ORIGINAL RESEARCH

EVALUATION OF THE PERFORMANCE OF PHASE CHANGE MATERIALS FOR OPTIMIZING ENERGY CONSUMPTION IN BUILDINGS CONSIDERING VARIOUS CONDITIONS

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Abstract:

Among energy consumers, the building sector accounts for more than 40% of consumption. Therefore, reducing energy consumption in buildings is one of the solutions to reduce fossil fuel consumption. The use of phase change materials is one of the solutions to reduce energy consumption in buildings. Considering different types and arrangements of these materials in external walls, the optimization of cooling and heating loads in the two cities of Shiraz and Bandar Abbas in Iran was investigated. The building in question was modeled in Design Builder software and then optimized with a genetic algorithm.The results showed that phase change materials with a temperature of 25 degrees, which are placed in the inner layer of the wall, have optimal performance in terms of cooling load. These materials can reduce electricity consumption by about 4.5 to 5.5 percent for all cities. According to economic studies, this project is not justified due to the long payback period (more than 50 years).

Keywords: Phase change materials, reducing energy consumption in residential buildings, Design Builder, different climates of Iran

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1.Introduction

The energy challenge in the future is inevitable, and its important reasons include increasing population growth, increasing living standards and indicators, increasing transportation and communications, and other issues [1]. Therefore, we must seek solutions to expand the use of new technologies with the aim of reducing energy consumption and demand, increasing energy production, especially renewable energy, using energy resources optimally and effectively, and increasing the efficiency of energy-consuming equipment. On the other hand, many existing energy sources are periodic in nature, meaning that in a certain time interval, the source is able to produce maximum energy or there is no possibility of further extraction and exploitation of the energy source[2].

From another perspective, the performance of many energy-consuming equipment, especially heating, cooling, and air conditioning systems, which are major factors in energy consumption, is such that their energy consumption is maximum during a certain time interval and their energy consumption may be minimized during the rest of the hours, which has a great impact on reducing the efficiency of equipment performance and reducing the possibility of optimal use of energy resources [3].

Therefore, energy storage can be one of the methods by which the efficiency of these equipment can be increased [4, 5]. That is, by distributing and expanding the required heating or cooling load evenly throughout the day, it allows the use of heating and cooling equipment with smaller dimensions and lower power, which have higher efficiency and lower initial investment. Among energy consumers, the building sector accounts for about 40 percent of energy consumption, and therefore optimizing energy consumption in buildings is important [6]. According to the above, the use of energy storage methods is one of the solutions that can be used to reduce building energy consumption.

To assess the real sustainability of a building, the largest part of the energy consumption of buildings still relates to the operational part, which is influenced by several factors such as the efficiency of HVAC systems [7], the insulation of doors and windows [8-11], losses due to thermal joints [12] and the uncertain thermal performance of the wall [13]. Recent advances in the last decades have led to the optimization of the thermal performance of vertical walls in terms of heat transfer. In addition, the occurrence of heat losses along opaque walls accounts for a large amount of the total energy loss of the building [14], so the use of insulated walls has become sufficiently necessary. In this context, the insulating material is a layer that mainly contributes to the overall thermal behavior of opaque walls in the autumn and winter seasons, which reacts to the external atmospheric conditions with its specific thermophysical properties [15]. Insulation materials must ensure acceptable performance throughout the entire life cycle of a building, but thermal performance is not the only factor to be considered when selecting an insulator. The popularity of these materials in the construction sector has begun to develop with a comprehensive approach that also considers non-thermal properties such as sound insulation, fire resistance, water vapor permeability and the impact on the environment and human health. As a result, the market for environmentally friendly, sustainable and locally available insulation materials, characterized by good insulation performance and low energy consumption, is growing rapidly [16]. In addition, several studies have shown that the use of PCM (phase change material) as energy storage systems in buildings can lead to significant energy savings [17]. Phase change materials (PCM) are materials used to control the temperature of heating systems. These materials naturally adapt to environmental fluctuations without the use of mechanical equipment and in a completely intelligent way, only through their inherent tendency to

change phase, leading to a reduction in energy consumption. Considering the importance of the issue of optimizing energy consumption in industries, power plants and buildings, thermal energy storage and the use of phase change materials have been of great interest to many researchers and scholars in recent years. In this work, phase change materials (PCM), their properties, classification and various applications in thermal energy storage systems in buildings will be studied.
Optimization of a system containing PCM in a wall using a dynamic numerical method is very important [18].
The use of PCM system using nanofluids has also been investigated using numerical and experimental methods [19].
Also, combining the storage system with concrete in order to reduce energy consumption has been investigated using an experimental method [20].
A comprehensive review of various studies on PCM storage devices and a comprehensive review of technologies on PCM storage devices have been conducted [21, 22].
The use of PCM in solar panels and building wall shells has also been investigated in several specific cases [23, 24].

