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A Systematic Analysis of Phase Change Material and Optically Advanced Roof Coatings Integration for Athenian Climatic Conditions

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Abstract: Energy retrofit solutions that concern a building's roof structure play a significant role in the enhancement of a building's thermal behaviour. This study investigates the integration of phase change materials (PCMs) with cool coatings (CCs) or thermochromic coatings (TCCs), namely, a PCM roof, a PCM-CC roof, and a PCM-TCC roof, as alternative and novel tactics for the simultaneous control of solar heat transfer and solar heat reflection. An energy simulation analysis with the DesignBuilder tool is conducted for a one-story residence and the climatic conditions of Athens. The simulation results indicate that, compared to the existing concrete roof construction, the PCM roof, PCM-CC, and PCM-TCC roof systems demonstrate energy savings that reach up to 13.55%, 16.04%, and 21.70%, respectively. The systematic analysis reveals that the increase in PCM's thickness leads to an increase in the total electricity savings of the buildings, but in the case of PCM-CC and PCM-TCC roof systems, they merely effect the cooling thermal loads. The mean phase transition temperature that favours the cumulative electricity savings is 28 °C in the case of PCM and PCM-TCC roof systems and 35 °C in the case of PCM-CC roof systems. The methodology of this study allows the design of efficient, integrated roof systems with advanced thermal and optical properties as energy retrofit solutions for Mediterranean climatic conditions.

Keywords: thermochromic; phase change material; latent storage; energy savings; retrofitting

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1. Introduction

Climate change and rapid global warming pose energy efficiency as an imperative need in the building sector. Predictions about future weather conditions indisputably agree that the global surface temperature will increase by 1.5 °C and 2.0 °C during the 21st century unless radical reductions in emissions of CO_2 and other greenhouse gases take place in the coming decades [1]. Numerous researchers have studied buildings' thermal performance when subjected to predicted future weather conditions to evaluate the impact of renovation interventions on the building's energy equilibrium. Pérez-Andreu et al. [2], for instance, focused on the Mediterranean climate change conditions and concluded that for every examined scenario, the future energy demand for heating will decrease, whereas, for cooling, it will increase. Pajek and Košir [3] confirmed that for locations characterized by warmer climates, like the Mediterranean basin, the cumulative thermal loads of a building will rise, as opposed to other locations with colder climates in which a building's thermal needs will be mitigated. In this alignment, Zhai and Helman [4], as well as Ciancio et al. [5] predicted, that the increment in a building's cooling demand will not be counterbalanced by the decrease in its heating demand, leading to an overall increase in global energy use.

Therefore, energy efficiency interventions that first focus on shielding the building against adverse summer conditions should be prioritized for cities with warmer climates.

An effective strategy to restrict a residential building's cooling loads is to enhance the thermal and optical properties of its roofing system [6]. Solar heat gains stemming from the roof's exposure to high-intensity solar irradiation account for a significant part of the building's cooling thermal loads [7]. According to the most recent report of the Hellenic Statistical Authority for the period 2011–2021 [8], the most energy-consuming type of building is the single-family house, with a mean primary energy consumption of 502.3 kWh/m^2. For the city of Athens and the wider region of Attica, single-family houses represent 18% of the city's households. More than half of these households, specifically 56%, were built before 1980, and therefore, no energy efficiency measures were applied at the time of the construction. According to the available statistical analysis data retrieved from the energy performance certificates, only 2.9% of the country's single-family houses have undergone energy efficiency renovations. Consequently, a properly structured renovation strategy for family houses with roofs should inarguably include the renovation of their existing roofing system.

Except for reinforcing the thermal resistance of a building's core, the utilization of high thermal mass materials is also indicated as an energy efficiency tactic [9]. The integration of phase change materials (PCMs) into the building's envelope as a passive energy efficiency system [10] can improve a building's thermal inertia [11], acting as a heat transfer modulator between the living space of a building and the ambient [12]. These materials present high heat capacity storage due to their latent heat storage mechanism in small temperature intervals, absorbing sensible heat in almost isothermal processes [11]. Additionally, Beemkumar et al. [13] and Pasupathy et al. [14] observed that the incorporation of PCM on a building's roof regulates the fluctuation of the room's temperature, restricting the mean peak indoor temperature by 1–2 °C and therefore enhancing the thermal comfort conditions. The PCM parameters, namely, thickness, latent heat, location on the building envelope, and phase change transition temperature range, should be properly adapted to a location's climatic characteristics to achieve optimal energy savings [15]. More specifically, Hamza et al. [16] focused their study on air-conditioned residences and concluded that the application of the PCM layer on the building's roof induces the maximum possible energy savings. Moreover, Jayalath et al. [17] concluded that a PCM roof layer with a mean transition temperature of 23 °C can lead to a 39% reduction in energy consumption for cooling and a 12% reduction in energy consumption for heating for a one-story residential building in Melbourne. Regarding various areas with a Mediterranean climate, Dardouri et al. [18] calculated that the modulation of the PCM layer on the roof has an immediate effect on the building's thermal loads, leading to a cumulative energy reduction in the range of 8% to 31.5%.

White, highly reflective, artificial roof coatings are a commercial [19] and widely tested solution for the mitigation of the building's sector cooling loads [20], especially for areas suffering from extreme heat waves [21]. Cool materials are defined by high solar reflectivity, higher than 70% [22], and high infrared emittance, higher than 75% [22], and therefore by a lower surface temperature compared to traditional materials when exposed to solar irradiation, abating the solar heat penetration to the interior [23]. Despite their high initial optical properties, artificial cool materials are prone to optical ageing, namely, diminishing solar reflectivity [24]. According to laboratory testing of white paints used as cool roofing coatings conducted by Antonaia et al. [25], acrylic paints display the best performance against photo-degradation. Despite their efficiency on a seasonal level, cool roof coatings may lead to an increase in energy demand during the heating period [26]. To counterbalance this drawback, cool materials and PCMs can be used as complementary retrofit techniques, negating the increase in heating demand and contributing to the building's cooling performance [27]. Triano-Juárez et al. [28] examined the installation of a PCM roof on a building in Mexico, with and without the application of reflective paint. The results indicated a 22% reduction in the cooling thermal load for the PCM roof with a non-reflective, grey coating and a minimum reduction of 58% for the PCM roof with the reflective coating. Lei et al. [27] calculated for the city of Singapore that the combination of PCM and a cool roof leads to 8.5% yearly energy savings, whereas the PCM roof leads to 1.4%. Similarly, Xu et al. [29] proved the superiority of the PCM roof with a cool coating to the cool roof in terms of yearly energy consumption for thermal loads, explaining that as heating demand increases, the advantages of the cool roof coating reduce, whereas the efficiency of PCM is strengthened.

Thermochromic coatings (TCC) are thermally adaptive materials that reversibly alter their optical properties as a function of the surface temperature [23]. The commercially available category of thermochromic materials is leuco dye-based thermochromic materials, which, however, are susceptible to photo-degradation [30]. The integration of PCMs with TCC allows synergy between the dynamic properties of the two technologies, allowing a balanced management of a building's heating and cooling demands [31]. Hu and Yu [32] studied a TCC roofing system, including an external PCM layer, and calculated that the total energy savings can reach up to 29% for various climatic zones of China. In another study for multiple cities in China, they examined three different roofing systems, namely, a thermochromic roof, a roof with a PCM external layer, and a thermochromic roof with a PCM external layer [33]. The yearly energy reduction can reach up to 13%, 15%, and 17%, respectively, with better performance for locations with a mild climate. Finally, Ji and Li [34] compared a PCM roof and a PCM with a TCC roof for the city of Shanghai, a city defined by both heating and cooling needs. They calculated that the PCM with a TCC roof outperformed the PCM roof by 39% in terms of yearly energy savings as well as in terms of performance of the phase change cycle of the PCM.

