Future performance evaluation of PCM integrated buildings under changing climate

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Abstract. The high energy consumption and associated carbon emissions due to the heating and cooling of buildings create a heavy environmental burden. One of the cost-efficient solutions to reduce the heating and cooling demands is to incorporate phase change materials (PCMs) in the building components, increasing the thermal mass of the building and providing latent heat thermal storage. However, the rising temperatures over the years will alter the effectiveness of PCM in building envelopes. In this study, four cities in Turkey with different climatic characteristics were selected. For each city, future weather files representing the climatic conditions of 2050 and 2080 were generated from the current weather data using CCWorldWeatherGen. A typical office building that utilizes gypsum wallboards was modeled with EnergyPlus as a reference case. Alternative energy models were generated by modifying the wallboard compositions (PCM melting temperature: 19-27°C). The building's annual heating and cooling energy demands were calculated for each city, year, and wallboard alternative. Generated data were analyzed to evaluate the future efficiency of the wallboards with the changing climate over the years in order to maximize the long-term performance gains from PCM incorporating wallboards. The results showed that the selection of the optimum PCM melting temperature of a location should not only depend on thermo-physical and layer properties of the PCM wallboard as the optimum melting temperature of the PCM is subject to change with rising temperatures. The impact of climate change should be considered to fully evaluate the long-term performance of the PCM wallboard in terms of energy use and CO_2 emissions.

1. Introduction

It is projected that energy consumption for the building sector will continue to heighten, with an annual average rate of 1.5% for the next 30 years, due to the growing world population, rising expectations in occupant thermal comfort, and larger indoor living environments. This contradicts the fact that CO_2 emissions in the building sector should be reduced by 77% to keep global warming below 2°C by 2050 [1].

Heating, ventilation, and air-conditioning (HVAC) systems are critical energy users in residential and non-residential buildings. IEA estimates that space heating and cooling with water heating are responsible for nearly 60% of global energy consumption in buildings [1]. Although heating has the largest share of energy consumption, it is expected that the energy used for heating will be shifted toward cooling due to climate change, and the efficiency and functioning of the current HVAC systems will be reduced drastically [2]. Therefore, instead of solely relying on air-conditioning systems, the applications of passive energy-saving systems should be considered in buildings. Previous studies show that incorporating thermal energy storage systems such as phase-changing materials (PCMs) into building envelopes is an effective way of enhancing the energy-saving performance due to high latent heat storage capacities of PCMs [3].

The performance of PCM-integrated building envelopes depends on several factors such as phase change temperature, the thickness of the PCM wallboard, and the location of the PCM layer. Although the importance of the factors mentioned above was studied in detail in the existing literature, the performance of PCM-integrated building envelopes under climate change is an understudied area. In the present study, PCM-integrated office buildings' cooling and heating energy saving performance in four different climatic regions were evaluated under the impact of climate change. For each city, future weather files representing the climatic conditions of 2050 and 2080 were generated from the current weather data using CCWorldWeatherGen. In order to find the optimum PCM melting temperature, alternative energy models were generated by modifying the wallboard compositions by changing the PCM melting temperature in the range of 19-27°C. The energy-saving and corresponding total CO_2 saving of each wallboard composition was found by comparing them with the reference building without PCM.

2. Methodology

This study focuses on the effect of climate change on the energy demand of buildings equipped with a PCM layer for different climatic conditions in Turkey. The selection of representative cities was made according to the TS 825 degree-day region (DDR) classification. **Table 1** shows the general climatic characteristics of the cities studied.

For each city, cooling/heating energy loads were simulated through EnergyPlus using Ladybug/Honeybee environmental plugins embedded in Rhinoceros/Grasshopper. The calculated heating/cooling loads from energy simulations were converted to energy demands (Q) by the coefficient of performance of the chiller (COP) and the boiler's efficiency. This study assumes an electricity-driven variable refrigerant flow (VRF) system for space cooling with a COP value of 3.0 and a natural gas boiler for space heating with a boiler efficiency of 86% [4].

Table 1. Selected cities according to TS 825 and their climatic characteristics.

