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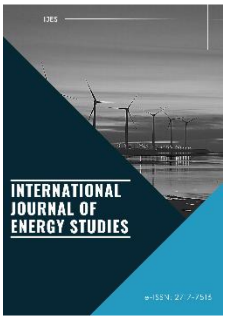

Research Article

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Energy demand assessment of health care clinics with phase change materials integrated into different facades orientations

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Highlights

- This study evaluated the energy performance of a health care building with PCM integrated on different facades.
- PCM integration on high solar exposure facades reduced cooling energy use by up to 24%.
- PCM application for internal and external wall achieved the highest energy savings.
- Limited winter phase change led to increased natural gas use in some scenarios.

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ABSTRACT

This study comprehensively analyzed the energy performance of a health care clinic (HC) building by simulating various phase change material (PCM) integration scenarios under the climatic conditions of Istanbul/Turkiye. PCM with a melting temperature of 25°C was applied to the building envelope in different orientations and combinations, and its effects on heating and cooling energy consumption were assessed. Results showed that PCM's impact on energy performance of the HC building varied based on the number and orientation of facades. During winter, phase change was often limited due to low ambient temperatures, resulting in increased natural gas consumption in scenarios with limited facade coverage. Conversely, in the cooling season, PCMs effectively reduced electricity demand, especially when applied to facades with high solar exposure. When active phase change occurred on both internal and external walls, savings increased to 1100 kWh (24%) in electricity and 71 kWh (1%) in natural gas. External wall-only applications led to a 791 kWh reduction in electricity but a 372 kWh increase in natural gas use. Among single-facade applications, the south facade was most effective in reducing cooling loads. Multi-facade configurations, particularly North+East+West and East+West+South, achieved up to 666 kWh in electricity savings. The results highlighted that optimal PCM integration strategies should consider facade orientation, surface coverage, and seasonal dynamics to enhance energy efficiency in HC buildings.

Keywords: Electricity consumption, Natural gas consumption, Phase change material, Health care clinic buildings

1. INTRODUCTION

Buildings account for approximately 36% of global energy consumption and 39% of carbon dioxide (CO_2) emissions, according to the International Energy Agency (IEA) [1]. In this context, it is projected that by 2050, heating and cooling demands in buildings will constitute more than 50% of the total global energy demand [2]. According to the Turkish Statistical Institute (TUIK), nearly 76% of the natural gas and electricity utilized in residential buildings across Turkiye is dedicated to heating and cooling spaces [3]. Although electricity consumption for cooling appears relatively low, this is largely due to the substantial energy demand of lighting systems and other electrical appliances operating throughout the year. Nonetheless, it is important to note that cooling systems, despite operating only during the warmer months, are characterized by high power consumption and should not be underestimated. Similarly, Similarly, heating systems are essential for maintaining comfortable indoors in residential and commercial buildings. These developments have increased interest in environmentally friendly and energy-efficient passive solutions within the building sector. Among the technologies proposed to enhance building energy efficiency, phase change materials (PCMs) have emerged as promising candidates [4]. These innovative materials, which have been applied in building envelopes [5], solar energy systems [6], vehicle batteries [7], and the agricultural sector [8], can store or release significant amounts of latent heat by undergoing phase transitions within specific temperature ranges [9]. This energy exchange occurs at nearly constant temperatures and is significantly higher than the sensible heat storage capacity of conventional materials. For example, typical organic PCMs such as paraffins or fatty acids can store approximately 150–250 kJ/kg of latent heat, depending on their chemical structure and purity. This makes them particularly suitable for passive thermal regulation applications, as they can absorb surplus heat when ambient temperatures exceed the PCM’s melting point and release it when the temperature drops. The magnitude and effectiveness of this thermal buffering depend on the PCM's thermal conductivity, specific heat, melting temperature, and latent heat of fusion, all of which must be carefully selected based on the target climate conditions and thermal comfort requirements of the indoor environment. When integrated into the building envelope, they help moderate indoor temperature fluctuations throughout the day and contribute to maintaining stable indoor thermal conditions.

Experimental and numerical studies in the literature have demonstrated that PCMs significantly reduce energy demands associated with both heating and cooling, thereby contributing to improved thermal efficiency and comfort levels [10–13]. In this context, PCMs are increasingly regarded as essential components in sustainable and energy-conscious building designs [14]. In a study conducted in Egypt’s hot climate, Anter et al. [15] observed that placing the PCM layer at a distance of 1.5 cm from both the interior and exterior wall surfaces led to a 66% decrease in cooling energy consumption. In a related study, Saurbayeva et al. [16] conducted an optimization analysis in a tropical climate and reported annual energy reductions between 18% and 43%. These results highlight the critical role of optimizing building design early in the planning process to enhance energy performance. Abilkhassenova et al. [17] utilized EnergyPlus software to simulate a PCM-integrated apartment building across 15 different climate zones and found that energy consumption decreased by approximately 32%, particularly in arid regions. Pırasacı and Sunol [18] investigated the PCM enhanced composite aggregates in buildings. Their findings indicated energy savings of 1.7% in Izmir, where cooling demand is dominant, and 0.22% in Erzurum, where heating needs are dominant; due to these relatively low values, the study concluded that PCM-aggregate integration may not be practical. On the other hand, Hamooleh et al. [19] developed a model that combined PCMs with insulation materials and assessed various scenarios across four cities in Iran, each representing different climatic conditions. Their study demonstrated significant improvements in energy efficiency, with heating-related electricity consumption reduced by 43% to 99% and cooling-related consumption by 38% to 51%, depending on the combination of a 5 cm PCM layer and insulation thicknesses ranging from 6.9 cm to 9.8 cm.

In the past two decades, population growth in Turkiye has significantly increased the demand for health care services. As a result, the number of hospitals has risen by approximately 25%, reaching 1,555 facilities, while the number of outpatient healthcare centers has increased to 33,394 [20–22]. Although this expansion in healthcare infrastructure has contributed positively to societal well-being, it has also led to a considerable rise in energy demand [23]. Inadequate indoor thermal comfort conditions in healthcare buildings may deteriorate patients' existing health conditions, necessitating the implementation of strict standards for indoor environmental quality [24]. Therefore, while the primary goal in the design of healthcare facilities is to ensure healthy indoor conditions, energy consumption often becomes a secondary concern. However, ensuring thermally comfortable and healthy indoor environments in a sustainable manner has now become a necessity that inherently demands energy efficiency.