2. TYPES OF PCM

Various researches have been conducted to neutralize undesirable behaviors and achieve the inherent capabilities of PCM materials, which has led to the production of various PCM products. These products are the result of efforts made to stop the unwanted behavior of PCMs and achieve the best performance.
Increasing thermal conductivity is usually achieved by combining with a material with high thermal conductivity. This is done by incorporating a new material into the PCM or by embedding the PCM inside the network of another material. The first method is to combine metallic or graphite materials in the form of fibers, foams or powders with the PCM material, and the second method is to infuse the PCM material into the graphite network. For PCMs that cannot be inserted into the network, there is another solution by mixing the PCM with graphite in a compounding process. In this method, lower thermal conductivity is achieved compared to the infiltration into the network.
All of the above methods improve the performance of PCMs, but certainly one of the best ways to achieve better performance is to encapsulate the PCM. The main purpose of this is to maintain the liquid phase of the PCM and prevent it from coming into contact with the environment (because it may damage the environment or change its composition). In addition, the capsule surface acts as a heat transfer surface. In some cases, the capsules are also used as a structural element, which increases mechanical stability. PCMs are divided into two categories depending on the size of the capsule: macrocapsules with dimensions between 1 and 1000 mm; and microcapsules with dimensions between 1 and 1000 µm [13, 14]. macrocapsules can accommodate from a few milliliters to several liters of PCM depending on their dimensions. Capsules are usually made in the form of metal or plastic containers or bags in different sizes and shapes. Consideration should be given to the volume of the containers so that excessive size does not cause freezing only at the sides, thereby reducing the thermal conductivity of the PCM and heat transfer.
Microencapsulation is the placement of PCM materials in liquid or solid form inside capsules with a solid shell with a diameter of 1 to 1000 µm. Due to the high surface area to volume ratio of the capsules, encapsulation increases the rate of heat transfer to the environment and also improves mechanical stability. Also, due to the reduction of molecular distances to microscopic levels, the problem of phase separation and cycle stability is also reduced. In addition, it is possible to combine microencapsulated PCM materials with other materials such as cement blocks, bricks, concrete and gypsum boards. The disadvantage of microencapsulation is that they increase the amount of subcooling. Most recent research on these materials has

been aimed at reducing the size to the nanoscale.

Figure 1 shows a photograph of a commercial paraffin microcapsule manufactured by the German company BASF, with a capsule diameter between 2 and 20 µm, taken by electron microscopy.