In this study, the application of a PCM roof, as well as the combination of a PCM roof with a cool coating or a thermochromic coating, is examined for a typical one-story residential building and the Mediterranean climatic conditions of Athens. The building energy simulation is conducted in DesignBuilder software [35] and aims to investigate the impact of the PCM roof on the building's thermal loads in a location with hot summers and cool winters. Four different commercially available PCMs are simulated, with mean phase transition temperatures between 15 °C and 35 °C and a variable PCM layer thickness between 2 cm and 6 cm. The integration of PCM with optically innovative materials is considered an alternative and novel solution for the improvement of a building's thermal response. Also, this study enriches the limited literature as far as the applications of PCM with TCCs are concerned [34] and examines the application of cool coatings (CCs) as a perennially appropriate retrofit solution. Therefore, the scope of this study is to systematically evaluate the synergy between PCM, CC, and TCC solutions, something that is missing from the current literature and can lead to significant energy savings. More specifically, a commercially available acrylic white paint with a high reflectivity index equal to 0.86 is used as a cool roof coating, whereas a thermochromic paint with a mean transition temperature of 34 °C and a variable reflectivity index of 0.42 and 0.72 is used as a thermochromic coating. The energy efficiency interventions on the building's roof are thoroughly investigated and compared, as far as their energy savings potential is concerned.

2. Material and Methods

In this section, the basic geometrical and thermophysical data of the building's envelope and the properties of the commercially available products of PCM, acrylic cool paint, and thermochromic paint will be discussed. Additionally, the simulation method of the examined retrofit technologies and the parameters of the sensitivity analysis of the study, conducted in the DesignBuilder software, will be analytically described.

2.1. Description of the Building

The examined building is a typical one-story, air-conditioned family house located in the city of Athens [36]. It is characterized by a gross area of 120 m^2, a concrete, externally insulated flat roof with a thermal transmittance value of 0.7 W/m^{2}K, brick walls with an intermediate layer of thermal insulation and a thermal transmittance value of 0.4 W/m^{2}K, and a concrete, thermally insulated ground floor of 0.7 W/m^{2}K. The window-to-wall ratio is equal to 13.25%, and the window's total thermal transmittance value and solar heat gain coefficient are equal to 2.5 W/m^{2}K and 0.636, respectively. The entire building envelope is painted with a typical non-reflective coating, with a reflectivity index of 0.6 and an emittance index of 0.8. The temperature setpoint is set at 20 °C for the winter period and at 26 °C for the summer period. The residence is equipped with split units of air-to-air heat pumps, which are characterized by a seasonal coefficient of performance of 4.0 and 4.5 for the heating and cooling seasons, respectively. More information about the examined building can be found in References [36,37], whereas Table 1 summarizes the building's main geometrical, thermal, and operational parameters.

Table 1. Geometrical, thermal, and operational data of the examined building.

Parameters	Values
Gross area [m^2]	120
Internal height [m]	2.85
U-value of external walls [W/(m^{2}K)]	0.4
U-value of roof slab [W/(m^{2}K)]	0.7
U-value of ground slab [W/(m^{2}K)]	0.7
Window-to-wall ratio [%]	13.25
Total U-value of windows	2.5
Solar heat gain coefficient of windows	0.636
Heating temperature setpoint [°C]	20
Cooling temperature setpoint [°C]	26
Number of occupants	4
Thermal load of the occupants [W/occupant]	80
Mean operating fraction of the occupants [%]	75
Specific lighting electrical load (per net area) [W/m^2]	5
Mean operating fraction of the lighting [%]	75
Specific appliances' electrical load (per net area) [W/m^2]	4
Mean operating fraction of the appliances [%]	75
Infiltration rate [ACH]	0.4
Natural ventilation [ACH]	0.4

2.2. Reference Scenarios for the Study

The existing state of the building, described in the previous section, is referred to as baseline scenario 1 of the present analysis. Baseline scenario 1 is the reference scenario against which every energy efficiency renovation technique is compared. Additionally, two secondary baseline scenarios are defined. First, baseline scenario 2 is the scenario where only the CC is applied on the building's roof. Every configuration of the PCM-CC roof system is compared with the baseline scenario and baseline scenario 2. Second, baseline scenario 3 is the scenario where only the TCC is applied to the building's roof. Similarly, every configuration of the PCM-TCC roof system is compared with both baseline scenario and baseline scenario 3.

2.3. Simulation Strategy

The building energy simulation model of the present study has been developed in the DesignBuilder software, and its thermal analysis outputs are validated in the study with ref. [36]. In this study, the finite difference solution algorithm, and specifically the fully implicit first-order finite difference scheme, in combination with the phase change method of hysteresis [38], was used for the solution of the phase change process of the investigated PCMs. The phase change method of hysteresis requires six parameters for the description of each of the solid and liquid states of the material. More specifically, the thermal conductivity, density, and heat capacity are needed to describe the solid and liquid states, whereas the melting and freezing curve of the phase change process of the material is determined by the high- and low-temperature differences of the melting or freezing curve and the peak melting or freezing temperature. The space discretization factor was chosen at 0.5 [38] and the timestep of the simulation at 5 min, namely, 12 timesteps per hour. The five commercially available PCMs from Rubitherm Technologies GmbH (Berlin, Germany) [39], with mean phase transition temperatures in the range of 15 °C to 35 °C, are summarized in Table 2.

Table 2. Properties of the phase change materials.

Parameter	RT15	RT22	RT28	RT35
Phase change area [°C]	10–17	20–23	27–29	32–38
Peak melting temperature [°C]	14	22	28	35
Peak freezing temperature [°C]	16	22	27	35
Thermal conductivity in both states [W/(m·K)]	0.2	0.2	0.2	0.2
Specific heat capacity [kJ/(kg·K)]	2	2	2	2
Heat storage capacity [kJ/kg]	155	190	250	160
Density of the solid state [kg/L]	0.88	0.76	0.88	0.86
Density of the liquid state [kg/L]	0.77	0.7	0.77	0.77

For the entire study, each PCM is installed externally on the building's roof with a variable thickness that ranges from 2 cm to 6 cm, and for the first part of the present study, the PCMs are covered with the reference coating of baseline scenario 1. Furthermore, for the second part of the study, the examined PCM's are covered with a cool coating (PCM-CC system). The selected cool coating is an acrylic white paint [40], with an initial solar reflectivity index of 0.86 and an emittance factor of 0.88. In the third part of the study, the integration of PCM with a thermochromic coating (PCM-TCC system) is investigated. The selected TC is characterized by a low reflectivity index of 0.42 and a high reflectivity index of 0.72 [41]. Its mean transition temperature is equal to 34 °C, and its transition temperature range is equal to 4 °C. In Table 3, the optical properties of all the examined coatings are given.

Table 3. Optical properties of the examined coatings.

	Parameter	Value
Reference coating	Reflectivity	0.6
	Emittance	0.8
Cool coating	Reflectivity	0.86
	Emittance	0.88
Thermochromic coating	Reflectivity—coloured state	0.42
	Reflectivity—white colour state	0.72
	Emittance	0.80

The reversible colour transition process of the thermochromic coating is modelled as a linear function of the coating's surface temperature and is analytically described in the Energy Simulation Manager extension of the DesignBuilder software in the form of a script. More specifically, the reflectivity value of the TC is dynamically adjusted at each timestep of the simulation according to the external surface temperature of the building's roof.

2.4. Climatic Conditions

The present study is conducted for the city of Athens [37°58′54′′ N, 23°43′51′′ E], a city located in the Mediterranean basin, characterized by hot, dry summers and cool, humid winters. The Mediterranean area has been recognized as a high-risk area for heat extremes with increased frequency [42]. According to the DesignBuilder weather library [43], the mean annual temperature is 17.9 °C, and the yearly fluctuation is between 2.1 °C and

37.0 °C. The heating degree days with a base temperature of 20 °C are equal to 1041, while the cooling degree days with a base temperature of 26 °C are equal to 588 [44]. In Figure 1, the daily statistics of the location's dry-bulb temperature and solar irradiation are illustrated.

