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# Energy Consumption Optimization Using Phase-Change Materials in The Tabriz Mellat Bank Head Office Building

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***Abstract:*** *In present study, Tabriz Mellat Bank head office building was specifically modeled using the design builder software, and, then Bio PCM (Bio phase-change) materials were used in its external walls. The present study consists of three sections. In the first section, the phase-change materials were used in the inner layer of the wall and each of them were simulated. In the second section, the phase-change materials were used in the middle layer, and finally, in the third section, all the phase-change materials were used in the outer layer of the building. Simulation was carried out using the energy simulation engine (Energy plus software). In this software, simulation is performed in hours using the weather data of Tabriz, which is in the TMY2 format. After obtaining annual energy consumption in each of the above-mentioned scenarios, in each layer, the best type of phase-change material was selected, and then, among them, the most effective material was selected. Simulation of 12 types of phase-change materials in three layers of the wall showed that the best result was obtained by using the m91q29 material with an annual energy consumption of 103706 kWh and the air source unitary heat pump and the worst result was obtained using the m27q29 material in the middle layer with an annual energy consumption of 13,216.1 kwh and a unitary heat pump. Moreover, simulation of different heat pumps showed that two air-to-water heat pump with integrated boiler and without boiler with an annual energy consumption of 37818.31 kWh had the best result and the worst results were observed in using GSHP unitary Water to air with an annual energy consumption of 111494.84 kwh. Considering the optimal PCM and heat pump, it was conclude that the best state is the case in which the m91q29 material is placed in the inner layer of the wall, and one of the two ASHP Air-to-water Heat Pump, Integrated Boiler, Water Convector and ASHP Air-to-water Heat Pump, Water Convector provides cooling or heating. Moreover, the weakest state is the case in which the m27q29 material is used in the middle layer and the water-to-air geothermal heat pump is used. Given the annual power consumption in the simple state (92438.79 kWh) and the optimal state (21861 kWh), it was concluded that using the optimal PCM and the most desired heat pump results in 76% reduction in power consumption, indicating the significant effects of these two parameters. Moreover, according to the numerical values of the annual power consumed by the heat pump in the simple state (92438.79 kWh) and the weakest state (88569 kWh), only 4.1% reduction in power consumption was observed.*

***Keywords:*** *Phase Change Material, Heat Pumps, Energy Consumption Optimization*

## INTRODUCTION

The permanent increase in greenhouse gas emissions as well as fuel prices are the main motivations for more effective use of renewable energy sources. In many parts of the world, direct solar radiation is considered as the most important source of energy. Scientists look for new and renewable energy sources across the world. One solution is to develop energy storage devices that are as important as the new energy sources. Energy storage in the right forms, that can be converted to required form, is a competition among the modern technologies. Energy storage not only reduces the disparity between existing energies and energy demand, but also improves the efficiency and reliability of energy systems. Energy storage will result in energy saving and make the systems more economical by reducing energy dissipation. In Iran, energy consumption in commercial and residential units is about 40% of total energy consumption (Torki, 2013). In this section, most of the used energy is the electrical energy and its most important uses are in heating and cooling and lighting. Over the past three decades, energy shortage and its high price, as well as environmental concerns, have made it necessary to prevent energy dissipation. In addition, the need for additional energy storage and elimination of the gap between energy production and consumption have been paid attention more than ever. Energy storage may be in the form of tangible heat in liquids and solids, binding energy (latent heat) or chemical energy (or products in a reversible chemical reaction) (Abhat, 1983; Garg et al., 2012).

Among the aforementioned thermal energy storage techniques, storing energy in the form of latent heat is more acceptable technique due to the high density of energy storage and its characteristics in storing heat at constant temperature due to phase change. The phase change can occur in the forms of solid-solid, solid-liquid, solid-gas, liquid-gas, and vice versa. In the solid-solid phase-change, the heat is stored during changing from a type of crystal to another one. These changes generally have low energy and small volume variation compared to the solid-liquid phase change. The most important materials in this type of phase change are organic solid solutions of Pentaerythritol (latent energy=323 kJ / kg and melting point=188 °C), Pentaglycerin (latent energy=216 kJ / kg = Cold energy and melting point= 81 °C), Lithium sulfate (latent energy=214 kJ / kg and melting point= 578 °C) and $KHF_2$ (latent energy=135 kJ / kg and melting point= 196 °C) (Cabeza, 2007; Athienitis et al., 1997).

This research is applicable in initial survey of zero-energy buildings. In these buildings, the first step is to determine the amount of energy required at different hours and then, to reduce these needs using common methods such as proper insulation, use of radiant light and heat of the sun, etc. In present study, the effect of using PCM materials on reducing building energy consumption will be studied.

The use of PCM in the wallboard was introduced in 1996 by Scalat et al. Their opinion was that using PCM in the wallboard of the building could keep the temperature in the desired indoor temperature range for a longer period after the ventilation system was turned off.

In 2007, Cabeza et al. presented a new method for bending cement and PCM using the concept of micro-encapsulation. In their proposed method, energy storage takes place, while tensile and compressive strengths and in general, their mechanical strength do not change even after 6 months compared to conventional concrete.

Zu et al. have developed a model by which the effects of various parameters such as thickness, conductivity, melting point and PCM latent heat capacity on the PCM layer used for the passive solar heating in the ceiling were shown. Based on their model, the used PCM layer should not have a latent heat less than $h_f$ = 120 kJ/kg and a conductivity coefficient less than k = 0.5 W/mK and its thickness should not exceed d = 20mm.

## Method

### Sample space

To analyze the effects of states and different phase change materials on the studied building, first, the sample space is defined. In this modeling, the Mellat Bank 6-storey building, which faces south, was considered. It was a civil building. Accordingly, the temperatures of zones in the heating and cooling were considered 20 and

24 ° C, respectively. The number of people per square meter was considered 0.111 based on the ASHRAE standards (i.e. per a square meter of space, 0.0188 people were considered) and the presence of people in the building was considered based on the timetable proposed by the software, which is based on the ASHRAE standards. The amount of warm water consumed per person per day was considered 0.2 liters, and the fresh air intake per person per second was considered 10 liters. The illuminance of the building was 150 lux and the heat generated by the equipment was 3.90 w / m2, and in this building, the air conditioning system is a heat pump. After the initial modeling of the building, it was tried to examine the effects of phase-change materials on the building. For this purpose, the phase-change materials available in the database of software were chosen. The software contains 12 types of PCM materials.

**Simulation method**

In order to simulate the building, first, layout and location of the phase-change material were examined.

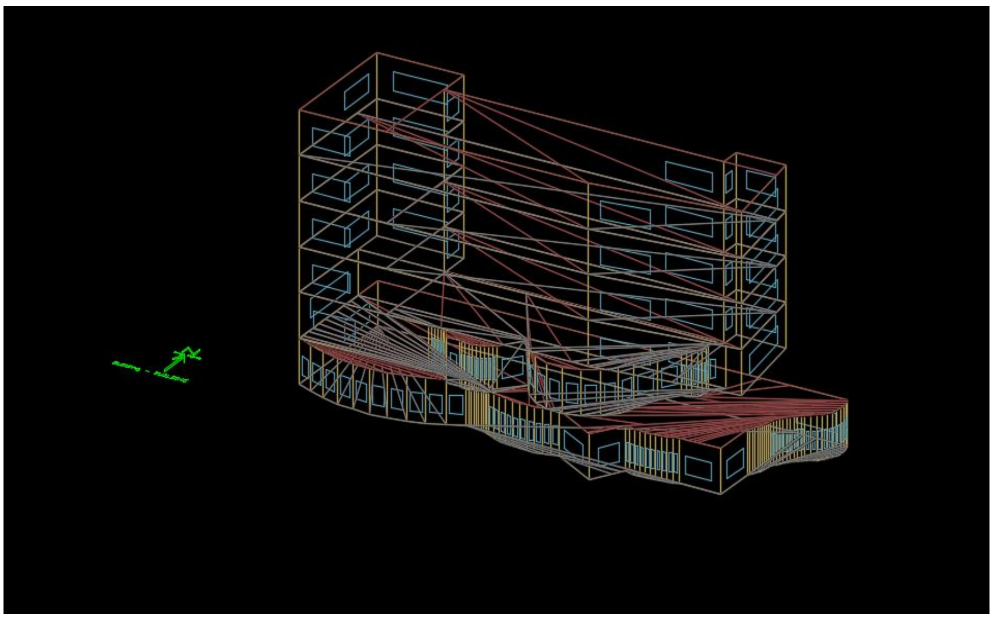

**Figure1.** The schematic form of the building

For this purpose, using the phase-change material in the outer walls of this building was examined, and then, the specifications of floor, ceiling and walls were determined in the state without using the phase-change material in the EnergyPlus software and the results of using different states and types of materials were obtained using aforementioned software. As previously mentioned, the building is located in Tabriz City and weather conditions of it were obtained from the database of EnergyPlus software. In the sample space, ceilings, facade and windows were in accordance with the main map and no changes were made to them. However, outer walls were examined and analyzed in two states: 1. a state including no change and no phase-change material; 2. a state including the changes in phase-change materials.

