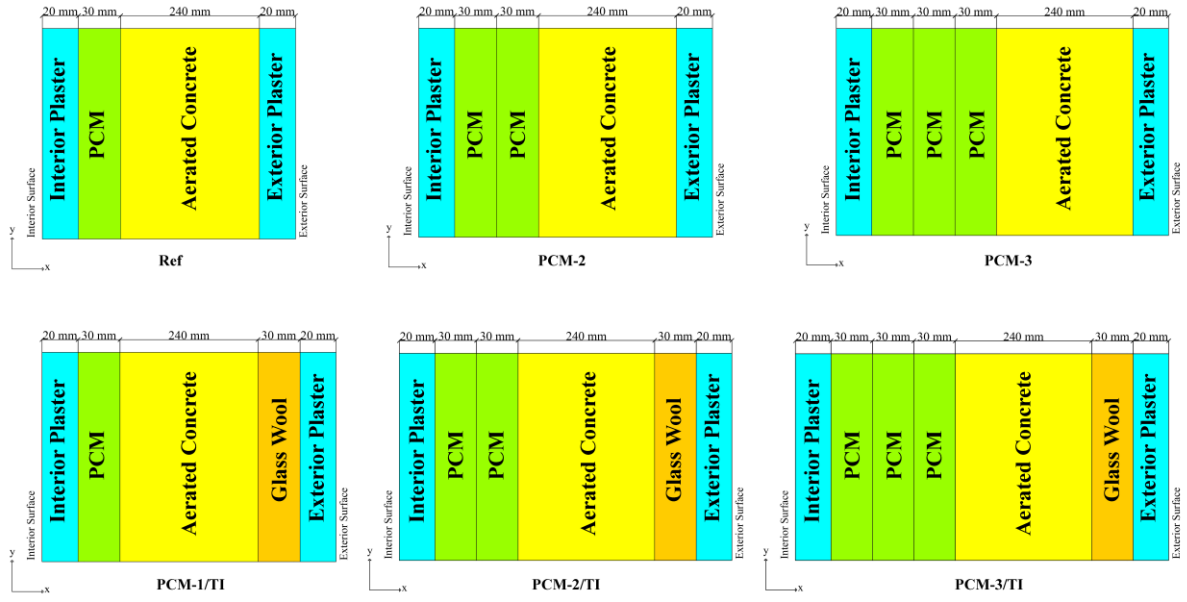


Fig. 2. Simplified drawing of wall sections simulated in the study

The wall sections were coded in [PCM-a] or [PCM-a/TI] format. PCM and TI represent phase change material and thermal insulation, respectively. “a” represents the number of layers of PCM.

2.2. Simulation Details

The analyzed building was intended for educational purposes, with working hours from 09:00 to 16:00. The building's occupancy rate was fixed at 0.55 occupants/m^2. Metabolic rates depend on the activities of the occupants in the education building. Furthermore, the use of equipment was entered into the simulation based on weekly usage rates. An illumination level of 3.4 W/m^2–100 lx of was taken into consideration, during working hours.

As an exterior temperature of 18 °C can maintain the inside at a comfortable temperature of 24 °C, hence, the heating or cooling requirements for any place are usually calculated according to this exterior baseline temperature (Menyhart & Krarti, 2017). The time-dependent variation of the outdoor temperature for the representative cities from January 20-22 and July 20-22 is shown in Fig. 3 respectively. According to this, the outdoor air temperatures in the cities located in two different climate zones are either below or above the reference temperatures. As a result, heating and cooling requirements arise to ensure sufficient thermal comfort. Since the winter and summer seasons represent the maximum heating and cooling energy requirements, respectively, the study focuses on the winter and summer periods, with the goal of reducing heating and cooling energy demand (Arumugam et al., 2022).