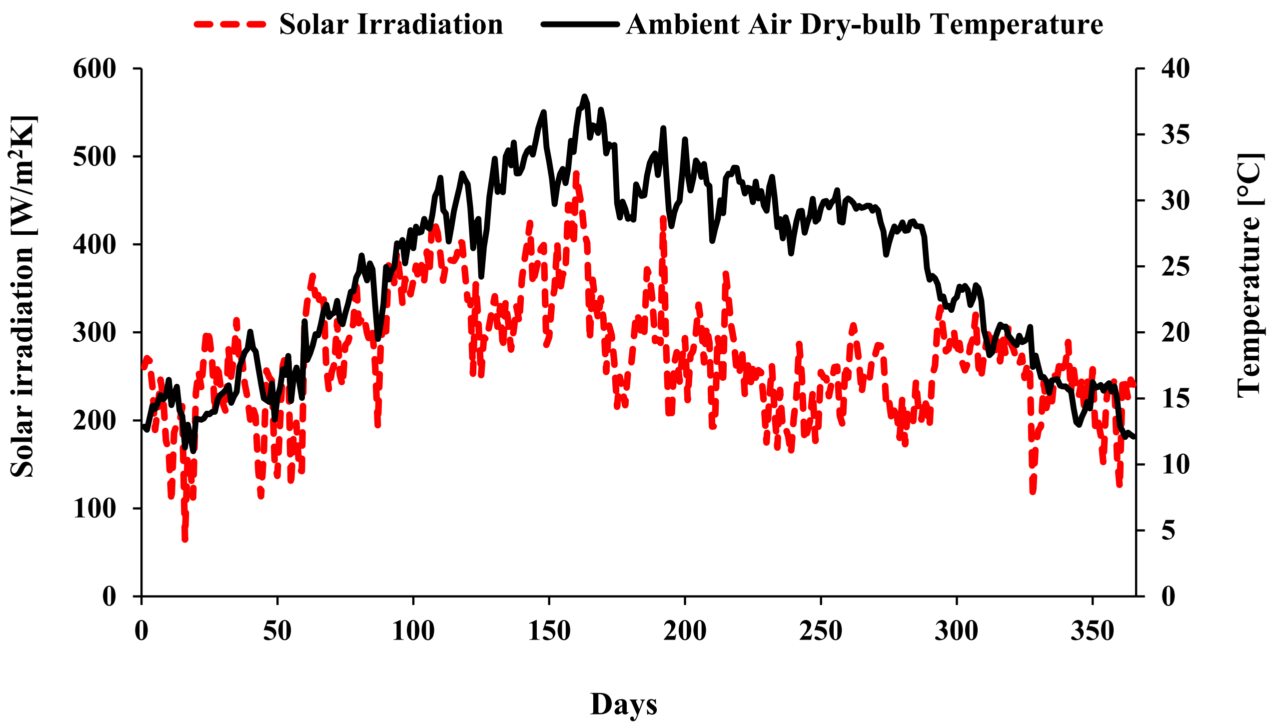


Figure 1. Daily statistics for the ambient air dry-bulb temperature and solar irradiation for Athens, Greece.

2.5. Basic Mathematical Formulation

The reflectivity (ρ) value of the TCC is altered according to an external thermal stimulus. When the coating is in its coloured state, it is characterized by a low reflectivity index (ρ_1), which is gradually increasing with the increase in the coating's temperature. Ultimately, in its colourless state (white), the thermochromic coating is characterized by a high reflectivity index (ρ_2). During the temperature transition interval, the reflectivity is simulated as a linear function of the temperature of the roof's external surface (T_{surf}), which is a reasonable assumption based on the literature studies with Refs. [45,46]. The reflectivity variation is described in Equation (1):

$$\rho = \begin{cases} \rho_1, & T_{surf} \le T_1 \\ \rho_1 + (\rho_2 - \rho_1) \cdot \frac{T_{surf} - T_1}{T_2 - T_1}, & T_1 < T_{surf} \le T_2 \\ \rho_2, & T_{surf} > T_2 \end{cases} \tag{1}$$

The examined building is equipped with reversible air-to-air heat pump split units. The coefficient of performance (*COP*) of the heat pump's heating operation is calculated as the fraction of the heat pump's instantaneous heating thermal production to electricity consumption:

$$COP = \frac{Q_{heat}}{P_{el_{heat}}} \tag{2}$$

The energy efficiency ratio (*EER*) of the heat pump's cooling operation is calculated as the fraction of the heat pump's instantaneous cooling thermal production to electricity consumption:

$$EER = \frac{Q_{cool}}{P_{el_{cool}}} \tag{3}$$

The seasonal coefficient of performance (*SCOP*) and seasonal energy efficiency ratio (*SEER*) are calculated by using the yearly energy loads.

$$SCOP = \frac{E_{heat}}{E_{el_{heat}}} \tag{4}$$

$$SEER = \frac{E_{cool}}{E_{el_{cool}}} \tag{5}$$

The heat balance on the inside face of the building's construction can be written as follows:

$$q''_{LWX} + q''_{SW} + q''_{LWE} + q''_{cond} + q''_{sol} + q''_{con} = 0 \tag{6}$$

where q''_{LWX} denotes the net longwave radiant exchange flux between surfaces in a zone, q''_{SW} stands for the net short-wave radiation flux to the surface from the lighting system, q''_{LWE} denotes the longwave radiation flux from equipment in the zone, q''_{cond} represents the conduction flux through the wall, q''_{sol} stands for the transmitted solar radiation flux absorbed at the surface, and q''_{con} denotes the convective heat flux to the air zone.

The heat balance on the outside face of the building's construction is:

$$q''_{asol} + q''_{LWR} + q''_{con} - q''_{cond} = 0 \tag{7}$$

where q''_{asol} represents the absorbed direct and diffuse solar (short wavelength) radiation heat flux, q''_{LWR} is the net long wavelength (thermal) radiation flux exchange with the ambient, q''_{con} is the convective flux exchange with the ambient, and q''_{cond} is the conduction heat flux per area into the wall.

The total heating energy load and electricity consumption of the building are calculated as follows:

$$E_{heat} = \int Q_{heat}\, dt \tag{8}$$

$$E_{el_{heat}} = \int P_{el_{heat}}\, dt \tag{9}$$

The total cooling energy load and electricity consumption of the building are calculated as follows:

$$E_{cool} = \int Q_{cool}\, dt \tag{10}$$

$$E_{el_{cool}} = \int P_{el_{cool}}\, dt \tag{11}$$

The building's total electricity consumption is calculated with the addition of the building's electricity consumption during the heating and cooling periods.

$$E_{el} = E_{el_{heat}} + E_{el_{cool}} \tag{12}$$

3. Results

The effect of the three examined roof systems, namely, the PCM system, the PCM-CC system, and the PCM-TCC system, on the building's thermal behaviour is analytically discussed in the present section. Each system is compared with baseline scenario 1, for which the thermal energy loads of the building are calculated at 37.69 kWh/m^2 for the heating period and 41.71 kWh/m^2 for the cooling period, while the yearly electricity consumption for heating and cooling is calculated at 18.69 kWh/m^2 [36].

3.1. Thermal Energy Load Reduction by the PCM Roof System

The application of PCM on the roof's external surface enhances the building's envelope thermal resistance and thermal mass, resulting in a decrease in the heating energy load for every examined PCM roof system. The thermal conductivity value of the four studied

PCMs is equal to 0.2 W/mK, and therefore the thermal transmittance value of the roof is modified uniformly for every PCM with the variation of the PCM's thickness. First, according to Figure 2a, the PCM with a mean transition temperature of 22 °C leads to the highest reduction of the energy demand for heating, for every examined thickness. For the specific PCM, the phase change process is triggered at a temperature level (20–23 °C) close to the building's heating setpoint of 20 °C. The specific heating energy load savings for the RT22 are calculated at 2.57 kWh/m^2 for a thickness of 2 cm, which corresponds to a 6.81% reduction, and reach up to 5.68 kWh/m^2 for a thickness of 6 cm, namely, a 15.07% decrease in the building's heating loads. On the other hand, the PCM with a mean transition temperature of 15 °C presents the poorest performance in restricting the building's heating demand, leading to heating load energy savings in the range of 3.56–8.78%. For this material, the phase transition process is realized between 10 and 17 °C, a temperature range lower than the building's desired indoor temperature, and therefore the PCM's thermal properties are not properly exploited.

