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PCM Phase Change Materials and Their Role in Reducing Residential Building Energy Consumption

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Original Research

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Abstract:

Attention to phase change materials in architecture as one of the new ways to reduce energy consumption has increased significantly worldwide. The aim of this article is to study the effects of using these materials and to determine the optimal conditions for using PCM in Tehran by simulating energy consumption. In this article, the types of phase change materials were studied and then the performance of a sample of them was simulated under different conditions (thickness and location) in a sample building in Tehran city to determine the optimal conditions for using PCM.

The optimum extent of energy consumption reduction occurs at low thicknesses of the phase change materials. As the thickness of PCM layer increases, the slope of the energy consumption reduction curve decreases, which is not economical due to the linear increase in the cost of using these materials. The best performance in reducing annual energy consumption by simulating energy consumption on an existing plan in Tehran is related to the east wall. Of course, if we simulate the performance of these materials in different walls by removing the interior walls and considering the entire building as one space with the same use, we will find that in this case the best performance is associated with the north wall, with a slight difference in the east and west walls.

Keywords: Phase change materials; PCM; Reducing residential building energy consumption; Heating and cooling set points; Electric heat pump

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1. Introduction

Apart from water, the best known PCM, salt hydrates are the main group of mineral PCMs [1]. The constituents of salt hydrates include a salt and water that combine to form a crystal network when frozen. These materials are sometimes used alone and sometimes as part of eutectic compounds. Their phase change temperature ranges from 15 to 117 degrees Celsius. Because of their low price and high availability, they are considered commercial [2]. Two examples of available and cheap salt hydrates are $CaCl_2{\cdot}6H_2O$ and $Na_2SO_4{\cdot}10H_2O$.

One of the advantages of these materials, which increase the efficiency of heat storage systems, is that they have a certain phase change temperature. In addition, the high thermal conductivity increases the rate of energy storage or release compared to other PCMs [3, 4]. Another characteristic is the high phase change enthalpy, which leads to smaller energy storage units. In addition, these materials experience less volume change than other PCMs during the melting or freezing process. One of the disadvantages of these materials is the formation of hydrates or other dihydrate salts within them, which in addition to the problems caused by phase separation and decomposition, also reduces the available volume for heat storage [5]. This problem can be reduced to some extent by using gels or concentrating mixtures. Another disadvantage is the corrosiveness of the salt hydrates in front of the storage containers, so the compatibility of

the containers with these materials must be tested before use. In addition, these materials have a higher degree of supercooling than other PCMs, which can be solved to some extent by adding core components [6].
Alawadhi has studied the thermal analysis of a brick containing PCM under hot weather conditions [7]. The use of PCM brick is expected to reduce the heat transfer from the outside, which occurs due to the absorption of heat gains in the brick during the day before it reaches the interior. In order to measure the effects of the different components in the brick design, this study also conducted a side study on the number and type of PCMs used and their position in the brick. The results show that the heat flux into the space can be reduced by 17.55% if three PCM cylinders are placed in the centerline of the brick. Increasing the amount of PCMs also has a positive effect on reducing the heat gain through the bricks [8].
The experimental results obtained by Kuznik et al. for frequent summer days show that the indoor temperature without PCM varies between 18.9 and 36.6 °C. While in the condition with PCM, the range of temperature fluctuation is between 19.8 and 32.8 degrees [9]. These results show that walls with PCM can reduce the temperature fluctuations by 4.7 degrees.
Ramakrishnan et al. studied the effect of phase change materials on reducing thermal stress caused by heat waves in Melbourne [10]. They used numerical methods and BioPCM for their study. The building under study is shown in figure 1. The results showed that the use of phase change materials can significantly reduce thermal stress and thus improve the health and comfort of occupants. They also showed that when selecting the phase change material, the temperature of the phase change and its quantity play an important role in its performance [11].
Panayiotou et al. first studied the performance of PCM in a residential building under Mediterranean conditions [12]. The three studied positions are shown in figure 2, 3, 4, where the parts from which each wall is divided are also shown. In all the cases studied, a PCM layer is also applied on the roof of the building, on the inside of the concrete slab just behind the plaster, as shown in the above figures. The reason for this is practical, such as protecting the material from being walked on and the fact that it cannot be placed inside the concrete slab, as this would affect the structural strength of the concrete slab. This can only be achieved by using microencapsulated PCM as described in many articles in the literature.
Baniasadi and his colleagues tried to optimize the thickness of PCM and the insulation layer from an economic point of view [13]. They used Energy Plus software for thermal modeling of the building shown in figure 5 and a genetic algorithm for optimization. For their study, they selected six cities in Iran, namely Tehran, Tabriz, Isfahan, Shiraz, Yazd, and Bandar Abbas. The optimization results showed that the optimal thickness for PCM is zero for all cities, while the value of the insulating layer changes depending on weather conditions. The optimal thickness of the insulating layer is close to zero in the southern parts of the country and more than 6 cm in cold areas [14].

2. Methodology

In this section, the problem of the wall containing phase change materials is first studied and explained by the numerical solution method and its heat transfer through the governing equations, and then the solution method through the Energy Plus software is explained. Next, the necessary parameters for the software are explained. Energy Plus and the Design Builder software are described.