TS 825 DDR	Köppen Climate Zone	Climate Characteristics	City	Latitude	Longitude
1	Csa	Mediterranean climate, hot summer	İzmir	27.14°E	38.42°N
2	Csa	Mediterranean climate, hot summer	Istanbul	28.97°E	41.00°N
3	Csb	Mediterranean climate, warm summer	Ankara	32.85°E	39.93°N
4	Dfb	Continental, warm summer humid	Kars	43.09°E	40.60°N

In order to simulate the future energy performance of the building, future weather files representing 2050 and 2080 were generated using CCWorldWeatherGen tool, which is based on the standard morphing method developed by [5]. The tool requires statistical 8760-h weather files in EPW format representing a typical meteorological year. Using the Intergovernmental Panel on Climate Change

(IPCC) Third Assessment Report model summary data of the Hadley Centre Coupled Model, version 3 with medium emission scenario (HADCM3 A2) [6], a baseline weather file is modified by combining morphing procedures to predict future year weather parameters such as mean temperature, relative humidity, solar irradiance, wind speed, atmospheric pressure, and precipitation [7].

A single-story hypothetical office building was selected as a case study (**Figure 2**). The building has a total floor area of 900 m^2 with four office zones (210 m^2 each) and one unoccupied core zone (60 m^2) dedicated to the service. The window-to-wall ratio was set to 0.3 in all directions, and the ceiling height throughout the building was 4.5 m. The building envelops elements were selected according to TS 825 Thermal Insulation Requirements in Buildings Standard [8], which recommends maximum U-values for each climatic DDR in Turkey.

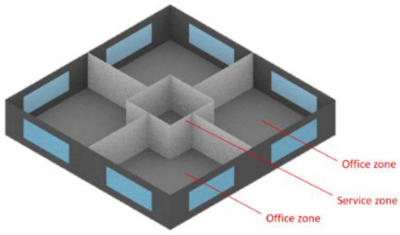

Figure 1. Schematic drawing of the case study building.

In this study, commercially available plasterboard (Knauf comfortboard), which is filled with 18% of Micronal® microencapsulated PCM, was chosen [9]. The physical properties of the PCM are given in **Table 2**.

EnergyPlus requires the selected PCM's enthalpy – temperature (h-T) curve to perform the energy simulation. To construct the h-T curve of the selected PCM, Eq. 1 [10] was used by introducing the physical properties of the selected plasterboard.

$$h(T) = C_{p,const}T + \frac{h_2 - h_1}{2}\ x\ \left\{1 + tanh\left[\frac{2\beta}{\tau}(T - T_m)\right]\right\} \quad (1)$$

Where C_p is the specific heat, T is temperature, h is the specific enthalpy, β is the inclination, τ is the width of the melting zone, and T_m is the melting point. Since the effect of climate change on the performance of different PCM melting points is investigated in this study, T_m was selected in the range of 19 - 27°C. β was taken as 1.4 as suggested by [11], and τ was taken as 3.

Table 2. Thermo-physical properties of Knauf smartboard. [9]

Peak melting temperature	25 °C
Thermal conductivity	0.23 W/m.K
Latent heat capacity	200 kJ/m^2
Specific heat capacity	13 kJ/m^2.K
Density	800 kg/m^3
Specific heat	1625 J/kg.K

To investigate the effects of PCM on the heating and cooling energy demand of the building, PCM integrated gypsum boards were installed on the inner surface of the external wall and roof. It should be noted that the U-value of the external wall and roof was adjusted by changing the thickness of the insulation layer to satisfy the mandated maximum U-value for each DDR. The building material properties for PCM-integrated external walls and roof are reported in **Table 3**.

The internal loads were set according to ASHRAE STANDARD 90.1-2013 [12]. Heating setpoint and setback temperatures were set to 21°C and 18°C, respectively; whereas cooling setpoint and setback temperatures were chosen as 25.5°C and 26.7°C, respectively. In addition, a fan-driven night flushing schedule was introduced during the cooling season between 15 April and 15 October. The night flushing was activated during unoccupied hours (22:00-6:00) with a fan flow rate of 1 m^3/s and fan efficiency of 0.7.

In order to evaluate the total energy use and corresponding CO_2-savings, calculated cooling and heating energy values were multiplied by unit greenhouse gas emission factors. The unit factors [13] were taken as 0.545 (kg CO_2-eq/kWh) and 0.181 (kg CO_2-eq/kWh) for cooling and heating systems, respectively.