**Specifications of the floor, ceiling and windows**

- **Specifications of windows**

In all walls, the windows constitute 30% of the walls. All windows are of transparent double-glazed windows with a thickness of 6 mm and an average of 13 mm air in the middle layer. It should be noted that its U-value is equal to 2.66 $^{wat}/_{m^2k}$.

- **Specifications of ceiling**

In all states, the used ceiling is the same as the original composition, and no change was made in the composition of the ceiling. Specifications of different materials have been taken from the tables presented in the 19th chapter of Iran's National Building Regulations and approved by the construction engineering organization. In Table 1, the full specifications of the outer, middle and inner layers as well as their thermal characteristics (required for analysis) are listed. The thermal characteristics of building materials listed in Tables 1 and 2, were derived from the tables presented in the 19th chapter of Iran's National Building Regulations.

**Table 1.** Characteristics of materials used in the roof

| Layer | Material | Thickness (m) | Thermal conductivity w/m°k | Density Kg/m3 | Reference standard |
|---|---|---|---|---|---|
| 1 | Moisture insulation | 0.0508 | 1.15 | 1000 | the 19th chapter of Iran's National Building Regulations |
| 2 | Cement coating | 0.0254 | 0.95 | 1800 | the 19th chapter of Iran's National Building Regulations |
| 3 | Pumice | 0.0508 | 1.15 | 1500 | the 19th chapter of Iran's National Building Regulations |
| 4 | Concrete block | 2032 | 1.63 | 2300 | the 19th chapter of Iran's National Building Regulations |
| 5 | Plaster | 0.0254 | 0.3 | 900 | the 19th chapter of Iran's National Building Regulations |

- **Floor**

After the roof, the composition of floor was introduced to the software. Similarly, the layers of floor were simulated in the software according to the main design presented by the designer. The characteristics of conductivity and density were also derived from the 19th chapter of Iran's National Building Regulations.

**Table 2.** Characteristics of materials used in the roof

| Layer | Material | Thickness (m) | Thermal conductivity w/m°k | Density Kg/m3 | Reference standard |
|---|---|---|---|---|---|
| 1 | Ceramic | 0.0254 | 0.85 | 1000 | CIBSE |
| 2 | Cement coating | 0.0254 | 0.95 | 1800 | the 19th chapter of Iran's National Building Regulations |
| 3 | Heavyweight concrete | 0.2032 | 1.15 | 2300 | the 19th chapter of Iran's National Building Regulations |
| 4 | Plaster coating | 0.0254 | 0.3 | 900 | the 19th chapter of Iran's National Building Regulations |

- **Outer walls**

In present study, the outer wall were analyzed once with the same main composition, and then, different layouts were applied to them. In order to determine the optimal state, locations of the phase-change materials were changed by changing the composition of wall layers. Each layout has been studied, but because of limited space available for this article, only the results of third layout are presented here.

**1. The first layout: using the phase-change material in the inner layer**

As the name of this layout suggests, in this arrangement, the phase-change material is placed in the inner layer of the building. In this case, the phase-change material is placed in the inner layer of the wall, cement is placed in the outer layer, followed by cement coating, cement block, glass wool insulation and phase-change material, respectively and eventually, finish and plaster products are located.

**2. The second layout: using the phase-change material in the outer layer**

In this case, the phase-change material is placed in the outer layer of wall, after the finishing cement and cement blocks. In this case, the phase-change material is closer to the outer layer. Insulation, which is glass wool in our sample space and has a thickness of 130 mm, is placed in the inner layer.

**3. The third layout: using the phase-change material in the middle layer**

In the third state, the phase-change material is located between the two insulating layers located in the middle layer of wall. In this case, the phase-change material is placed in the middle layer and covered on both sides by the insulating layers with half the thickness of the previous state.

**Table 3.** Properties of the wall components in the state of using PCM in the middle layer

| Layer | Material | Thickness (m) | Thermal conductivity w/m°k | Density Kg/m3 | Reference standard |
|---|---|---|---|---|---|
| 1 | Cement coating | 0.01 | 0.95 | 1800 | the 19th chapter of Iran's National Building Regulations |
| 2 | Tile | 0.1 | 0.95 | 1800 | the 19th chapter of Iran's National Building Regulations |
| 3 | Glass wool insulation | 0.65 | 1.15 | 1500 | the 19th chapter of Iran's National Building Regulations |
| 4 | Bio PMC | Each material has its specific value | Each material has its specific value | Each material has its specific value | the 19th chapter of Iran's National Building Regulations |
| 5 | Glass wool insulation | 0.65 | 1.15 | 1500 | the 19th chapter of Iran's National Building Regulations |
| Plaster | | 0.0254 | 0.3 | 900 | the 19th chapter of Iran's National Building Regulations |

**Data analysis**

- **Hourly heat pump energy consumption in warm months, PCM in middle layer**

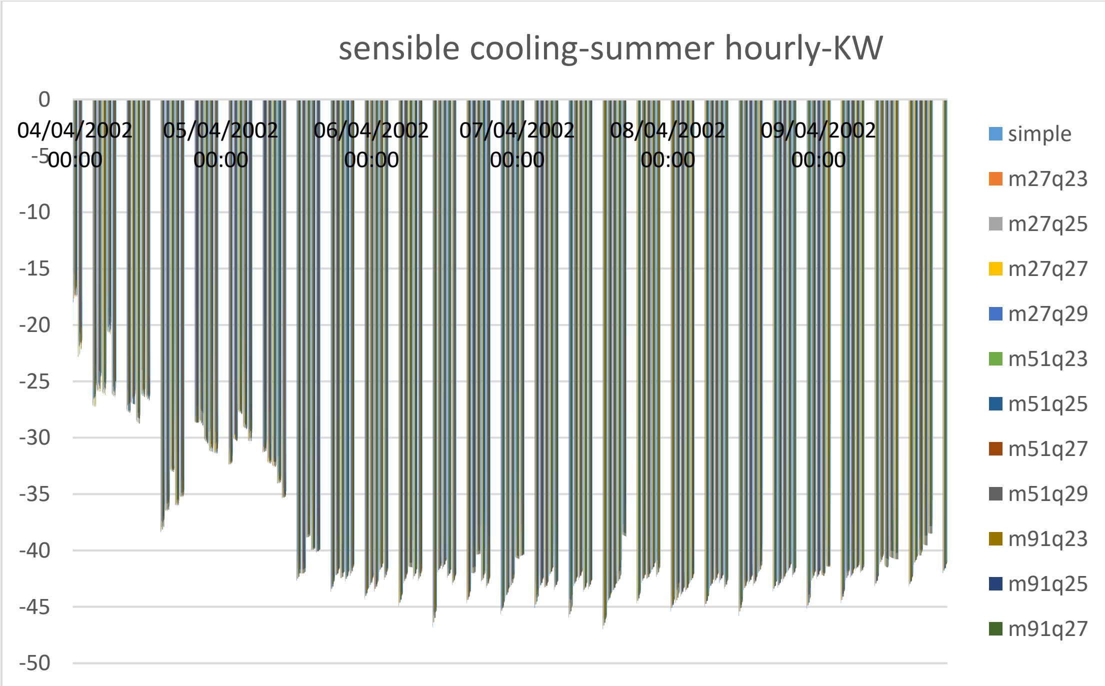


**Figure 2.** Hourly heat pump energy consumption for each of 12 PCM in warm season and in the middle-layer layout

It can be concluded that the m91q25 material consumes less energy of heat pump.

- **Daily heat pump energy consumption in the design week and warm months**

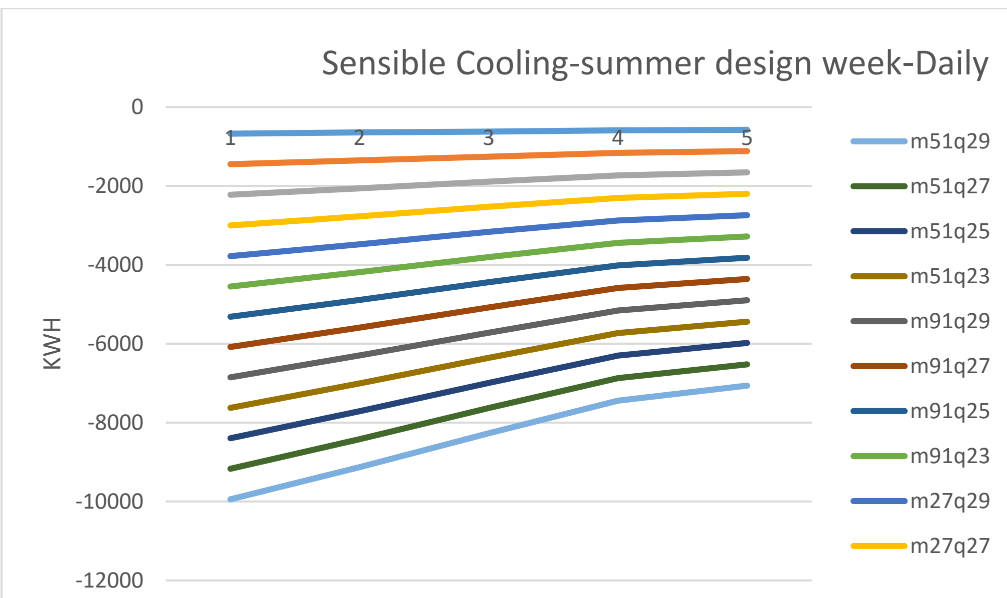


**Figure 3.** Heat pump energy consumption in cool days of design week and with the middle-layer layout

By averaging energy consumption of all 12 phase-change materials in the days of design week, the m91q27 material, with the average energy consumption of 643 kWh, is more optimal than other materials. However, compared to simple state with the energy consumption of 622 kWh, it consumes greater energy.