2.1 Building description

In this section, the mathematical relations for modeling the roof and building walls with a layer of organic phase change material with a phase change temperature of 28 degrees Celsius in two hot, humid and cold climates (cities of Tehran and Tabriz) are presented. For this purpose, the heat transfer model is presented. One dimension was considered using explicit finite difference method and coding was done using C++ software. Meteorological information including hourly air temperature, wind speed and wind direction extracted from the website of Iran Meteorological Organization and the average weather conditions and duration of sunshine. They were created on the meteorological basis of Spark 1.

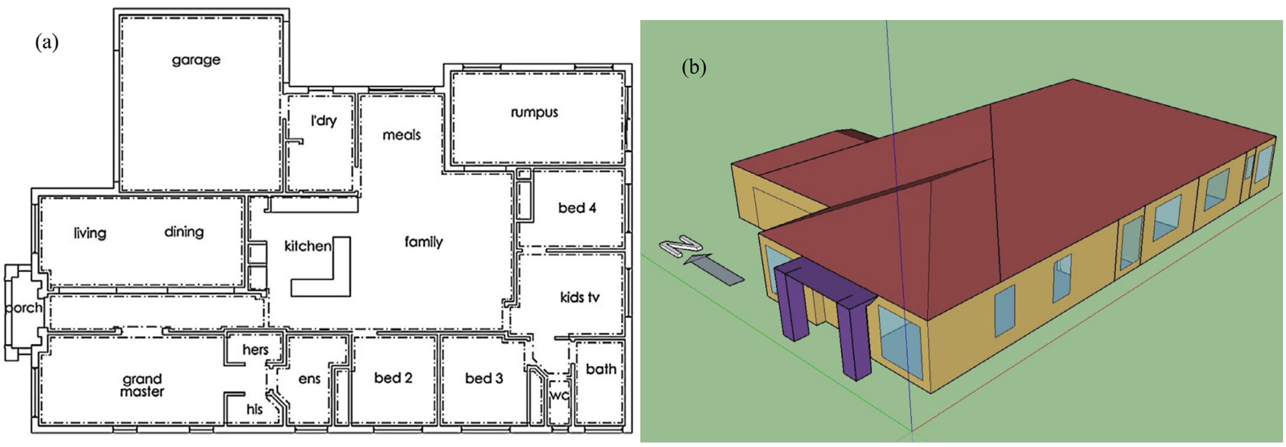

Figure 1. The building examined in the study by Ramakrishnan.

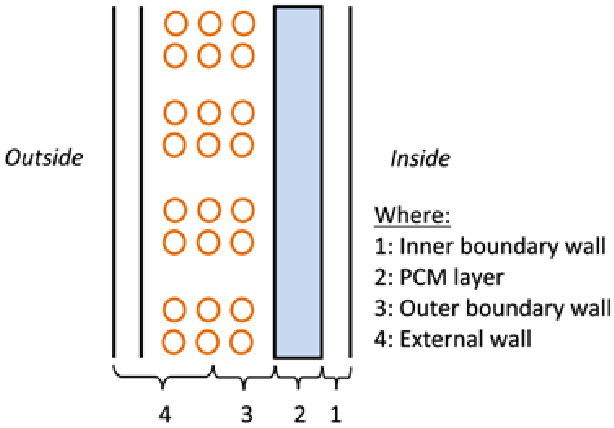

Figure 2. First arrangement for PCM.

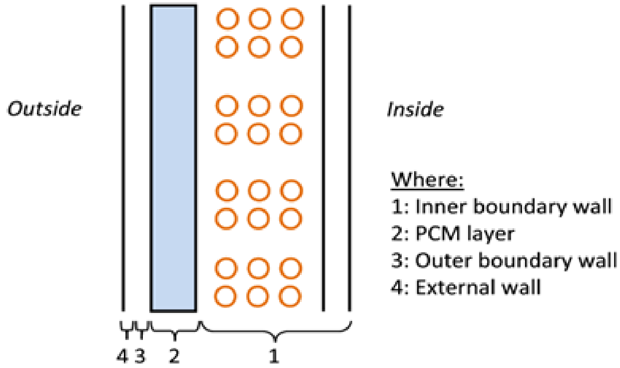

Figure 4. The third arrangement for PCM.

2.2 Roof and wall structure

External boundary conditions for the roof include displacement and radiation, and internal conditions include natural displacement. For radiation, the monthly average of solar radiation from reference [15] was chosen. For the forced motion of the flat roof as a function of wind speed, the model of Smith [16] was used, with wind speed and displacement heat transfer coefficient given.

$$h_c = 5.11 v_\infty^{0.78} \tag{1}$$

According to the studies and tests conducted on the structure of ordinary roofs, the phase change material should be placed between two layers and close to the outer layer of the roof. The proximity of the phase change material to the outside causes the absorption of the heat of the day when the sun shines, regulating the internal temperature of the building. And it reduces the heat entering into the interior of the house.

