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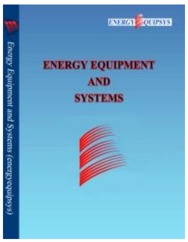

On the effect of using phase change materials in energy consumption and CO_2 emission in buildings in Iran: a climatic and parametric study

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ABSTRACT

Energy crisis, global warming and other environmental issues are what motivate researchers to find new strategies to reduce energy consumption in buildings. Recently, using phase change materials (PCM) in the building's envelopes has drawn significant attention as an energy-saving method, which helps in increasing the building's thermal capacity. In the present research, the effects of the main thermal parameters including climate conditions, PCM layer thickness and its position, wall thermal resistance, and type of HVAC system on the PCM energy-saving potential has been investigated using EnergyPlus software. A climate study has been undertaken in Iran which may be categorized into five climatic regions. Basing on the results, an effective PCM layer is almost 2–4 cm in thickness, and is embedded in the most interior layer of the wall. This conclusion does not depend on the type of HVAC system. In addition, the results showed that the southern strip of Iran, with a warm humid climate, and a relatively high solar irradiation, has the greatest potential to embed PCMs in the building's envelopes as a factor for reducing its energy demand. This research and its results are useful in getting a better understanding of the PCMs and their effects on reducing the building's energy consumption and CO_2 emission.

Keywords: Phase Change Material, Energy-Saving Method, CO_2 Emission Reduction, Climate Study, EnergyPlus.

1. Introduction

Increasing concerns about the lack of energy resources, global warming, and environmental pollution have been the motivating factors for researchers to develop energy-saving strategies. According to the report of the International Energy Agency (IEA, 2009), Iran is the world's 10th biggest emitter of CO_2. The energy-environmental study of Shafie-Pour et al. suggested that in the absence of price reforms, the damage to health due to air pollution in Iran will be nine billion dollars by 2019. In addition, they reported that the building sector is responsible for 20–25% of the total CO_2 emission in Iran [1]. The HVAC system energy demand of buildings has a considerable potential in reducing their total energy consumption. In this respect, one of the most highly regarded solutions is using solar energy to reduce the consumption of fossil fuel energy. Several methods have been developed in both passive and active forms to use the energy of the sun effectively. Absorbing solar energy at daytime and releasing it back to the building at nighttime is one of the traditional ways of using solar energy. In recent decades, materials that are named phase change materials (PCM), whose phase can be changed during the process of

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energy absorption have been investigated by many researchers,. PCMs offer more energy storage capacity and less temperature fluctuation with respect to traditionally used materials due to their having a high latent capacity. In addition, they are much lighter than the conventional materials used as building thermal mass. There have been several investigations into the incorporation of PCMs into buildings' envelopes ever since the first reported application in 1940 [2]. Kuznik et al. showed that using PCMs in a building's envelopes reduces the overheating effects and daily fluctuations of the indoor temperature as well as the annual energy consumption of the HVAC system [3]. It has been also reported by Halford and Boehm that the peak-load time can be shifted in order to reduce the load on the electricity network [4].

In a case study where PCM was used as a radiant floor system coupled with a heat pump, the result of Mazo et al. suggested that besides the time shifting of the peak load, the energy consumption of the building may reduce up to 18% compared to the conventional solution [5]. In another research work, Ahmad et al. showed that a wallboard containing PCM material subjected to periodical thermal variation on its external surface caused a time lag between external and internal thermal evolutions as well as a reduction in the surface temperature inside [6]. Experimental investigation of Castell et al. regarding PCM's performance in Mediterranean climate in warm season showed that without the HVAC system, using PCM may reduce the maximum inside temperature and its fluctuations. In addition, using PCM in a building equipped with the HVAC system results in up to 15% saving in its annual energy consumption [7]. Silva et al. used PCM on a brick-constructed cube in a climate-controlled chamber. Basing on the results, the PCM layer can reduce the inside temperature of the cube from 10 °C to 5 °C in addition to shifting the peak load time up to 3 hours [8]. De Gracia et al. showed that using PCM in a ventilated facade during winter periods can have a significant effect on the thermal behavior of the building and cause a huge reduction in energy consumption of the HVAC system [9].