- **Monthly heat pump energy consumption in the middle-layer layout**

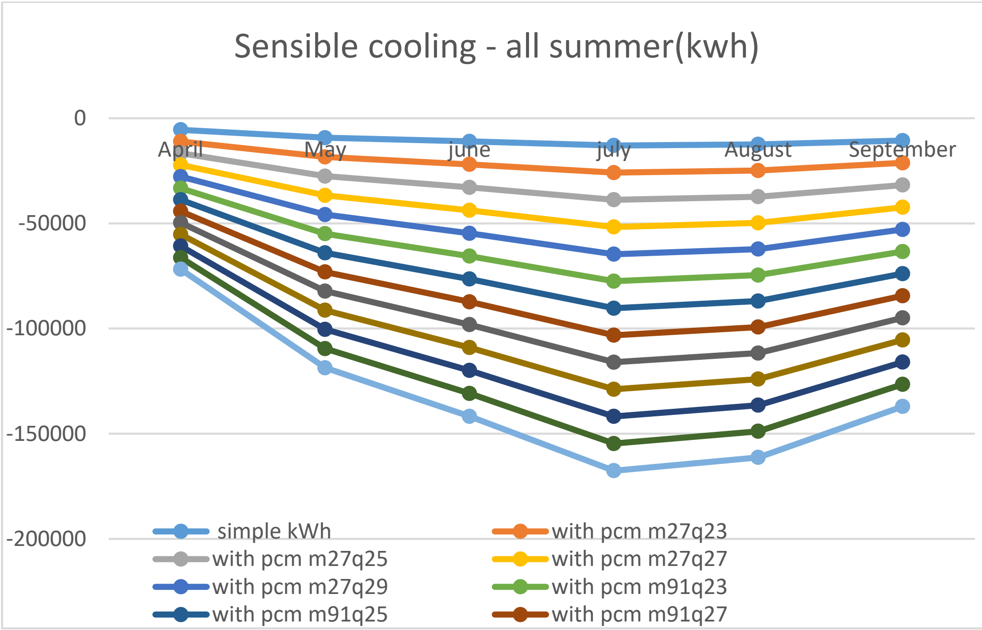


**Figure 4.** Heat pump energy consumption in cool months and with the middle-layer layout

Comparing the averages shows that the m91q25 material with the average energy consumption of 10187.7 kWh is more optimal than the simple state with the average energy consumption of 10311.73 kWh and it consumes less energy.

- **Hourly heat pump energy consumption in cool season**

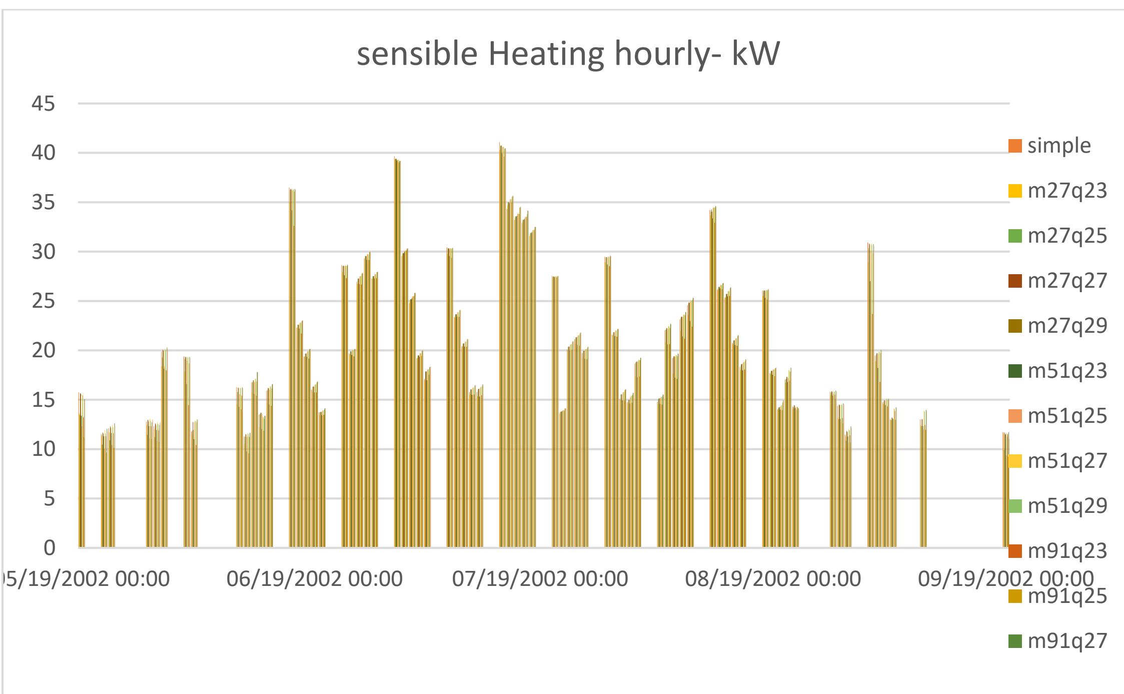


**Figure 5.** Hourly heat pump energy consumption in cool days and with the middle-layer layout

It can be concluded that among the 12 phase-change material studied, the m91q23 material produces lower energy than other materials for heating the building.

- **Daily heat pump energy consumption in cool season and design week**

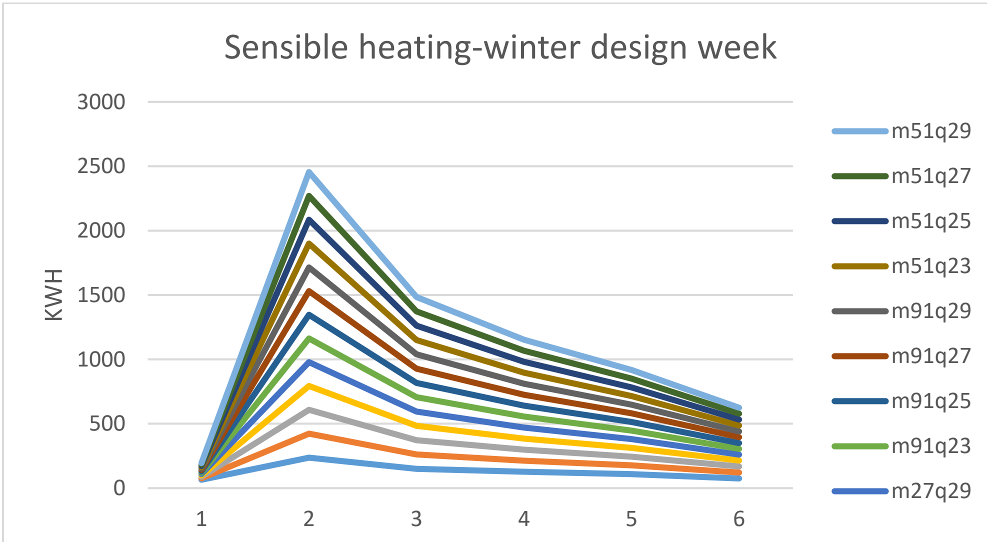


**Figure 6.** Daily heat pump energy consumption in the design week and with the middle-layer layout

By averaging, it was observed that the m91q25 material became more optimal and used less energy than the simple state with the average energy consumption of 126.86 kWh.

- **Monthly heat pump energy consumption in cool season**

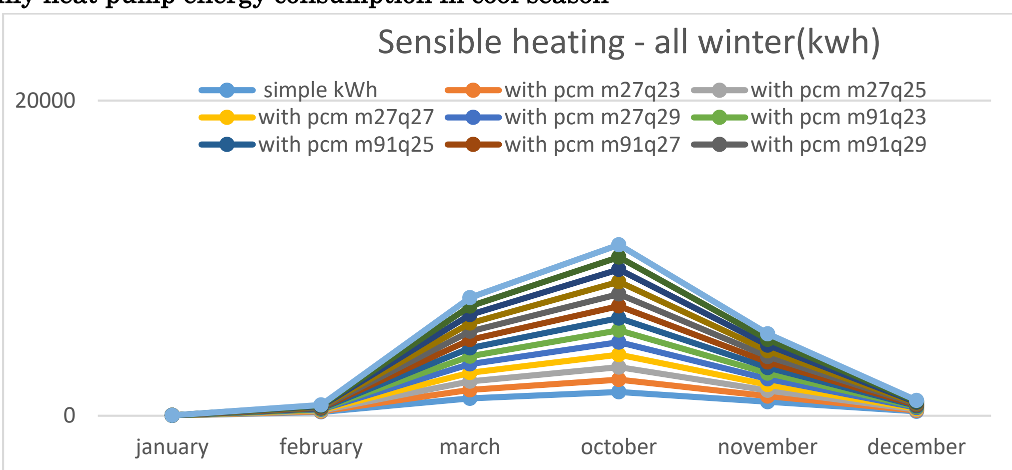


**Figure 7.** Heat pump energy consumption in cool seasons and with the middle-layer layout

By averaging the energy consumption of all 12 materials, it was found that the m91q23 material with an average energy consumption of 284.11 kWh played more significant role in reducing energy consumption compared to the simple state with the average energy consumption of 669.76 kWh as well as other materials. Now, comparing 11 other materials shows that the m27q27 material with the average energy consumption of 301.26kWh yields the weakest result compared to others, while the same material consumes half the energy of a simple state.