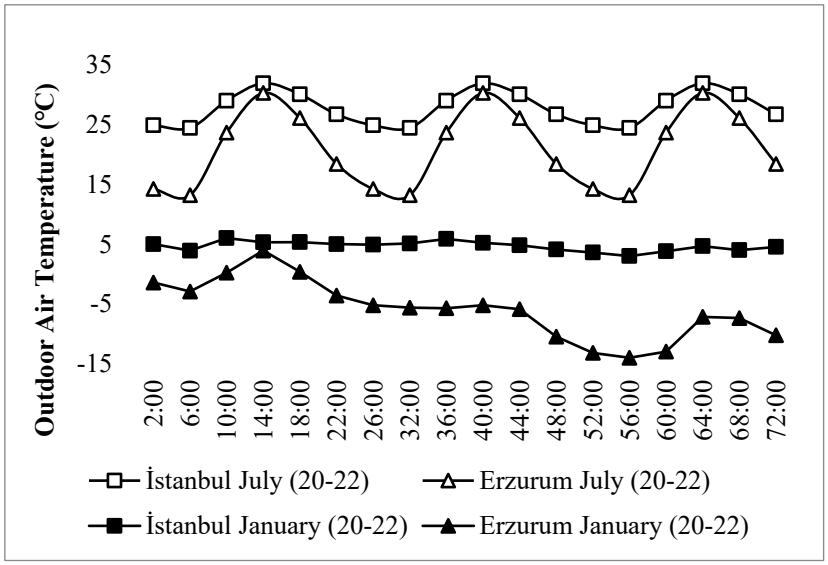


Fig. 3. The outdoor air temperature-time graph for the representative cities

The thermal comfort range was defined as 19 °C for the heating period and 26 °C for the cooling period. Accordingly, mechanical systems are activated only when the indoor temperature falls below 19 °C or exceeds 26 °C. The heating demand of the building is met through a natural gas-based system, while the cooling demand is fulfilled using an electrically powered system. All heating, cooling, and ventilation requirements are provided by mechanical systems, and the impact of natural ventilation was excluded from the simulations by setting it to "off." DesignBuilder® software was used for the simulations. To accurately simulate the phase change process of the PCM, a computational technique known as the "Finite Difference Calculation Method" was selected (U.S. Department of Energy, 2021)

The effects of multiple-layered PCM and TI integration on the thermal performance of the building envelope were assessed by considering indoor temperature reduction (ITR) values. The term "ITR" describes the decrease in the maximum interior temperature of the simulated building (with multiple-layered PCM and PCM+TI) compared with the reference building (without PCM and TI). The mechanical systems were turned off during the ITR calculation to mitigate the risk of changing the thermal performance of the building envelope.

The effects of the multiple-layered PCM and TI on the energy performance of buildings were determined by considering the annual energy savings. The annual energy savings is the amount of energy saved when PCM and TI are incorporated into a building envelope. The annual energy saving, as a ratio (ESR), was calculated to represent the percentage of energy saved by incorporating the PCM and TI, according to Equation (1):

$$ESR = \frac{\text{EC (without PCM / TI)} - \text{EC (with PCM / TI)}}{\text{EC (without PCM / TI)}} \text{ x } 100\ (\%) \quad (1)$$

Where EC is energy consumption (kWh). The ESR and EC values were determined when the mechanical system was active between 07:00 and 24:00 with 100% efficiency and was inactive between 00:00 and 07:00.

The economic viability of wall sections incorporating PCM-TI combinations, designed for different climatic zones of Türkiye, was assessed by considering two key indicators: energy cost savings (ECS) and payback period (PP). Initially, ECS was calculated in accordance with Equation (2) (M'hamdi et al., 2022):

$$ECS = (\mathrm{ES_{summer}} * \mathrm{EC}) + (\mathrm{ES_{winter}} * \mathrm{NC}) \quad (2)$$

ES_{summer} and ES_{winter} (kWh) represent the difference between the annual total cooling and heating energy consumption of the building with simulated alternative wall sections compared to that of the reference wall section. EC denotes the electricity cost, while NC symbolizes the natural gas cost. According to the Turkish Statistical Institute (TÜİK, 2022), the annual average electricity cost in Türkiye is 139.1 kuruş/kWh, and the natural gas cost is 29.5 kuruş/m³.