Table 3. Thermal characteristics of exterior wall and roof construction. [14]

Material	d (m)	λ (W/m.K)	ρ (kg/m^3)	C_p (J/kgK)	R (m^{2}K/W)
Exterior Wall					
Cement plaster	0.03	0.72	1762	840	0.042
EPS	0.03 – 0.06	0.035	22	1500	-
Brick wall	0.14	0.33	600	800	0.410
PCM gypsum board	0.02	0.23	800	1625	-
Gypsum plaster	0.02	0.51	1200	840	0.040
Insulated roof					
Glasswool	0.08 – 0.15	0.04	18	670	-
Reinforced concrete	0.12	2.50	2400	840	0.050
PCM gypsum board	0.02	0.23	800	1625	-
Gypsum plaster	0.02	0.51	1200	840	0.040

3. Results

Figure 2 shows the monthly average dry-bulb temperature for representative cities considering 2020, 2050, and 2080 climatic conditions. The projections indicate that climate change resulted in a warming trend for all cities. From 2020 to 2080, the average annual dry-bulb temperature will rise by 4.2 (+23.6%), 4.8 (+36.2%), 4.8 (+29.6%), and 5.2 °C (+106.0%) for Izmir, Ankara, Istanbul, and Kars. Inland cities (Ankara and Kars) experience higher temperature rise differences than the coastal cities (Izmir and Istanbul) due to the fact that the high heat capacity of water acts as a stabilizing force moderating the warming [2].

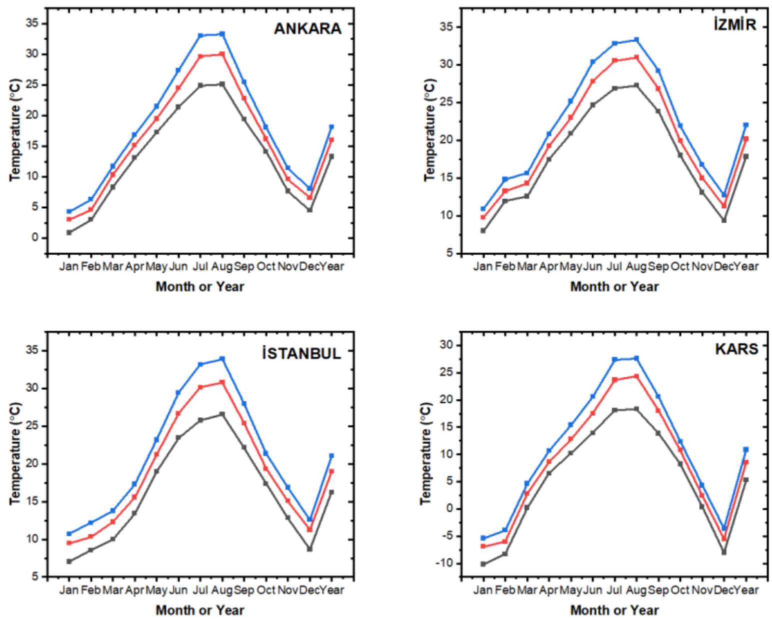

Figure 2. Monthly average dry-bulb temperatures for Ankara, İzmir, İstanbul, and Kars. (Black, red, and blue lines represent 2020, 2050, and 2080, respectively.)

It can be expected that rising dry-bulb temperatures will result in decreasing heating energy use and increasing cooling energy use of buildings [15][16][17]; however, the future energy performance of PCM integrated buildings is not easy to predict as there is a growing complexity of the thermal behavior of the building envelope when the PCM is integrated. Several factors such as thermo-physical properties of the PCM, the location and thickness of the PCM-integrated layers in the envelope are crucial to predict the thermal behavior of the building; thus, a holistic approach that considers all of the influential parameters is required to assess the performance of the PCM integrated buildings. Among all other factors, it was shown that the PCM melting temperature in different climate conditions is the most critical factor in improving the energy performance and thermal comfort in naturally and mechanically ventilated buildings [10]. Therefore, as a first step, this study focuses on the different PCM melting temperatures with their future energy saving potentials and corresponding CO_2 emissions.