**Examination of phase-change materials**

Finally, to determine which of these materials yields the best result, the annual energy consumption of each of them was examined. According to the annual energy consumption table, for a simple state, annual energy consumption is equal to 138580.48 kWh.

- **Inner layer**

Figure 8 shows the annual energy consumption of the materials in the state of using them in the inner layer.

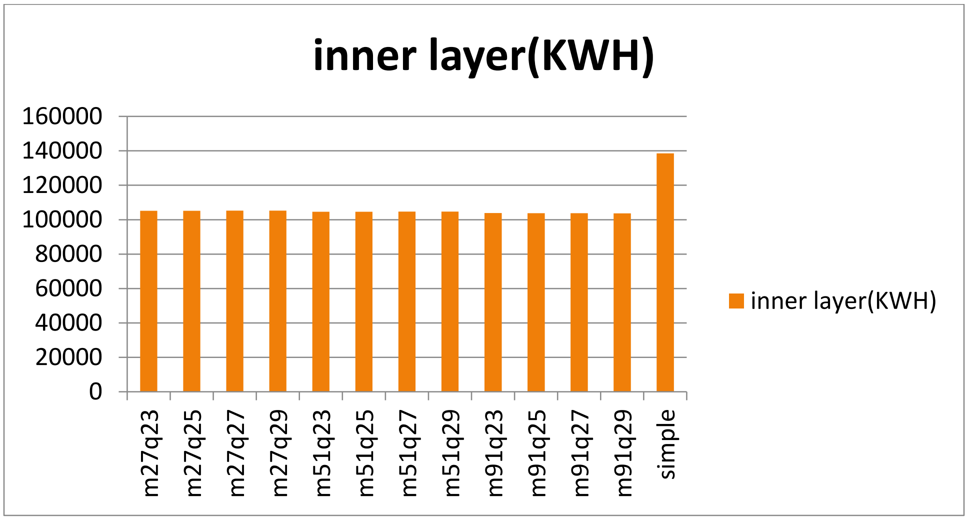


**Figure 8.** Comparison of 12 phase-change materials in the inner layer

In the inner layer, m91q29 material with the energy consumption of 103706 kWh and with the m27q29 material with the energy consumption of 105226.63 kWh, uses the lowest and highest energy in the inner layer, respectively.

- **Middle layer**

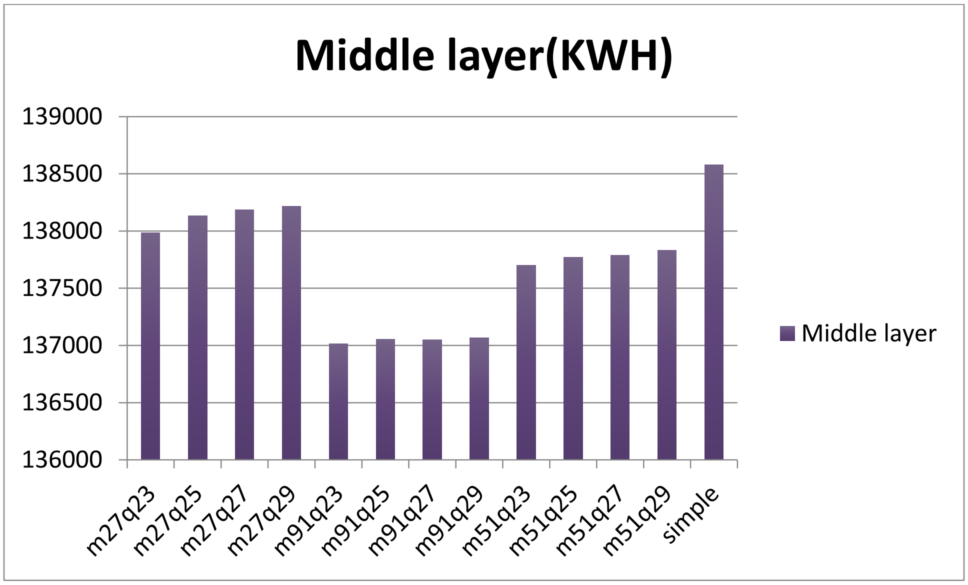


**Figure 9.** Comparison of 12 phase-change materials in the middle layer

By comparing the annual energy consumption of all phase-change materials in the middle layer, it was found that m91q23 material with the energy consumption of 137015.5 kWh consumes the lowest energy compared to other materials while m27q29 material with the energy consumption of 138216.1 kWh, consumes highest energy compared to other PCMs.

- **Outer layer**

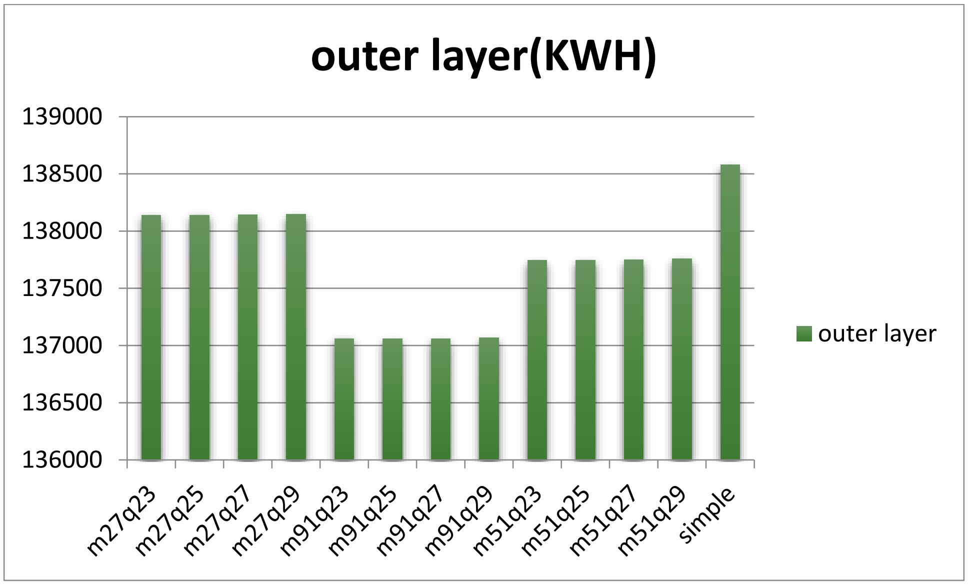


**Figure 10**. Comparison of 12 phase-change materials in the outer layer

By comparing all phase-change materials used in the middle layer in terms of the annual energy consumption, it was found that the m91q25 material with the energy consumption of 137056.5 kWh consumes the lowest energy compared to other materials, while the m27q29 material, with the energy consumption of 138146.74 kWh, consumes the highest energy compared to other PCMs. Of course, compared to the simple state, significant reduction in energy consumption was observed while compared to the optimal state in this layer, no significant increase was observed.

**Comparison of layers with each other**

To compare layers with each other, the annual energy consumption of all the materials are presented on the same chart:

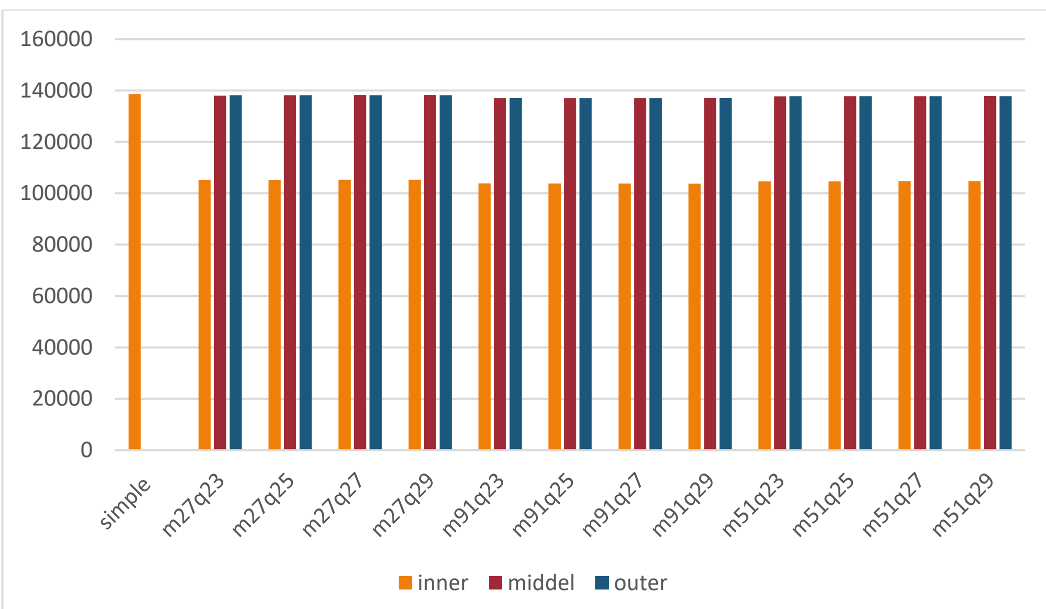


**Figure 11.** Comparison of the layers in terms of annual energy consumption of all 12 PCM

According to Fig. 11 and numerical comparison of energy consumption, the m91q29 material with the energy consumption of 103706 kWh in the inner layer yields the lowest annual energy consumption and is an optimal material and in contrast, m27q29 material with the energy consumption of 138216.1 kWh in the middle layer yields the weakest result.