Furthermore, as far as the building's thermal performance during the cooling period is concerned, Figure 2b illustrates the cooling load energy savings achieved for every examined PCM. The PCM with a mean transition temperature of 28 °C demonstrates the most efficient performance, resulting in energy load savings of 2.59 kWh/m^2 or a reduction of 6.21% for a 2 cm thickness and energy load savings of up to 5.83 kWh/m^2 or a reduction of 13.98% for a 4 cm thickness. The maximum energy savings for cooling are achieved for the thickness value of 4 cm instead of the thickness value of 6 cm as it occurs for the heating thermal loads. This can be explained by the fact that the extensive increase in the PCM's thickness can result in an extensive increase in the roof's total thermal resistance value and thermal capacity, and therefore, during nighttime, when the ambient temperature is decreased and solar heat gains are eliminated, the building's procedure of dissipating heat to the ambient is decelerated. The phase transition process for this PCM occurs within the temperature range of 27 °C to 29 °C which is closer to the cooling temperature setpoint of 26 °C compared with the other investigated PCMs. For RT22 and RT35, the building's cooling energy loads are increased with smaller thickness values, while RT15 is calculated to consistently improve the building's thermal.

For the selection of the optimal combination of PCM material and thickness, Figure 2c summarizes the yearly electricity savings of each examined configuration. RT28 is the most efficient in reducing the building's total energy consumption for heating and cooling at the examined thickness. This is justified by the fact that for the examined building, the use of PCM proved to be more efficient in abating the cooling thermal loads, which, for the baseline scenario, are calculated to outweigh the building's heating loads. More specifically, the specific electricity savings amount to 1.06 kWh/m^2, which is equal to a reduction of 5.65% for a 2 cm thickness, and the specific electricity savings amount to 2.53 kWh/m^2 or a reduction of 13.55% for a 6 cm thickness, representing the highest energy savings achieved.

3.2. Thermal Energy Load Reduction by the PCM-CC Roof System

In the second section of the present study, the PCM-CC system is examined as an energy efficiency solution. For a detailed investigation of each technology's effect on the building's thermal loads, the results of the integration of the PCM-CC roof system are compared to baseline scenario 1, as well as to the scenario in which only the cool roof coating is applied, referred to as baseline scenario 2. For baseline scenario 2, the building's thermal energy loads are computed at 50.20 kWh/m^2 for heating and 22.40 kWh/m^2 for cooling, with a respective yearly electricity consumption of 17.53 kWh/m^2.

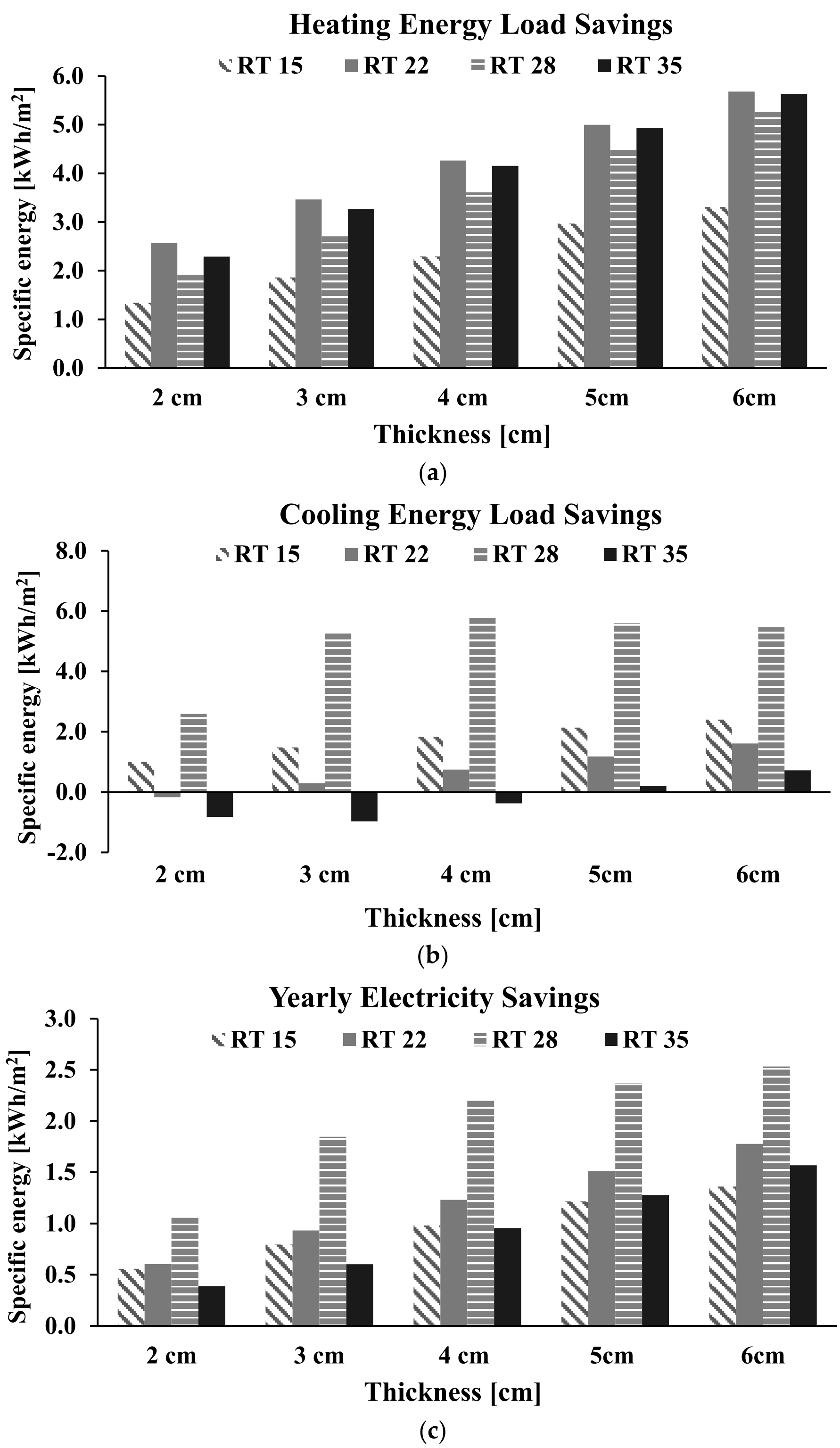
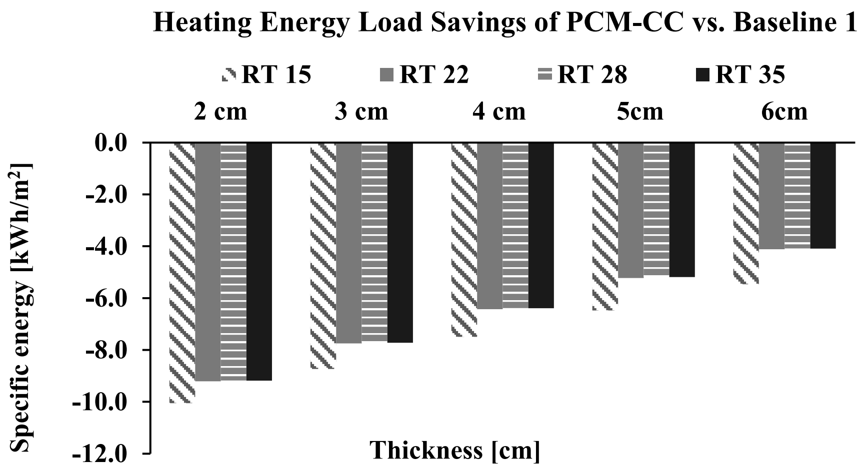
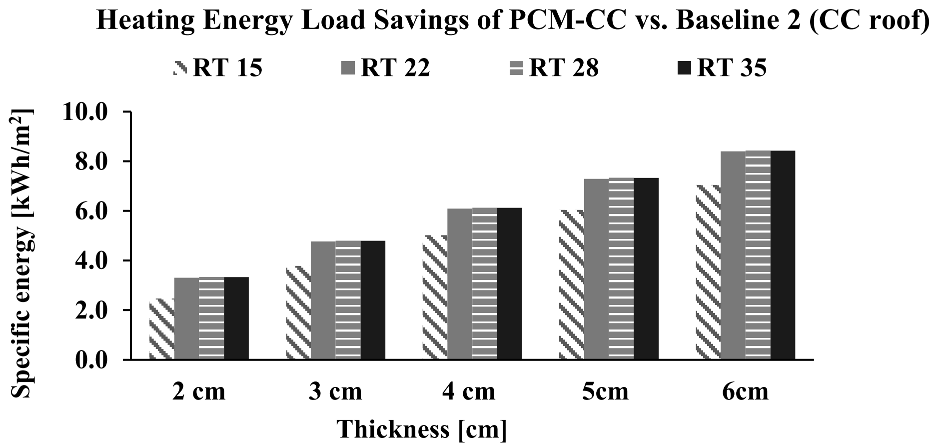