Although most of the research works are case studies, nevertheless, there have been several attempts to develop simulation tools which can simulate the performance of PCM with a reasonable precision, and to investigate the effect of the design parameters on the effectiveness of the PCM layer. ESP-r and EnergyPlus are two examples of programs which have been enhanced to model PCMs, and their performances have been validated previously [10, 11, 12]. The direction of the PCM-embedded wall, position of the PCM layer, enthalpy of fusion, temperature of phase change, mass of PCM, insulation R-value, climate parameters and the type of HVAC system, may all be considered as the most important factors which can affect the effectiveness of the PCM layer.

In this research, the effect of PCM implementation in reducing the energy consumption and CO_2 emission of a single-storey building in Iran has been studied numerically using EnergyPlus software. As a special part of the investigation, Iran has been divided into five climatic regions to evaluate the effect of climate on the effectiveness of PCM. This research, and its results, may provide a better understanding of the effect of PCM on saving a building's energy demand, reducing CO_2 emission, and improving comfort conditions.

2. Materials and Methods

As shown in Fig. 1, a single-storey shopping center has been investigated. It is assumed that there is no shading on the shopping

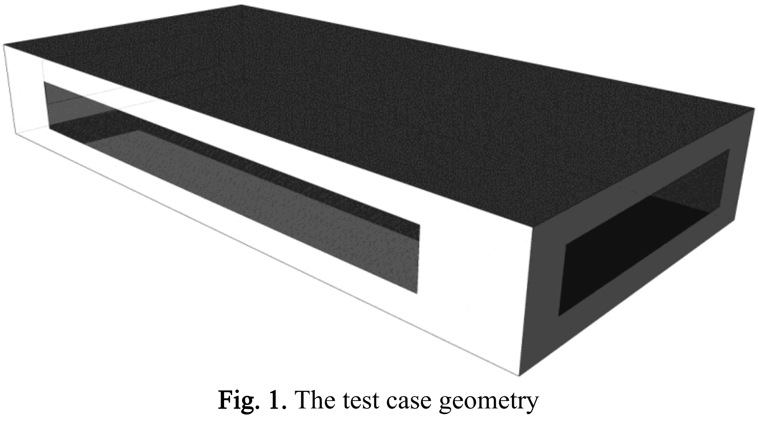

Fig. 1. The test case geometry

center has been investigated. It is assumed that there is no shading on the shopping center from nearby buildings or structures. Table 1 shows the geometrical and physical specifications of the building and its installations. The thermal resistance of the building's envelopes is based on the Iranian National Building Code (MRUD) [13].

Table 1. Geometrical and physical specifications of the test case

Dimensions	
Building	24×12×4 m
Large window	18×2 m
Small window	9×2 m
Total Heat Transfer Coefficients	
Wall	0.6 W/m2K
Roof	0.3 W/m2K
Windows	2.7 W/m2K
Phase Change Material	
Melting point	29 °C
Density	860 kg/m3
Latent heat	219 kJ/kg
Thermal conductivity	0.2 W/m.K
Internal Loads	
Lighting	20 W/m2
People	5 m2/person

EnergyPlus is an open-source tool which is widely used to simulate and analyze the thermal load and the energy demand of buildings based on the ASHRAE method of heat balance algorithm. The conduction and transfer of heat through the building's envelopes is usually formulated by using the Conduction Transfer Functions (CTF) to implement the effect of a building's thermal capacity. The CTF method reduces the governing equations into a set of linear ODEs with constant coefficients. Although the CTF method is fast and sufficiently accurate to simulate materials with constant properties, it fails in predicting the behavior of advanced materials such as PCM, whose properties are temperature-dependent. Accordingly, the Conduction Finite Difference (CondFD) algorithm has been incorporated into EnergyPlus [14].