**Examination of different heat pumps**

Now, with the knowledge of the most optimal phase-change material, the different states of heat pump are examined. It should be noted that in all the simple states (without materials), as well as the states of separately using of phase-change materials, air source unitary heat pump was used

- **Effects of unitary heat pump efficiency on energy consumption**

First, the various efficiencies of the unitary heat pump (air source) are examined to determine the optimal state.

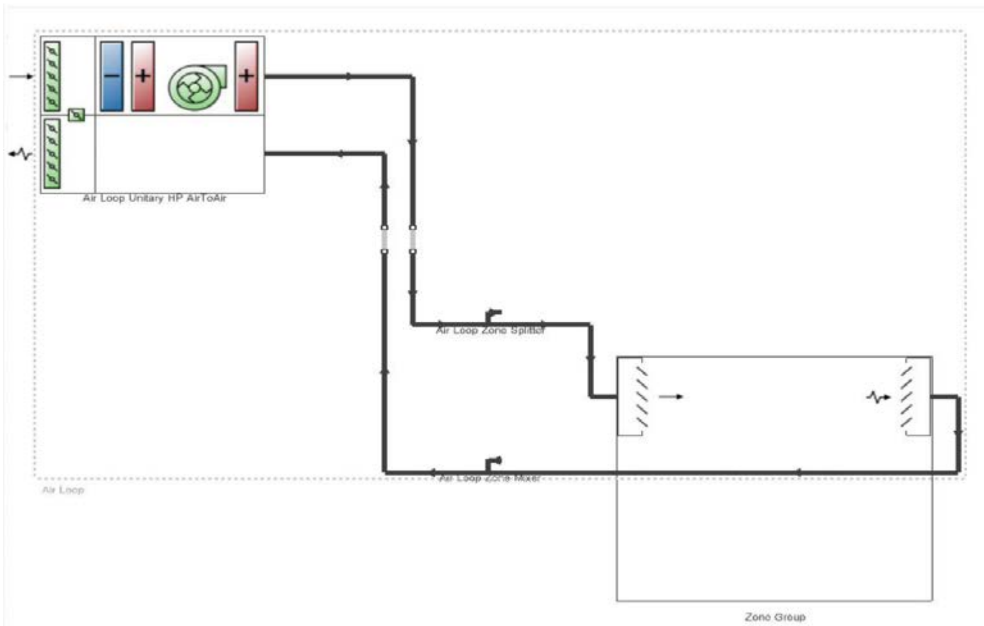


**Figure 12.** Unitary Heat Pump

As shown in Figure 13:

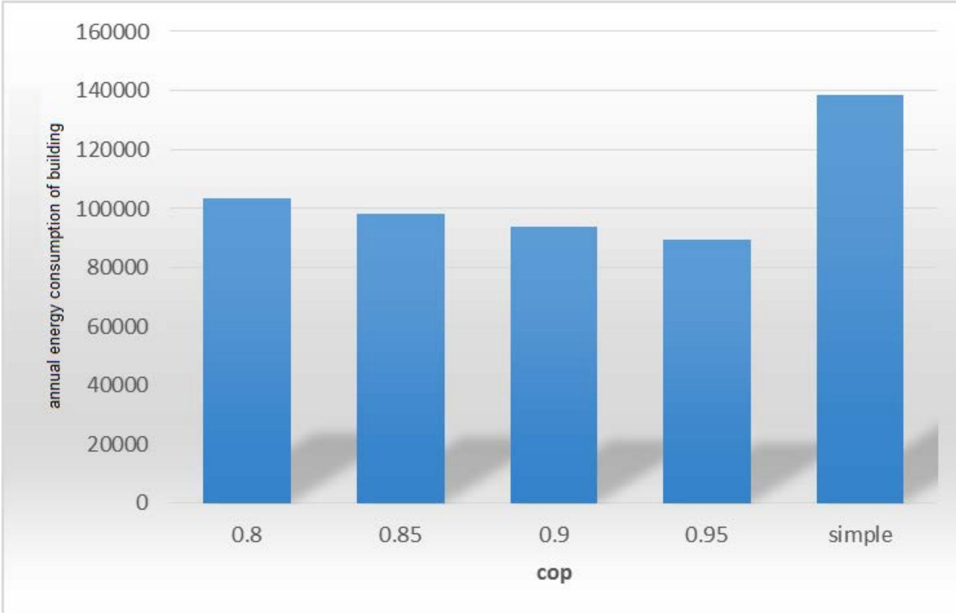


**Figure 13.** Annual energy consumption variations based on the variations of COP of heat pump

Given that the efficiency of 80% was calculated in the case where the optimal material, i.e. m91q29, was in the inner layer, by considering other parameters constant and increasing the efficiency of unitary heat pump (air source), the annual energy consumption decreased as expected and in the efficiency of 95%, the least energy was consumed.

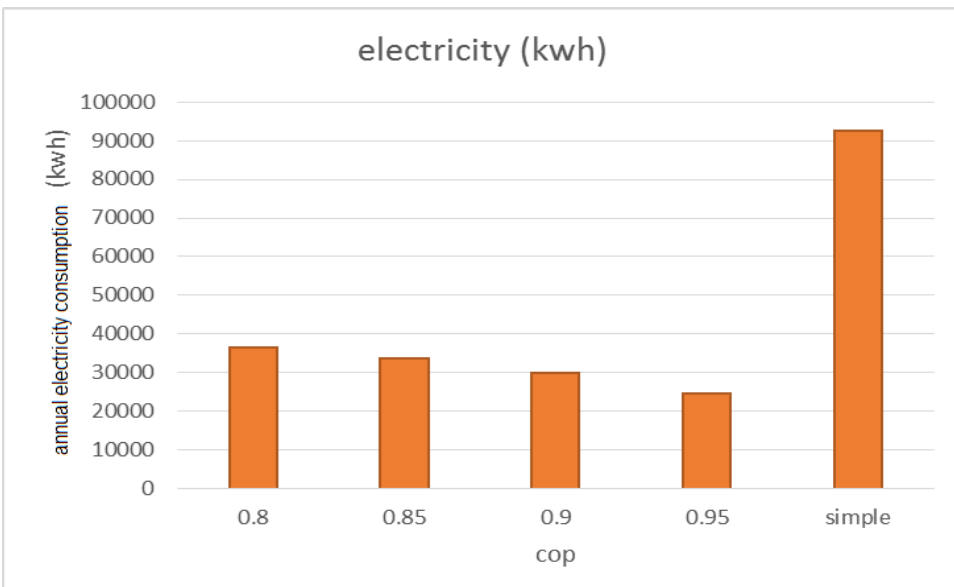


**Figure 14.** Annual power consumption variations based on the variations of COP of heat pump

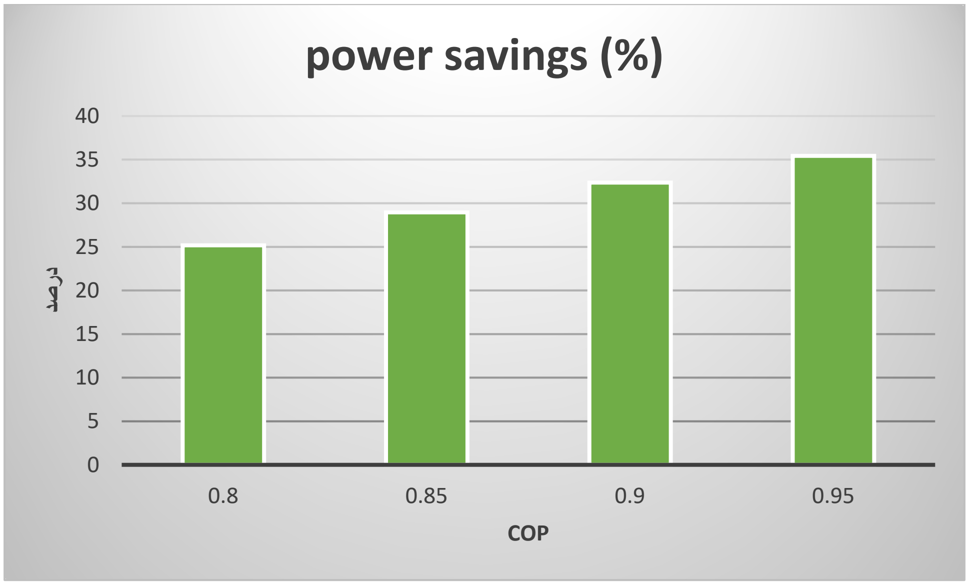


**Figure 15.** Changes in power savings based on the variations of COP of heat pump

According to Fig. 15, with the increase in the efficiency of power energy, the cost of power energy decreased such that, with the highest efficiency, the most energy savings was observed.
According to the power energy consumption chart, in the case without any phase-change material, the heat pump consumed 92438.79 kWh of electricity and 37800000 Rials was spent for it per year. But in the case of using the most optimal phase-change material and unitary heat pump, if the heat pump work at the efficiency of 80%, it would consume 36391.34 kWh power energy per year and 14880000 Rials will spent for it per year. As shown in Fig.15, the higher the efficiency, the lower the power consumption, the higher the savings, so that the most energy savings is obtained at the efficiency of 0.95.