Assareh et al. [25], in their study aimed at achieving a net-zero energy hospital, investigated the use of PCMs in the heating and cooling systems of a three-story hospital building. Their results indicated that PCM integration reduced heating loads by 2,850 kWh, cooling loads by 310 kWh, and carbon emissions by 417 kg. Zhang et al. [26], in a study focusing on environmental sustainability, highlighted the potential of PCM applications to reduce carbon emissions in hospital buildings. By applying a specially designed algorithm, they determined the optimal PCM thickness to be 2.97 mm and estimated annual energy savings of 6.4 kWh/m2 for imaging areas and 14.95 kWh/m2 for outpatient zones by incorporating PCM layers within the walls. Alnaqi et al. [24] analyzed the thermal performance of a PCM-integrated medical complex using an artificial neural network approach, and reported that PCM integration reduced heating loads by 15,751 kBtu/h and cooling loads by 129,923 kBtu/h. Yun et al. [27] researched the effectiveness of PCMs in controlling temperature fluctuations in temporary post-disaster shelters, educational buildings, and healthcare facilities. Their study showed that indoor temperatures in PCM-equipped structures were approximately 5oC lower.

Compared to hospitals, health care clinics (HCs) are smaller-scale facilities that typically provide outpatient services and are often constructed using lightweight structural systems. Nonetheless, maintaining comfortable indoor conditions in these facilities is vital for the well-being and healing process of patients. Given that the lack of thermal comfort may negatively affect patients' existing health conditions, achieving a balance between energy efficiency and comfort is of great importance in these buildings. In this context, Balali and Valipour [28] emphasized that the implementation of passive strategies in HC buildings is a fundamental approach to both supporting patient health and enhancing sustainability through reduced energy consumption. Similarly, Tzuc et al. [29] conducted an energy simulation for an outpatient facility located in a tropical climate region, integrating passive strategies such as insulation materials, reflective surface coatings, and green roofs. The results indicated that these measures improved the building's energy efficiency by 11%. Furthermore, the use of inverter-based air conditioning systems and reflective wall paints yielded up to 28% enhancement in energy performance and enabled a reduction of approximately two tons in CO_2 emissions. Yüksel [30] evaluated the effects of integrating various PCMs with diverse melting points into a primary health care building under two distinct climate conditions through simulations, focusing on energy demand, CO_2 emissions, and thermal comfort. The study revealed that the use of PCMs with suitable melting temperatures led to significant reductions in annual electricity and natural gas consumption and improved dissatisfaction rates by 6–7% under certain climate conditions. Additionally, using multi-criteria decision-making methods, RPCM25C with a melting temperature of 25ºC was identified as the most appropriate PCM type for the Csa climate classification.

In the literature, numerous studies have investigated the impact of PCM technology on energy performance in various building types, including residential buildings [15], apartment complexes [17], hospitals [25], and outpatient care centers [29]. However, most of these studies have focused either on residential units or large-scale, energy-intensive healthcare facilities, such as hospitals. The energy-related impacts of PCM applications in smaller-scale HC buildings, structures found in nearly every neighborhood in Turkiye where thermal comfort is critical for patient well-being, have not been sufficiently addressed. Moreover, existing studies have typically evaluated PCM scenarios involving the entire building envelope and have rarely examined the performance of PCM applied selectively to different orientations [30].

In this study, to address these research gaps, a simulation analysis was conducted on a single-story standalone HC building located in Istanbul, Turkiye, which falls under the Csa climate classification according to the Koppen–Geiger system. A PCM with a melting temperature of 25ºC, as proposed by [30], was applied to different facades of the building. Using the EnergyPlus software, the study comprehensively evaluated the effects of PCM integration on the building's annual energy demand, considering electricity and natural gas consumption separately. Thus, the study not only demonstrated the practical applicability of passive energy strategies in small-scale healthcare buildings through empirical data, but also provided a unique, data-driven contribution to the literature by supporting the theoretical propositions presented in previous studies [28–30].

2. METHODOLOGY

2.1. Climate Characteristics

Owing to its large land area and varied geographic characteristics, Turkiye encompasses cities that experience different climate classes based on the Koppen–Geiger classification. Istanbul (41º0′44″N, 28º58′34″E), which spans both the Asian and European continents and has a population approaching 15 million, is the largest city in Turkiye in terms of population distribution (Fig. 1). The city is characterized by a transitional climate between the Black Sea and the Mediterranean regions and is classified as Zone 2 according to [31], and as Csa (hot-summer Mediterranean climate with mild winters and hot, dry summers) based on the Koppen-Geiger climate classification [32]. In addition, annual temperature extremes in Istanbul vary between -11ºC and +40ºC, while the average relative humidity is approximately 75%.

In this study, the integration of PCM into a healthcare clinic assumed to be in Istanbul/Turkiye, was investigated using a comprehensive simulation model. The average outdoor climate data used in the simulations are presented in Fig. 2.

Figure 1. Location of Istanbul on Turkiye map

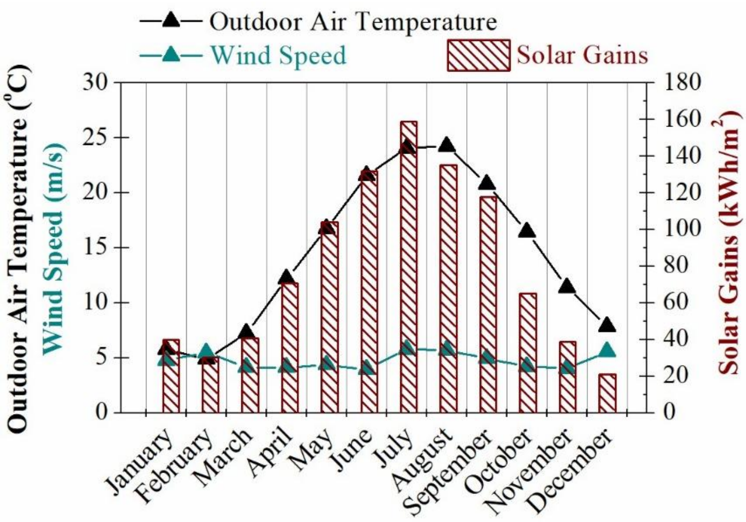

Figure 2. Average outdoor conditions for Istanbul [33]

2.2. Building Model

The simulation studies were conducted using the EnergyPlus V25.1 simulation engine, which enables the evaluation of various performance criteria such as user comfort, indoor air quality, energy efficiency, and carbon emissions. EnergyPlus adopts the enthalpy-porosity approach to accurately simulate the thermal storage and release characteristics of PCMs and allows for detailed modeling of phase change behavior. The enthalpy-porosity method physically represents melting-freezing transition processes by accounting for temperature-dependent enthalpy values and latent heat effects. Additionally, to characterize the change in thermal conductivity during the phase transition, the porosity of the material is incorporated into the calculations. This approach enables more accurate predictions of the contributions of PCM-integrated building components in terms of energy consumption [34,35].