PP (year) obtained from different PCM-TI combinations in the simulated buildings was calculated according to Equation (3):

$$PP = \frac{[(\mathrm{C_{PCM}} * \mathrm{V_{PCM}}) + (\mathrm{I_{PCM}} * \mathrm{W_{PCM}})] + [(\mathrm{C_{TI}} * \mathrm{V_{TI}}) + (\mathrm{I_{TI}} * \mathrm{W_{TI}})]}{\mathrm{ECS}} \quad (3)$$

C_{PCM} and V_{PCM} represent the cost (TL/kg) and volume (m³) of the PCM, respectively, while I_{PCM} indicates the installation cost (TL/day) and W_{PCM} denotes the number of workers required for PCM installation (Table 4). Similarly, C_{TI}, V_{TI}, I_{TI}, and W_{TI} refer to the cost, volume, installation cost, and number of workers required for the installation of the TI material, respectively. During the calculation of installation costs, it was assumed that the reference building with dimensions of 500x400x300 cm, can be completed in one working day by two workers, whereas the building with integrated PCM-TI requires two working days in total, requiring each worker to work one full day.

Table 4. Parameters used in ECS and PP calculations

Parameters	Values
PCM Cost (TL/kg)	30 mm: 68.82
TI (glass wool) Cost (TL/kg)	30 mm: 84.00
PCM-TI Volume (m^3)	30 mm: 1.3806
PCM-TI Area (m^2)	46.02
PCM Production Facility	Kocaeli (Coral)
TI Production Facility	Adana (İzocam)
Daily Wage of a Worker (TL/gün)	2500

2.3. Climate Conditions

In this study, Istanbul, representing the temperate-humid climate characteristics, and Erzurum, representing the cold climate region of Türkiye, were selected. Hourly environmental conditions, such as temperature, solar radiation, atmospheric humidity, and wind speed, are available in the DesignBuilder® software database. These data were validated by comparing them with the data provided by the Turkish State Meteorological Service (İl ve İlçeler İstatistikleri, 2024).

Table 5. Solar radiation intensities and sunshine durations in selected cities

	Months														
Cities	1	2	3	4	5	6	7	8	9	10	11	12	kWh/m^2-year	Altitude	Sunshine (h/day)
İstanbul	41	56	95	129	166	180	184	161	127	83	50	36	1389	40	5.9
Erzurum	70	91	132	138	162	181	193	174	142	103	68	56	1511	1890	6.7

The solar radiation intensities and sunshine duration data for the selected cities were obtained from the Türkiye Solar Atlas (Türkiye Güneşlenme Potansiyeli Atlası, 2010), which was prepared by the Meteorological Service of Türkiye (Table 5).

Istanbul represents the 2nd (temperate-humid) climatic region and is under the influence of the Mediterranean, Marmara, and Black Sea climates. In Istanbul, summer is hot and dry, and winter is warm and rainy. The annual average temperature is 16.4 ºC, and the average number of rainy days is 116.5. In addition, strong winds are effective during certain periods in Istanbul (İl ve İlçeler İstatistikleri, 2024). The annual total solar radiation intensity is 1389 kWh/m^2, and the average daily sunshine duration is 5.9 hours (Türkiye Güneşlenme Potansiyeli Atlası, 2010).

Erzurum is located in the 5th climate region and has the coldest climate conditions in Türkiye. Summer is warm and dry; winter is very cold and snowy; and spring is rainy. The lowest average temperature is -20 ºC. Snowfall usually starts in October and continues until late April. The annual average temperature is 5.8 ºC, and the average number of rainy days is 122.1. Harsh climatic conditions are further exacerbated by winds (İl ve İlçeler İstatistikleri, 2024). The annual total solar radiation intensity is 1511 kWh/m^2, and the average daily sunshine duration is 6.7 hours (Türkiye Güneşlenme Potansiyeli Atlası, 2010).

3. Results and Discussion

3.1. Effects of PCM Layers on the Thermal Performance of the Building Envelope

Fig. 4 shows the indoor temperature reduction for three peak days in January and July, to determine the effect of the number of PCM layers on the thermal performance of building envelopes with integrated PCM and PCM-TI.