On the other hand, when the outside air cools down at night, the phase change material can go through the freezing process and is ready for use again during the day. The thickness of the phase change material is considered variable to compare the efficiency of different thicknesses. Another roof using a layer of a type 2 salt hydrate phase change material with a phase change temperature of 72 degrees Celsius was compared as a reference roof with a roof containing an organic phase change material (paraffin). Because of this 72 degrees Celsius phase change temperature is chosen so that the phase change material does not have the possibility to melt in the reference wall, so the efficiency of kerosene with a phase change temperature of 28 degrees Celsius is compared with it and the two roofs have the same thickness. To evaluate the numerical results, the results obtained for the roof were compared with the experimental results in the reference [17].

Boundary conditions for the wall include radiation and displacement on the outside and natural displacement on the inside. Heat transfer in the north, south, and east walls was simulated by solving the one-dimensional heat transfer equation using the explicit finite difference method with C++ software. The thickness of the phase change material was considered variable, and another wall with a layer of salt hydrate phase change material with a phase change temperature of 72 degrees Celsius was considered as a reference wall, under the condition that the phase change material in the reference wall does not melt. To allow comparison with the wall with the organic phase change material, it was simulated. If the insulation is in the wall structure, the best place for the phase change material is after the insulation layer. In this case, the temperature variation is minimized [18]. The forced displacement as a function of wind speed can be calculated for the outer surface of the wall according

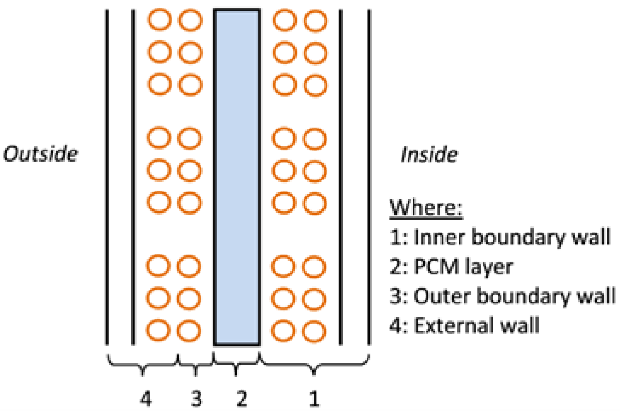

Figure 3. The second arrangement for PCM.

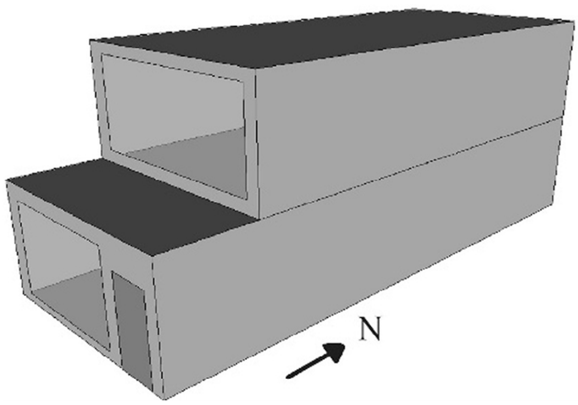

Figure 5. The building investigated in the study of Baniasadi.

to equation (2).

$$\begin{aligned} &\text{For windbreak wall } h_c = 5.15V_\infty^{0.81} \\ &\text{For windbreak wall } h_c = 3.5V_\infty^{0.76} \\ &\text{Normal displacement } h_c = 3 \end{aligned} \tag{2}$$

The indoor temperature of the building was assumed to be 25 degrees Celsius, and the simulation was performed for all months of the year. The internal temperature of the building was considered constant in order to evaluate the divine effect of the phase change material when the internal temperature was constant and the weather conditions were changing.

2.3 Mathematical formulation

To formulate the ceiling and the wall mathematically, the following hypotheses were considered:

- Heat transfer in the one-dimensional ceiling and wall and heat transfer in other directions are neglected.
- The thermal conductivity of roof and wall building materials (except the phase change material) is assumed to be constant and does not change with temperature.
- The phase change material is homogeneous and isotropic.
- The interfacial resistance is negligible.
- The ceiling and the wall initially have a uniform temperature T_i.
- The value of C_P for the phase change material is calculated in terms of equation (3):

$$\begin{aligned} C_P &= C_{PS} T < T_m - \Delta T \\ C_P &= C_{Pl} T > T_m + \Delta T \\ C_P &= C_{Pm} T_m - \Delta T < T < T_m + \Delta T \end{aligned} \tag{3}$$

The most common mathematical models for calculating the heat capacity of the phase change in heat transfer problems in phase change materials are the enthalpy and heat capacity methods.