This study, which is a continuation of Ref. [30] based on the selection of the optimal PCM for a two-story primary health care center, developed a numerical model of a detached single-story HC building located in Istanbul to determine on which facades the PCM is more effective [30]. The building design considered five treatment rooms, a wide corridor area, and a occupancy capacity of 25 people. The building has a single story with a floor area of 14.5 m × 14.5 m (210 m^2) and a 2.7 m height (Fig. 3). A U-value of 0.4 W/m^2K was calculated for the roof, and 0.6 W/m^2K for the ground slab, as elements of the building envelope.

In Ref. [30], the integration of three PCM types (BioPCM, InfiniteRPCM, and Enerciel) with different melting temperatures into a primary health care (PHC) building located in the Csa (Antalya) and Dfb (Erzurum) Koppen-Geiger climate zones was evaluated through simulation-based analyses. The study comprehensively examined their impacts on energy consumption, PMV-PPD values, CO_2 emissions, and thermal comfort of occupants. The findings revealed that the RPCM25C type offered optimal energy savings and environmental performance under both climate conditions. Therefore, for the walls constituting the HC building envelope, InfiniteRPCM with a melting temperature of 25°C, identified as suitable for the Csa climate in Ref. [30], was selected. This choice was based on the typical climatic characteristics of the region, where daytime temperatures frequently reach or exceed 25°C, rendering this PCM effective in reducing cooling loads during warmer periods. Although the standard indoor comfort temperature is around 22°C, the phase change at 25°C helps to moderate indoor temperature fluctuations by absorbing excess heat when temperatures rise above this threshold. Due to the relatively low PCM thickness of 0.0121 m and the effective insulation levels (U-value of approximately 0.4 W/m^2K for both interior and exterior walls), the risk of excessive heating during winter and the potential increase in cooling load are mitigated within the model scenarios. Nevertheless, it is acknowledged that using PCM with a melting temperature above the setpoint temperature may limit thermal storage benefits in some cold conditions. Based on the specified thickness and material density of 1540 kg/m^3, the PCM amount was calculated to be approximately 18 kg/m^2 of external wall surface, balancing thermal performance and practical implementation considerations. PCM was applied to the building's exterior and interior walls, exterior walls, single facades (North, South, East, West), two facades (North+West, South+East, North+East, South+West, East+West, North+South), and three facades (North+East+South, North+East+West, North+West+South, West+East+South). Meanwhile, the windows used in the building are conventional double-glazed systems consisting of two 3 mm glass panes separated by a 13 mm air gap, with a U-value of 2.7 W/m^{2}K, and were planned with a window-to-wall ratio of 30%, consistent with the literature [36]. The visible light transmittance and total solar energy transmittance of the windows are 62%, while the direct solar radiation transmittance is 54%. Detailed information regarding the physical and thermal characteristics of all building envelope components is presented in Table 1.

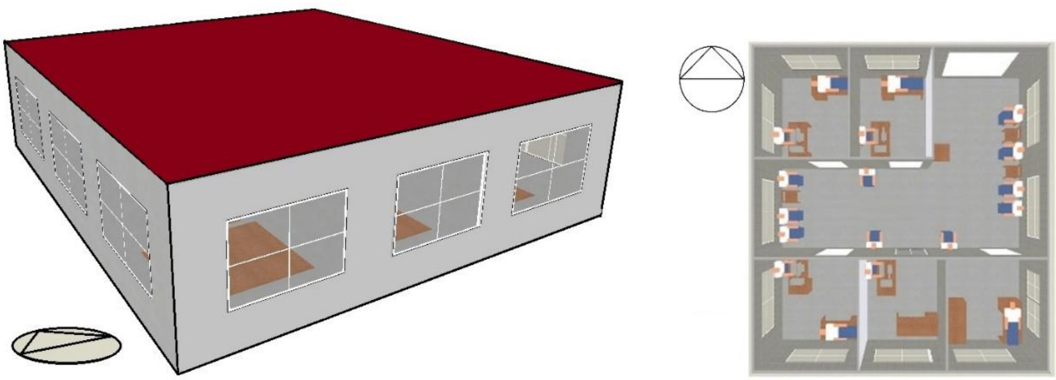

Figure 3. Model of HC building [30]

Table 1. Characteristics of the materials forming the HC building [30,37]

	Material	**Thickness** (m)	**Density** (kg/m^3)	**Thermal Conductivity** (W/m.K)	**Specific heat** (J/kg.K)
Wall	Inner cement plaster	0.01	950	0.16	840
	PCM (Melting temp.: 25ºC)	0.0121	Liquid:1540 Solid:1540	Liquid:0.54 Solid:1.09	Liquid:3140 Solid:3140
	Aerated concrete	0.3	750	0.24	1000
	Insulation	0.04	35	0.034	1400
	Outer cement plaster	0.01	950	0.16	840
Floor	Flooring block	0.14	650	0.14	1200
	Aerated concrete	0.1	750	0.24	1000
Roof	Roof insulation	0.06	20	0.035	1100
	Roofing felt	0.02	960	0.19	837
	Brick	0.1	1000	0.3	840

In systems involving phase transitions, the rate at which thermal energy is absorbed or released varies depending on the type of PCM used. Due to the high viscosity and internal resistance of the PCM in its liquid state, and considering that its layer thickness in building components is significantly smaller than the vertical dimension, the fluid motion remains negligible. Under such assumptions, the thermal effects caused by phase transitions can be calculated using Eq. 1.

$$\frac{\partial(\rho c_P T)}{\partial t} = Phase\ change + \frac{\partial}{\partial x}\left(k\frac{\partial(T)}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial(T)}{\partial y}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial(T)}{\partial y}\right) \quad (1)$$