According to Fig. 4a and 4b, the highest indoor temperatures in both climate regions were observed between 14:00-18:00, while the lowest indoor temperatures were recorded at 06:00. According to Fig. 4c and 4d, the highest indoor temperatures across all climate regions were detected between 14:00-16:00. For the three peak days in January, the highest indoor temperature of the reference building was recorded in Istanbul (13.40 ºC). During the midday hours, when solar radiation is at its peak, the indoor temperatures of reference buildings were lower than those of buildings with integrated PCM. On the same dates, the lowest indoor temperatures of the reference buildings during the night were 5.12 ºC in Istanbul and -7.06 ºC in Erzurum. For the three peak days in July, the highest indoor temperature in the reference building was recorded in Istanbul at 38.86 ºC. During the night, the indoor temperatures of reference buildings with single-layered PCM were lower than those of buildings with multiple-layered PCM, for the three peak days in January, while they were higher for the three peak days in July. In other words, the building envelope with the most significant temperature fluctuations throughout the day was the reference wall section with single-layered PCM.

The integration of multiple-layered PCM in the interior region and TI in the exterior region of the reference building's wall section results in a decrease in indoor temperature reduction (ITR). In other words, multiple-layered PCM prevents sudden temperature changes in the external environment from affecting the indoor environment, allowing users to feel thermally more comfortable indoors. The multiple-layered PCM and TI in the building envelope prevent sudden temperature fluctuations in the external environment from impacting the indoor environment, enabling users to feel thermally comfortable indoors.

During the midday hours, when the highest outdoor temperatures are experienced during both winter and summer, integrating a three-layered PCM into the inner section of the building envelope and TI into the outer section (PCM-3/TI) provided a higher percentage of ITR compared to the reference wall and sections with only multi-layered PCM in all climate regions. In the winter period, the three-layered PCM provided an ITR of 0.38 ºC in Istanbul and 0.33 ºC in Erzurum, and adding TI to these sections in the outer region resulted in higher ITR values (0.51 ºC and 0.49 ºC, respectively).