Figure 3 shows the energy-saving potentials of the PCM plasterboard with different melting temperatures between 19-27 °C. The energy-saving potential (ΔQ_{SAVING}) and efficiency (φ_{eff}) are calculated using Eq. 2 and Eq. 3:

$$\Delta Q_{SAVING} = Q_{NO-PCM} - Q_{PCM-T_m} \quad (2)$$

$$\varphi_{eff} = \left(\frac{Q_{NO-PCM} - Q_{PCM-T_m}}{Q_{NO-PCM}}\right) \times 100 \quad (3)$$

where Q_{NO-PCM} represents the cooling or heating energy demand when the building envelope is without PCM, and Q_{PCM-Tm} represents the energy demand when PCM with a melting point, T_m is used.

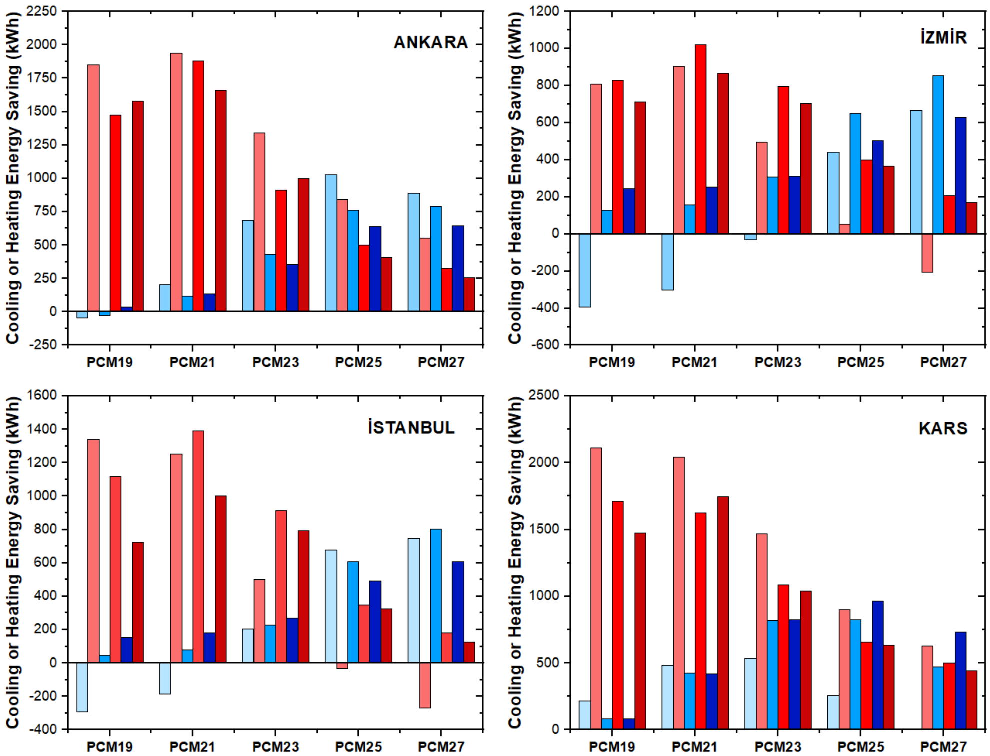

Figure 3. Cooling and heating energy-saving values for PCMs with different melting points (Blue: Cooling energy-saving and Red: Heating energy saving. Light, medium, and dark colors represent 2020, 2050, and 2080 values.)

As shown in **Figure 3**, the heating and cooling performance of the PCMs change with different PCM melting temperatures and changing climates. Due to higher diurnal temperature variations, the inland cities (Ankara and Kars) achieve greater cooling and heating savings than coastal cities (Istanbul and Izmir). In addition, the current thermal insulation standards perform poorly in reducing cooling loads as they target reducing the heating energy demand. However, the heating energy demand will decline considerably under climate change impact, while heavily insulated buildings will need to tackle the growing overheating problem [2].

