Megaron, Vol. 21, No. 3, pp. 349–360, September 2026

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2026.25564

Article

Climate-responsive roof design: phase-change materials and cool-roof coatings across Türkiye's six climate zones

Niloufar Ziasistani[1], İrem Sözen Aka[2], Andrés Meana-Fernández[1], Antonio J. Gutierrez Trashorras[1]

[1]Department of Energy, University of Oviedo, Gijón, Spain
[2]Department of Interior Architecture, Istanbul University, İstanbul, Türkiye

ARTICLE INFO

Article history
Received: 15 August 2026
Revised: 16 September 2026
Accepted: 28 September 2026

Key words:
Phase-change material (PCM); cool-roof coating; climate zones; energy efficiency; office building.

ABSTRACT

Roof material and coating decisions are typically finalized early in design, yet climate-specific evidence for choosing among roof-integrated phase-change materials (PCMs), high-reflectance cool roofs (CR), and their combination remains limited. This study evaluates all three strategies via annual EnergyPlus simulations of a standardized office model across Türkiye's six TS 825 climate zones (Mersin, Şanlıurfa, İstanbul, Ankara, Van, and Erzurum). Five inorganic PCM products with nominal melting temperatures of 21, 23, 25, 27, and 29 °C were tested individually before the best-performing temperature in each city was paired with the cool-roof finish. Performance was assessed from annual ideal-load heating and cooling demand, with total demand defined as their sum. The optimal PCM reduced total demand by 4.24–10.15%, with the preferred melting temperature shifting from 25 °C in cooling-dominated Mersin to 21 °C in cold Erzurum; 23 °C was optimal in the other four cities. The cool roof reduced cooling demand in every city but increased heating demand, producing net annual savings of only 0.22% in Erzurum and up to 5.86% in Mersin. The combined strategy achieved the lowest total demand in five cities, with savings of 8.00–11.92%. Van was the exception: its optimal PCM alone saved 10.01%, whereas the combined case saved 6.33%, indicating that the coating and PCM were not universally additive. The findings show that PCM transition temperature should be matched to local operating conditions and that cool roofs require an annual heating–cooling assessment rather than a cooling-only evaluation.

Cite this article as: Ziasistani, N., Sözen Aka, İ., Meana-Fernández, A., Trashorras, AJG. (2026). Climate-responsive roof design: phase-change materials and cool-roof coatings across Türkiye's six climate zones. Megaron, 21(3):349–360.

INTRODUCTION

Reducing the heating and cooling requirements of buildings is an important component of improving operational energy performance. Because the building envelope controls heat exchange between indoor and outdoor environments, modifications to walls and roofs can reduce thermal loads and improve indoor conditions. Phase-change materials (PCMs) have received considerable attention in this context because they can store and release latent heat within

***Corresponding author**
*E-mail address: Uo290587@uniovi.es

Published by Yıldız Technical University, İstanbul, Türkiye
This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

a limited temperature range (Faraj et al., 2021). Cool-roof materials represent another passive strategy, using high solar reflectance and thermal emissivity to reduce the solar energy absorbed by the roof (Saber, 2021).

Roofs are particularly exposed to solar radiation and fluctuations in outdoor temperature. When incorporated into a roof, a PCM can absorb heat during melting and release the stored energy during solidification, thereby attenuating and delaying heat transfer. However, its effectiveness depends on factors such as melting temperature, latent-heat capacity, thickness, position within the construction and local climatic conditions (Rathore et al., 2022). Seasonal analyses have also demonstrated that PCM performance can vary substantially with phase-transition temperature and environmental conditions (Tunçbilek et al., 2020).

Cool-roof performance is similarly climate-dependent. Increasing roof solar reflectance generally decreases roof-surface temperature and cooling demand, but the annual benefit varies according to climatic conditions and the balance between heating and cooling requirements (Rincón et al., 2024). During winter, a reflective roof may reduce beneficial solar heat gains and consequently increase heating demand (Ascione et al., 2018). Therefore, evaluating cooling demand alone may overestimate the annual benefit of a cool roof, particularly in heating-dominated climates.

Previous studies have investigated radiative-cooling roofs and PCM-integrated roof systems under different environmental conditions (Kim et al., 2020; Tang et al., 2024). Other studies have specifically evaluated combined PCM–cool-roof configurations through experimental and numerical approaches (Yang et al., 2019). A review by Rawat et al. further demonstrated the growing interest in integrating latent-heat storage with reflective roof technologies (Rawat et al., 2022). Nevertheless, direct comparisons using an identical building model, a common roof construction and the same range of PCM melting temperatures across multiple climate zones remain limited.

Furthermore, the energy benefits of PCM and cool-roof technologies should not automatically be assumed to be additive when the two measures are applied together. A reflective exterior finish changes the thermal conditions experienced by the underlying roof layers and may therefore influence PCM melting and solidification. The combined configuration must consequently be simulated as a coupled system and compared directly with the individual strategies.

Roof material and coating decisions are generally finalized during the early design phase, before the mechanical systems are sized or optimized. Architects therefore need climate-specific, comparative evidence for choosing between passive envelope strategies such as PCM integration and cool-roof coatings. Without such evidence roof specifications tend to default to convention rather than to tested climate performance, particularly in a country as climatically diverse as Türkiye.

Accordingly, the present study investigates one flat-roof office model in six representative Turkish cities, each corresponding to one of the six climate zones defined by the Turkish Standard for Thermal Insulation Requirements in Buildings, TS 825 (TSE, 2024). Five nominal PCM melting temperatures, 21, 23, 25, 27 and 29 °C, were initially evaluated for each city. The city-specific optimal PCM was subsequently compared with a TiO_2–SiO_2 cool-roof coating and a combined PCM–cool-roof configuration. The objectives were to: (i) identify the preferred PCM melting temperature for each climate, (ii) quantify the annual heating–cooling trade-off associated with the cool roof, and (iii) determine whether the combined measures exhibit synergistic, additive or antagonistic behavior.

BACKGROUND

Roof-integrated phase-change Materials

PCMs provide thermal storage by absorbing energy during melting and releasing it during solidification. This process increases the effective heat-storage capacity of a building component within the material's phase-transition range (Faraj et al., 2021). When incorporated into roofs, walls or other envelope elements, PCMs can reduce temperature fluctuations, delay peak heat transfer and potentially reduce space-conditioning demand.