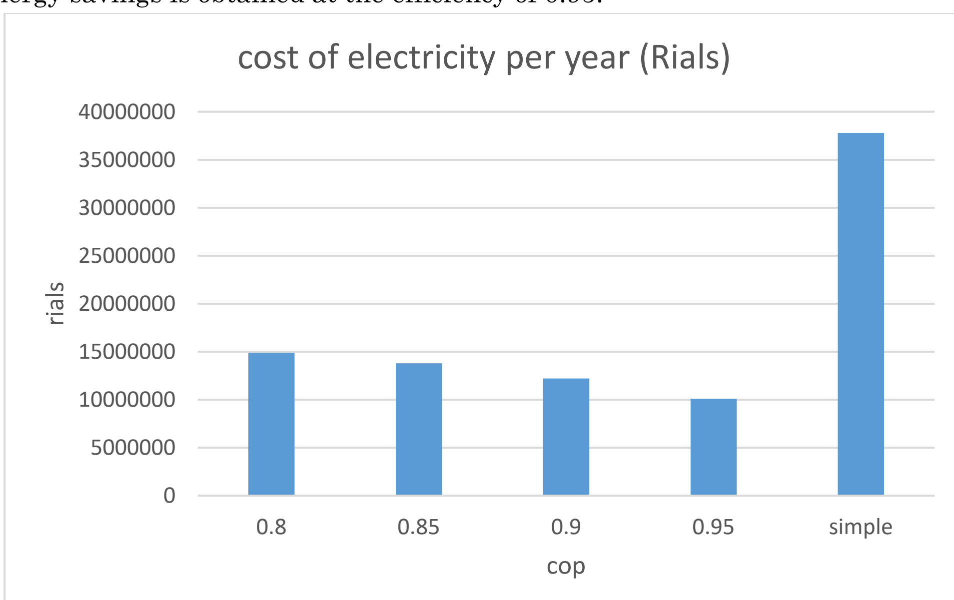


**Figure 16.** Changes in the cost of electricity based on the variations of COP of heat pump

Since the price of 1 kWh electricity in Tabriz City is 409 Rials, in the case with no phase-change material, and with 80% efficiency, the cost of electricity per year was estimated 37800000 Rials, which reduced to 1480000 Rials by coupling the best material, i.e. m91q29 and with 80% efficiency. In the best case, the 95% efficiency, the annual cost of electricity was estimated 10090000 Rials, that in comparison with the case without phase-change material and with the 80% efficiency, reductions of 2771000 and 4710000 Rials in the annual cost were achieved, respectively.

- **Comparison of different heat pumps in terms of annual energy consumption**

In the following, 6 different types of heat pumps are examined in order to determine the optimum heat pump in terms of energy consumption reduction.

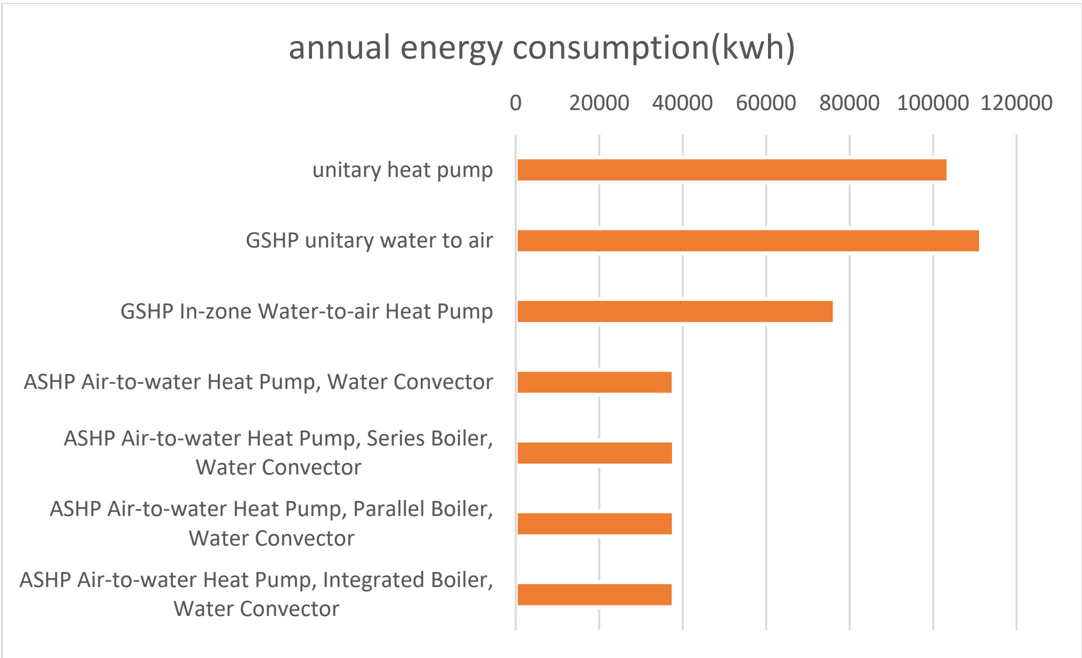


**Figure 17:** Annual energy consumption of various heat pumps

Comparing the heat pumps presented in Fig. 17 in the annual energy consumptions shows that ASHP Air-to-water Heat Pump, Integrated Boiler, Water Convector and ASHP Air-to-water Heat Pump, Water Convector with annual energy consumption of 37818.31 kWh were the most optimal heat pumps.