Figure 2. Energy savings of the PCM system compared to baseline scenario 1 for the (**a**) heating energy load, (**b**) cooling energy load, and (**c**) yearly electricity demand.

First, Figure 3a,b illustrate the heating energy load savings induced by the PCM-CC roof system compared to baseline scenario 1 and baseline scenario 2, respectively. The addition of a cool coating adversely affects the building's heating demand, regardless of the PCM's mean transition temperature. However, when compared to baseline scenario 2, the integration of PCM into the cool roof system enhances the building's thermal performance during the winter period. According to Figure 4a, the PCM-CC roof system has a positive overall effect on the building's cooling load. Additionally, compared to the RT28 PCM roof system, which leads to energy savings for cooling between 2.59 kWh/m^2 and 5.83 kWh/m^2, the RT28 PCM-CC roof system is calculated to induce energy savings for cooling that are in the range of 15.25 kWh/m^2 to 15.69 kWh/m^2. However, Figure 4b indicates that, when compared with the scenario where only the CC is applied, the PCM component does not further reduce the building's cooling loads. Finally, Figure 5 summarizes the total electricity savings achieved for every PCM-CC roof system. According to the calculations, the RT35 PCM-CC roof system results in the highest electricity savings at every examined thickness value. More specifically, the computed total specific electricity savings are equal to 1.91 kWh/m^2, or a reduction of 10.21% for a 2 cm thickness, and 3.0 kWh/m^2, or a reduction of 16.04% for a 6 cm thickness value. Contrary to the PCM roof system, the PCM-CC roof significantly diminishes the building's cooling loads, but due to the adverse effect of the CC's high reflectivity on the building's heating loads, the PCM-CC roof system is less effective at diminishing the building's total electricity consumption.



(**a**)



(**b**)

Figure 3. Heating energy load savings of the PCM-CC roof system compared to (**a**) baseline scenario 1 and (**b**) baseline scenario 2.

3.3. Thermal Energy Load Reduction by the PCM-TCC Roof System

An alternative solution is the integration of a PCM material with a thermochromic roof coating. For a thorough examination of each technology's effect on the building's thermal loads, the examined PCM-TCC roof systems are compared to baseline scenario 1, as well as to the scenario where only the thermochromic roof coating is applied, referred to as baseline scenario 3. For baseline scenario 3, the thermal energy loads of the building are calculated at 38.25 kWh/m^2 for the heating period and 31.0 kWh/m^2 for the cooling period, while the yearly electricity consumption is calculated at 16.45 kWh/m^2.

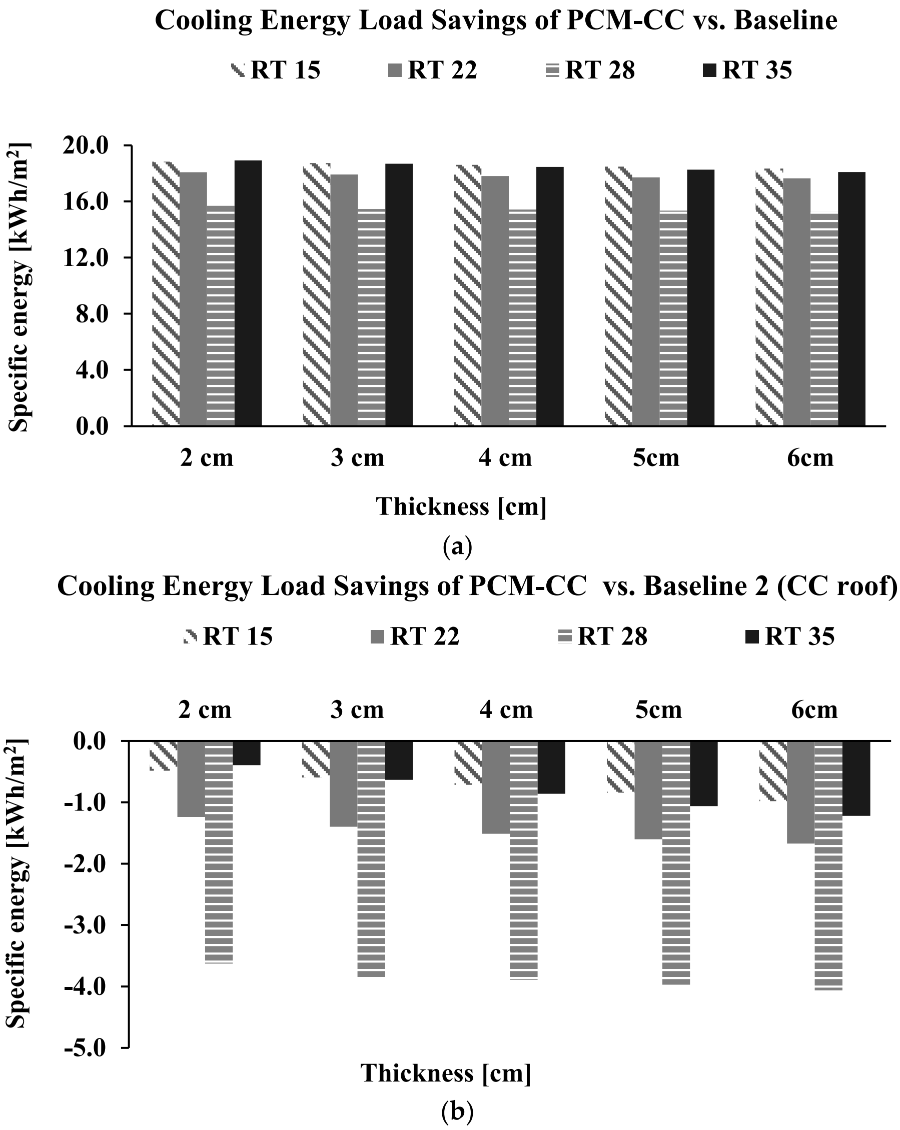
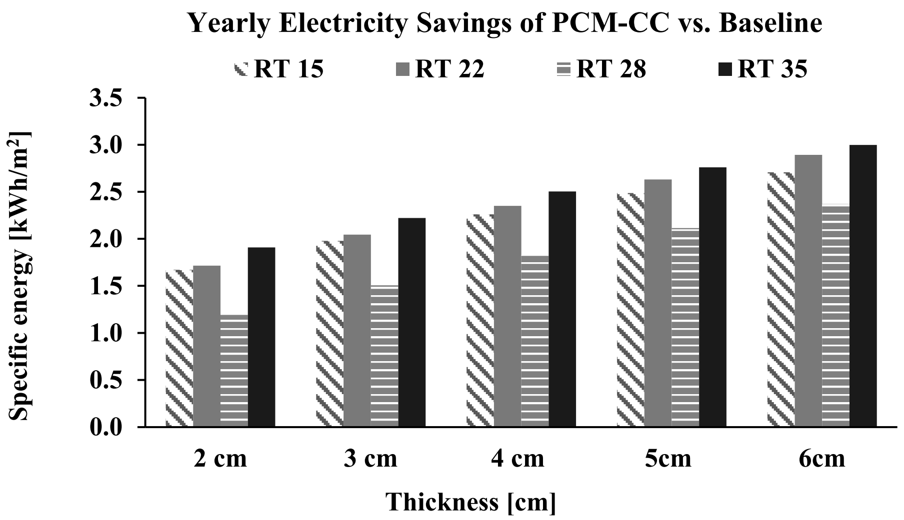
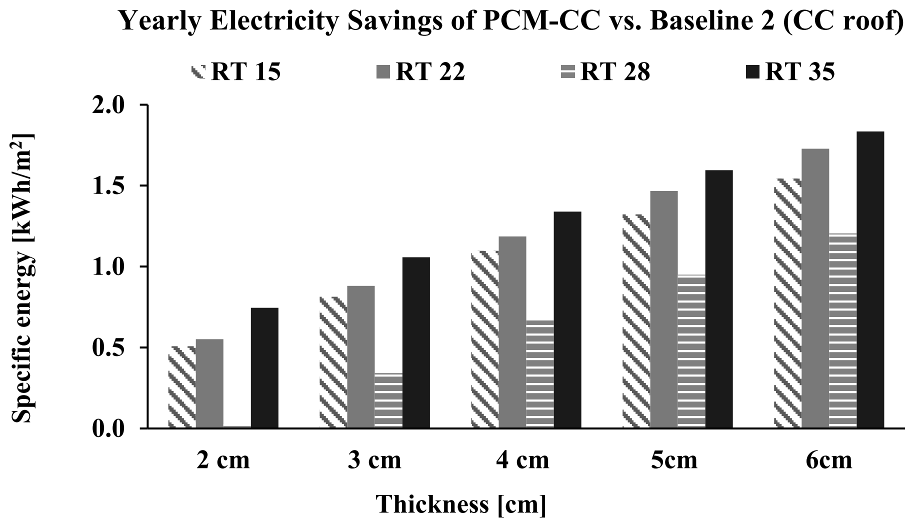