The thermal performance of a PCM-integrated envelope depends on the relationship between the phase-transition temperature and the temperature cycle experienced by the material. PCM performance is also affected by latent-heat capacity, thermal conductivity, layer thickness, position, envelope construction and local climatic conditions (Rathore et al., 2022). If the transition range is unsuitable, the PCM may remain predominantly solid or liquid, restricting effective melting and solidification and limiting the use of its latent-heat capacity.

Tunçbilek et al. showed that the seasonal and annual performance of PCM-integrated building components is strongly affected by climatic conditions and the selected phase-transition temperature (Tunçbilek et al., 2020). Azimi et al. similarly demonstrated the importance of optimizing PCM selection and application parameters for the specific building and climate under investigation (Azimi et al., 2025). Tokuç et al., evaluated a flat roof containing a single PCM layer across Türkiye's four climatic zones for only cooling season and reported substantial reductions in cooling load (Tokuç et al., 2017). These findings indicate that selecting a PCM solely according to peak summer outdoor temperature may not produce the lowest annual heating and cooling demand.

Recent research has also examined more advanced PCM roof configurations. Tang et al. experimentally investigat-

ed a radiative-cooling roof incorporating dual PCMs under hot-summer and warm-winter climatic conditions (Tang et al., 2024). Kim et al. evaluated PCM-containing materials for cool-roof applications and reported reductions in roof-surface and indoor temperatures (Kim et al., 2020). Although these studies demonstrate the potential of PCM roof systems, their findings also emphasize that performance is closely related to material selection and operating conditions.

In addition to material selection and operating conditions, the PCM configuration and integration method can influence envelope performance. Experimental evidence indicates that changing the position of the PCM layer and the associated thermal resistance can improve latent-heat utilization compared with a fixed PCM arrangement (Li et al., 2024). EnergyPlus simulations of PCM-integrated façades have also shown that PCM composition and melting characteristics can substantially affect annual heating and cooling loads (Azadani & Ardekani, 2025). In Türkiye specifically, Arıcı et al. found that the optimum position of PCM within a wall assembly shifted from an inner to an outer layer between milder and colder cities (Arıcı et al., 2020). These findings demonstrate that PCM performance depends not only on transition temperature but also on material composition, position within the envelope, and interaction with the surrounding construction.

Cool Roofs and Combined Systems

Cool roofs employ exterior materials with high solar reflectance and thermal emissivity. These optical properties reduce the proportion of incident solar radiation absorbed by the roof and facilitate heat rejection to the outdoor environment (Saber, 2021). As a result, cool roofs generally reduce daytime roof-surface temperatures, inward heat transfer and cooling demand.

The magnitude of this benefit depends on climate, roof insulation and building operation. Studies of office buildings across different Spanish climate zones have demonstrated that the effects of cool roofs on cooling demand, annual energy demand and thermal comfort vary with climatic conditions (Rincón et al., 2024). Ascione et al. specifically investigated the winter energy penalty of reflective roofs and showed that reduced solar absorption can increase heating requirements (Ascione et al., 2018). Therefore, both heating and cooling demands must be considered when evaluating annual cool-roof performance.

Recent reviews have further emphasized that cool-roof performance depends on more than solar reflectance and thermal emittance. Roof material selection, insulation level, coating durability, weathering, construction thickness, cost, and local climate can influence the practical energy benefit (Basyouni & Mahmoud, 2024). These factors reinforce the need to evaluate cool-roof configurations under the climatic and construction conditions in which they will be applied.

Other studies have reported similar heating–cooling trade-offs. Yazdani and Baneshi compared dynamic cool roofs and green roofs under different climatic conditions, demonstrating the importance of climate-responsive roof selection (Yazdani & Baneshi, 2021). Application of a cool coating to a laboratory building reduced cooling demand but increased heating demand (Kolokotsa et al., 2012). These findings confirm that a cool roof's annual performance cannot be determined solely from its cooling-season benefit.

Combining a cool roof with PCM introduces two thermal-control mechanisms: solar-gain reduction at the exterior surface and latent-heat storage within the roof construction. Yang et al. experimentally and numerically investigated a PCM cool-roof system and reported reductions in roof-surface temperature (Yang et al., 2019). Rawat et al. reviewed combined PCM–cool-roof applications and reported potential improvements in thermal comfort and building energy performance (Rawat et al., 2022).

However, the two measures may not operate independently. A highly reflective coating can reduce the magnitude of the temperature variation transmitted through the roof, potentially changing the degree of PCM melting and solidification. Therefore, the performance of a combined PCM–cool-roof configuration should be determined directly rather than estimated by adding the savings obtained from the two individual measures. In the present study, this relationship is evaluated using an interaction indicator that distinguishes synergistic, additive and antagonistic behavior.

From a design perspective, TS 825 establishes minimum envelope insulation requirements for each climate zone but provides no guidance on complementary passive strategies such as PCM integration or cool-roof coatings. Consequently, climate-specific guidance for selecting or combining these measures remains limited. This study addresses this gap by evaluating both strategies, individually and in combination, across Türkiye's six TS 825 climate zones.

METHODOLOGY

Building and Simulation Model

A simple two-story office model was developed using DesignBuilder version 7.3.0.040 (DesignBuilder) and simulated with its integrated EnergyPlus version 9.4.0 (EnergyPlus) engine. Six timesteps per hour, corresponding to 10-minute intervals, were used. The rectangular building was aligned with the cardinal directions, with its 10 m façades facing north and south and its 9 m façades facing east and west. The same external geometry was used in all cities, including a gross flat-roof area of 90.00 m^2. The gross window-to-wall ratio was defined as the total exterior win-

dow-opening area divided by the total above-ground gross exterior wall area. Based on a window-opening area of 24.78 m² and a gross exterior wall area of 205.20 m², the resulting ratio was 12.08%. The roof construction, internal-gain densities, schedules, and HVAC settings were retained across the climate cases. The assigned DesignBuilder HVAC template was a four-pipe fan-coil unit with an air-cooled chiller.