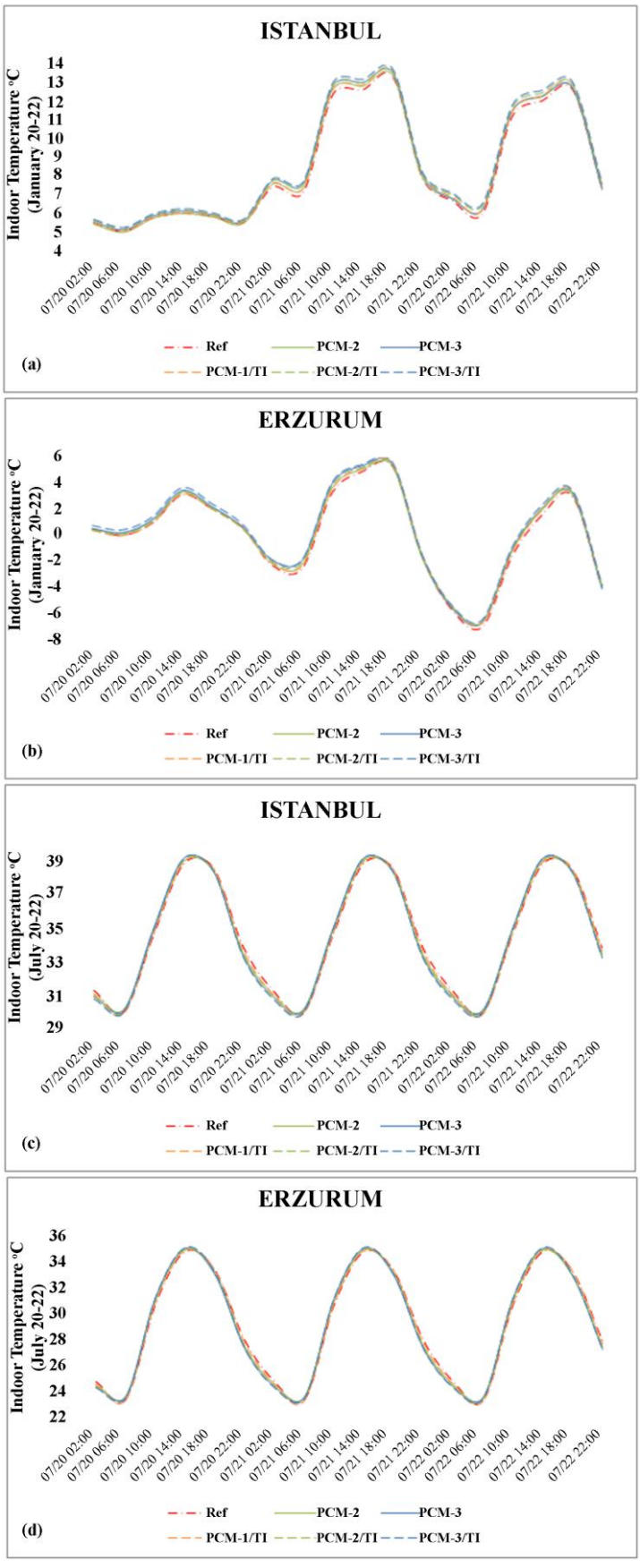


Fig. 4. The reference, indoor temperature reduction for three peak days in January and July of buildings with PCM and PCM-TI integrated: (a) Istanbul (January 20-22); (b) Erzurum (January 20-22); (c) Istanbul (July 20-22); (d) Erzurum (July 20-22)

In the summer period, increasing the number of PCM layers also increased the ITR. When TI was integrated, increasing the number of PCM layers resulted in a more effective ITR, similar to the effect observed in buildings with PCM integration. When the number of PCM layers was increased to three (PCM-3), it provided an ITR of 0.56 ºC in Istanbul and 0.64 ºC in Erzurum compared to the reference building. With the integration of TI (PCM-3/TI), a constant ITR was obtained in Erzurum, while a higher ITR value of 0.60 ºC was achieved in Istanbul.

The higher ITR values obtained in both the PCM-a and PCM-a/TI integrated wall sections, compared to the reference building, can be explained by Fourier's Law. According to Fourier's Law, integrating materials with low thermal conductivity into the building envelope prevents heat from transferring from the more intense environment to the less intense one, thereby increasing the thermal resistance of the building envelope and enabling the maintenance of comfort conditions indoors (Garrido et al., 2001). However, the ITR values obtained in the PCM-a section are lower than the ITR values achieved in the PCM-a/TI section in both climate regions.

In conclusion, increasing the number of PCM layers significantly contributes to the improvement of thermal comfort by reducing ITR. The integration of multiple-layered PCM into the building envelope helps stabilize indoor conditions by balancing external temperature variations. This is particularly effective in climates where temperature reduction during the day is significant. In winter, it prevents sudden indoor cooling, thus reducing heating demand, while in summer, it mitigates overheating, thereby reducing cooling loads. The integration of TI into the building envelope ensures the controlled release of heat stored by the PCM, further diminishing the impact of sudden temperature changes on indoor conditions. In this context, the results obtained in this study indicate that increasing the number of PCM layers directly affects ITR, and, when used in conjunction with TI, this effect is further enhanced.

In this study, the ideal section for winter and summer periods was identified to be the three-layered PCM in the PCM-a/TI wall section, providing the highest thermal comfort. Literature studies have identified the ideal sections for wall configurations containing PCM in the inner and outer regions and TI in the outer region as follows: two-layered PCM for Kocaeli (Türkiye) (Arıcı et al., 2022), three-layered PCM for the inner region in İzmir (Türkiye) (Ilgar & Terhan, 2024), and two-layered PCM for both inner and outer regions in Kansas City (USA) (Asghari et al., 2024). Indeed, these findings align with the data presented in the literature.

3.2. Effects of PCM Layer on the Energy Savings of the Building Envelope

Fig. 5 shows the annual total heating and cooling energy consumption for buildings with PCM and those with PCM-IY integrated walls during the winter and summer periods.