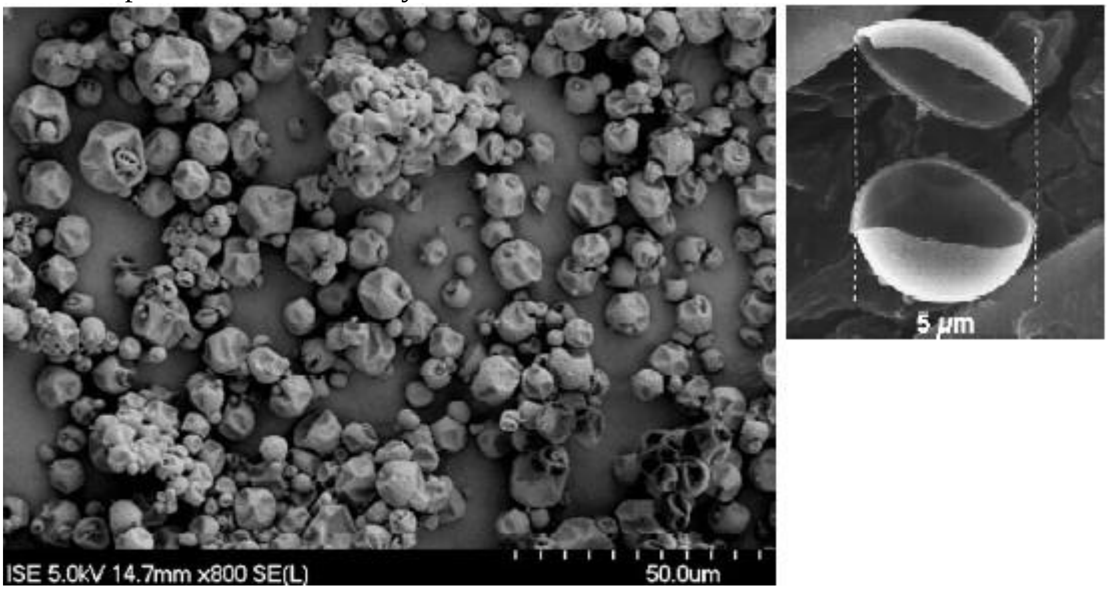

Figure 1. Electron microscope image of microcapsules manufactured by BASF (left) and an image of an opened microcapsule (right)

2.1 PCS

A special type of PCM is widely used in thermal storage systems. PCSs absorb and release latent energy during a phase change process in such a way that they always remain liquid. A good example of a PCS is obtained by mixing microencapsulated PCMs with water. In this case, the phase change material stores or releases latent heat, while the water acts as a carrier fluid. This allows the slurry to remain liquid even when the microencapsulated phase change material has undergone freezing. A PCS increases the storage density and therefore the capacity of the thermal storage system. Because more energy is transferred per unit volume of fluid, it ultimately improves the heat transfer coefficient. In practical applications (in active heating and cooling systems), PCS is usually stored in a tank and pumped through a piping network. This improves heat transfer coefficients and the use of smaller heat exchangers. One of the problems with using slurries is stratification due to the density difference between the phase change material and the heat transfer fluid. This creates layers with a higher content of PCM and, as a result, higher viscosity. Therefore, pumps with higher power are needed to circulate the slurry in this case. Another form of PCS is the emulsion slurry, which is obtained by directly mixing the PCM with a fluid (usually water). Compared to microcapsule slurries, these slurries do not contain shells that may decompose inside the system. However, since they tend to separate over time, they are less stable.

2.2 SSPCM

These materials are stable composites formed by dispersing PCM within another phase of material such as polyethylene. Their use has attracted attention due to their properties such as high heat capacity, acceptable thermal conductivity, and ability to maintain shape and form during the phase change process, thus eliminating the need for storage chambers. Figure 2 shows a paraffin-type PCM sheet with a stabilized shape.

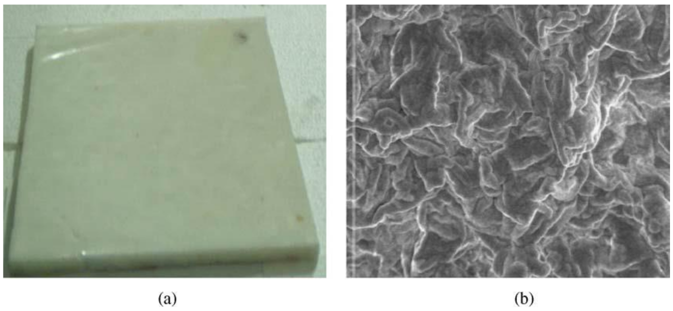

Figure 2. (a) Image of a PCM plate with stabilized shape (b) Image taken of the plate by electron microscope

3. MODELING

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 point of view. The general flow of this study is summarized in Figure 3.