The windows had a U-value of 1.8 W/(m²·K), a solar heat gain coefficient of 0.691, a direct solar transmittance of 0.624, and a visible transmittance of 0.744. Infiltration was modelled at a constant rate of 0.50 air changes per hour. Mechanical ventilation supplied 10 L/s of outdoor air per person according to the occupancy schedule, while natural ventilation was disabled. The occupancy, lighting, and equipment densities were 0.111 people/m², 15 W/m², and 11.77 W/m², respectively. Table 1 summarizes the main geometric, operational, and simulation parameters of the reference office building.

Figure 1 shows the building developed in DesignBuilder and used for all climate simulations.

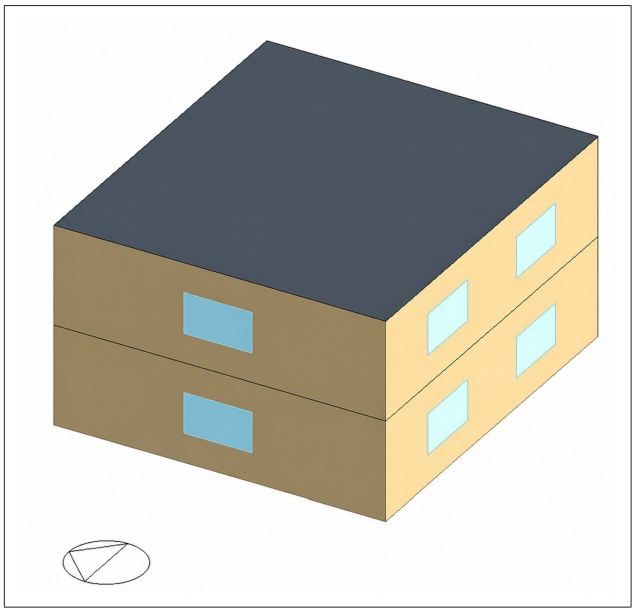

Figure 1. 3D model of the case study building.

Climate Locations and Weather Data

Six cities were selected to represent the six climate zones used in the current Turkish thermal-insulation framework (TSE, 2024). The corresponding EnergyPlus Weather (EPW) files were used for the simulations (Lawrie, 2026). Table 2 presents the selected cities, their TS 825 climate zones, and geographical information.

Table 3 summarizes the envelope constructions used in the simulations. To isolate the effects of climate and the investigated roof modifications, the roof construction and its U-factor were kept constant across all six cities. The wall and ground-floor insulation thicknesses were selected with reference to the recommendations for the corresponding TS 825 climate zones, while the remaining construction layers were kept consistent across the models (TSE, 2024).

Table 1. Main building and simulation parameters

Parameter	Value used in the model
Gross roof area	90.00 m²
Window opening area	24.78 m²
Gross window-to-wall ratio	12.08%
Activity template	Office
Operating schedule	Monday–Friday 09:00–17:00, Saturday–Sunday off
Heating setpoint / setback	22 °C / 12 °C
Cooling setpoint / setback	24 °C / 28 °C
Assigned HVAC template	Fan Coil Unit (4-Pipe), Air cooled Chiller
Simulation period	1 January–31 December

Roof Configurations

A flat-roof geometry was used in all simulations. The base roof had a U-factor of 0.24 W/(m²·K) and consisted, from outside to inside, of a 4 mm bituminous membrane, 120 mm XPS insulation, 2 mm vapor-barrier membrane, 150 mm lightweight cast-concrete deck, and 15 mm gypsum plasterboard. The base case contained no PCM.

For the PCM cases, a 20 mm PCM layer was placed between the concrete deck and the gypsum plasterboard. PCM heat transfer was calculated using the finite-difference method with a fully implicit first-order scheme and the hysteresis model. The melting and freezing peaks were set 1 °C above and below each nominal transition temperature, respectively, with a 1 °C temperature difference on either side of each peak. Five PCMs, InfiniteRPCM21C, InfiniteRPCM23C, InfiniteRPCM25C, InfiniteRPCM27C, and InfiniteRPCM29C, with nominal transition temperatures of 21, 23, 25, 27, and 29 °C, respectively, were evaluated while all other model parameters remained unchanged. For each city, the PCM configuration with the lowest annual total thermal demand was selected for the combined PCM and cool-roof case. In this study, "optimal PCM" refers to the best-performing option among the five tested nominal transition temperatures.

For the cool-roof case, the roof geometry and construction were retained, and only the exterior surface properties were modified by applying a TiO_2–SiO_2 coating with a solar absorptance of 0.05 and thermal emittance of 0.91 (Benmoussa et al., 2023). The combined configuration incorporated

Table 2. Representative cities and weather-file locations

Zone	City	Latitude (°N)	Longitude (°E)	Elevation (m)
1	Mersin	36.78	34.60	3.0
2	Şanlıurfa	37.45	38.90	822.0
3	İstanbul	40.97	28.82	49.7
4	Ankara	39.97	32.86	891.0
5	Van	38.47	43.33	1670.3
6	Erzurum	39.95	41.19	1756.6

both the city-specific optimal 20 mm PCM layer and the cool-roof finish. The thermophysical and optical properties of the cool-roof coating are presented in Table 4.

The main thermophysical properties of the investigated PCMs are summarized in Table 5.

Table 6 summarizes the simulated roof configurations and their key modeling parameters.

Performance Indicators

Annual total thermal demand was calculated as the sum of annual heating and cooling demands:

$$Q_{total} = Q_{heating} + Q_{cooling}$$

The energy saving of each scenario relative to the base roof was calculated as:

$$S_i = 100 \times (Q_{base} - Q_i)/Q_{base}$$

where positive values indicate a reduction in annual thermal demand and negative values indicate an energy penalty.

For the combined PCM and cool-roof configuration, the interaction term was calculated as:

$$\Delta S_{int} = S_{PCM+CR} - (S_{PCM,\,opt} + S_{CR})$$

Positive values indicate a synergistic interaction, values close to zero indicate an approximately additive effect, and negative values indicate an antagonistic interaction.