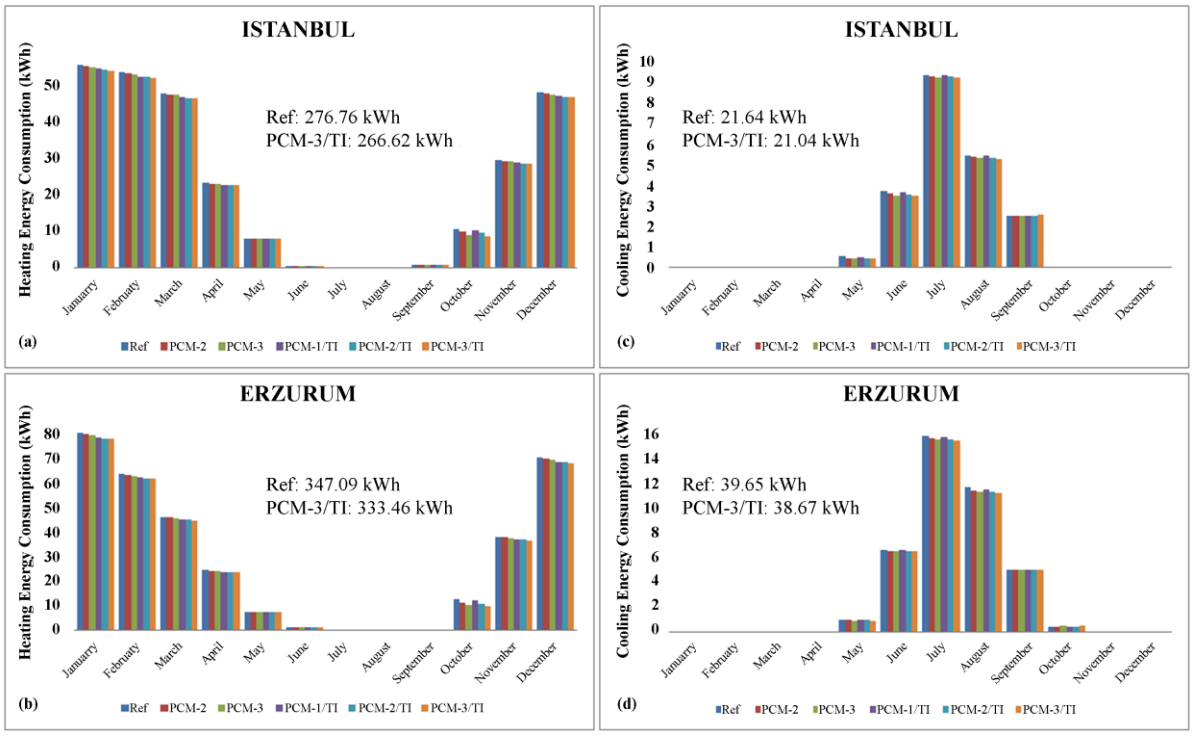


Fig. 5. The reference, total heating and cooling energy consumption of buildings with PCM and PCM-TI integrated walls: (a) Istanbul (Heating); (b) Erzurum (Heating); (c) Istanbul (Cooling); (d) Erzurum (Cooling)

In Istanbul, during the winter period, the annual total heating energy consumption of the reference building is 276.76 kWh. With the PCM-3 wall section, this consumption decreases to 271.81 kWh, and with the integration

of PCM-3/TI, it further decreases to 266.62 kWh. In Erzurum, the annual total heating energy consumption of the reference building is 347.09 kWh. The use of PCM-3 in the wall section reduces this to 340.44 kWh. With the integration of TI in this wall section, the annual total heating energy consumption is determined to be 333.46 kWh. Based on these findings, it can be stated that integrating multiple-layered PCM and TI together in the wall sections yields positive results in terms of heating energy savings during the winter period (Fig. 5a, Fig. 5b).