Under phase change conditions, the interface may even disappear. Moreover, phase changes usually occur under non-isothermal conditions. In this case, tracking the interface may become difficult or impossible. Therefore, from a computational point of view, it is advantageous to present the equations in a new form. Using the heat capacity method for kerosenes, the heat capacity of the phase change is calculated according to equation (4), where L is the latent heat, ΔT is the half-life of the phase change, and C_{Pl} or C_{Ps} is the heat capacity of the phase change material. They are in liquid and solid states. In this method, the heat capacity is assumed to change linearly with temperature.

$$C_{Pm} = \frac{L}{2\Delta T} + \frac{C_{PS} + C_{Pl}}{2} \tag{4}$$

The nodal grid is shown for the ceiling and the wall. Based on the above assumptions, the equations and boundary conditions for the roof are given in equation (5):

$$\begin{aligned} &k\frac{\partial^2 T}{\partial X^2} = \rho c \frac{\partial T}{\partial t} \quad 0 < x < L \\ &-k\frac{\partial T}{\partial X} = q_{rad} + h \circ (T_\infty - T_{x=0}) \quad X = 0 \end{aligned} \tag{5}$$

q_{rad} is calculated only in sunny hours and considered zero in the other hours.

$$-k\frac{\partial T}{\partial X} = h_i(T_{x=L} - T_{room}) X = L \tag{6}$$

When the phase-changing substance is in the liquid state, equation (6) is transformed into equation (7) due to natural displacement:

$$k\frac{\partial^2 T}{\partial X^2} + h\Delta T = \rho c \frac{\partial T}{\partial t} \tag{7}$$

The natural displacement at the interface in the phase change state in kerosene is defined as equation (8), where T_m is the phase change temperature, β is the coefficient of expansion, μ is the kinematic viscosity, g is the acceleration due to gravity, C_{Pl} is the heat capacity in the liquid state, and h is the heat transfer coefficient. It is everywhere.

$$h = 0.072\left[\frac{g\left(\frac{T_w - T_m}{2}\right)\rho_l^2 c_{Pl} k_l^2 \beta}{\mu}\right]^{\frac{1}{3}} \tag{8}$$

3. Materials and methods

In this section, we discuss an example building using different types of phase change materials with different placement modes, considering the different climates in Iran in the Design Builder software. Finally, the proposed optimal mode is studied from the economic and environmental points of view. The general flow of this study is summarized in Fig. 6.

The building under study is a 4-story building with a total area of 828 square meters. The floor plan of the building is shown in Fig. 7. Each floor consists of two units, and each unit contains a kitchen, a bathroom, a toilet, two bedrooms, a dining room, and a reception room. The materials used for the building walls are listed in Table 1, and the schematic form of the materials is shown in Figs. 8 to 10.

The system used to heat and cool the building is a PTHP heat pump that includes a cooling coil, a heater, a constant volume fan and an electric heat pump. It should be noted that the desired system was selected in accordance with ASHRAE requirements. The set points for heating and cooling are 26 and 20 degrees Celsius, respectively.

3.1 The investigated climates

One of the factors affecting the performance of PCM is the weather conditions in the region. Therefore, two Iranian cities with different climatic conditions were investigated in this study.