To simulate materials with temperature-dependent thermal characteristics, EnergyPlus applies the Conduction Finite Difference Method (CondFDM). This approach segments the material surface into nodes through an automated meshing process and allows for either semi-implicit (Crank-Nicolson) or fully implicit numerical schemes. The spatial interval between nodes, denoted as 'Δx,' is determined by the spatial discretization parameter 'c,' which is the reciprocal of the Fourier number, in combination with the time increment 'Δt' and the thermal diffusivity 'α' of the material (Eq. 2). Furthermore, Eq. 3 describes the implicit finite difference equation used to compute transient, one-dimensional heat transfer through building components that incorporate PCM layers. Here, 'T_i^j' indicates the temperature at node 'i' and time step 'j', while 'k_i^j' represents the corresponding thermal conductivity. The conductivity between adjacent nodes is obtained through linear interpolation. The enthalpy of the PCM is derived based on a temperature-dependent enthalpy-temperature function (ETF), as shown in Eq. 4. At each time step, the specific heat capacity 'C_P', which varies with temperature, is recalculated using Eq. 5.

$$\Delta x = \sqrt{a\ c\ \Delta t} = \sqrt{\frac{a.\Delta t}{Fo}} \quad (2)$$

$$\rho\ c_P\ \Delta x\ \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left(\frac{k_{i+1}^{j+1} - k_i^{j+1}}{2}\right)\frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + \left(\frac{k_{i-1}^{j+1} - k_i^{j+1}}{2}\right)\frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \quad (3)$$

$$h_i = ETF(T_i) \quad (4)$$

$$c_P = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \quad (5)$$

2.3. Occupancy and HVAC Operation Profiles

To analyze the energy performance of the HC building, it was assumed that heating is provided by natural gas and cooling by electricity. The study by Yuan et al. [38] reported that the comfort temperature range in hospitals is generally between 22ºC and 26ºC. Therefore, the heating system in the model was designed to operate continuously when the indoor air temperature drops below 22ºC, and the cooling system to activate when the temperature rises above 26ºC. Ventilation was modeled to operate continuously at a constant air change rate of 4 ACH, as specified in references [30,39].

The building occupancy scenario was limited to 10% occupancy during weekdays from 08:00 to 17:00. User-related parameters affecting indoor conditions were defined based on seasonal clothing insulation values of 1.5 clo for winter, 0.5 clo for summer, and 1.0 clo for transitional seasons. The metabolic activity level was kept constant at 1.8 met for all periods. Additionally, the energy impact of equipment that increases internal gains, such as computers, lighting systems, and medical devices, was also considered. The power density for these devices was modeled as 18 W/m^2 during operating hours and 10 W/m^2 outside operating hours [30].

2.4. Validation of Model

Validation constitutes a critical step in enhancing the credibility of simulation-based research and verifying the robustness of the outcomes [40]. In this regard, the performance of the developed model was assessed through a comparative analysis with the comprehensive study conducted by Lingfan et al. [41], following a similar approach adopted by Yüksel [30] (see Fig. 4). In their investigation, Lingfan et al. calibrated their simulation models using empirical data from Chengdu, subsequently applying them to cities with varying climatic conditions, namely Harbin, Lhasa, and Guangzhou, to explore the impact of PCM integration on energy efficiency. Given the shared emphasis on PCM's contribution to energy reduction and the methodological alignment in modeling strategies, these studies offer a robust benchmark for comparison. The findings revealed that, consistent with [30], the present model exhibited a deviation of approximately 5 kWh in electricity consumption during winter and around 12 kWh in natural gas use during summer. These relatively minor discrepancies affirm the model's capacity to deliver accurate and reliable predictions across diverse climatic contexts, thereby validating its generalizability and practical applicability.

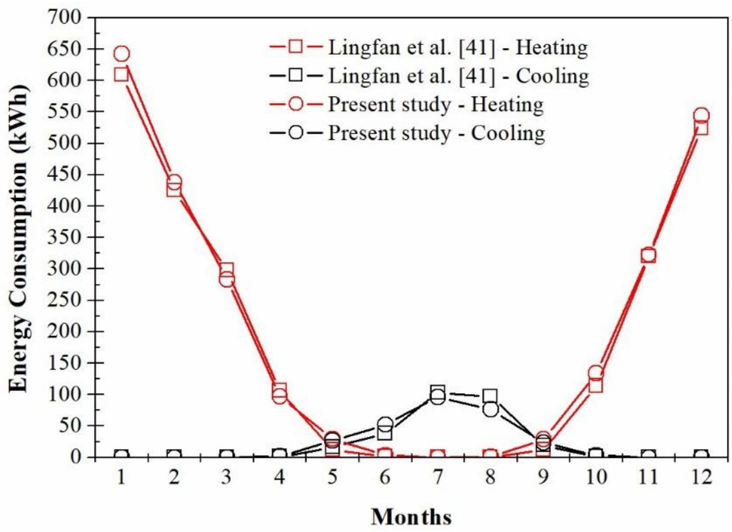

Figure 4. Validation of the simulation model [41]

3. RESULTS AND DISCUSSION

In the present study, the impact of PCM integration on building energy performance in a HC building was investigated by comparing electricity and natural gas consumption under different wall application scenarios, including all interior and exterior walls, only exterior walls, a single facade, two facades, and three facades. In the graphs, the black lines represent electricity consumption from cooling, while the green lines indicate natural gas consumption from heating. The findings related to different facade configurations reveal that the effectiveness of PCM in reducing energy consumption is closely related to facade orientation and integration strategy.

Fig. 5 shows the monthly electricity and natural gas consumption values for the HC building under four different conditions: without PCM, with PCM applied to all interior and exterior walls, with PCM applied only to exterior walls, and with PSM (Phase Stable PCM), which was included to isolate the thermal mass effects of PCM without any phase transition. Evaluating the PSM scenario, which represents a reference case limited to sensible heat storage, enabled the isolation of the thermal benefits gained specifically through the latent heat effect of PCM. This distinction clarified the direct contribution of phase change on thermal regulation.