According to Fig. (5c and 5d), in Istanbul, during the summer period, the annual total cooling energy consumption of the reference building is 21.64 kWh. With the integration of PCM-3, this energy consumption decreases to 21.13 kWh. With the integration of TI in this wall section, the annual total cooling energy consumption is determined to be 21.04 kWh. In Erzurum, a cold climate region, the annual total cooling energy requirement is 39.65 kWh, reduced to 38.89 and 38.67 kWh with the use of PCM-3 and PCM-3/TI, respectively. A higher annual total cooling energy consumption is calculated in Erzurum, compared to Istanbul. This indicates that the average air temperature of the region is not the only significant parameter affecting heating and cooling energy consumption in buildings. Typically, global solar radiation intensity increases as the altitude of a region rises (Qu et al., 2021). The solar radiation intensity for the representative cities is obtained from the Türkiye Solar Potential Atlas prepared by the Turkish Meteorological Service (Türkiye Güneşlenme Potansiyeli Atlası, 2010). Table 5 shows that solar radiation intensity increases gradually with altitude in Istanbul and Erzurum. The altitudes of Istanbul and Erzurum are 40 m and 1890 m, respectively. Due to the higher altitude in Erzurum, greater solar radiation intensity results in more heating of the building envelope during midday, thus allowing the PCM to store more energy and increasing the cooling load. The solar radiation intensities in Istanbul and Erzurum are 1389 KWh/m² and 1493 KWh/m², respectively. Therefore, the total cooling energy consumption for the building may be higher. It can be concluded that when designing passive buildings using PCM technology, it is important not to rely solely on climate classification, but also to consider other geographical factors such as altitude and solar radiation intensity.

During the winter period, the highest energy savings were achieved in the wall section, containing three-layered PCM in the inner region and TI in the outer region, with the (PCM-3/TI) having values of 3.66% in Istanbul and 3.93% in Erzurum. Similarly, during the summer period, the highest energy savings were also obtained with the PCM-3/TI wall section, achieving 2.77% in Istanbul and 2.47% in Erzurum. Based on all these findings, it has been determined that the combined use of three-layered PCM in the inner region and TI in the outer region offers advantages. These advantages include annual heating and cooling energy savings compared to the reference building with single-layered PCM.

3.3. Economic Findings

Fig. 6 shows the calculated values of the key economic parameters such as ECS and PP in determining the economic effectiveness of building envelopes with PCM and PCM-TI combinations.

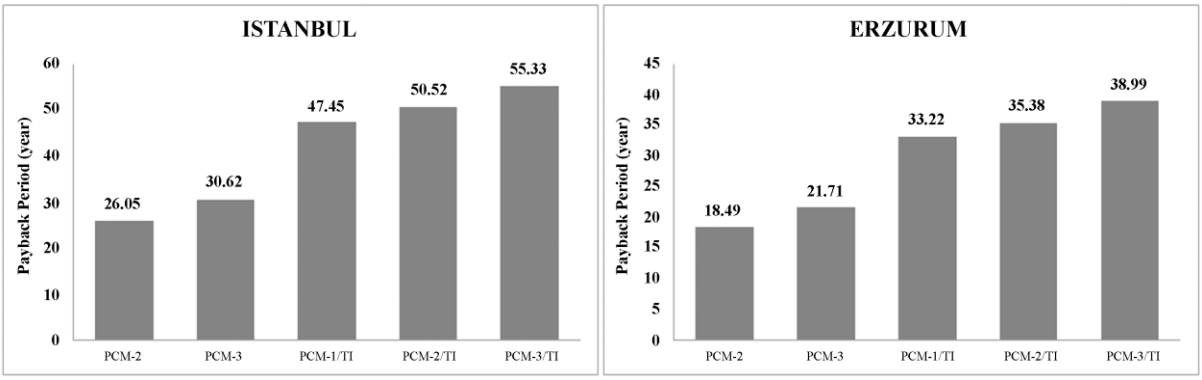


Fig. 6. Payback periods according to climate zones

Istanbul's temperate humid climate conditions result in buildings being exposed to both heating and cooling loads (İl ve İlçeler İstatistikleri, 2024). Therefore, the use of PCM-TI combinations to enhance the energy efficiency of the building envelope is of great importance. When only multiple-layered PCM is used in Istanbul (PCM-2, PCM-3), the PP is determined as 26.05 years and 30.62 years, respectively. Even without TI integrated, these relatively long PP are primarily due to the temperate and humid climate characteristics of Istanbul, which limit the thermal effectiveness of PCM, and the cost of the materials used in the building envelope, which extends the PP relative to the energy savings achieved. The use of PCM-TI further increases the PP. The PCM-3/TI combination, which provides the best thermal performance for both the heating and cooling seasons, results in a PP of 55.33 years.