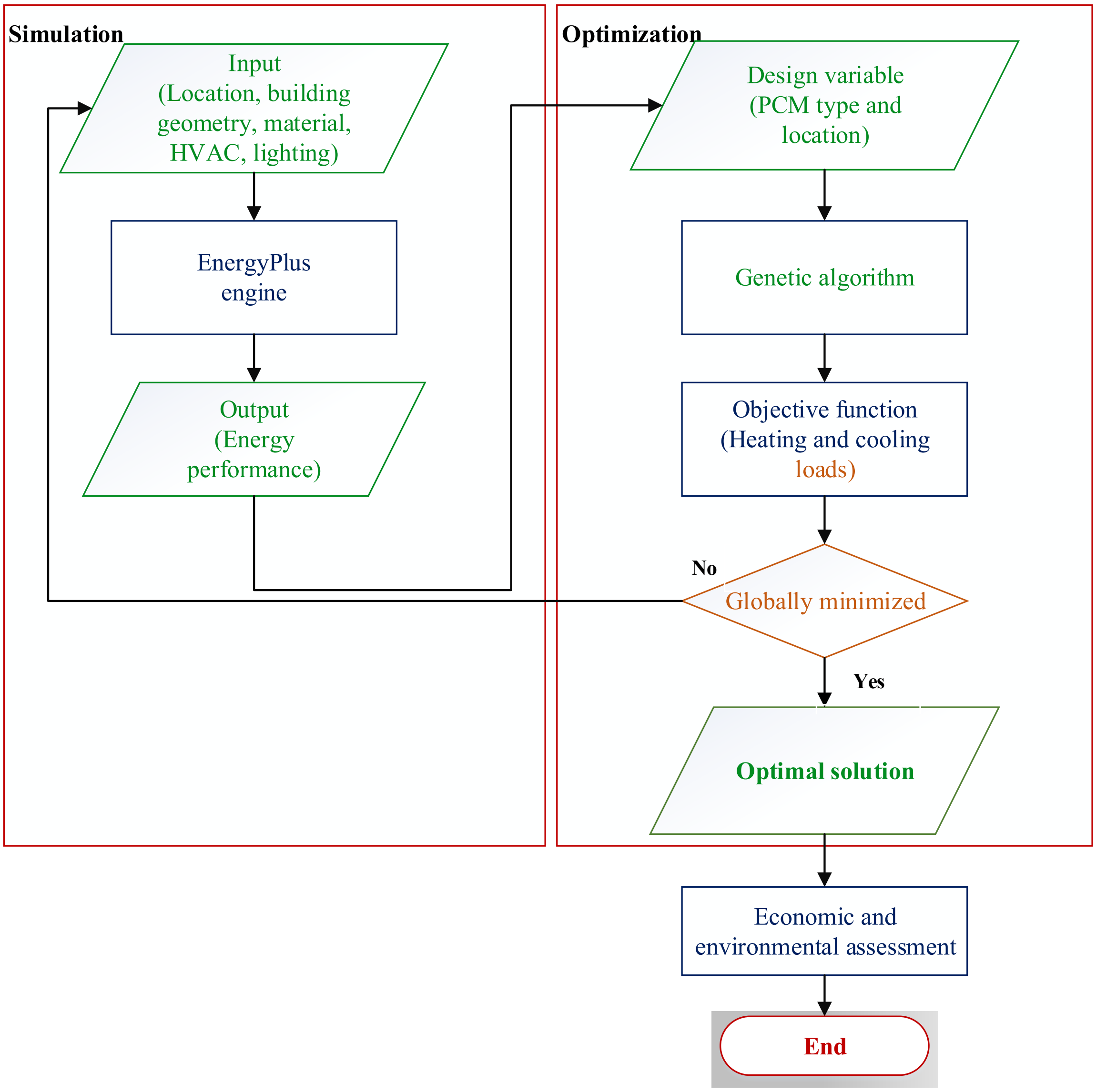

Figure 6. Study process.

1. Tehran

Tehran is located in an area between two valleys of the mountains and the desert and on the southern slopes of Alborz. Geographically, the city is located at 51 degrees 17 minutes to 51 degrees 33 minutes east longitude and 35 degrees 36 minutes to 35 degrees 44 minutes north latitude. The current extent of Tehran ranges from 900 to 1800 meters above sea level. This altitude decreases from north to south. Thus, the altitude in Tajrish Square in the north of the city is about 1,300 meters and in Railway Square, which is 15 kilometers lower, it is 1,100 meters. Tehran has a semi-arid climate. It is cooler in the north of the city than in other parts of the city due to its higher altitude. The barren structure, the presence of old gardens, parks and green areas along the highways, and the lack of industrial activities in the north of the city have also contributed to the fact that the air in the northern areas is on average 2 to 3 degrees Celsius cooler than in the southern areas of the city.

2. Tabriz

Tabriz is located in the west of East Azarbaijan Province and in the far east and southeast of the Tabriz Plain. The city is bordered by the Pekechin and Aun Bin Ali mountains to the north, the Gozni and Bababaghi mountains to the northeast, the Payan Pass to the east, and the slopes of the Sahand Mountains to the south.
Tabriz is bounded on the north, south, and east by the mountains and on the west by the flat land of the Tabriz plain and the salt marshes of Talcherud (Ajichai), and has developed into a relatively large pit or intermediate mountain plain. The altitude of this city varies from sea level from 1348 meters in Marand highway to 1561 meters in Zafaranieh district and the general slope of the land of Tabriz is towards the city center and then towards the west. The road distance between this city and Ardabil is 219 km, Zanjan 280 km, Urmia 149 km and Tehran 599 km. The area of Tabriz increased almost 20 times from 1901 to 1986, so that the

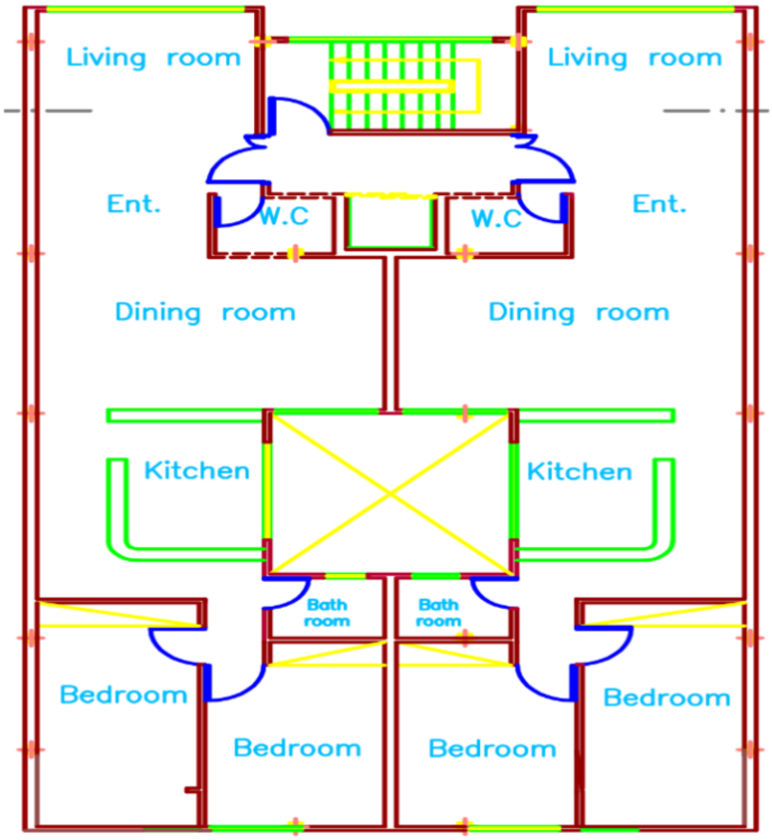

Figure 7. building plan.

area of this city increased from 7 square kilometers in 1901 to 17.7 square kilometers in 1956, 45.8 square kilometers in 1976 and finally 140 square kilometers in 1986. In 2005, the area of Tabriz grew to 237.45 square kilometers, of which 25.22 square kilometers, or 11% of the city's total area, was made up of obsolete structures.