The CondFD algorithm uses the implicit finite difference scheme to numerically solve the discretized energy equation over the building's envelopes:

$$\rho c_p \Delta x \frac{T_i^{new} - T_i^{old}}{\Delta t} = k_W \frac{T_{i+1}^{new} - T_i^{new}}{\Delta t} - k_E \frac{T_{i-1}^{new} - T_i^{new}}{\Delta t} \quad (1)$$

where:

$$k_W = \frac{k_{i+1}^{new} + k_i^{new}}{2}$$

$$k_E = \frac{k_{i-1}^{new} + k_i^{new}}{2}$$

The grid space is automatically set as:

$$\Delta x = \sqrt{c.\alpha.\Delta t} \quad (2)$$

where α is the thermal diffusivity, and the spatial discretization constant, c, has a default value of 3 [10, 11].

In order to solve the system of Eq.(1) the CondFD method is coupled with an enthalpy-temperature function which is usually extracted through experimental data:

$$c_p = \frac{h_i^{new} - h_i^{old}}{T_i^{new} - T_i^{old}} \quad (3)$$

During the recent years, some researchers have used EnergyPlus to investigate the thermal behavior of PCMs whose attempts led to validation of the EnergyPlus algorithm [15].

Paraffin-based PCMs are flammable which makes them inappropriate to be used in residential or commercial buildings. Recently, bioPCM has been developed as a new generation of PCMs which shows similar thermal characteristics as the paraffin-based ones, but without any flammability. These materials may be simply encapsulated in discrete blocks. Melting-freezing process of PCMs is a continuous phenomenon; as a result, PCMs usually have a "mushy" state during melting, and whose thermal properties must be measured experimentally. Figure 2 presents the enthalpy-temperature curve of a typical bioPCM which has been used in this study [15].

To predict the annual CO_2 emission of the building from its annual energy consumption, the CO_2 emission factor has been used. According to the report of IEA, in this study, the CO_2 emission factor has been assumed to be 536 (gr CO_2 per kWh) [16].

To perform a climate study, Iran may be categorized into five main climatic regions,

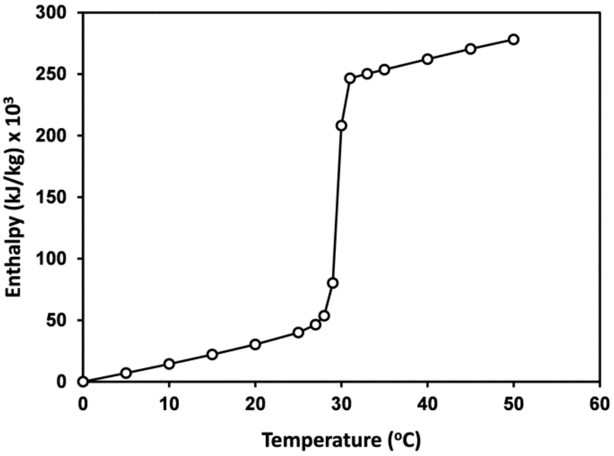

Fig. 2. Enthalpy-temperature curve of the bioPCM [15]

as depicted in Fig. 3. Four cities of Bandar Abbas, Yazd, Tehran and Tabriz have been selected as typical representatives of warm-humid, warm-dry, moderate, and cold climatic areas, respectively. As the Mediterranean climate provides no motivation to incorporate PCMs in its buildings' envelopes, it has not been investigated in this study. In Table 2, the outdoor design conditions of the abovementioned cities have been tabulated.