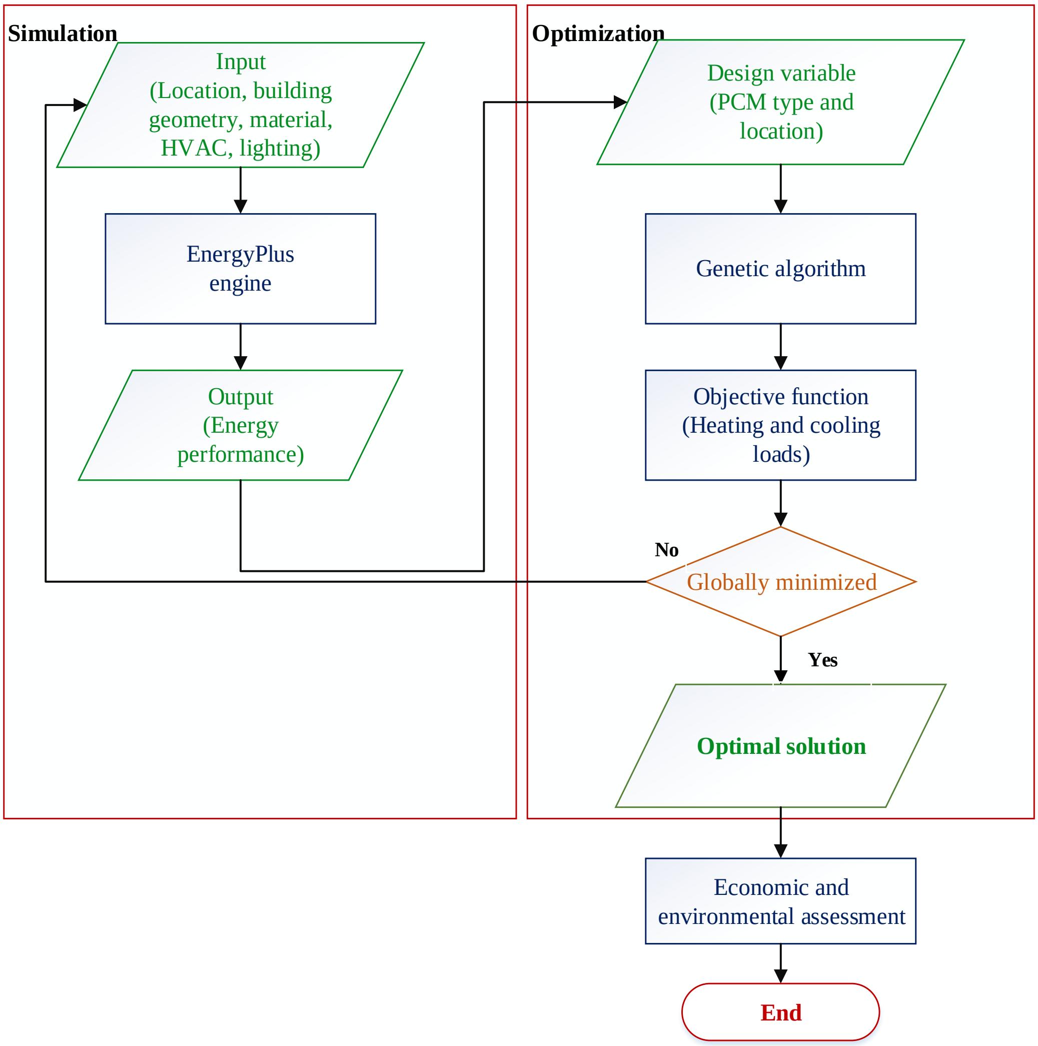

Figure 3. Study process

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 Figure 4. 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 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.

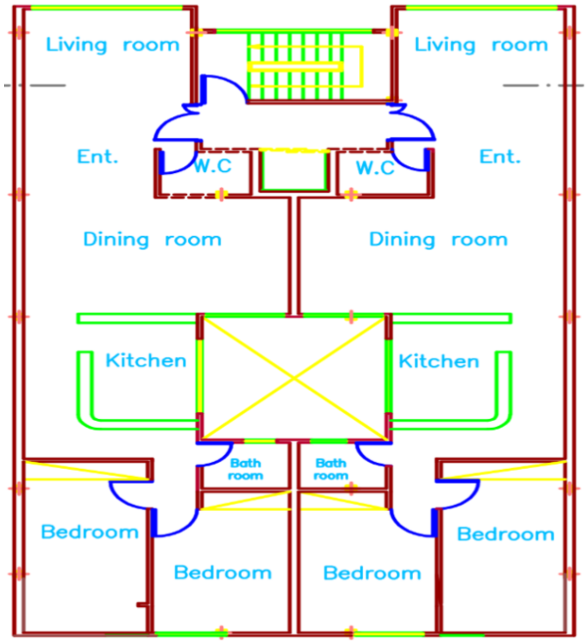

Figure 4. Building plan

The materials used for the building walls are listed in Table 1

Table 1. Materials used in the building

Materials	Specific Heat (kJ/kg.K)	Density (kg/m3)	Thickness (m)	
Brick work	800	1700	0.1	External Wall
XPS Extruded Polystyrene - CO2 Blowing	1400	35	0.0795	
Concrete block	1000	1400	0.1	
Gypsum plastering	1000	1000	0.013	
Asphalt	1000	2100	0.01	Ceiling
MW Glass Wool (rolls)	840	12	0.14	
Air gap	-	-	0.2	
Plasterboard	896	2800	0.013	

Urea formaldehyde foam	1400	10	0.1327	The Floor
Cast concrete	1000	2000	0.1	
Floor screed	840	1200	0.07	
Timber flooring	1200	650	0.03	

The placement of phase change materials is shown in Figures 5 to 7.