RESULTS AND DISCUSSION

Sensitivity to PCM Melting Temperature

The annual heating, cooling, and total demands show a clear non-monotonic response to PCM melting temperature (Figure 2). The best temperature was 21 °C in Erzurum, 25 °C in Mersin, and 23 °C in Van, Ankara, İstanbul, and Şanlıurfa. These optima reduced annual total demand by 10.15%, 4.24%, 10.01%, 7.49%, 6.37%, and 7.23%, respectively. The result demonstrates that the warmest climate did not simply favor the highest tested transition temperature. Instead, useful performance depended on matching the PCM transition range to the roof's operating cycle.

Figure 3 shows that PCM performance strongly depended on the relationship between the melting temperature and the thermal conditions within the roof. Lower-temperature PCMs generally performed better in colder cities, where the temperature at the PCM layer was more likely

Table 3. Envelope constructions and calculated U-factors used in the simulations

Component	Applicable cities (TS 825 zone)	Construction / insulation	U-factor (W/(m²·K))
Flat roof	All six cities (Zones 1–6)	4 mm bituminous membrane, 120 mm XPS, 2 mm vapor barrier, 150 mm lightweight concrete, 15 mm gypsum plasterboard	0.24
External wall	Mersin (1)	20 mm cement plaster, 80 mm EPS, 200 mm concrete, 15 mm gypsum plaster	0.42
External wall	Şanlıurfa (2), İstanbul (3), Ankara (4)	20 mm cement plaster, 100 mm EPS, 200 mm concrete, 15 mm gypsum plaster	0.35
External wall	Van (5), Erzurum (6)	20 mm cement plaster, 150 mm EPS, 200 mm concrete, 15 mm gypsum plaster	0.24
Ground floor	Mersin (1), Şanlıurfa (2), İstanbul (3), Ankara (4)	30 mm floor finish, 40 mm lightweight concrete, 1.5 mm bituminous membrane, 100 mm XPS, 1 mm bituminous membrane, 75 mm lean concrete, 100 mm gravel fill	0.26
Ground floor	Van (5), Erzurum (6)	30 mm floor finish, 40 mm lightweight concrete, 1.5 mm bituminous membrane, 120 mm XPS, 1 mm bituminous membrane, 75 mm lean concrete, 100 mm gravel fill	0.22

Table 4. Properties of the TiO_2–SiO_2 cool-roof coating (Benmoussa et al., 2023)

Material	Thermal conductivity (W/(m·K))	Density (kg/m³)	Specific Heat (J/(kg·K))	Thermal emissivity	Solar absorptance	Solar reflectance
TiO_2–SiO_2 coating	4.80	3,970	683	0.91	0.05	0.956

Table 5. Thermophysical properties of the investigated PCM (Terhan & Ilgar, 2023)

Material	Nominal transition temperatures (°C)	Density (kg/m³)	Thermal conductivity, liquid/solid (W/(m·K))	Latent heat (kJ/kg)	Specific heat (J/(kg·K))
InfiniteRPCM	21, 23, 25, 27, 29	1,540	0.54/1.09	200	3,140

Table 6. Simulated roof configurations

Case	Roof modification	Key modeled variable
Base	Flat roof	U=0.241 W/(m²·K)
PCM21–PCM29	20 mm PCM between concrete and gypsum	Nominal melting temperature 21, 23, 25, 27, or 29 °C
CR	High-reflectance exterior coating	Solar absorptance 0.05, emittance 0.91
PCMopt + CR	City-specific optimal PCM plus coating	Both modifications applied

PCM: phase-change material; CR: cool roofs

to enter the 21–23 °C transition range and subsequently decrease below it, favoring repeated melting and solidification. Accordingly, PCM21 achieved the highest energy saving in Erzurum (10.15%), while PCM23 was optimal in Van (10.01%), Ankara (7.49%), İstanbul (6.37%), and Şanlıurfa (7.23%). In cooling-dominated Mersin, the optimum shifted to PCM25, although the resulting saving was lower (4.24%). This may be related to the relatively high roof insulation level and the cooling control strategy, which reduced the contribution of the PCM to the total building energy demand.

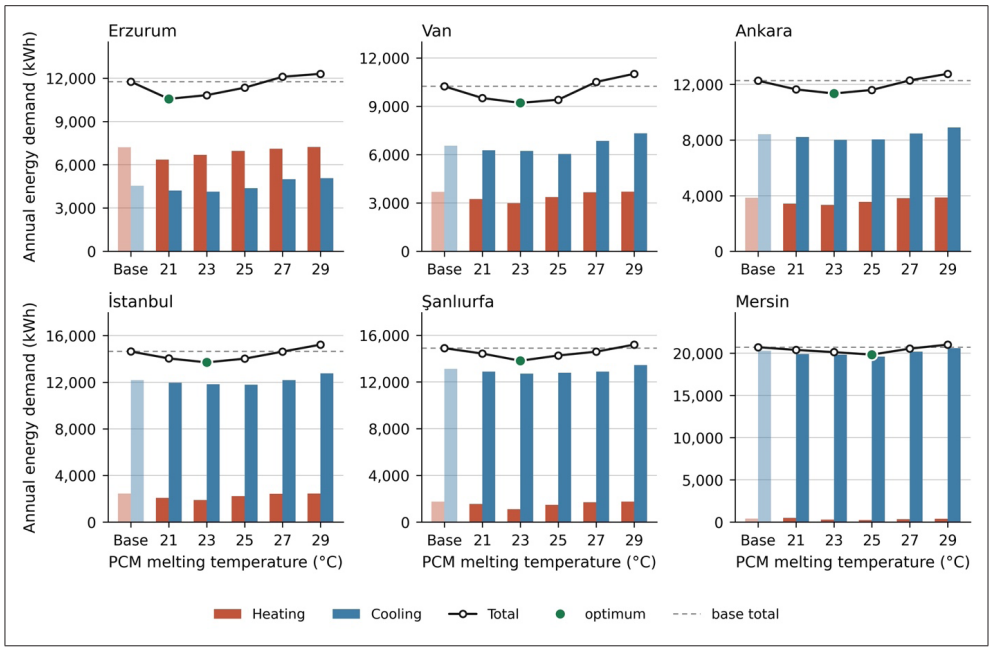

Figure 2. Annual heating, cooling, and total thermal demand for the base roof and the five PCM melting temperatures. Green markers identify the minimum-total-demand PCM in each city.