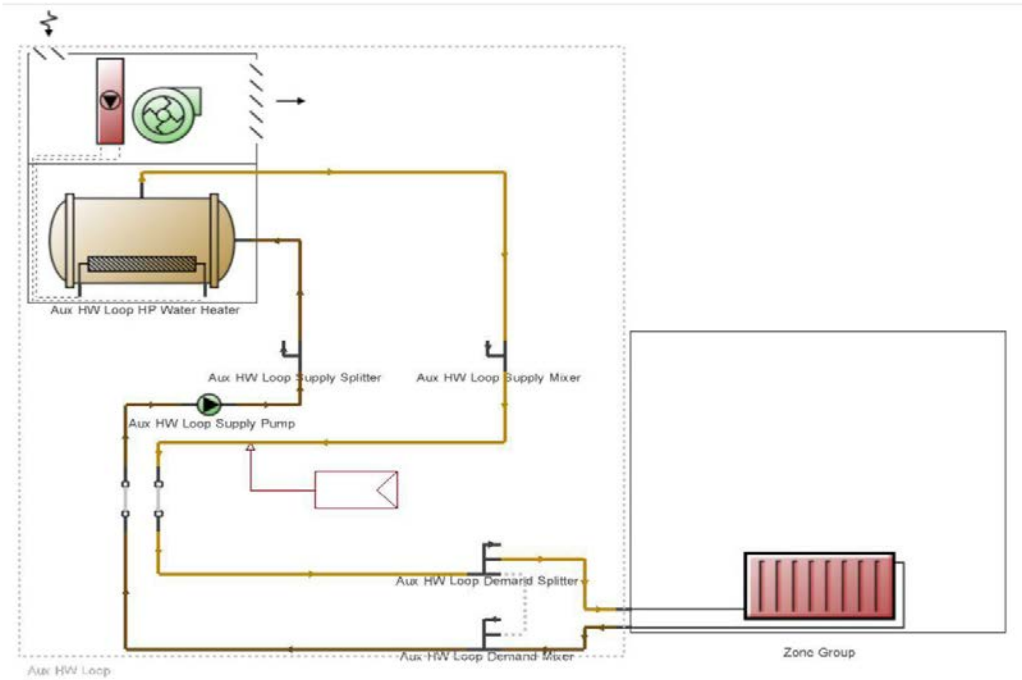


**Figure 18:** ASHP Air-to-water Heat Pump, Integrated Boiler, Water Convector

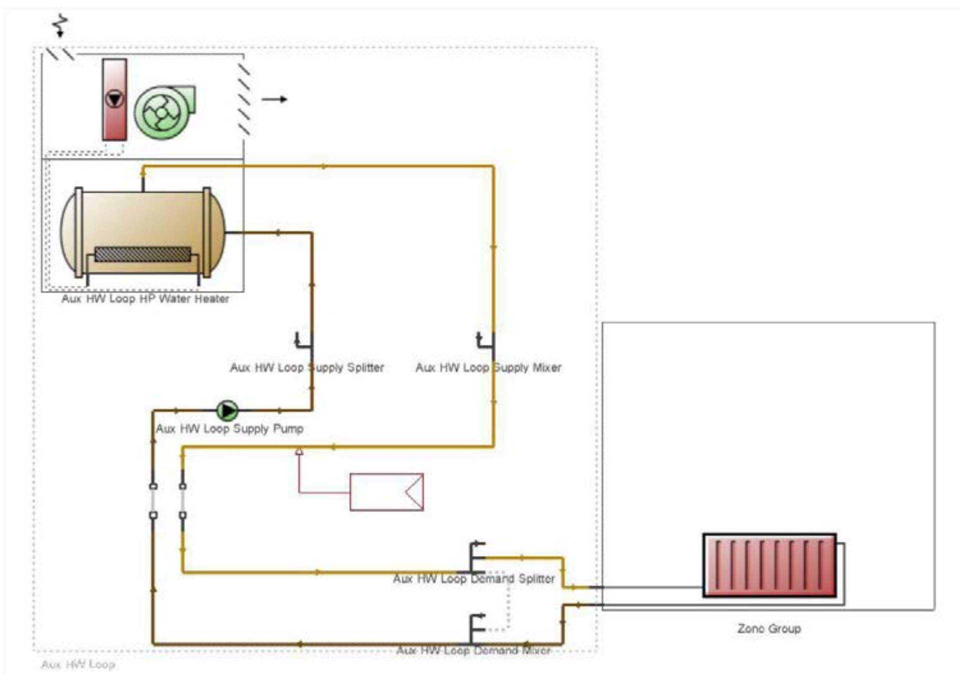


**Figure 19.** ASHP Air-to-water Heat Pump, Water Convector

## Conclusion

### Optimum PCM and Heat Pump

- Optimum PCM

With the simulation of 12 phase-change materials in three layers of the wall (the inner layer, (middle layer) between the two thermal insulation, the outer layer), it was found that using the m91q29 material with an annual energy consumption of 103706 kWh and the air source unitary heat pump produced the best result.

- **Optimum heat pump**

With the simulation of different heat pumps, it was concluded that the two ASHP Air-to-water Heat Pump, Integrated Boiler, Water Convector and ASHP Air-to-water Heat Pump, Water Convector with annual energy consumption of 37818.31 kWh produced the best result.

- **Combination of optimal states**

Considering the optimal PCM and heat pump, it was conclude that the best state is the case in which the m91q29 material is placed in the inner layer of the wall, and one of the two ASHP Air-to-water Heat Pump, Integrated Boiler, Water Convector and ASHP Air-to-water Heat Pump, Water Convector provides cooling or heating.

- **Annual energy consumption, electricity consumption and electricity costs in the optimal state**

By considering the annual energy consumption for this state and the annual power consumption of heat pump, the annual cost of electricity is estimated. Then, it is compared with the cost of electricity in the case without phase-change material and with unitary heat pump.

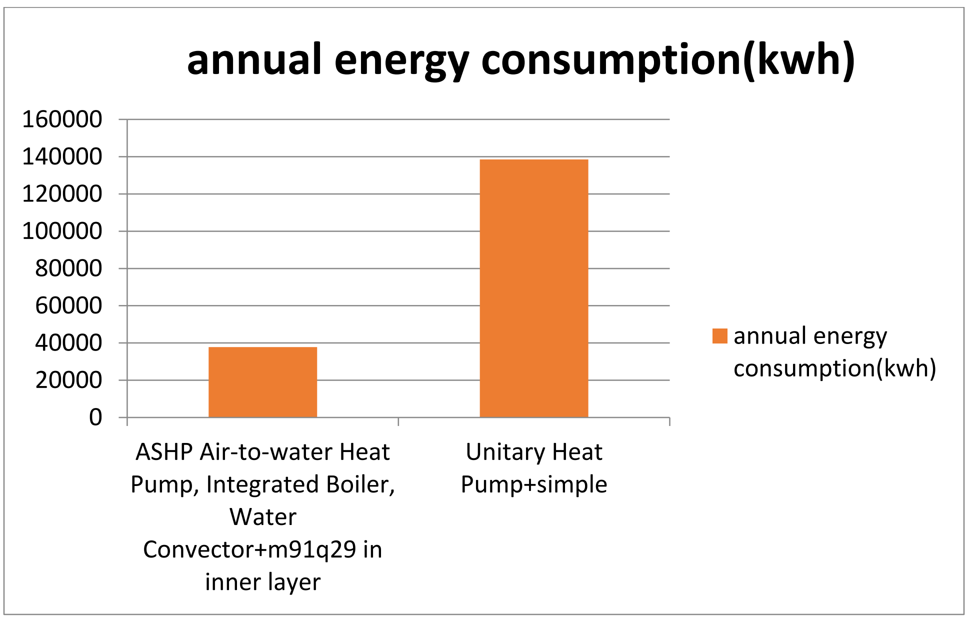


**Figure 20.** Annual energy consumption in the optimal and simple states

According to Fig. 20, the annual energy consumption in the case without PCM and with the Unitary Heat pump is 138580 kwh, and in the optimum state, it is equal to 37818.31 kw.

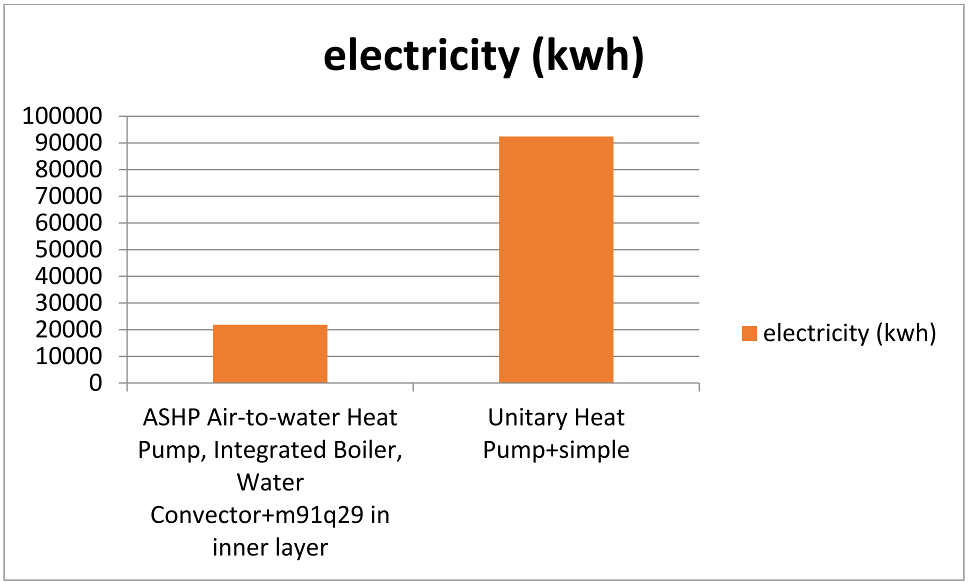


**Figure 21:** Annual electricity consumption in the optimal and simple states

According to the annual electricity consumption in the simple state (92438.79 kWh) and the optimal state (21861 kWh), it is concluded that using the optimum PCM and optimum heat pump resulted in a significant 76% reduction in power consumption, indicating the effect of these two parameters.

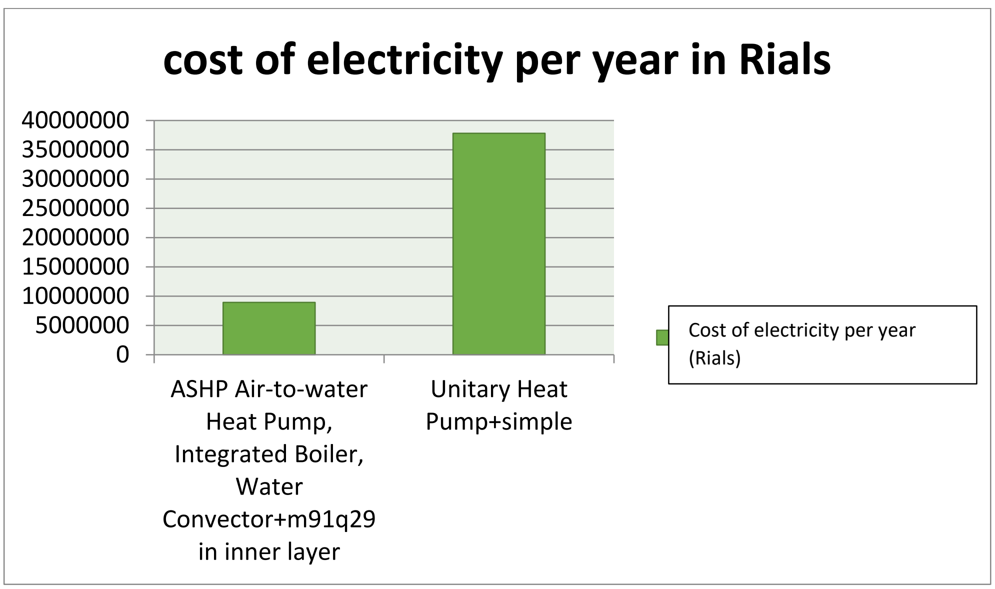


**Figure 22.** Annual cost of electricity in the optimal and simple states

According to Fig. 22, and the comparison of the annual electricity costs of a simple state (37800000 Rials), and the optimum state (8900000 Rials), a reduction of 2890000 Rials in the annual cost of electricity is observed, which is the same as 76% reduction.