Figure 4. Cooling energy load savings of the PCM-CC roof system compared to (**a**) baseline scenario 1 and (**b**) baseline scenario 2.

According to Figure 6a, the PCM-TCC roof system has a positive effect on the heating energy loads of the building, regardless of the PCM material used. The maximum energy savings for heating are attained with the RT22 PCM-TCM system. Specifically, a decrease ranging from 2.48 kWh/m^2 to 5.63 kWh/m^2 is achieved for PCM thicknesses of 2 cm to 6 cm, respectively, which is equivalent to a reduction of 6.58% to 14.93%. According to this, the RT22 PCM-TCC roof system is found to lead to slightly lower energy savings in comparison with the RT22 PCM roof system, which is calculated to lead to energy savings that vary between 2.57 and 5.68 kWh/m^2. Figure 6b illustrates the complementary energy savings achieved by the PCM in combination with the thermochromic coating. The PCM-TCC demonstrates no heating penalties regardless of the PCM's mean transition temperature and thickness, as opposed to the PCM-CC rood system.



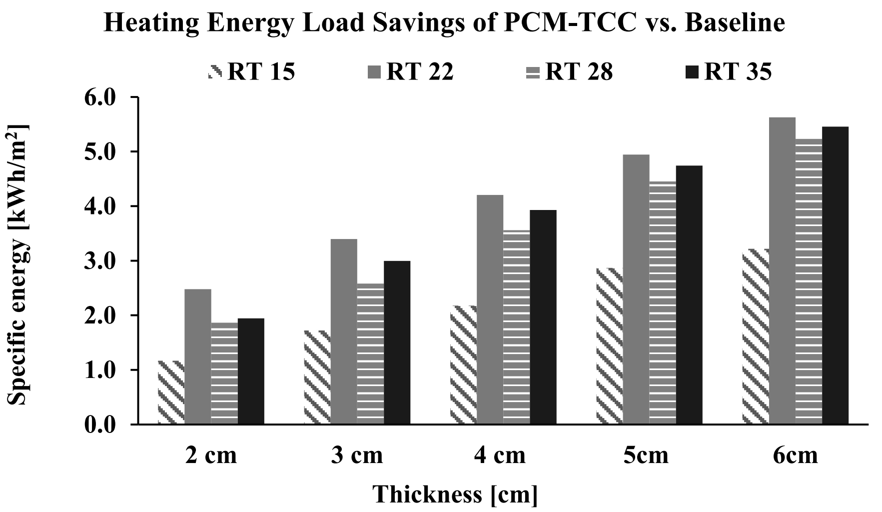
(**a**)



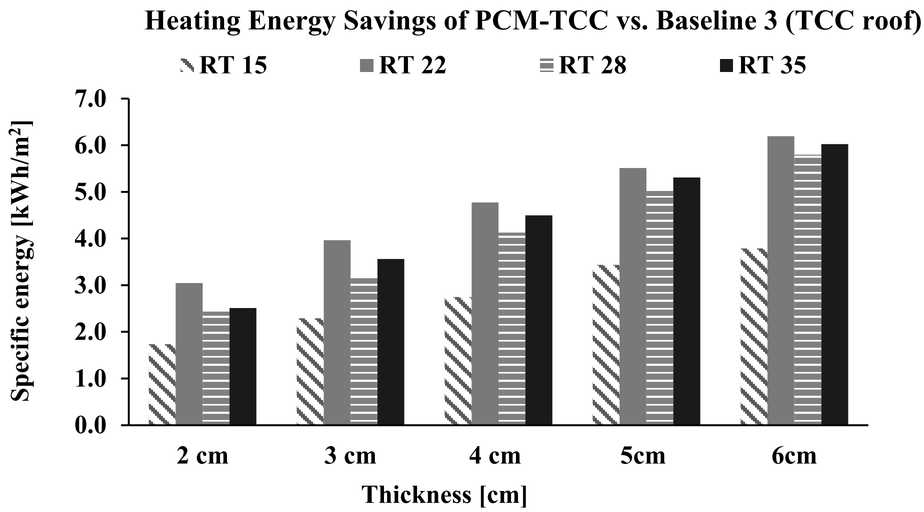
(**b**)

Figure 5. Yearly electricity savings of the PCM-CC roof system compared to (**a**) baseline scenario 1 and (**b**) baseline scenario 2.

Furthermore, according to Figure 7a, the PCM-TCC systems lead to a decrease in the building's cooling demand for every examined PCM-TCC system. The maximum energy savings for cooling are attained by the RT28 PCM-TCC system for a 3 cm to 6 cm thickness value. The respective specific cooling load energy savings are computed at 11.61 kWh/m^2 to 12.36 kWh/m^2, corresponding to a reduction of 27.83% to 29.64%. For the cooling design, PCM materials contribute to complementary energy savings through the proper combination of PCM's mean transition temperature and thickness in conjunction with the thermochromic coating. Specifically, the RT28 PCM roof system leads to energy savings for cooling that are calculated between 2.59 kWh/m^2 and 5.83 kWh/m^2, whereas the TC roof system is found to reduce the building's total cooling thermal loads by 10.7 kWh/m^2. Overall, the PCM-TCC roof system alleviated the building's total electricity consumption for heating and cooling. The most efficient PCM-TCC system is the RT28 PCM-TCC system, which, according to Figure 8a, results in specific electricity savings of 2.77 kWh/m^2 to 4.06 kWh/m^2 for PCM thicknesses of 2 cm to 6 cm, or equally a yearly electricity reduction of 14.82% to 21.70%.