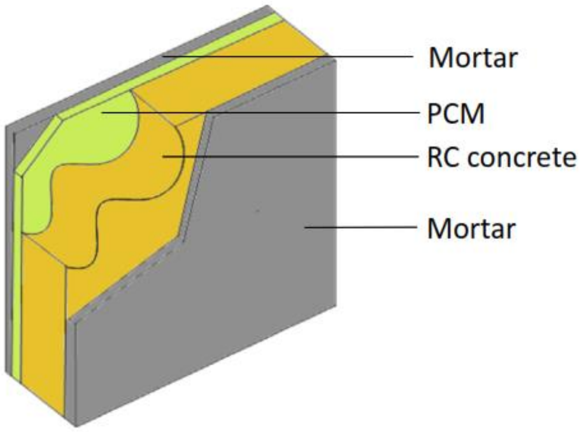

Figure 5. Types of PCM placement

The use of PCM on the roof has a significant effect on delaying peak temperatures and delays the peak temperature time by about 3 hours compared to conventional buildings. The thickness of the PCM and the slope of the roof are also factors affecting the thermal behavior of the roof.

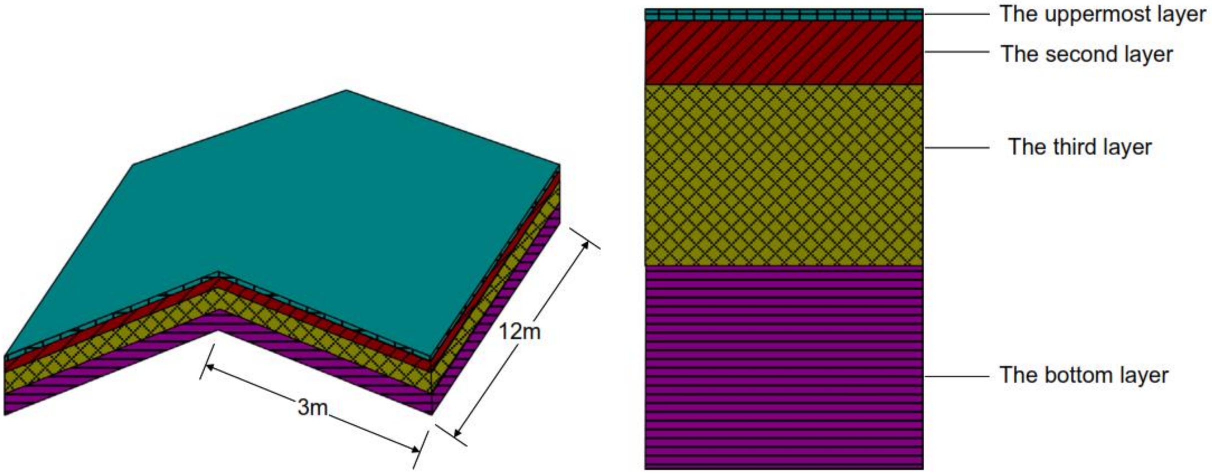

Figure 6. PCM placement on the roof

The optimal location of the PCM is close to the outer layer of the wall if the layer thickness, heat capacity, and melting temperature are high, while it is close to the inner layer if the inner surface temperature of the wall is high.

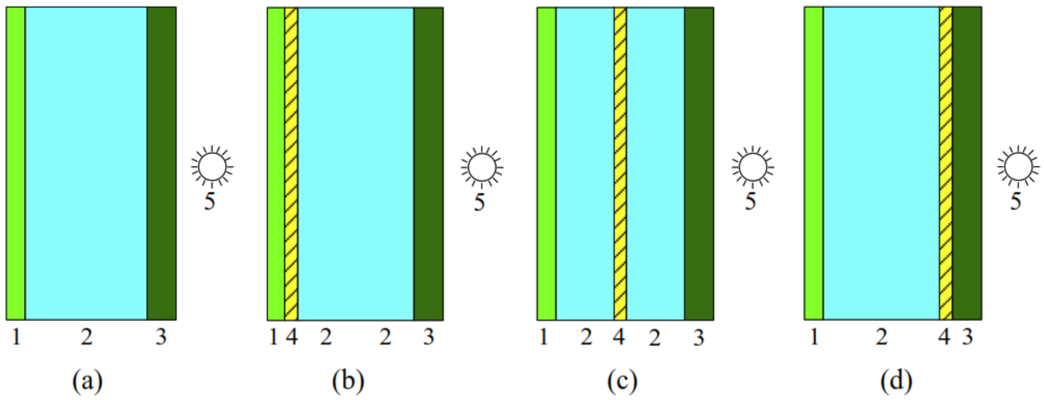

Figure 7. PCM placement in the external wall (yellow color indicates PCM)