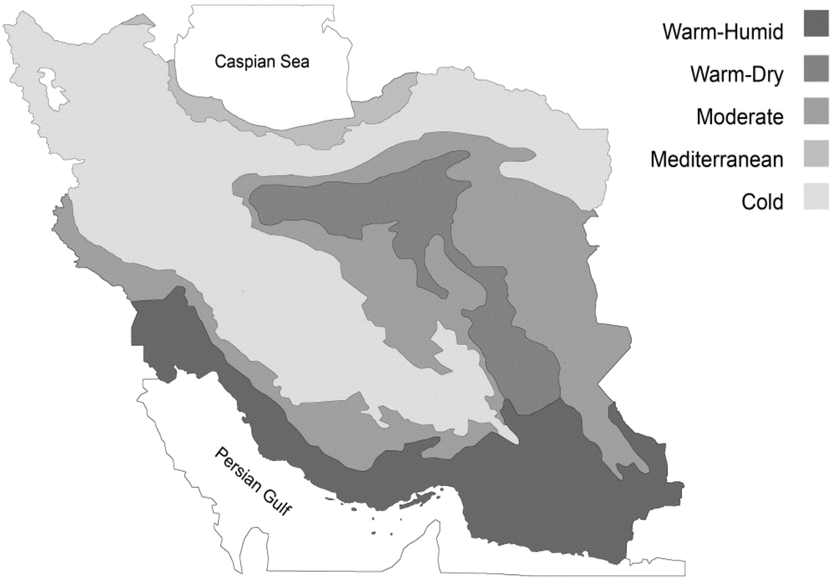

Fig. 3. Climatic areas of Iran

Table 2. Outdoor design conditions of the representative cities

Station	Latitude (°N)	Elevation (m)	Heating	Cooling		
			DB (°C)	DB (°C)	WB (°C)	DR (°C)
Bandar Abbas	27.2	10	7.5	40.6	31.9	9.4
Yazd	31.9	1219	-5.3	40.0	18.3	15.0
Tehran	35.7	1219	-6.7	38.9	23.8	15.0
Tabriz	37.8	1365	-10.8	33.9	18.0	13.3

3. Results and Discussion

3.1. PCM layer location and thickness

The location of the PCM layer in the construction of the wall may affect its effectiveness significantly. To find out the most efficient configuration, three cases have been studied, as shown in Fig.4. As the thermal capacity and the thermal resistance of most masonry materials are low enough, only the insulation and the PCM layers have been considered.

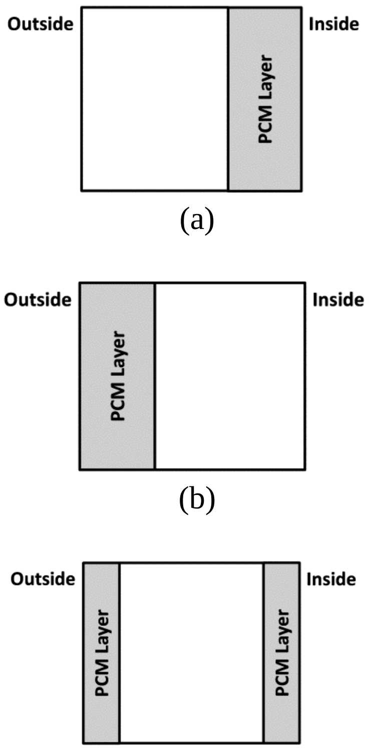

Fig. 4. Schematic of the locations of the PCM layer: (a) inside, (b) outside, (c) both sides

Figure 5 shows the effect of the PCM layer's location on its annual energy saving potential in typical all-air (air-cooled package) and all-water (water-cooled fan coil) HVAC systems. The results show that in all conditions, regardless of the climate and the type of HVAC system, the greatest saving may be attained using PCMs in the most interior layer. The PCM layer absorbs the irradiation energy and liquefies during daytime. At nighttime, as the outdoor air temperature falls to below the PCM melting temperature, it re-solidifies and releases the absorbed heat. As the insulating PCM layer is installed in the most interior layer, the location of the PCM results in an improvement in its performance by allowing more energy exchange with the inside air. As a result, the peak load on the HVAC system would be decreased and shifted, more than in other cases. This conclusion is in accordance with the previous experimental and numerical research works in a single-room building in the USA [15].