During the cooling season (June–September), the electricity consumption in the reference scenario without PCM ranged between approximately 17–51 kWh/day, while the application of PCM to both interior and exterior walls reduced this range to 13–40 kWh/day. PCM, with a melting temperature of 25ºC, was observed to be more effective during the hotter months (July and

August), leading to a reduction of up to 11 kWh/day. In the milder cooling months (June and September), the electricity savings were lower, with an average of 6 kWh/day. When PCM was applied only to the exterior walls, the savings were more limited, yielding approximately 7 kWh/day during the hottest months and 4 kWh/day during the milder months. In the PSM scenario, where no phase change occurred, an average electricity saving of 1 kWh/day was recorded during all warm months. Therefore, it was concluded that approximately 1 kWh/day of savings in all PCM cases originated from the thermal mass of the material alone.

In the heating season (January, February, and December), the natural gas consumption in the scenario without PCM was around 61 kWh/day on average. Interestingly, applying PCM to all walls slightly increased consumption to approximately 63 kWh/day. However, in the PSM scenario, a minor reduction of 1 kWh/day compared to the reference case (without PCM) was observed. These findings suggested that PCM with a melting point of 25ºC is more effective in cooling-dominant climates and may require additional heating energy in winter to initiate phase transition. Nevertheless, the significant reduction in electricity consumption during summer, up to 11 kWh/day, largely outweighs the modest increase of about 2 kWh/day in heating demand during winter months.

Results underscored the importance of climate-specific PCM selection and seasonal performance evaluation in passive energy strategies. While PCMs offer considerable cooling energy savings in Mediterranean climates, their winter performance may not always be favorable unless the melting point is optimally matched to indoor temperature ranges.

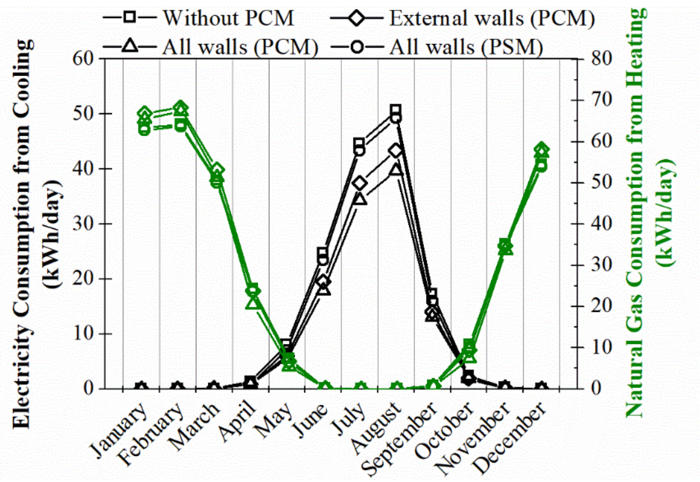

Figure 5. Monthly electricity and natural gas consumption of the HC building for PCM and PSM scenarios

Fig. 6 presents the monthly electricity and natural gas consumption values for a HC building in scenarios where PCM is integrated into only one external facade (North, South, East, or West) and into all external facades.

During the heating months of January, February, March, and December, the average natural gas consumption was approximately 58 kWh/day in the case without PCM, while this value increased to 61 kWh/day when PCM was applied to all external walls. This average remained almost unchanged across all single-facade configurations. The lowest average natural gas consumption, with a slight difference of 0.5 kWh/day, was observed when PCM was applied to the South facade. Moreover, compared to the no-PCM scenario, the maximum increase in natural gas consumption was 4 kWh/day (February) for all-facade PCM applications, whereas the lowest increase (3 kWh/day) was recorded in the case of PCM integrated into the South.

In the cooling season (June, July, August, and September), the average electricity consumption was 34 kWh/day in the no-PCM case and 29 kWh/day when PCM was applied to all external walls. For single-facade PCM applications, the maximum average electricity consumption was 31 kWh/day (North), while the minimum was 30 kWh/day (West). While PCM integration into all facades provided a maximum electricity saving of 7 kWh/day (July), the highest saving among single-facade applications was achieved by applying PCM to the West facade, resulting in a 5 kWh/day reduction. Notably, the greatest daily electricity saving in a single-facade scenario was observed in the South facade application, with 6 kWh/day in August.

These results indicate that multi-facade PCM applications significantly reduce building thermal loads and cooling demand, whereas single-facade applications provide a more limited but still notable energy saving compared to the no-PCM scenario. Particularly, the West facade performed more efficiently than the north, likely due to its greater exposure to afternoon solar radiation, which enables more effective thermal storage and release by the PCM. Therefore, while single-facade PCM installations can improve energy performance, multi-facade or strategically targeted facade applications are recommended for maximum efficiency.

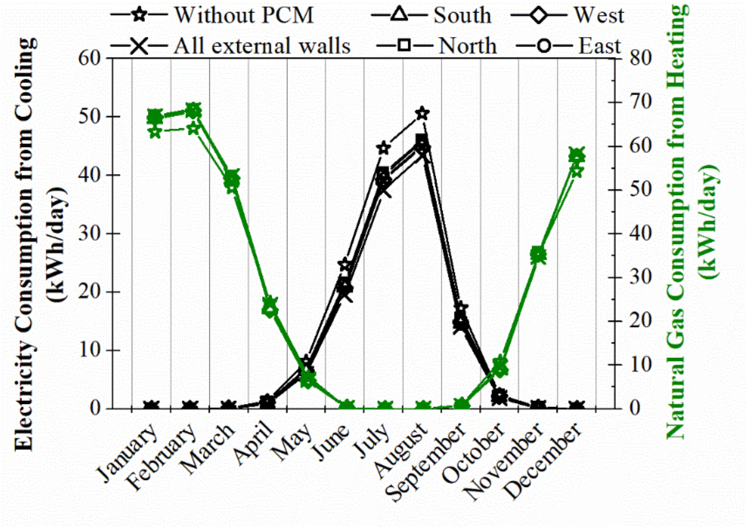

Figure 6. Monthly electricity and natural gas consumption for single-facade PCM integration scenarios

Fig. 7 illustrates the monthly electricity and natural gas consumption values for scenarios where PCM is integrated into dual facade orientations (North+East, East+West, North+West, North+South, East+South, or South+West), as well as into all exterior facades.