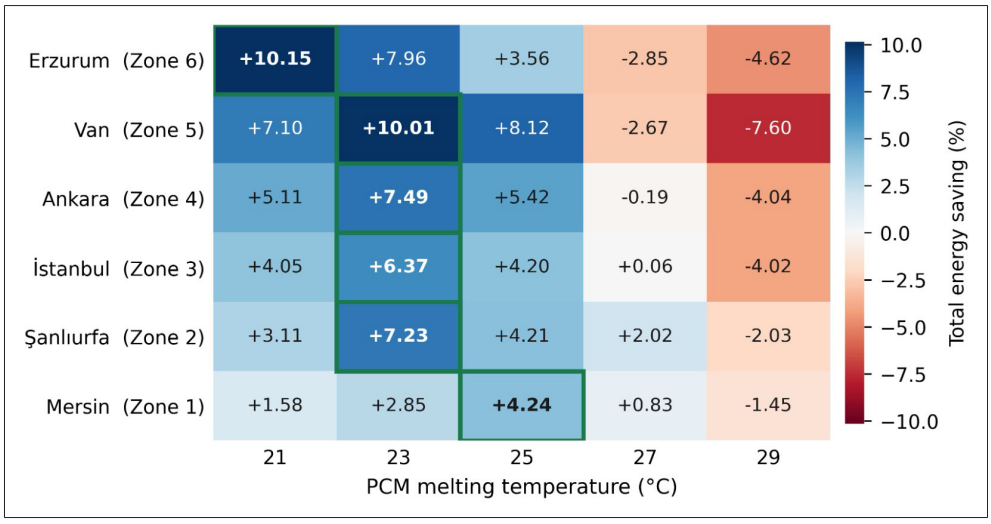

Figure 3. Total annual thermal-demand saving relative to the base roof for each PCM melting temperature. Green outlines identify the city-specific optimum, negative values denote an energy penalty.

In contrast, the effectiveness decreased as the melting temperature increased. PCM27 provided only limited benefits in Mersin, İstanbul, and Şanlıurfa and increased energy demand in Ankara, Van, and Erzurum. PCM29 increased total energy demand in all cities, with penalties ranging from 1.45% in Mersin to 7.60% in Van. A possible explanation is that the temperature at the PCM layer did not remain within the higher transition ranges sufficiently often to allow effective melting and solidification. Consequently, the latent heat storage capacity may have been only partially activated, while sensible heat storage and changes in heat-transfer timing could have reduced the overall benefit. These findings indicate that PCM selection should consider the annual thermal conditions at the PCM location and the balance between heating and cooling demand rather than relying solely on peak outdoor summer temperatures.

The climate-dependent optimum identified here is consistent with previous studies emphasizing that the phase-transition temperature must be matched to the PCM's operating conditions. For example, the transition temperature of an internal PCM layer should be selected according to the air-conditioning schedule and indoor thermal conditions (Tang et al., 2024). In contrast, a substantially higher transition temperature of 44 °C was selected for a PCM installed near the exterior roof surface in Seoul (Yang et al., 2019). This difference can be attributed to the different PCM locations and the thermal conditions experienced by the material. In the present study, the PCM was placed between the concrete deck and gypsum plasterboard, where its operating temperature was more closely influenced by indoor conditions. The poor performance of PCM27 and PCM29 therefore suggests that a higher transition temperature is not necessarily advantageous, even in warmer climates, if the PCM cannot complete effective melting and solidification cycles.

Optimal PCM, Cool Roof, and Combined Strategy

Table 7 compares the city-specific optimal PCM, cool-roof, and combined configurations. The optimal PCM produced annual thermal-demand savings in all six cities, whereas the cool roof created a trade-off between reduced cooling demand and increased heating demand. Consequently, the effectiveness of each strategy varied according to the local balance between heating and cooling requirements.

Table 7. Annual total thermal-demand savings relative to the base roof

City	Optimal PCM	PCM-saving (%)	CR-saving (%)	PCM + CR saving (%)	Lowest-demand strategy
Erzurum	21 °C	10.15	0.22	11.92	PCM + CR
Van	23 °C	10.01	3.44	6.33	PCM alone
Ankara	23 °C	7.49	4.14	11.53	PCM + CR
İstanbul	23 °C	6.37	2.76	9.55	PCM + CR
Şanlıurfa	23 °C	7.23	4.24	11.48	PCM + CR
Mersin	25 °C	4.24	5.86	8.00	PCM + CR

PCM: phase-change material; CR: cool roofs

The cool roof was most effective in cooling-dominated Mersin, where the cooling reduction clearly exceeded the associated heating penalty. Its net benefit was generally lower in colder climates. In Erzurum, for example, the cool roof increased heating demand by approximately 529 kWh while reducing cooling demand by approximately 555 kWh, resulting in a net annual saving of only 0.22%. This near balance illustrates why considering cooling demand alone can overestimate the annual effectiveness of a reflective roof in heating-dominated locations.

Figure 4 presents the corresponding annual heating and cooling demands in absolute terms. The combined strategy achieved the lowest total demand in five of the six cities. Van was the exception: the optimal PCM alone achieved a saving of 10.01%, compared with 6.33% for the combined configuration. Therefore, adding a reflective coating to a successful PCM roof does not necessarily provide an additional benefit, demonstrating the importance of evaluating the two measures as a coupled system.

A component-level comparison provides further insight into the performance of the three strategies. For the city-specific optimal PCM, both heating and cooling demand decrease in every city, although their relative contributions vary with climate. Heating reduction constitutes a substantial share of the benefit in colder locations, whereas cooling reduction becomes increasingly important in warmer climates (Figure 5a).

A different pattern is observed for the cool roof. Its high solar reflectance reduces absorbed solar radiation and lowers cooling demand in all cities. However, it also limits beneficial solar gains during the heating season, resulting in higher heating demand. The net annual benefit therefore depends on whether the cooling reduction is sufficient to compensate for the heating penalty (Figure 5b).

This heating and cooling trade-off is consistent with previous studies showing that reflective roof coatings can increase winter heating requirements despite providing substantial cooling-season benefits (Ascione et al., 2018). Conversely, considerable reductions in roof heat gain have been reported under tropical, cooling-dominated conditions (Yang et al., 2018). These contrasting findings support the present results: cool roofs provide their greatest annual benefit where cooling demand dominates, whereas their winter penalty can offset much of the cooling benefit in colder climates.