In Fig.6, the effect of the PCM layer's thickness on the energy saving potential is depicted. To make the results more meaningful, the energy saving has been presented in a nondimensional form using the maximum energy saving. It is obvious that a higher mass of PCM provides more thermal capacity and leads to more energy saving, irrespective of the climate and the type of HVAC system. However, as the layer is increased in thickness, its thermal capacity would be large enough to not contribute in the energy absorption process completely. As a result, the effectiveness of the PCM declines exponentially, as depicted in the figure. As the thickness of the layer exceeds almost 4 cm, the energy-reducing effect of the PCM changes less than 5%.

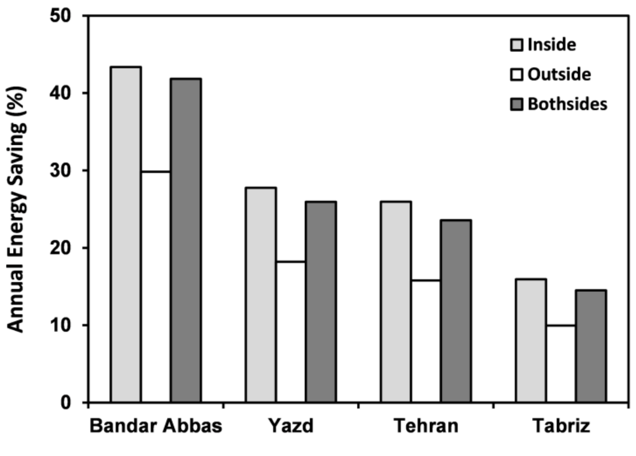

Fig. 5. The effect of PCM layer location on its effectiveness

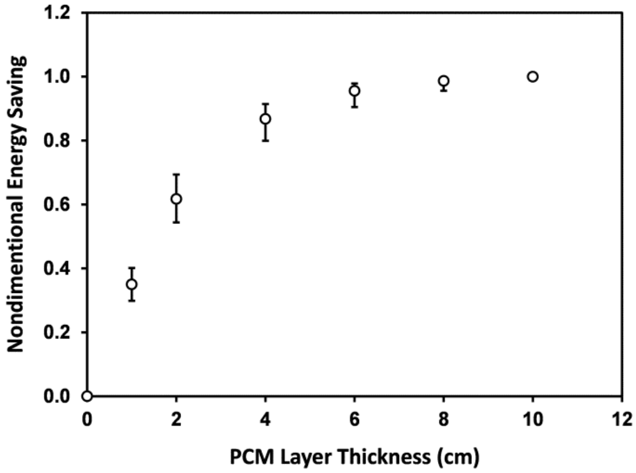

Fig. 6. The effect of PCM layer thickness on its effectiveness

3.2. Wall thermal resistance

The effect of the building envelope's thermal resistance on the nondimensional energy saving is shown in Fig.7. On the basis of the results, the effectiveness of the layer of PCM declines as the wall is more resistant due to decrement in the building's energy losses. However, as shown in Fig.7, Bandar Abbas presents a unique trend where there is an optimum thermal resistance in which the layer of PCM gives the best performance. This feature is almost independent of the type of HVAC system. As Bandar Abbas is located in the warm-humid region, it may be assumed that the specific effect of the envelope's thermal resistance on the building's energy saving is due to the high humidity content of the outdoor air. Reexamination of the analyses of building energy relating to other cities with similar climates, such as Abu Dhabi, also supports this idea. To verify this assumption, the building's annual energy consumption was analyzed with no outdoor air. The results do not depict any optimum value for the thermal resistance of the wall, and the nondimensional energy savings increases monotonically with the wall's thermal resistance.