During the cooling season, compared to the average electricity consumption without PCM (34 kWh/day), energy savings of 1.9, 2.6, 2.3, 2.8, 2.6, and 3.5 kWh/day were achieved for the North+East, North+South, North+West, East+South, East+West, and South+West configurations, respectively. The fact that the lowest and highest savings were observed when PCM was placed on the North+East and South+West facades, respectively, indicates that the angle of solar incidence directly influences PCM's impact on cooling loads. However, these savings were 3.8, 3.1, 3.4, 3.0, 3.1, and 2.2 kWh/day lower than those observed in the full-facade PCM scenario for the same orientation combinations. The full-facade application achieved a more balanced thermal distribution across the building envelope, reducing localized heat gains and resulting in higher electricity savings. In contrast, PCM applications limited to two facades provided localized benefits but only marginal improvements in the building's overall energy performance.

During the heating season, compared to the average natural gas consumption without PCM (58 kWh/day), the dual-facade PCM applications on North+East, North+South, North+West, East+South, East+West, and South+West resulted in increased consumption of 4.4, 4.2, 4.4, 4.0, 4.2, and 3.9 kWh/day, respectively. Since PCM was exposed to temperatures low to trigger phase transitions during winter, it behaved as passive thermal mass, absorbing the limited solar gains during the day. Because this absorbed heat was not effectively released into the indoor space, the heating system demand increased. Additionally, compared to the full-facade PCM scenario, the same orientation combinations exhibited 0.9, 0.6, 0.9, 0.4, 0.7, and 0.4 kWh/day higher natural gas consumption, respectively.

Although it was expected that integrating PCM into two facades would result in lower heating energy consumption compared to full-facade application, the findings indicated otherwise. This may be attributed to the concentration of PCM on highly sun-exposed facades in dual-facade applications, which likely caused more heat absorption without phase change. This, in turn, increased thermal resistance and hindered the attainment of the desired indoor temperature, thus raising natural gas consumption. Although the full-facade application involved more PCM material, the contributions from poorly sunlit facades were minimal, limiting the overall increase in energy use. Nevertheless, the full-facade configuration likely facilitated more uniform thermal interactions and mitigated peak heat absorption from any single orientation. As a result, inefficient or delayed heat release led to increased heating demand.

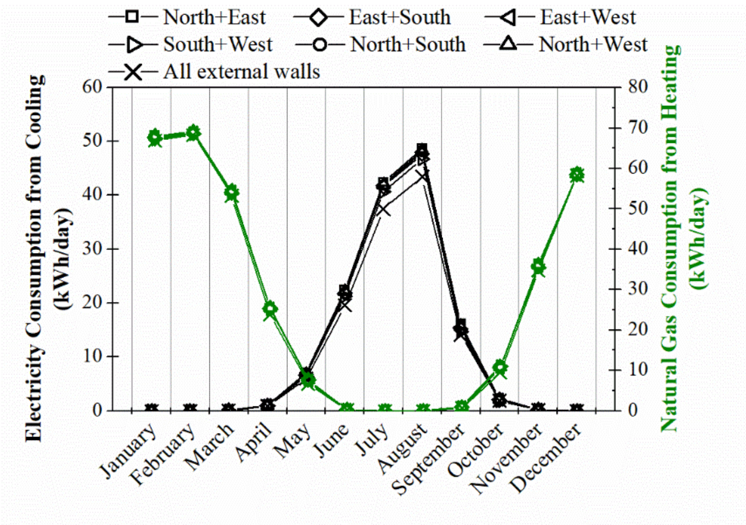

Figure 7. Monthly electricity and natural gas consumption for two facade PCM integration scenarios

Fig. 8 demonstrates the monthly electricity and natural gas consumption values for scenarios where PCM was integrated into all external facades and three-facade orientations (North+East+South, North+East+West, North+South+West, or East+West+South).

Compared to the average natural gas consumption of 58 kWh/day in the case without PCM, the three facade PCM configurations exhibited increases of 3.9, 3.6, 4.1, and 3.6 kWh/day, respectively. Like the two facade configurations, during the winter season, ambient temperatures were insufficient to trigger phase change; thus, PCM behaved merely as a passive thermal mass storing limited solar gains. Furthermore, compared to the full facade PCM scenario, the same three facade orientations resulted in slightly higher natural gas consumption, with respective increases of 0.3, 0.1, 0.6, and 0.1 kWh/day. However, these values were still lower than those observed in two facade configurations. Therefore, increasing the amount of PCM used in the building, and distributing it more homogeneously rather than concentrating it only on sun-exposed facades, contributed to mitigating the adverse impact on heating loads. Even under conditions where PCM could not undergo phase transition due to low temperatures and thus could not release heat actively, a more balanced thermal interaction was achieved, preventing excessive system loading. Additionally, the wider surface area coverage of PCM in the three facade applications may have helped avoid localized heat accumulation, thereby contributing to a more stable indoor temperature.

In terms of cooling, compared to the average electricity consumption of 34 kWh/day in the no-PCM scenario, the North+East+South, North+South+West, North+East+West, and East+West+South configurations achieved energy savings of 3.8, 4.7, 3.5, and 4.7 kWh/day, respectively. However, these savings were lower by 1.9, 1.0, 2.1, and 1.0 kWh/day compared to the savings achieved in the full facade PCM scenario, where a total reduction of 28.6 kWh/day was recorded for the same orientation combinations. Hence, employing PCM on a greater number of facades contributed to a more balanced thermal distribution across the building envelope, leading to reduced local heat gains and higher levels of electricity savings.

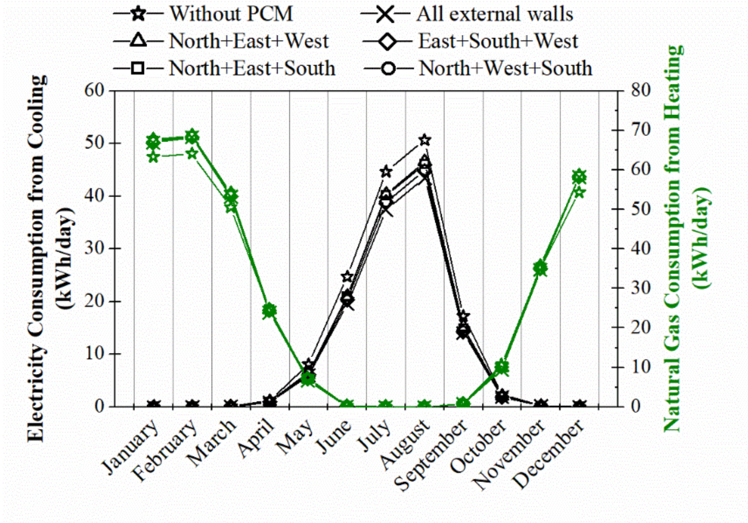

Figure 8. Monthly electricity and natural gas consumption for three facade PCM integration scenarios

Table 2 presents the annual total electricity and natural gas consumption data for all PCM application scenarios considered for different facades of the HC building. Compared to the reference scenario without PCM, the scenario in which PCM was used solely in its phase-stable mode (PSM) provided electricity and natural gas savings of 223 kWh and 152 kWh, respectively, due to the thermal mass effect. This indicated that PCM, through its passive properties such as thermal conductivity, reduced electricity consumption by approximately 4.9% and natural gas consumption by 1.6%. Additionally, the findings obtained for PSM and PCM were consistent with those reported in Refs. [42–44].