4. Results and discussions

In this part, the results of ecological and economic simulation and investigation are presented. It is worth mentioning. Seven different modes were considered to find the optimal and ideal model to reduce electricity consumption for cooling and heating the buildings in Tehran and Tabriz. These seven modes include the basic model, the use of green roofs, the use of green roofs with phase change materials (M182Q23-M182Q25-M182Q27) when the phase change material is in the inner wall, and the use of green roofs with phase change material M182Q25 when the phase change material is in the middle and outer wall of the wall. The reason for using the heat capacity of 182 in this study is the optimal and acceptable condition of this heat capacity for the climate in Iran compared to other heat capacities. For the sake of comprehensibility and to avoid repetition of the results, it should be noted that, for example, the tem-

Table 1. Materials used in the building.

Specific Heat (kJ/kg.K)	Density (kg/m^3)	Thickness (m)	Materials	
800	1700	0.1	Brick work	External Wall
1400	35	0.0795	XPS Extruded Polystyrene - CO_2 Blowing	
1000	1400	0.1	Concrete block	
1000	1000	0.013	Gypsum plastering	
1000	2100	0.01	Asphalt	**Ceiling**
840	12	0.14	MW Glass Wool (rolls)	
-	-	0.2	Air gap	
896	2800	0.013	Plasterboard	
1400	10	0.1327	Urea formaldehyde foam	**The Floor**
1000	2000	0.1	Cast concrete	
840	1200	0.07	Floor screed	
1200	650	0.03	Timber flooring	

Figure 8. The schematic diagram of the external wall.

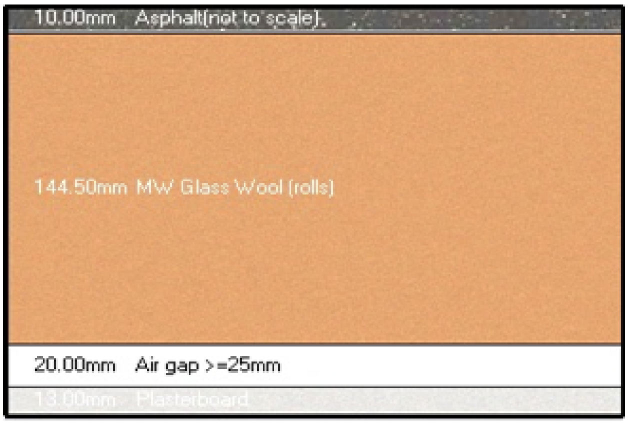

Figure 9. Schematic figure of the roof.

Figure 10. Schematic figure of the floor.

perature of 25 degrees, which is the average temperature of 23 degrees and 27 degrees, which are among the temperatures studied in this research to analyze and compare the results of the phase change is selected using materials, in the middle boundary and the outer surface of the wall.

1. Tehran

Seven optimal modes for the building in Tehran were studied. Figure 11 and 12 compare the monthly consumption of heating and cooling loads, respectively. According to Fig. 11, the electricity demand for heating in Tehran is highest from November to March and lowest from April to October. The highest amount of electric energy for heating is required in January, December, February, March and November. The highest amount of electrical energy for heating is consumed in all seven cases studied for the basic model, except in March for the green roof model.

Figure 12 shows that electricity consumption is required in four months of the year, from May to August, to meet the cooling load of the desired site. The maximum load required to supply the cooling load for Tehran city for each of the seven modes studied corresponds to August, July, June, and May, respectively. For each of the mentioned four months, the amount of electrical energy required in the base state is the highest compared to the other studied states from May to August and corresponds to 433.47, 6052.54, 6432.75 and 6641.99 kilowatt hours, respectively. This shows the reduction in energy consumption when green roofs and phase change materials are used. Reduction in electricity consumption in May, June, July, and August for GRM182Q25out (4173/74 kWh), GRM182Q27 (5802/82 kWh), GRM182Q25 middle (6178/37), and GRM182Q25 out (6373/02), respectively. Kilowatt hours) compared to the baseline condition. According to the obtained results, the best method to reduce energy consumption for cooling Tehran city for four months is GRM182Q27 mode, which leads to a reduction of electricity consumption by 3.95% compared to the baseline mode.

2. Tabriz

Seven optimal conditions were studied for the building in Tabriz. Figure 13 and 14 compare the monthly consumption of heating and cooling loads, respectively.

Figure 13 shows that the heating load is needed in 6 months of the year, January to March and October to December. The highest electricity consumption for heating is in the month of January for all seven modes, and the lowest consumption among the 6 months mentioned is in the month of October. After the month of January, the month of December is the month with the highest consumption of electrical energy.

For all states and months studied, the Bir ground state has higher power consumption than other states, and the lowest value in the ground state is for the time when GR M182Q23 is used.