**The worst state**

- **The weakest PCM**

According to different simulations of three layers of the wall, the worst result was obtained by using the m27q29 material in the layer between two insulations with an annual energy consumption of 13.2816.1 kwh and an unitary heat pump.

- **The weakest heat pump**

Also, according to the simulation of different heat pump, the worst result was obtained by using the GSHP unitary water to air with an annual energy consumption of 111494.84 kwh / h, which uses higher energy than even our unitary heat pump. It should be noted that in these simulations, these heat pumps were coupled with the optimal PCM in the inner layer of the wall.

- **Combination of the weakest states**

  Considering the weakest PCM and heat pump, it was conclude that the weakest state is the case in which the m27q29 material is placed in the middle layer of the wall, and GSHP unitary Water to air is used.

- **Annual energy, power consumption and electricity costs in the weakest state**

By considering the annual energy consumption in this state and the simple state:

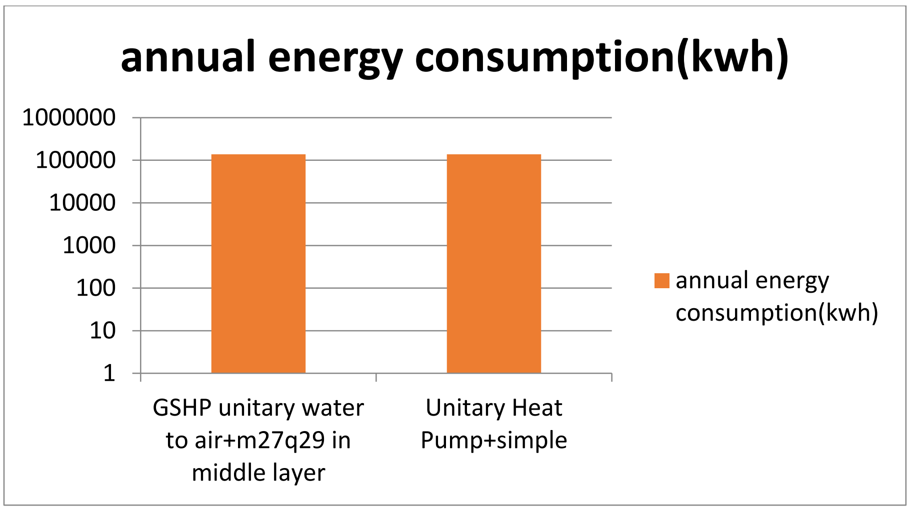


**Figure 23:** Annual energy consumption in the weakest and simple states

By comparing the average annual energy consumptions of the simple state (138580 kwh) and the weakest state (138494.84 kwh) and according to Fig. 23, it is concluded that there is a slight difference (85.16 kwh) between them.

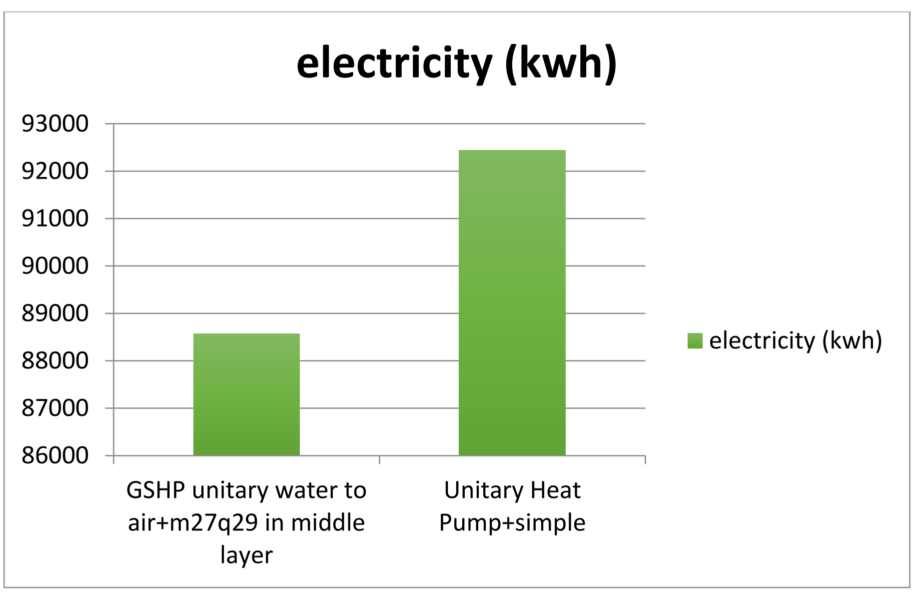


**Figure 24.** Annual electricity consumption in the weakest and simple states

Given the numerical value of annual electricity consumption of the heat pump in the simple state (92438.79 kWh) and in the weakest state (88569 kWh), it is concluded that the electricity consumption decreased only by 4.1%.

Figure 25. Annual cost of electricity in the weakest and simple states

Given the annual cost of electricity consumed by the heat pump in the simple state (37800000 RIALS) and the weakest state (36220000 Rials), it is observed that the cost of electricity decreased only by 3.3%.

**Energy savings in the optimum and the weakest states**

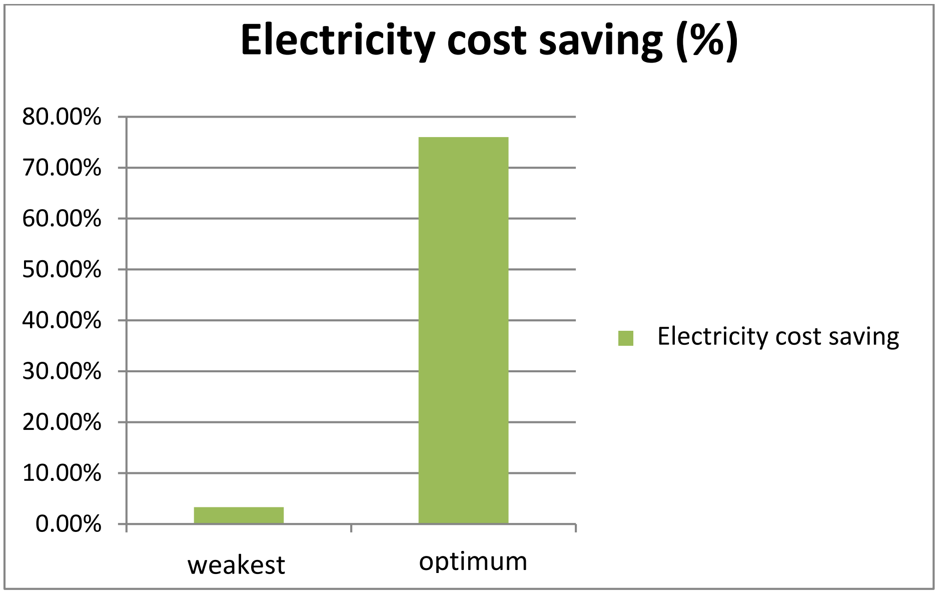


**Figure 26:** Energy savings in the optimum and the weakest states.

By comparing the optimum and weakest states in the annual energy consumption, annual electricity consumption of the pump and the annual cost of electricity, it is concluded that the wisest state is the optimum state and in the weakest state, significant reduction is not achieved.

**Return on investment**

The price of Bio PCMs in the market, which is available as a roll, and in the size of 2000mm × 470mm × 15mm (thickness × width × length) is 1140000 Rials. The dimensions of simulated 4-storey building are 10×10, so the total area of walls is 480 m². Accordingly, by assuming a distance of 3 meters between the floors, we have:

$$(3 \times 10)\ m^2 \times 4 \times 4 = 480\ m^2$$
$$2 \times 0.47 = 0.94\ m^2$$

By dividing the former value by the later and multiplying the product by the price of Bio PCM, the amount of 582120000 Rials is the amount that should be spent if the builder uses these materials to store energy. Given the cost of annual energy savings due to the use of these material in the building, it will be possible to return the cost within 20 years, so perhaps, there are probably few people to use this material. In the weakest state, it will be possible to return the cost within 368 years.

**Suggestions**

- To study the phase-change materials in buildings with different land uses (civil, commercial, sports hall, etc.) in warm and cold climates and to compare them with each other

- To couple the phase-change materials with different air conditioning systems and to analyze them economically.
- To couple solar heating and cooling systems with phase-change materials in different walls and to identify the optimal state.

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