Erzurum, located in the fifth-degree climate zone, is one of the coldest cities in Türkiye; and the long and snowy winter months significantly increase the heating demand (İl ve İlçeler İstatistikleri, 2024). In buildings with wall sections containing only multiple-layered PCM (PCM-2, PCM-3), the PP are calculated as 18.49 years and 21.71 years, respectively. The PCM-3/TI combination, which provides optimal thermal performance for both the heating and cooling seasons, results in a PP of 38.99 years.

The effect of the increase in the number of PCM layers on the PP results in a rise in investment costs, and limited savings beyond a certain point. The longer PP for PCM-3 compared to PCM-2 in both climate zones indicates that the contribution of each additional layer to thermal performance continues to diminish, and an optimal cost-effectiveness limit can be reached.

Moreover, while the use of PCM in conjunction with TI improves thermal performance in both Istanbul and Erzurum, it further extends the PP. The calculated PP of 55.33 years (Istanbul) and 38.99 years (Erzurum) for the PCM-3/TI combination highlights the need for careful optimization of integrated solutions in terms of cost-effectiveness. Consequently, the increase in the number of PCM layers contributes to energy performance, although it requires a cost-benefit balance at different scales for each climate zone. As is well known, according to the Turkish Building Earthquake Regulation (2018), the economic lifespan of buildings is generally considered to be 50 years (Türkiye Bina Deprem Yönetmeliği, 2018). Since the PP obtained in this study is calculated as less than 50 years for all the scenarios examined, the combined use of PCM-TI in the same wall section can be considered an economically viable solution. The PP values for the PCM-3/TI combination, which provides the best thermal performance for both heating and cooling periods, are 55.33 years for Istanbul and 38.99 years for Erzurum. While the result for Istanbul is on the borderline in terms of economic sustainability when compared to the building's lifespan, it is evident that this integration is more advantageous in colder climate regions such as Erzurum.

4. Conclusions

The possibilities of using multiple-layered PCM to improve the thermal performance of an educational building and reduce annual heating and cooling energy consumption have been investigated. The results obtained from the studies conducted within this scope are as follows:

- In wall sections where both PCM and TI are used, not only climate classification but also other geographical factors such as altitude and solar radiation intensity should be considered. Although the average air temperatures in Erzurum are lower than in Istanbul, the solar radiation intensity is higher due to the city's higher altitude. This results in an increased heat gain in the building envelope during midday hours, leading to higher cooling energy consumption.
- During the winter period, using a wall envelope with three-layered 30 mm PCM (with a melting temperature of 21 ºC) on the interior and 30 mm TI on the exterior results in energy savings during the summer period, using three-layered 30 mm PCM (with a melting temperature of 27 ºC) on the interior and 30 mm TI on the exterior (PCM-3/TI) results in energy savings of 2.47-3.93% compared to the use of single-layered PCM (Ref).
- The combinations of PCM-TI, as well as the increase in the number of PCM layers, are the primary factors that increase the PP. However, considering the high thermal comfort provided by the combination of multiple-layered PCM and TI for both heating and cooling periods; along with the reduced ITR throughout the day; and higher total heating and cooling energy savings, the use of this combination is beneficial.
- The PP values obtained by increasing the number of PCM layers being shorter than the typical building economic lifespan of 50 years, demonstrate that the combination of multiple-layered PCM and TI offers a viable and cost-effective solution. However, the calculation of the PP for the three-layered PCM and TI combination (PCM-3/TI) as 55.33 years in Istanbul indicates that this integration does not provide the same economic advantage for all climate regions. This situation arises from the temperate and humid climate conditions in Istanbul, which limit the thermal efficiency of PCM, and the cost of the materials used in the building envelope, which extends the PP comparison to the energy savings achieved. However, in Erzurum, the PP (18.49-38.99 years) being shorter than the building's economic lifespan suggests that increasing the number of PCM layers improves the ITR and enhances the thermal efficiency of the building envelope that by providing energy savings.

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