The monthly cooling load consumption for all seven modes studied in Tabriz city is shown in Fig. 14. The amount of load required for cooling the desired site in Tabriz is for the months of May to August. It is highest in the months of July, August, June and May. The best mode in terms of reducing energy consumption is GR M182Q25, and the highest energy consumption is in the base mode.

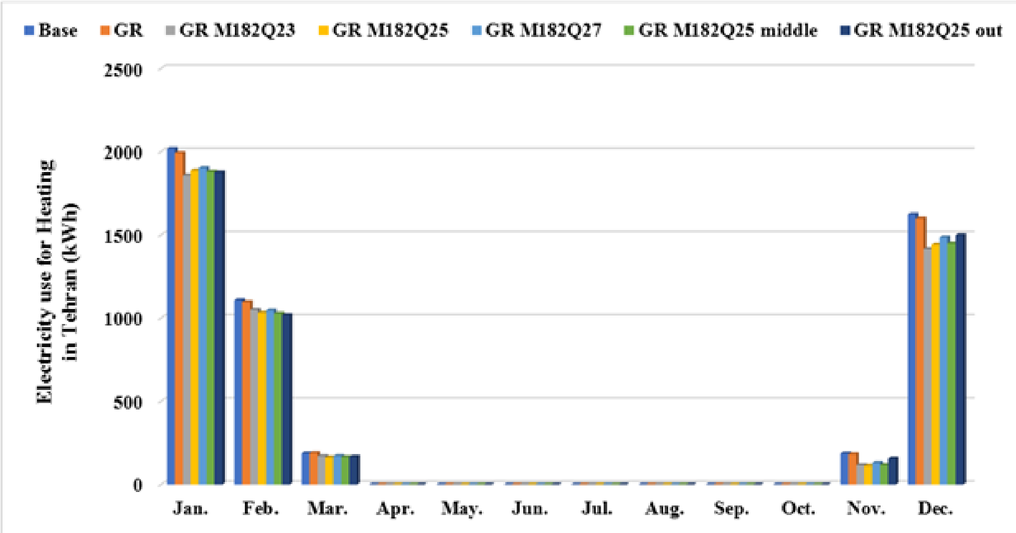

Figure 11. Monthly consumption of heating load for all seven investigated modes in Tehran city.

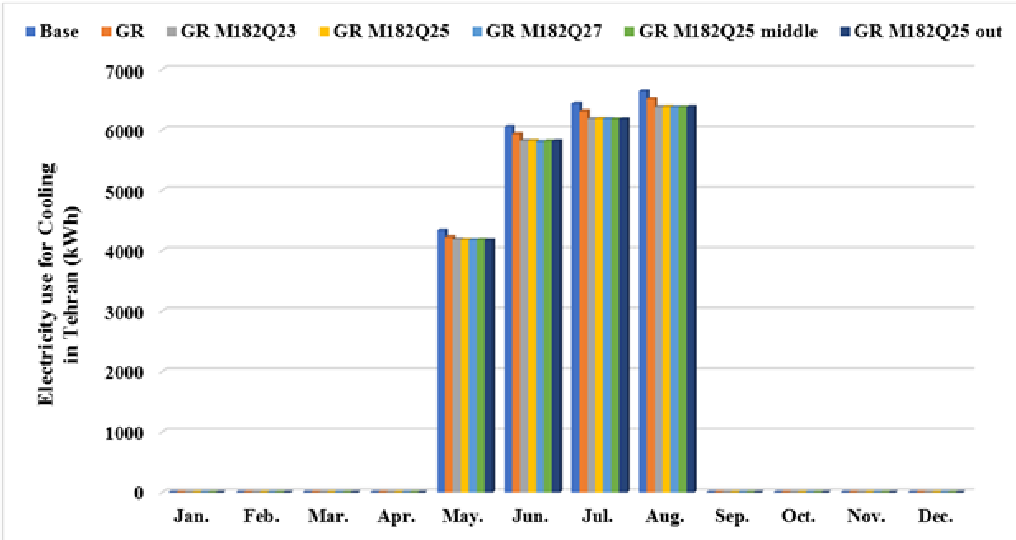

Figure 12. Monthly consumption of cooling load for all seven investigated modes in Tehran city.