As a consequence, the layer of PCM would be more effective in a building with relatively low thermal resistance. Well-insulated envelopes reduce the heat flux going to the layer of PCM. As a result, the mass of the PCM whose phase has been changed would be reduced, and this leads to the reduction of the PCM layer's performance. It is inferred that good insulation reduces the PCM layer's contribution in the reduction of the building's energy consumption. The results show that for the simulated building, the non-dimensional energy saving would be almost constant as the wall's value of thermal conductivity is more than 0.125 W/m.K.

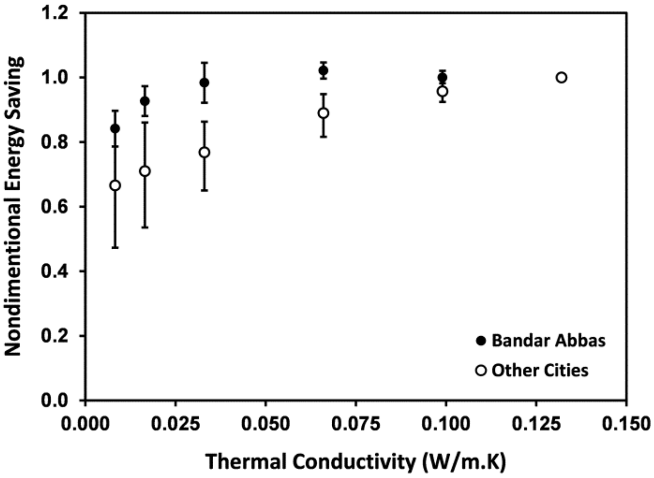

Fig. 7. The effect of wall thermal resistance on the effectiveness of PCM

3.3. Exposure direction

To find out which wall is more suitable for incorporating the layer of PCM, the contribution of five exposure directions was evaluated, as shown in Fig.8. To provide a more meaningful index, a nondimensional energy saving which provides the energy saving due to using PCM in a specific direction to the total energy saving, is used in Fig.8. On the basis of the results, in all conditions, regardless of the climate region or type of HVAC system, the building's roof is the most susceptible to exposure to warrant installation of the PCM layer. This is due to the fact that as the subject building is of a single storey, the most irradiation energy during daylight would be over its roof. As a result, PCM embedded on the roof shows the best effectiveness. The results predict that in high-rise buildings whose roof contribution is almost negligible, the west wall shows a better potential than the other walls to reduce the building's energy consumption by using PCM. As a west wall absorbs more solar irradiation in the afternoon, it is more capable of reducing the maximum cooling load and to shift its time. As the maximum cooling load is delayed, the HVAC system load would be more uniform, which leads to a reduction in its energy demand.

3.4. Climate

One of the most important features which may affect the effectiveness of an energy-saving strategy is the weather condition. To scan the effect of climate on the PCM layer's potential in reducing the building's annual energy consumption, four representative cities, including Bandar Abbas, Yazd, Tehran and Tabriz have been considered, as these cover all the important climatic regions of Iran.

As shown in Fig.9, using a layer of PCM in the wall construction leads to the highest energy saving in Bandar Abbas among all cities. It is believed that this is mainly due to the high solar irradiation in Bandar Abbas in which the annual energy demand is mainly attributed to the cooling system. In warm months, the layer of PCM changes completely to the liquid phase by absorbing the irradiation energy during the heat of the day, causing it to use its maximum potential in reducing the building's energy consumption. Yazd has an almost similar condition, although the energy saving due to using PCM layers would be somewhat less than Bandar Abbas. Tabriz, a city in the cold climate region, has the least potential for using PCM as an energy saving tool. In Tabriz, the annual heating energy is almost eight times greater than for cooling. In most days of winter and