For Izmir and Istanbul, PCM21 and PCM27 show higher heating and cooling energy savings performance, respectively. Although the melting temperature for the higher-performing PCMs remains the same for these cities, overall cooling and heating saving values change from 2020 to 2080. In particular, by 2080, cooling saving values drop from 665 kWh (φ_{eff} = +3.9%) to 627 kWh (φ_{eff} = +2%) for Izmir and 748 kWh (φ_{eff} = +6.4%) to 609 kWh (φ_{eff} = +2.4%) for Istanbul. On the other hand, heating saving efficiencies increase from +18.7% to +53.5% for Izmir and +15.1% to 63.6% for Istanbul. However, the energy-saving values for these cities do not change significantly, and the increase in the saving efficiency can be attributed to the significant reduction in heating energy demand by 2080.

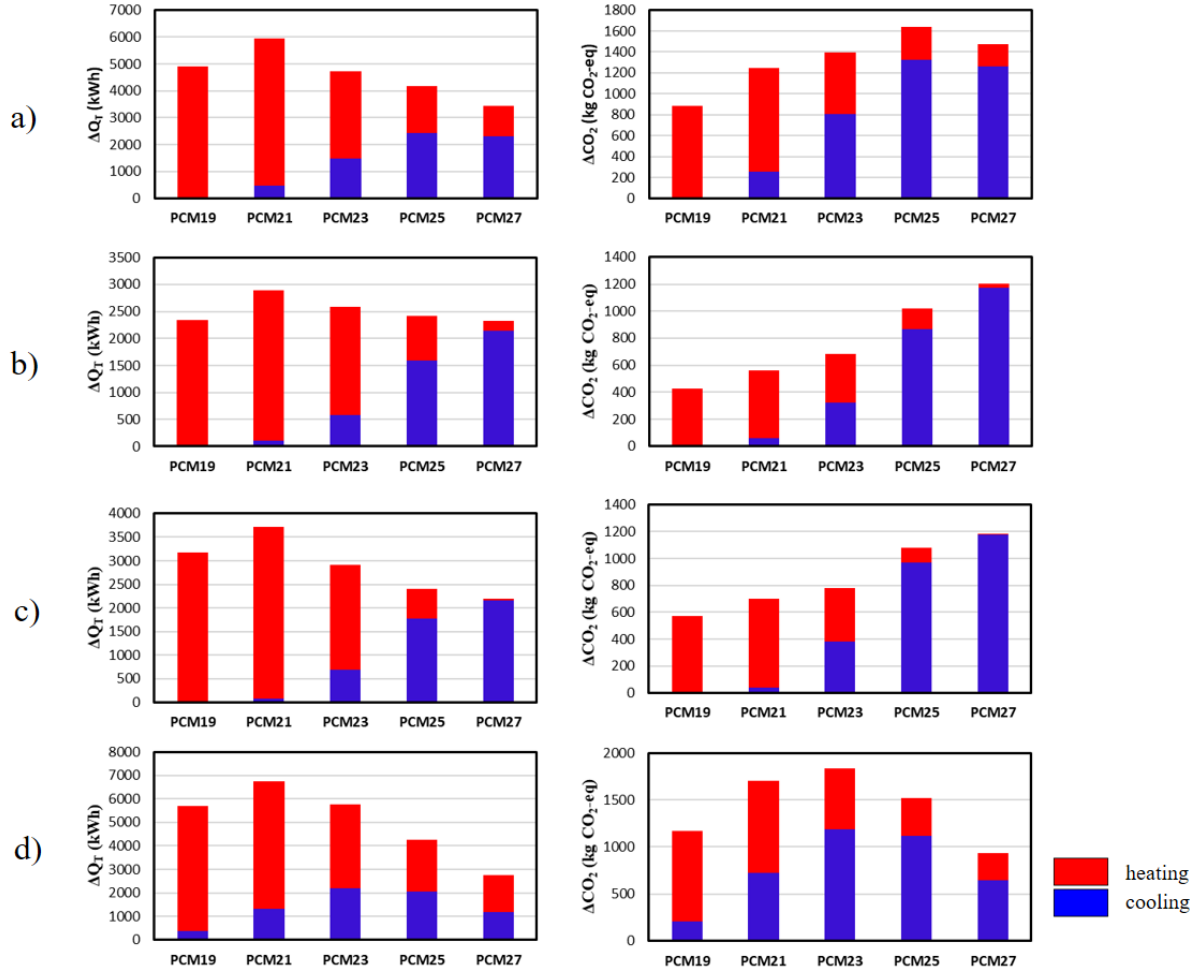

Figure 4. Cumulative* energy (*ΔQ_T*) and global warming potential (*ΔCO_2*) savings for a) Ankara, b) Izmir, c) Istanbul, d) Kars. (* Total of 2020, 2050 and 2080 values)