When the two measures are combined, the cooling reduction is greater than that achieved by either strategy individually in every city. Nevertheless, the reflective coating diminishes part of the heating benefit obtained with PCM alone and, in Van, causes heating demand to exceed the base-case value. The results indicate that the two technologies have complementary thermal functions, but their combined benefits are not necessarily additive and remain climate-dependent (Figure 5c).

Interaction Between PCM and Cool Roof

For the combined configuration, the interaction between the two measures was quantified. Because PCM and the cool-roof coating both act on the same roof heat flux, they

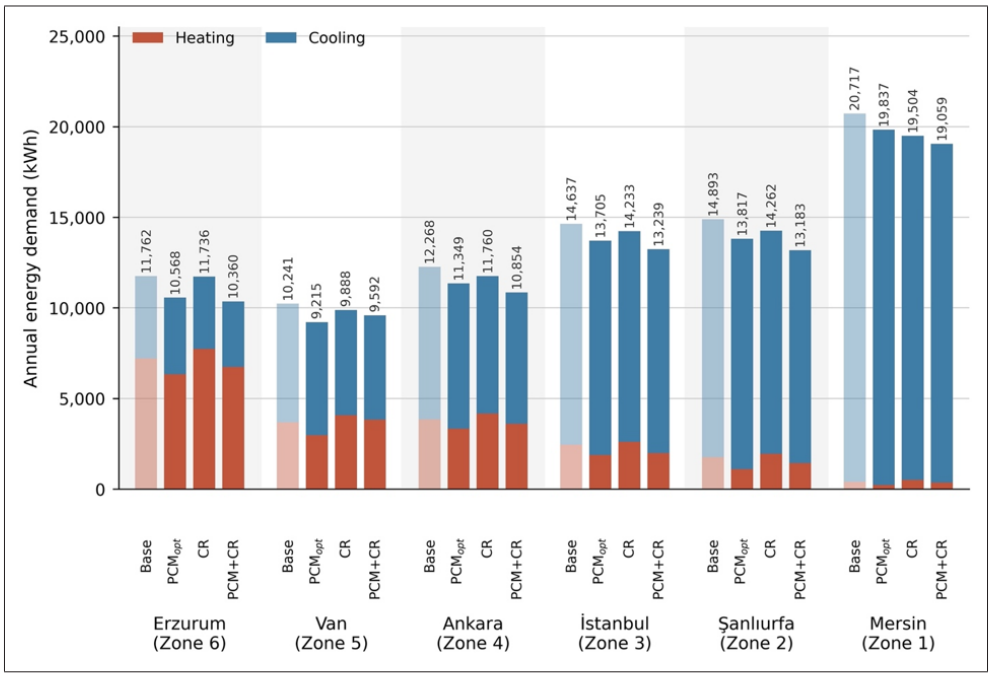

Figure 4. Annual heating and cooling demand for the base roof, city-specific optimal PCM, cool roof, and combined PCM–cool-roof cases. Labels show total annual thermal demand.

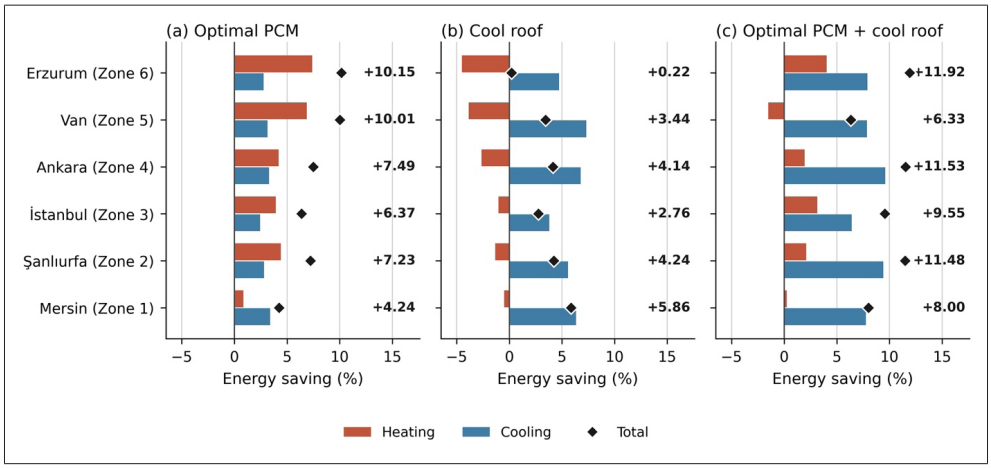

Figure 5. Contributions of heating and cooling to the annual thermal-demand savings achieved by **(a)** the optimal PCM, **(b)** the cool roof, and **(c)** the combined PCM and cool-roof system. The black diamonds show the total saving for each city.

interact with each other. Therefore, their individual savings cannot be simply added. This deviation from additivity was quantified as an interaction effect, calculated as:

$$\Delta S_{int} = S_{PCM+CR} - (S_{PCM,\,opt} + S_{CR})$$

where S_{PCM+CR} is the total annual saving of the combined PCM-and-cool-roof configuration, $S_{PCM,\,opt}$ is the saving achieved by the city-specific optimal PCM alone, and S_{CR} is the saving achieved by the cool-roof coating alone, each expressed in percent relative to the base roof of the same city, so that ΔS_{int} is reported in percentage points. Positive values indicate a synergistic interaction, values near zero indicate an additive effect, and negative values indicate an antagonistic interaction.

The interaction effect was calculated for each city (Figure 6). Erzurum showed a positive interaction of approximately +1.54 percentage points, while İstanbul and Şanlıurfa were nearly additive (+0.42 and +0.02 points). Ankara was also close to additive (−0.11 points). By contrast, Mersin (−2.10 points) and especially Van (−7.13 points) showed antagonistic interaction.

A plausible explanation is that the cool roof lowers the temperature amplitude at the PCM layer and thereby changes the frequency or completeness of melting and solidification. This interpretation is consistent with the direction of the results but cannot be confirmed from annual load totals alone. Direct analysis of PCM phase fraction, enthalpy, or layer temperature would be needed to establish the mechanism. For design purposes, the practical implication is already clear: the PCM should be re-optimized after the exterior optical properties are changed rather than assuming the independently optimal PCM remains optimal in the combined roof.