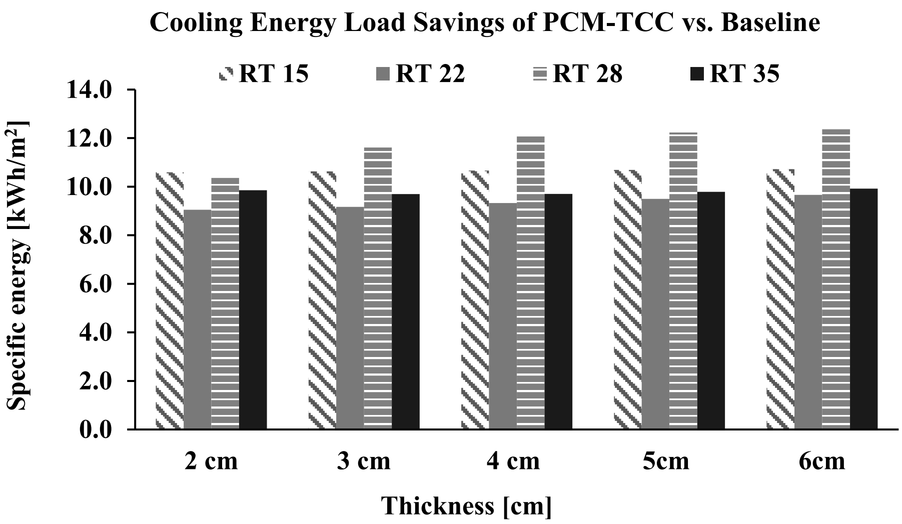


(**a**)



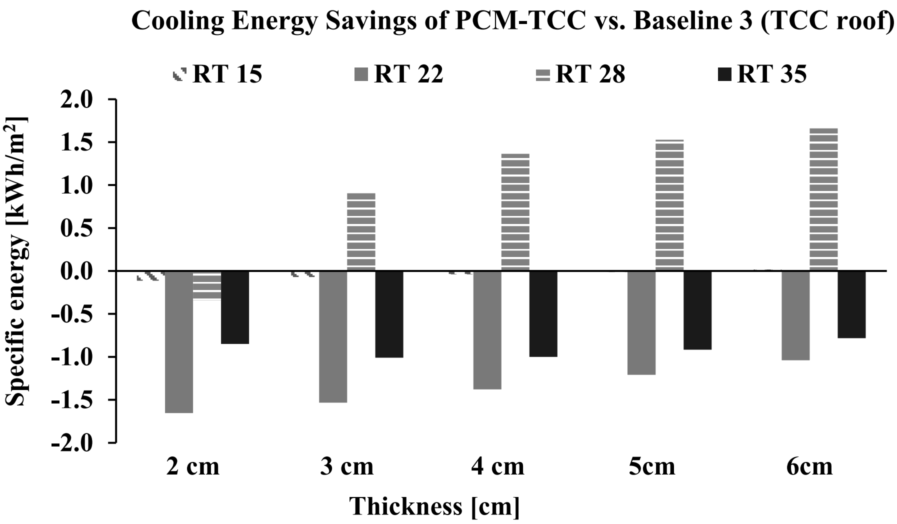
(**b**)

Figure 6. Heating energy load savings of the PCM-TCC roof system compared to (**a**) baseline scenario 1 and (**b**) baseline scenario 3.



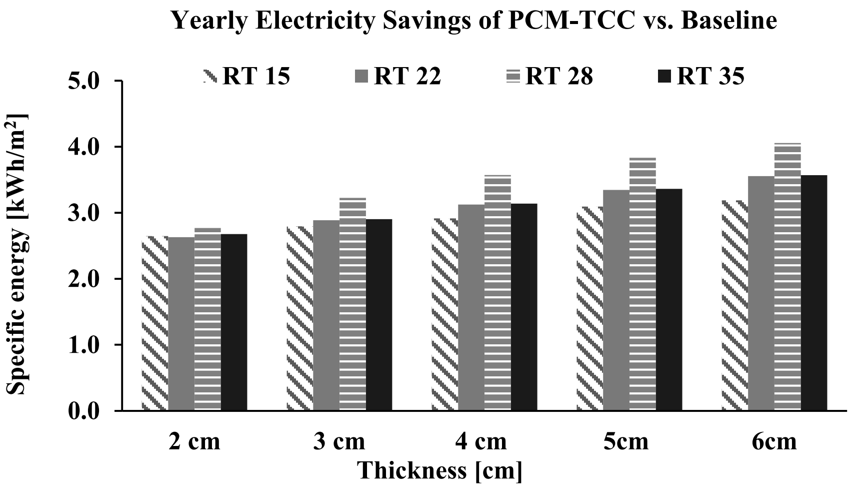
(**a**)

Figure 7. *Cont.*

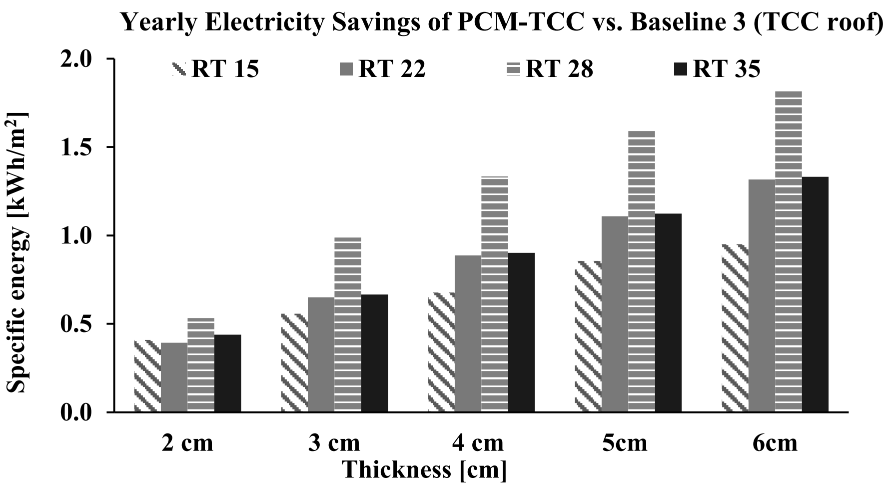


(**b**)

Figure 7. Cooling energy load savings of the PCM-TCC roof system compared to (**a**) baseline scenario 1 and (**b**) baseline scenario 3.



(**a**)



(**b**)

Figure 8. Yearly electricity savings of the PCM-TCC roof system compared to (**a**) baseline scenario 1 and (**b**) baseline scenario 3.

4. Discussion

The integration of PCM material externally into the building's roof is computed to result in important energy load savings for the climatic conditions of Athens. However, the improper combination of a PCM's mean transition temperature and thickness proves to be ineffective or have a negative impact on a building's energy equilibrium. Tables 4–6 summarize the building's heating, cooling, and electricity loads for the optimum PCM, PCM-CC, and P-TCC examined roof systems.

Table 4. Heating energy load of the building for the optimum PCM, PCM-CC, and PCM-TCC roof systems.

Specific Heating Energy Load [kWh/m^2]					
	PCM Thickness [cm]				
Roof system	2	3	4	5	6
RT28 PCM	35.77	34.98	34.08	33.19	32.42
RT35 PCM-CC	46.87	45.41	44.08	42.88	41.78
RT28 PCM-TCC	35.82	35.10	34.13	33.23	32.46

Table 5. Cooling energy load of the building for the optimum PCM, PCM-CC, and PCM-TCC roof systems.

Specific Cooling Energy Load [kWh/m^2]					
	PCM Thickness [cm]				
Roof system	2	3	4	5	6
RT28 PCM	39.12	36.45	35.88	36.12	36.24
RT35 PCM-CC	22.79	23.03	23.26	23.46	23.62
RT28 PCM-TCC	31.35	30.10	29.65	29.48	29.35

Table 6. Total electricity demand for heating and cooling of the building for the optimum PCM, PCM-CC, and PCM-TCC roof systems.