For Ankara and Kars, the melting temperature of the higher-performing PCMs changes with changing climate. The highest heating and cooling energy savings and efficiencies in 2020 were achieved in Ankara with PCM21 (1937 kWh, +12.3%) and PCM25 (1029 kWh, +12.3%). In 2050, for the same city, PCM21 (1882 kWh, +21.1%) and PCM27 (787 kWh, +5.7%) give the highest heating and cooling energy savings with decreasing cooling saving efficiency due to the rising cooling loads. By 2080, the melting temperature of PCM will remain the same for both the highest cooling and heating saving values; however, the cooling energy-saving potential decreases further (645 kWh, +3.4%). For Kars, PCM19 (2111 kWh, +5.3%) and PCM23 (533 kWh, +31.1%) show the high potentiality of energy saving in 2020, especially for heating demand. Since the average annual temperature for this city substantially increases by +106.0% from 2020 to 2080, it can be expected that phase change will be more frequently activated, and the PCM will be able to exploit its storage potential for higher PCM melting temperatures fully. With rising PCM melting temperatures, PCM21 (1745 kWh, +7.0%) and PCM25 (964 kWh, +11.6%) show higher performance in 2080.

In order to evaluate the corresponding total CO_2 saving (ΔCO_2) due to the use of PCM plasterboard under the changing climate, the total energy saving (ΔQ_T) for each PCM melting point in discrete years was considered. In other words, it was assumed that there would be no replacement of the PCM plasterboard throughout the lifetime of the building, and cumulative PCM energy saving performance was investigated considering 2020, 2050, and 2080 energy use. The results are shown in Figure 4.

As shown in **Figure 4**, total energy saving varies depending on PCM melting temperatures. Since the performance of the PCM and cooling/heating energy demand are subject to change with global warming, the overall performance of the PCM plasterboard should be investigated considering the cumulative effect of the climate change. For instance, PCM21 for heating and PCM25 for cooling show a higher performance in Ankara; however, using PCM21 resulted in higher total energy saving (5940 kWh) if 2020, 2050 2080 are examined together. Furthermore, using PCM25 instead of PCM21 resulted in better environmental performance (1640 kg CO_2-eq/m^2 and 1243 kg CO_2-eq/m^2) as the carbon intensity of cooling is much higher than heating. The results indicate that the climate change effect should be considered while selecting the most effective PCM melting temperature.

4. Conclusions

This study evaluated PCM-integrated office buildings' cooling and heating energy performance in four different climatic regions under the impact of climate change considering 2050 and 2080 climatic conditions. In order to find the optimum PCM melting temperature, alternative energy models were generated by modifying the wallboard compositions by selecting the PCM melting temperature in the range of 19-27°C. Each wallboard composition's energy-saving and CO_2-saving performance were compared with the reference building that does not contain PCM.

The results confirmed that the PCM wallboard performance is directly affected by the climatic conditions as the inland cities (Ankara and Kars) achieve more significant cooling and heating saving values than coastal cities (Istanbul and Izmir) due to higher diurnal temperature differences. Due to the increased cooling loads, the cooling energy-saving efficiency of PCM was reduced in each city, whereas decreasing heating loads resulted in increased heating energy-saving efficiency. Furthermore, the optimum melting temperature of the PCM is subject to change with rising temperatures. The results indicate that the selection of the optimum PCM melting temperature of a location should not only depend on the thermo-physical and layer properties of the PCM wallboard, and the impact of climate change should be considered to fully evaluate the long-term performance of the PCM wallboard in terms of energy use and CO_2 emissions. Validation of the model with real data from an existing system with PCM will be conducted in a future work.

Acknowledgments

This research was supported by TUBITAK-Royal Academy of Engineering TSP Programme project TESBE: Thermal energy storage in building elements under grant No. 220N292 and EU H2020 Project SolarTwins: Solar Twinning to Create Solar Research Twins under grant agreement No. 856619.

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