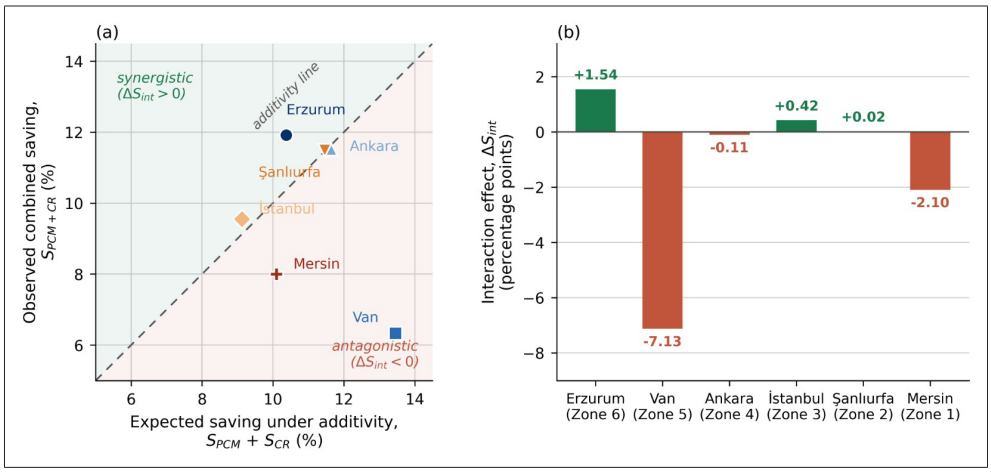

Figure 6. Interaction between the city-specific optimal PCM and cool roof. **(a)** Observed combined saving versus the sum of individual savings; points above the additivity line indicate synergy. **(b)** Interaction term ΔSint in percentage points.

Previous investigations of combined PCM and reflective-roof systems reported reductions in roof-surface temperature, indoor temperature, or cooling load under predominantly cooling-season conditions (Tang et al., 2024) (Yang et al., 2019). However, these studies did not quantify whether the annual benefit of the combined system equaled the sum of the benefits obtained from the individual measures. The present results extend this evidence by showing that the interaction may be synergistic, approximately additive, or antagonistic depending on climate. Therefore, cooling improvements observed over short monitoring periods should not automatically be interpreted as evidence of an additive annual energy benefit.

Implications for Climate-responsive Roof Design

The results support a climate-responsive roof selection procedure. A cool roof is attractive in cooling-dominated Mersin, whereas a lower-temperature PCM is more important in cold Erzurum. In the intermediate zones, a 23 °C PCM gave the best individual PCM result, but the value of adding the cool roof depended on the heating–cooling balance and interaction with the PCM. Reporting only cooling savings would therefore overstate annual benefits, particularly in heating-dominated locations. These results translate into practical, climate-zone specific guidance for architects specifying flat roof systems in Türkiye:

- Zone 1 (Mersin): The cool-roof coating alone achieved a saving of 5.86%, while the combined configuration increased the saving to 8.00%. Although the combined configuration produced the lowest thermal demand, its additional benefit over the cool roof alone was 2.14 percentage points.
- Zone 2 (Şanlıurfa) and Zone 4 (Ankara): PCM (23 °C) combined with the cool roof is recommended, with the two measures behaving near-additively (11.48% and 11.53% combined, respectively).
- Zone 3 (İstanbul): The combined strategy produced the lowest thermal demand and showed an approximately additive interaction, with a combined saving of 9.55%.
- Zone 5 (Van): PCM (23 °C) alone is recommended; adding cool-roof coating here is counterproductive, reducing realized savings from 10.01% to 6.33% due to an antagonistic interaction.
- Zone 6 (Erzurum): The combined strategy produced the lowest thermal demand, with a positive synergistic interaction and a combined saving of 11.92%.

These recommendations are intended as a starting point for schematic-design decision-making rather than a substitute for project specific simulation, and should be revisited when the roof construction, glazing ratio, or the occupancy pattern differs from the reference model described in Section 3.1.

Study Limitations

The study is comparative rather than a calibrated prediction of a specific occupied building. It uses ideal thermal loads, a single office geometry, one PCM thickness and position, and an initially clean high-reflectance surface. Aging, moisture, cost, embodied impacts, equipment efficiencies, demand peaks, and PCM state variables were outside the present scope. These limitations should be addressed before translating thermal-demand savings directly into operational energy, emissions, or economic savings.

CONCLUSION

The study demonstrated that PCM melting temperature and cool-roof application are climate dependent choices rather than fixed specifications. The evaluations were performed across six selected cities from Türkiye's six TS 825 climate zones and the results have revealed significant differences. The optimal PCM melting temperature ranged from 21 °C in Erzurum to 25 °C in Mersin, with 23 °C optimal in the four intermediate zones, and reduced annual heating plus cooling demand by 4.24-10.15%. A poorly matching 29 °C PCM produced an energy penalty in every city, underscoring that melting temperature must be carefully selected according to climate rather than assumed.

The cool-roof coating consistently reduced cooling demand but increased heating demand, so its net annual benefit was far more climate-dependent than a cooling-season assessment alone would suggest. Its annual saving ranged from 0.22% in Erzurum to 5.86% in Mersin. Combining PCM with the cool roof achieved the lowest overall demand in five of the six cities, with savings of up to 11.92%. Van is the only city where the combined system underperformed the PCM-only case, confirming that the two measures cannot be assumed additive and must instead be evaluated, and where necessary re-optimized as a coupled system.