External boundary conditions for the roof include displacement and radiation, and internal conditions include natural displacement

$$h_c = 5.11 v_\infty^{0.78} \quad (1)$$

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. speed can be calculated for the outer surface of the wall according to equation (2).

$$h_c = 5.15 V_\infty^{0.81} \quad \text{For windbreak wall}$$
$$h_c = 3.5 V_\infty^{0.76} \quad \text{for windbreak wall} \quad (2)$$
$$h_c = 3 \quad \text{Normal displacement}$$

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.

4. 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 Ti.

-The value of Cp for the phase change material is calculated in terms of equation (3):

$$C_P = C_{PS} \; T < T_m - \Delta T$$
$$C_P = C_{Pl} \; T > T_m + \Delta T \quad (3)$$
$$C_P = C_{Pm} \; \mathrm{T_m} - \Delta\mathrm{T} < T < T_m + \Delta T$$

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 Cpl or Cps 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.

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

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):

$$k\frac{\partial^2 T}{\partial X^2} = \rho c\,\frac{\partial T}{\partial t} \;\; 0 < x < L$$
$$-k\frac{\partial T}{\partial X} = q_{rad} + h_{\circ}(T_{\infty} - T_{X=0})\; X = 0 \quad (5)$$

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

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

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

$$k\frac{\partial^2 T}{\partial X^2} + h\Delta T = \rho c\,\frac{\partial T}{\partial t} \quad (7)$$

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

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

5. RESULTS AND DISCUSSION

The modeling results have been considered for the two cities of Bandar Abbas and Shiraz. Seven cases have been investigated for each of the cities and optimal cases are obtained. In addition to energy calculations, economic calculations have also been performed and are presented.

5.1 Bandar Abbas

Seven optimal cases have been studied for a building located in Bandar Abbas. Figure 8 compares the monthly cooling load consumption. Due to the very hot weather in the area, there is no need for heating load in any of the months of the year.

It is observed that the highest and lowest electrical energy consumption is in July and March. This value is zero in January, February, November and December and the cooling and heating systems are off. The base model and the green roof consume more energy than the other models studied. The lowest electric energy consumption and the most efficient model, in March, GR M182Q25 with an electric energy consumption of 3985.68 kWh with a 3.21% reduction in electric energy consumption compared to the base model, in April and May, GR M182Q27, with an electric energy consumption of 5122.18 and 7342.21 kWh respectively and a 4.32% and 4.29% reduction in energy consumption compared to the base model, in June to September, GR M182Q25 with an electric energy consumption of 8045.99, 9048.70, 58.38 and 8974 kWh respectively and a 3.92%, 3.69%, 3.78% and 3.79% reduction in energy consumption compared to the base model and in October GR M182Q23, with 6262.21 kWh and 3.52% reduction in consumption compared to the base model is the best case. The highest and lowest annual electrical energy consumption are respectively related to the base model (58758.88 kWh) and GR M182Q27 (56553.31 kWh). The best model for reducing electrical energy consumption among the seven relevant cases for Bandar Abbas is GR M182Q27, which has a 3.75% reduction in electrical energy consumption compared to the base model.