Specific Electricity Demand [kWh/m^2]					
	PCM Thickness [cm]				
Roof system	2	3	4	5	6
RT28 PCM	17.64	16.84	16.49	16.32	16.16
RT35 PCM-CC	16.78	16.47	16.19	15.93	15.69
RT28 PCM-TCC	15.92	15.47	15.12	14.86	14.64

For the heating design, the most efficient PCM is RT22, characterized by a lower mean transition temperature of 22 °C. On the other hand, for the cooling design, the most effective PCM is RT28, defined by a higher mean transition temperature of 28 °C. The highest possible seasonal thermal load energy savings are achieved with a PCM defined by a mean transition temperature similar to the building's seasonal indoor temperature setpoint. This conclusion is validated by the study of Dardouri et al. [18], who focused their study on various locations of Mediterranean climatic conditions in Tunisia and calculated that a PCM with a lower melting temperature of 21 °C is more effective for maximizing heating energy savings, while a PCM with a higher melting temperature of 29 °C allows higher cooling energy savings. Additionally, the increase in the PCM's thickness allows the reduction of the cumulative electricity demand for heating and cooling, with the reduction ranging from 5.65% to 13.55%. For the city of Athens, RT28 is calculated to result in the maximum electricity savings at every thickness. This is explained by the effectiveness of PCMs in reducing the building's cooling energy loads, as Jayalath et al. [17] have also concluded in their study for the location of Melbourne. According to their study, as far as the heating thermal loads are concerned, the integration of PCM into a building's roof can lead to energy savings of 12%. This result is in agreement with the energy savings calculations for heating for the PCM roof system in the present study (6.81% to 15.07%).

The integration of cool coating into the PCM roof system leads to further cooling energy savings when compared to the PCM roof system, as Lei et al. [27] also established. However, for the climatic conditions of Athens, PCM and CC are proven to have no complementary effect on reducing the building's cooling energy loads, since a CC roof system is calculated to contribute to higher cooling energy savings (46.3%) than the PCM-CC roof system (43.37% to 45.36%). Additionally, the increase in the PCM's thickness merely increases the cooling load's energy savings. However, as far as the total electricity demand is concerned, the PCM-CC roof system presents superior performance to the PCM system. Specifically, the PCM roof system results in a 5.65% to 13.55% reduction of the total electricity demand, whereas the PCM-CC roof system results in a 10.21% to 16.04% reduction for the respective PCM thickness values. This result is also confirmed by the study of Xu et al. [29], who researched the optimization of the cool coatings applicability in buildings through their integration with PCMs.

The integration of PCM with TCC is calculated to demonstrate both heating and cooling energy savings, which is a fact confirmed by the study of Ji and Li [34]. Specifically, the PCM-TCC roof system results in the highest heating and cooling energy savings among the PCM, PCM-CC, and PCM-TCC roof systems, and therefore in the highest electricity savings (14.82% to 21.70%). Furthermore, in contrast to cool coating and PCM, thermochromic coating and PCM present a complementary relationship in the reduction of the building's total electricity demand, according to Table 6. Specifically, the PCM roof system is calculated to decrease the building's cumulative electricity consumption by up to 13.55%, while the PCM-TCC reduction is up to 21.70%. The study of Hu and Yu [33] also proved the superiority of the PCM-TCC roof system against the PCM roof system as far as mild climates are concerned. Specifically, they found that the integration of a PCM-TCC roof system can lead to energy savings for heating and cooling equal to 17%, a result that is in agreement with the energy savings calculations for the examined building in the present study.

5. Conclusions

This study evaluates the energy savings attained by different roof systems (PCM, PCM-CC, and PCM-TCC) as energy retrofit solutions for a one-story residence in the city of Athens. The respective energy retrofit solutions are implemented on the external surface of the building's roof construction. The synergy between the PCM technology and the cool or thermochromic coating, as well as the efficiency of each technology separately, is investigated. The variation in the PCM's thickness is also considered. The main findings retrieved from the present study include:

- The improper combination of a PCM's mean transition temperature and thickness has no or a negative impact on a building's thermal loads.
- The PCM roof system with a mean transition temperature of 22 °C leads to the maximum heating energy savings (from 6.81% to 15.07%), while the PCM roof system with a mean transition temperature of 28 °C demonstrates the highest cooling energy savings (from 6.21% to 13.98%).
- The CC roof system is calculated to contribute to higher cooling energy savings (46.3%) than the PCM-CC roof system (43.37% to 45.36%). For the climatic conditions of Athens, PCM and CC are proven to have no complementary effect on reducing the building's cooling energy loads.
- The PCM-CC roof system alleviates the increase in heating thermal loads compared to the CC roof and leads to further electricity savings (from 10.21% to 16.04%) compared to the PCM roof for the respective PCM thicknesses.

- The PCM-TCC roof system with a mean transition temperature of 35 °C is calculated to demonstrate both heating (from 5.16% for a 2 cm thickness to 14.48% for a 6 cm thickness) and cooling energy savings (from 23.63% for a 2 cm thickness to 23.79% for a 6 cm thickness) compared to the existing concrete roof system of baseline scenario 1. The PCM-TCC roof system leads to the highest electricity savings, compared to the PCM and PCM-CC roof systems, which range between 14.82% and 21.70%.
- The solutions of PCM and TCC demonstrate complementary positive effects on the building's cooling thermal loads. Specifically, the RT28 PCM roof system leads to energy savings for cooling that are calculated up to 13.98%, the TC roof system is found to reduce the building's total cooling thermal loads by 25.66% kWh/m^2, and the RT28 PCM-TCC roof system is calculated to reduce the building's cumulative energy demand for cooling up to 29.64%.
- The increase in the PCM's thickness for the PCM-CC and PCM-TCC roof systems merely increases the cooling load's energy savings.
- The PCM roof system is calculated to decrease the building's cumulative electricity consumption by up to 13.55%, while the PCM-TCC by up to 21.70%.
- For the climatic condition of Athens, the maximum electricity savings for heating and cooling are achieved with RT28 for the PCM and PCM-TCC roof systems and with RT35 for the PCM-CC roof systems.
- The increment in the PCM's thickness increases the total electricity savings for every examined roof system, namely, the PCM, PCM-CC, and PCM-TCC roof systems.

This study confirms the prospects of integrating PCMs with cool or thermochromic coatings as an effective retrofit intervention. A further improvement in the restriction of a building's thermal loads could be achieved through the integration of a PCM with an innovative, thermally adaptive material that combines the distinctive features of the cool coatings, namely, high reflectivity during the summer months, and of the thermochromic coatings, namely, adjustability in the weather conditions [47]. These would include the setting of the proper optical properties of the coating as well as the thermal properties and thickness of the PCM layer. Moreover, in the future, there is a need to conduct an economic investigation by taking into consideration the PCM cost as a function of its thickness, aiming to determine the optimal thickness from an economic point of view.

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Abbreviations

Nomenclature

COP	heating mode coefficient of performance
E	energy, kWh
EER	cooling mode coefficient of performance/energy efficiency ratio
P_{el}	electricity, W
Q	thermal load, W
SCOP	seasonal energy efficiency ratio (heating mode)
SEER	seasonal energy efficiency ratio (cooling mode)
T	temperature, °C
U-value	thermal transmittance, W/m^{2}K

Greek Symbols

ρ	solar reflectivity
Subscripts and superscripts	
asol	absorbed direct and diffuse solar (short-wavelength) radiation heat flux
cond	conduction flux through the wall
con	convective heat flux to an air zone
cool	cooling
el	electricity
heat	heating
sol	transmitted solar radiation flux absorbed at surface
surf	roof's external surface
Abbreviations	
ACH	air changes per hour
CC	cool coating
LWR	long-wavelength (thermal) radiation flux exchange with the air and surroundings
LWE	long-wave radiation flux from equipment in a zone
LWX	long-wave radiant exchange flux between surfaces in a zone
PCM	phase change material
PCM-CC	combination of phase change material with cool coating
PCM-TCC	combination of phase change material with thermochromic coating
SW	short-wave radiation flux from lights
TCC	thermochromic coating

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