These findings support a climate-responsive approach to roof design in Türkiye, in which PCM melting temperature and cool-roof applications are evaluated together for each climate zone rather than applied as a single national specification. Future work should examine PCM phase fraction and layer temperatures, optimize the PCM within the combined roof, assess peak-load and comfort effects, and include coating aging, system efficiency, life-cycle cost, and embodied impacts.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

REFERENCES

Arıcı, M., Bilgin, F., Nižetić, S., & Karabay, H. (2020). PCM integrated to external building walls: An optimization study on maximum activation of latent heat. *Applied Thermal Engineering*, 165, 114560. https://doi.org/10.1016/j.applthermaleng.2019.114560

Ascione, F., De Masi, R. F., Santamouris, M., Ruggiero, S., & Vanoli, G. P. (2018). Experimental and numerical evaluations on the energy penalty of reflective roofs during the heating season for Mediterranean climate. *Energy*, 144, 178–199. https://doi.org/10.1016/j.energy.2017.12.018

Azadani, H. N., & Ardekani, A. (2025). Effect of applying phase change materials (PCM) in building facades on reducing energy consumption. *Next Energy*, 6, 100210. https://doi.org/10.1016/j.nxener.2024.100210

Azimi, M., Mahdavinejad, M., & Yeganeh, M. (2025). Economic optimization of PCM use for enhanced energy efficiency in passive buildings: A case study in Egypt. *Solar Energy*, 300, 113876. https://doi.org/10.1016/j.solener.2025.113876

Basyouni, Y. A., & Mahmoud, H. (2024). Affordable green materials for developed cool roof applications: A review. *Renewable and Sustainable Energy Reviews,* 202, 114722. https://doi.org/10.1016/j.rser.2024.114722

Benmoussa, Y., Ezziani, M., Djire, A.-F., Amine, Z., Khaldoun, A., & Limami, H. (2023). Simulation of an energy-efficient cool roof with cellulose-based daytime radiative cooling material. Materials Today: Proceedings, 72, 3632–3637. https://doi.org/10.1016/j.matpr.2022.08.411

DesignBuilder Software Ltd. (n.d.). *DesignBuilder* (Version 7.3.0.040) [Computer software]. https://designbuilder.co.uk/

Faraj, K., Khaled, M., Faraj, J., Hachem, F., & Castelain, C. (2021). A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. *Journal of Energy Storage*, 33, 101913. https://doi.org/10.1016/j.est.2020.101913

Kim, H. G., Kim, Y.-S., Kwac, L. K., Park, M., & Shin, H. K. (2020). Role of phase change materials containing carbonized rice husks on the roof-surface and indoor temperatures for cool roof system application. *Molecules*, 25(14).

Kolokotsa, D., Diakaki, C., Papantoniou, S., & Vlissidis, A. (2012). Numerical and experimental analysis of cool roofs application on a laboratory building in Iraklion, Crete, Greece. *Energy and Buildings*, 55, 85–93. https://doi.org/10.1016/j.enbuild.2011.09.011

Lawrie, L. K., & Crawley, D. B. (2026). Development of global typical meteorological years (TMYx). https://climate.onebuilding.org

Li, W., Rahim, M., Wu, D., El Ganaoui, M., & Bennacer, R. (2024). Experimental study of dynamic PCM integration in building walls for enhanced thermal performance in summer conditions. *Renewable Energy*, 237, 121891. https://doi.org/10.1016/j.renene.2024.121891

Rathore, P. K. S., Gupta, N. K., Yadav, D., Shukla, S. K., & Kaul, S. (2022). Thermal performance of the building envelope integrated with phase change material for thermal energy storage: An updated review. *Sustainable Cities and Society*, 79, 103690. https://doi.org/10.1016/j.scs.2022.103690

Rawat, M., Singh, D., & Buddhi, D. (2022). Thermal performance of cool roofs incorporated with phase change materials: A review. Materials Today: Proceedings, 69, 392–400. https://doi.org/10.1016/j.matpr.2022.09.066

Rincón, L., Gangolells, M., Medrano, M., & Casals, M. (2024). Climate change mitigation and adaptation in Spanish office stock through cool roofs. *Energy and Buildings*, 323, 114738. https://doi.org/10.1016/j.enbuild.2024.114738

Saber, H. H. (2021). Experimental characterization of reflective coating material for cool roofs in hot, humid and dusty climate. Energy and Buildings, 242, 110993. https://doi.org/10.1016/j.enbuild.2021.110993

Tang, H., Chen, W., Lyu, Y., Liu, W., Li, C., & Li, C. (2024). Experimental study of a novel radiative cooling-dual phase change material roof under hot summer and warm winter climate. *Journal of Building Engineering*, 95, 110309. https://doi.org/10.1016/j.jobe.2024.110309

Terhan, M., & Ilgar, G. (2023). Investigation of used PCM-integrated into building exterior walls for energy savings and optimization of PCM melting temperatures. Construction and Building Materials, 369, 130601. https://doi.org/10.1016/j.conbuildmat.2023.130601

Tokuç, A., Yesügey, S. C., & Başaran, T. (2017). An evaluation methodology proposal for building envelopes containing phase change materials: The case of a flat roof in Turkey's climate zones. *Architectural Science Review*, 60(5), 408–423. https://doi.org/10.1080/00038628.2017.1343179

TSE. (2024). *Thermal insulation requirements for buildings* (TS 825:2024). Turkish Standards Institution (TSE).

Tunçbilek, E., Arıcı, M., Bouadila, S., & Wonorahardjo, S. (2020). Seasonal and annual performance analysis of PCM-integrated building brick under the climatic conditions of Marmara region. *Journal of Thermal Analysis and Calorimetry*, 141(1), 613–624. https://doi.org/10.1007/s10973-020-09320-8

U.S. Department of Energy. (n.d.). *EnergyPlus* (Version 9.4.0) [Computer software]. https://energyplus.net/

Yang, J., Mohan Kumar, D. l., Pyrgou, A., Chong, A., Santamouris, M., Kolokotsa, D., & Lee, S. E. (2018). Green and cool roofs' urban heat island mitigation potential in tropical climate. *Solar Energy*, 173, 597–609. https://doi.org/10.1016/j.solener.2018.08.006

Yang, Y. K., Kim, M. Y., Chung, M. H., & Park, J. C. (2019). PCM cool roof systems for mitigating urban heat island – An experimental and numerical analysis. *Energy and Buildings*, 205, 109537. https://doi.org/10.1016/j.enbuild.2019.109537

Yazdani, H., & Baneshi, M. (2021). Building energy comparison for dynamic cool roofs and green roofs under various climates. *Solar Energy*, 230, 764–778. https://doi.org/10.1016/j.solener.2021.10.076