In the scenario where the phase change effects were also active (PCM applied to both internal and external walls), annual electricity and natural gas savings were calculated as 1100 kWh and 71 kWh, respectively. These corresponded to reductions of approximately 24% in electricity and 1% in natural gas consumption compared to the reference scenario. The results revealed that PCM was particularly more effective in reducing the load on electrically powered cooling systems, whereas its impact on natural gas systems used for heating remained limited. Furthermore, the data obtained from the scenario involving PSM and PCM use on all internal and external walls showed that approximately 81 kWh of natural gas was consumed during the phase change process in winter, which supported the findings of the study conducted by Arıcı et al. [45].

In the scenario where PCM was applied only to the external walls, electricity consumption was reduced by 791 kWh, while natural gas consumption increased by 372 kWh. This finding indicated that integrating PCM solely into the external walls of HC buildings could, in some cases, limit heat gains and increase heating loads, thereby highlighting the importance of also incorporating PCM into internal walls.

Among single-facade applications, the scenario where PCM was applied to the South facade stood out with 3991.9 kWh of electricity and 9690.9 kWh of natural gas consumption. This suggested that PCM provided an effective cooling contribution on the south facade, which received the most intense direct solar radiation. Similarly, low electricity consumption (3990.3 kWh) was observed for the West facade application, indicating that the high solar gains in the afternoon were effectively managed by PCM. Interestingly, applying PCM only to the East facade (4083.2 kWh) resulted in greater electricity savings compared to the North facade (4128.2 kWh). This difference suggested that the PCM on the east facade, which was exposed to direct sunlight in the morning hours, offered more effective energy management.

Among the multi-facade combinations, the greatest electricity savings and the smallest increase in natural gas consumption were achieved in scenarios where PCM was applied to the North+East+West and East+West+South facades, with savings of 666 kWh and 450 kWh, respectively. These results demonstrated that PCM applications had more pronounced and favorable effects in reducing electricity consumption related to cooling. It was determined that the heat stored during the PCM's phase change reduced cooling loads, thereby decreasing the operating time of air conditioning systems and consequently electricity consumption.

In conclusion, facade orientation and surface coverage were critical factors in the architectural integration of PCM, and prioritizing facades with high solar radiation potential emerged as a key strategy for enhancing energy efficiency.

Table 2. Total annual energy consumption according to PCM integration scenarios on facades

Facades Scenarios for PCM Integration	**Electricity Consumption (kWh) *(-: Benefit, +: Harm)**	**Natural Gas Consumption (kWh) *(-: Benefit, +: Harm)**
Without PCM (Reference scenario)	4586.1	9459.1
All facades and all walls (PSM)	4362.8 (-5%)	9306.8 (-2%)
All facades and all walls (PCM)	3486.9 (-24%)	9387.8 (-1%)

All facades and external walls (PCM)	3795.1 (-17%)	9831.5 (+4%)
North	4128.2 (-10%)	9778.2 (+3%)
East	4083.2 (-11%)	9734.3 (+3%)
South	3991.9 (-13%)	9690.9 (+3%)
West	3990.3 (-13%)	9714.9 (+3%)
North and East	4313.8 (-6%)	10097.9 (+7%)
North and South	4208.9 (-8%)	10087.1 (+7%)
North and West	4258.5 (-7%)	10119.8 (+7%)
East and South	4185.9 (-9%)	10044.8 (+6%)
East and West	4212.0 (-8%)	10063.1 (+6%)
South and West	4083.7 (-11%)	10035.3 (+6%)
North, East and South	4045.5 (-12%)	9960.6 (+5%)
North, West and South	3920.5 (-15%)	9908.9 (+5%)
North, East and West	4086.3 (-11%)	9985.7 (+6%)
East, West and South	3920.5 (-15%)	9908.9 (+5%)

**Negative values indicate a reduction (benefit) in electricity and natural gas consumption, whereas positive values represent an increase (harm).*

Table 3 compares the energy performance outcomes of the present simulation-based study with those of previous research conducted under varying climatic and building conditions. In the current study, the integration of InfiniteRPCM with a melting temperature of 25ºC into healthcare clinics located in a Mediterranean climate (Koppen-Geiger: Csa) resulted in a 24% reduction in electricity consumption and a 1% decrease in natural gas use (Table 2).

Yüksel [30] investigated the performance of different commercial PCMs, including BioPCM, InfiniteRPCM, and Winco Technologies Enerciel, within primary healthcare centers situated in both Mediterranean (Csa) and continental (Dfb) climates. Depending on the melting temperature and the climate zone, the study reported a broad range of energy savings from 17% to 57%. Yari et al. [46] employed a PCM with a melting point of 24 °C in a general building model located in a hot-dry climate (ASHRAE 3B) and reported a notable 61.8% reduction in energy demand. In contrast, Zhang et al. [47] focused on hospitals in a cold climate zone and integrated an inorganic salt hydrate PCM with a melting range of 23–33ºC. Their results indicated a more modest improvement, with 3–6% energy savings, likely due to different thermal needs and baseline energy consumption levels in colder climates. These differences between studies could be attributed to several factors:

- The different and limited operational hours of HVAC systems,
- The specific building typology and load profile of health clinics, where internal gains are moderate and demand patterns are tightly scheduled,

- The facade-based PCM integration strategy, as opposed to full-envelope or zone-based PCM applications adopted in some earlier studies.