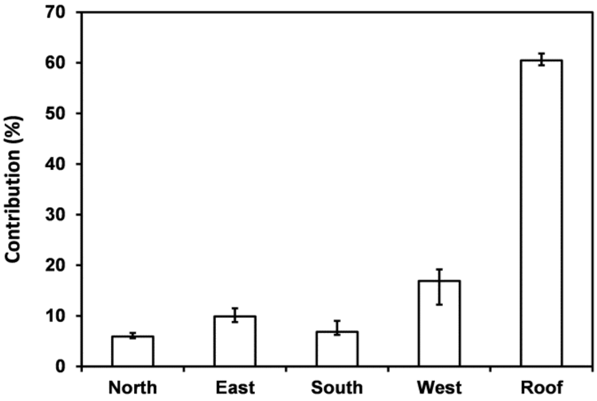

Fig. 8. The effect of direction of exposure on the effectiveness of the PCM layer

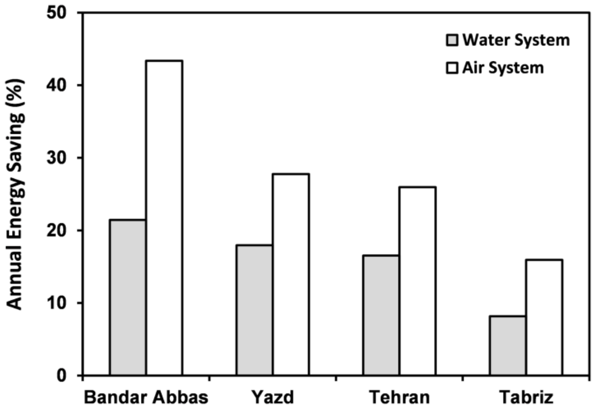

Fig. 9. The effect of climate conditions on the effectiveness of the PCM layer

autumn, the PCM layer phase does not change completely due to the relatively low solar irradiation coupled with the outside temperature. These conditions lead to a relatively low performance of the PCM layer in reducing a building's annul energy consumption.

Table 3 shows the annual reduction in CO_2 emission per m^2 of the building due to using the PCM layer. As shown in the Table, Yazd is associated with the highest reduction in CO_2 emission. Despite the lower effectiveness of the PCM layer in Yazd, the total energy demand is relatively higher than in Bandar Abbas which has moderate winters. Accordingly, by using the PCM layer in the building's envelopes in Yazd, the annual amount of CO_2 emission is reduced far more than in Bandar Abbas.

4. Conclusion

In this research, the effect of using PCM in buildings' envelopes was studied numerically using EnergyPlus software. The results showed that:

1. Regardless of the climate conditions and the type of HVAC system, a PCM layer gave its best performance when it was embedded in the most interior layer of the wall with respect to the insulation layer.

2. Increasing the thickness of the layer of PCM nonlinearly modifies its performance. In all cases, the improvement in the performance of the layer of PCM would be almost diminished when exceeding a thickness of 4 cm.

3. The thermal resistance of the building's envelop has an almost linear effect on its energy demand. Consequently, the layer of PCM would be more effective as it is used in a building with relatively poor insulation.

4. In a single-storey building, the roof is the best place to incorporate the layer of PCM. As the roof is exposed to solar irradiation all day, it has more potential to absorb solar energy than the other sides of the building have.

5. The southern strip of Iran, which has a warm-humid weather and a high solar irradiation, is the most favorable region to use PCMs. In Bandar Abbas, the reduction of a building's annual energy consumption may be up to 40% for the studied test case.

6. Using the PCM layer in the building's envelope has the potential of reducing 5.31–8.65 (kg/m^2) in CO_2 emission at the different climatic regions of Iran. The results suggested that Yazd and Bandar Abbas are associated with the highest and lowest annual reduction in CO_2 emission levels, respectively.

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Table 3. The potential of using the PCM layer in reducing CO_2 emission

Station	Annual reduction in CO_2 emission (kg/m^2)	
	Air system	Water system
Bandar Abbas	6.65	5.31
Tabriz	7.41	5.07
Tehran	8.60	6.86
Yazd	8.65	7.23

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