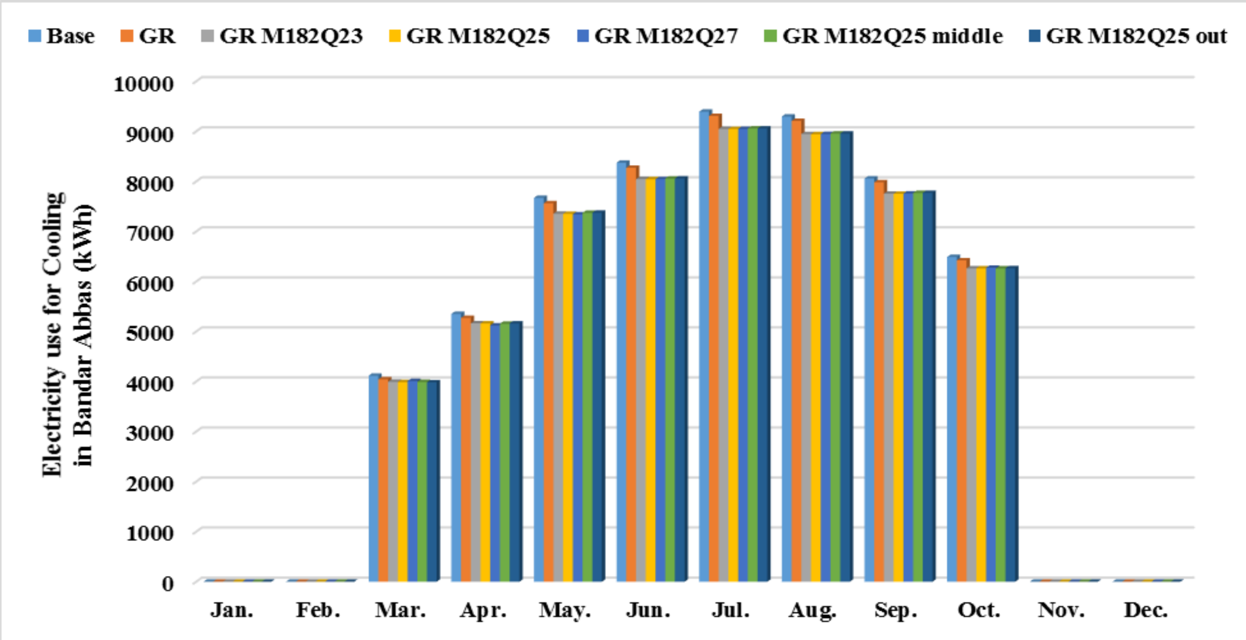

Figure 8. Monthly cooling load consumption for all seven cases studied in Bandar Abbas city

Shiraz

Seven optimal modes have been studied for a building located in Shiraz. In Figure 9 and Figure 10, the monthly heating and cooling load consumption are compared, respectively. The heating load required in Shiraz is for 5 months of the year, and in the remaining months of the year, there is no need for electrical heating load, these months are January, February, March, November and December. The highest amount required to supply the heating load is for the basic mode. And the best mode for saving electrical energy consumption to supply the heating load is for the GR M182Q25 mode. The average highest heating load required for Shiraz is for the months of January and December, respectively, and the lowest amount is for March.

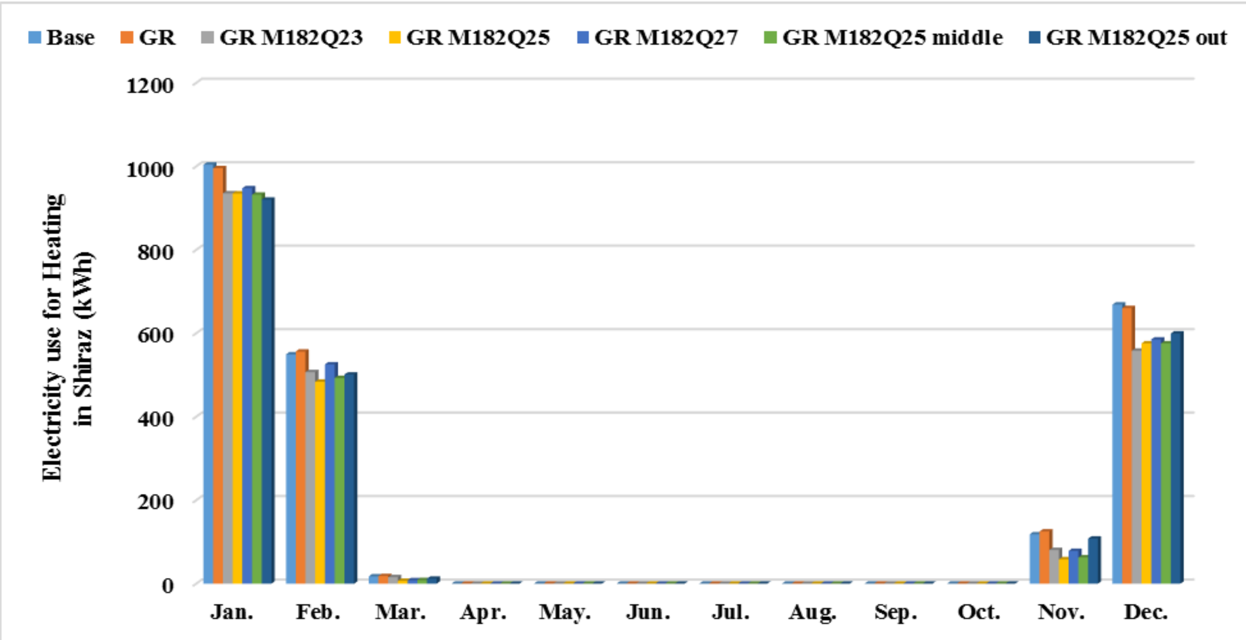

Figure 9. Monthly heating load consumption for all seven studied cases in Shiraz city