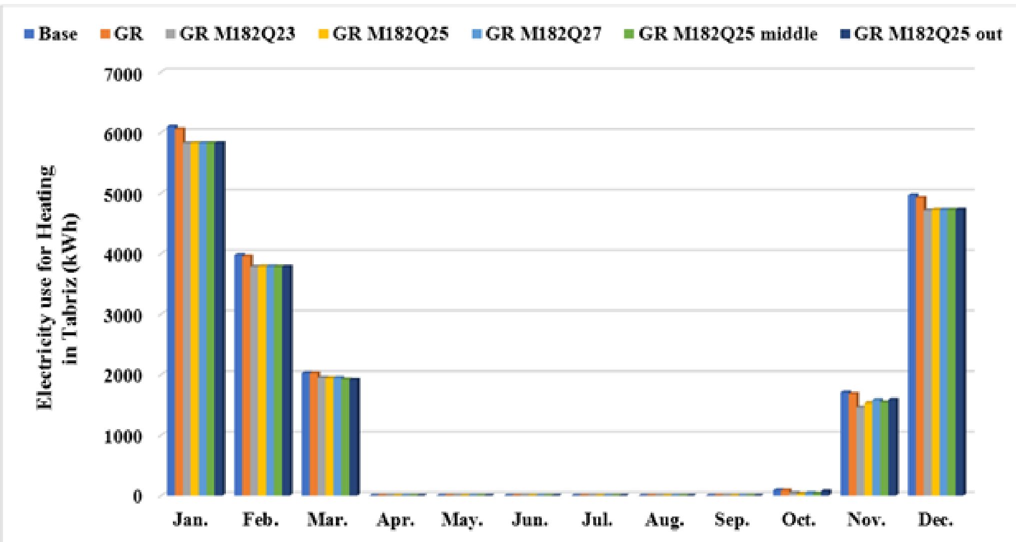

Figure 13. Monthly consumption of heating load for all seven investigated modes in Tabriz city.

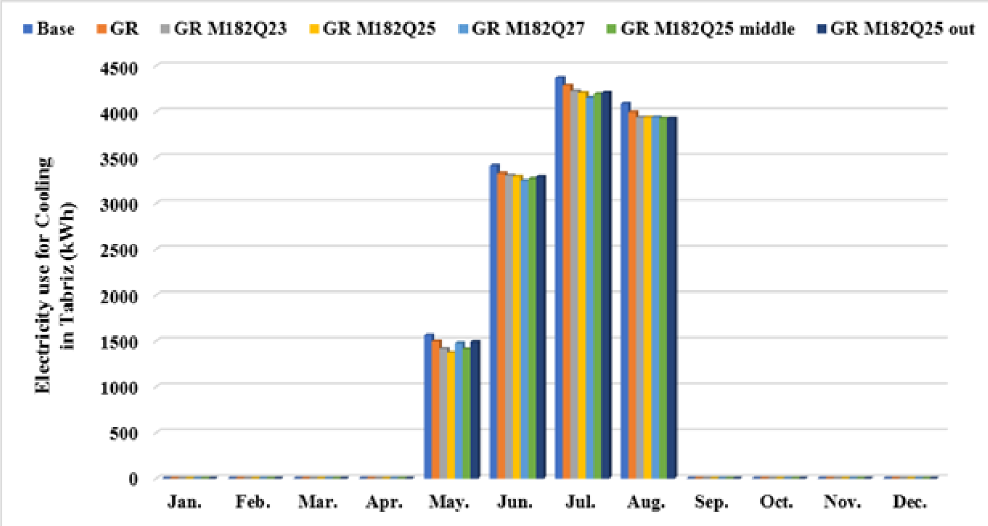

Figure 14. Monthly consumption of cooling load for all seven investigated modes in Tabriz city.

4.1 Economic analysis

In this part, we will study the case that has the lowest power consumption from an economic point of view. For Tehran GR M182/Q27, for Tabriz GR M182/Q25. Table 2 shows the investment costs. The results of the economic analysis are shown in Table 3. As you can see, the payback period for all cities is more than 50 years, which indicates that the use of PCM is not economical in Iran. The net present value is also negative. In this study, we optimized the cooling and heating loads by considering different types and arrangements of PCM in the exterior walls of a residential building under different climatic conditions. Then, the optimal conditions were studied from the economic and environmental points of view. The results of this study are shown below.

In Tehran, the best power consumption mode for the cold months of the year is GR M182Q23 mode, where power consumption has been reduced by 10% compared to the base model. For the electrical load required for cooling Tehran city, the electricity consumption is reduced in May, June, July and August respectively for GRM182Q25out (4173.74 kWh), GRM182Q27 (5802.82 kWh), GRM182Q25 middle (37/ 6178) and GRM182Q25 out (02.6373 kWh) compared to the baseline condition.

According to the obtained results, the best method to reduce energy consumption for cooling Tehran city for four months is GRM182Q27 mode, which leads to 3.95% reduction in electricity consumption compared to the basic mode.

To meet the load required for heating Tabriz city after the month of January, most of the electricity consumption is in the month of December.

For all states and months studied, the ground state consumes more electrical energy than other states, and the lowest value in the ground state is for the time when GR M182Q23 is used. The amount of load required to cool the desired site in Tabriz is highest during the months of May to August. The highest value is for July, August, June and May. The best mode to reduce energy consumption is GR M182Q25, and the highest energy consumption is in the basic mode.

The highest and lowest annual electrical energy consumption are for the base model (58758.88 kWh) and GR M182Q27 (56553.31 kWh), respectively.

For both cities, the payback period is more than 50 years, indicating the uneconomical use of PCM in Iran. The net present value is also negative.

Table 2. Investment cost.

Investment cost (USD)	Price (USD/m^2)	PCM type
48948	55	GR M182/Q25
33564	37	GR M182/Q27

Table 3. Net present value and payback period.

NPV (15 years) Dollar	PB	City
-32,245.48	77.8	Tehran
-31,185.30	87.3	Tabriz

Authors contributions
All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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