These comparisons demonstrate that the effectiveness of PCM integration is highly dependent on building type, climate conditions, and the thermal characteristics of the selected material. The outcomes of the present study fall within the range of reported values in the literature and confirm the potential of PCM applications to enhance energy efficiency in healthcare buildings, particularly in warm climates.

Table 3. Total annual energy consumption according to PCM integration scenarios on facades

Study	PCM Type (Melting temp.	Building Type (Climate)	Findings
Present Study	InfiniteRPCM (25°C)	Health care clinics (Koppen-Geiger: Csa)	24% electricity savings 0.8% natural gas savings
Yüksel [30]	BioPCM (21, 23, 25, 27, 29°C), InfiniteRPCM (18, 21, 23, 25, 29°C), Winco Technologies Enerciel (21, 23, 29°C)	Primary healthcare centers (Koppen-Geiger: Csa and Dfb)	17-57% energy savings
Yari et al. [46]	PCM (24°C)	General building description (ASHRAE index: 3B)	61.8% energy savings
Zhang et al. [47]	Inorganic salt hydrate PCM (23-33°C)	Hospitals (Cold climate zone)	3-6% energy savings

3.1. Economic Evaluation

To evaluate the economic viability of integrating PCM into the building envelope, a detailed cost-benefit analysis was conducted based on the reductions and increases in annual electricity and natural gas consumption across different facade scenarios. The total PCM requirement was calculated using a thickness of 0.0121 m and a density of 1540 kg/m^3, yielding approximately 18.63 kg/m^2. For a total facade area of 260 m^2, this corresponded to a total mass of approximately 4,844 kg. Considering a latent heat capacity of 250 kJ/kg (0.0694 kWh/kg), the total thermal energy storage capacity of the system was estimated to be 336.2 kWh. Based on Pompei et al. [48], the investment cost of PCM systems was taken as 8 €/kWh. The corresponding cost savings and payback periods for each configuration were presented in Table 4.

Table 4. Updated investment cost and payback period for various PCM scenarios

Scenario	All facades and all walls	South and West	North, West and South	North, East and South	All facades and ext. walls

Electricity Saving (kWh/year)	1099.2	595.8	665.6	540.6	791
Natural Gas Saving (kWh/year)	71.3	-576.2	-449.8	-501.5	-372.4
Total Energy Saving (kWh/year)	1170.5	19.6	215.8	39.1	418.6
Cost Saving (€/year)*	181.7	3	33.5	6.1	64.9
PCM Required (kWh)	336.2	207.4	233.7	233.7	259.4
Investment Cost (€) (For 8 €/kWh [48])	2,690 €	1,660 €	1,870 €	1,870 €	2,075 €
Payback Period (years)	14.8	533.3	55.8	306.6	31.9

**Assumed rates: electricity = 0.18 €/kWh; natural gas = 0.08 €/kWh.*

As shown in Table 4, the “All facades and all walls” scenario resulted in the highest total energy and cost savings, with 1,170.5 kWh/year and 181.7 €/year, respectively. Despite this, the payback period was approximately 14.8 years due to the relatively high initial investment. In the partial coverage scenarios, such as “South and West” or “North, West and South,” total energy savings were significantly lower, 19.6 kWh/year and 215.8 kWh/year, leading to extended payback periods of 533.3 and 55.8 years, respectively. The “All facades and external walls” option provided moderate savings (418.6 kWh/year) with a payback period of 31.9 years. These results showed that the payback period was highly dependent on both the extent of PCM coverage and the resulting energy savings. While full-coverage scenarios yielded better performance, economic feasibility remained limited under the assumed unit cost of 8 €/kWh.

4. CONCLUSION

The energy performance of an HC building was comprehensively analyzed by simulating different PCM (Melting temperature: 25°C) integration scenarios within the scope of this study. In the simulations, the building was modeled under the climatic conditions of Istanbul, and the effects of applying PCM to the building envelope in various orientations and combinations on heating and cooling energy consumption were revealed.

The study determined that the impact of PCM applications on energy performance varied depending on the number and orientation of the facades. During the winter months, due to low ambient temperatures preventing phase change, PCMs were unable to actively release heat, thus behaving merely as passive thermal storage materials. This situation, especially in scenarios where PCM was applied to only one, two, or three facades, resulted in limited solar gains not being effectively transferred indoors, leading to an increase in natural gas consumption. However, as the number of PCM-applied facades increased, the rise in natural gas consumption became more limited, indicating that a more homogeneous distribution of PCM on the building surface could help balance negative thermal loads on the system.

In contrast, an opposite effect was observed during the cooling season. The use of PCM on facades exposed to high levels of solar radiation enabled effective phase change, which contributed to reducing electricity consumption. However, applications on only one, two, or three facades were insufficient to reduce local heat gains, thereby preventing maximum electricity savings from being achieved. On the other hand, full-facade PCM applications provided a more balanced heat distribution across the building envelope, resulting in significant reductions in cooling loads and improvements in energy efficiency. The implementation of PCM on both the inner and outer walls, allowing for effective phase change, significantly enhanced energy saving performance by cutting electricity consumption by 1100 kWh (24%) and reducing natural gas demand by 71 kWh (1%).

These results showed that PCM applications should consider not only the orientation but also the number of facades involved and the distribution pattern on the building envelope. Especially considering seasonal variability, optimizing PCM facade configurations would play a critical role in balancing heating and cooling loads and enhancing building energy efficiency.

Evaluating the performance of PCMs under future climate scenarios may play a critical role in the development of long-term energy strategies. In this context, it is recommended that future studies conduct facade scenario analyses based on different climate conditions. A comparative investigation of PCM integration in other building elements, such as roofs and floors, in addition to internal and external walls, would be important for a comprehensive thermal performance analysis. Furthermore, analyzing PCM performance for different building functions (e.g., rehabilitation centers, operating rooms) is suggested to better understand the scalability of its application.

NOMENCLATURE

CondFDM	Conduction Finite Difference Method
ETF	Enthalpy-Temperature Function
HC(s)	Health Care Clinic(s)
IEA	International Energy Agency

PCM(s)	Phase Change Material(s)
PSM	Phase Stable PCM
TUIK	Turkish Statistical Institute
U-value	Heat Transfer Coefficient, W/m^{2}K

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Ahmet Yüksel: Conducted the literature research, performed the simulations, analyzed the results, and wrote and revised the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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