The cooling load required in Shiraz city is for 4 months of the year and there is no need for electrical load for cooling in the rest of the year.

The highest cooling load required for all months of the year is for the basic mode. The best mode is to use GR M182/Q25 Middle.

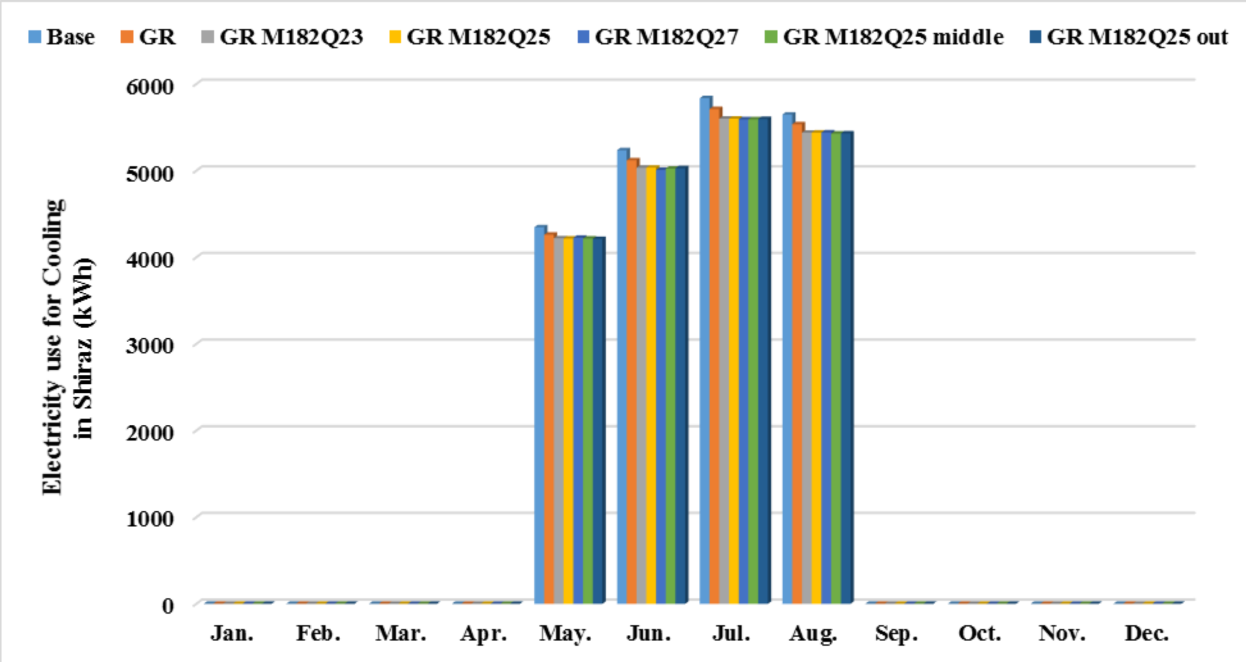

Figure 10 - Monthly cooling load consumption for all seven studied cases in Shiraz city

5.2 Economic Analysis

Table 2 shows the investment cost. The results of the economic analysis are presented in Table 3. As can be seen, for all cities, the payback period is more than 50 years, which indicates that the use of PCM in Iran is not economical. The NPV is also negative.

Table. 2. Investment cost

PCM type	Price (USD/m2)	Investment cost (USD)
GR M182/Q25	55	48948
GR M182/Q27	37	33564

Table. 3. Net present value and payback period

City	PB	NPV (15 years) Dollar
Bandar Abbas	54.2	-30,123.26
Shiraz	111	-46,106.39

6. CONCLUSION

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, Shiraz and Bandar Abbas. 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 point of view. for all cities, the payback period is more than 50 years, which indicates that the use of PCM in Iran is not economical, The NPV is also negative.

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