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Phase change materials (PCM) as a passive system in the opaque building envelope: A simulation-based analysis

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ABSTRACT

The ongoing energy crisis is a critical issue in both scientific and managerial spheres within the building and construction industry. While low-cost strategies to reduce energy consumption offer advantage to stakeholders, this study primarily advocates the use of phase change materials (PCM) to enhance the management of cooling and heating loads in buildings. Using DesignBuilder simulations, this research is demonstrated on Iran as a case study representing a developing country. The findings reveal that integrating PCM into buildings can reduce energy consumption by approximately 6 %. Furthermore, a quantitative comparison of building efficiency based on Energy Use Intensity (EUI) calculations highlights the benefs of alternative materials. Specifically, a 5.6 % reduction in EUI was observed with PCMs while nano-paints contributed a 1.8 % reduction. Although these reductions may seem modest compared to other techniques, they represent significant progress toward green building objectives in both developed and developing nations. The case study, conducted in a region experiencing four seasons, highlights the substantial potential of PCM systems for managing both cooling and heating energy demands. Notably, the reciprocal performance improvement of PCMs sets them apart from conventional systems that typically target one aspect of energy management. The research also includes comprehensive thermodynamic and heat transfer analyses, economic assessments, sustainability evaluations, and exergy analysis. These analyses demonstrate that the PCM scenario is more favorable compared to other strategies, such as no thermal insulation and the use of nano-paints. Furthermore, this study emphasizes the alignment of the proposed PCM integration with Sustainable Development Goal 7 (Affordable and Clean Energy Targets). The results provide a compelling argument for the adoption of PCM technology by highlighting its role in improving energy efficiency, supporting sustainable development, and addressing the energy crisis effectively."

1. Introduction

The current discussion on sustainable building practices has become more urgent due to the ongoing global energy crisis. In response to this challenge, numerous research initiatives have been undertaken to explore novel approaches for improving energy efficiency in the building and construction sector. The incorporation of Phase Change Materials (PCM) as a passive system in building envelopes across various climates has recently garnered considerable attention [1–5]. However, the urgency to enhance energy efficiency is increasing a due to limited energy resources, rising energy carrier costs, and environmental pollution caused by the widespread reliance on fossil fuels. Fossil fuels

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account for approximately 84 % of the global primary energy consumption. Although there has been a decline in recent years due to the growing adoption of renewable energy sources, fossil fuels still dominate energy consumption [6]. In addition, Iran's energy consumption is 2.5 times higher than the global average [7], and only a maximum of 1.3 % of this energy comes from renewable sources [8]. According to data from the International Energy Agency (IEA), Iran's residential sector has consistently contributed a substantial proportion of the country's energy consumption (Fig. 1). In 2020, it accounted for approximately 27 % of the country's total final energy usage, primarily due to inadequate adherence to construction principles and the use of suboptimal materials.

Considering the residential sector's larger share of Iran's final energy consumption compared to other sectors like industry, transportation, and agriculture (Fig. 2), optimizing energy use can be achieved by reducing energy demand, using energy efficiently, recovering heat and cold, and utilizing energy from the surrounding air and ground. Employing a method that can maintain indoor air temperature at the desired level for longer periods can significantly reduce energy needs. This is crucial because cooling or heating a space to maintain thermal comfort can account for up to 60–70 % of the total energy consumption in non-industrial buildings [9,10]. Table 1 presents various concepts for achieving this objective through heating and cooling solutions.

Ongoing research has focused on developing efficient and feasible technologies to minimizing energy consumption in buildings. Heat energy is lost through convection, conduction, and radiation as energy transfers from the warmer internal air to the colder external air across the building envelope [19]. The primary causes of heat energy loss in buildings are typically thermal bridges (TB), air exchange between interior and outdoor areas, and air leakage through walls, roofs, windows, doors, and slabs [20]. Several studies have investigated the fundamental forms of energy loss in buildings, though the rates of energy loss may vary depending on the building's design and structure [21]. Fig. 3 demonstrates that walls and roofs are the primary sources of energy loss in a conventional structure. Developing energy storage devices is a method of conserving cold or hot energy that is either readily available or can only be generated at specific times of the day within a building [10]. TES (Thermal Energy Storage) plays a crucial role in conserving energy, addressing the gap between energy supply and demand, and enhancing the efficiency and reliability of energy systems [22]. The use of this technology in both passive and active systems enables effective utilization of thermal energy, load-shifting techniques, and harnessing waste energy [23]. Sensible heat storage (SHS), latent heat storage (LHS), thermochemical storage (TCS), or a combination of these methods can be employed for thermal energy storage (TES) by altering the internal energy of a material [24–26].

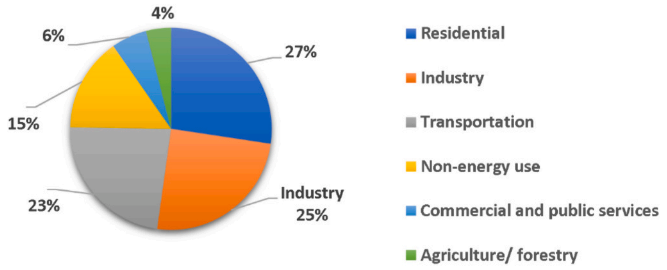


Fig. 2. Total final consumption (TFC) by sector Iran, 2020. Source: World Energy Balances 2022 [8].

Unlike sensible heat storage (SHS), which involves storing thermal energy by increasing the temperature of a solid or liquid [27], latent heat storage (LHS) is based on the absorption or release of heat when a storage material undergoes a phase change, such as from solid to liquid or from liquid to gas [28]. The fundamental principle of thermochemical systems lies in the energy acquired and released through the fully reversible chemical process of breaking and reforming molecular bonds [10,26]. Latent heat thermal energy storage is notable for its ability to store a large amount of energy in a small space while maintaining a constant temperature corresponding to the phase transition temperature of the phase change material (PCM) [22]. PCMs have a heat storage capacity five to fourteen times greater per unit volume compared to conventional storage media like water or rock. PCMs can be categorized based on various criteria, including phase change temperature [29], material properties (thermodynamic, kinetic, chemical, and economic), and material composition (organic, inorganic, or eutectic, such as paraffin, fatty acids, salt hydrates, etc.) [10]. While no single material can completely satisfy all of this properties [30], phase change temperature, a thermodynamic attribute, is a crucial factor in choosing PCMs due to its substantial impact on the overall heat transfer mechanism [29]. An appropriate phase change material (PCM) must possess a transition temperature that falls within the required temperature range [22].

Phase change materials (PCMs) have been extensively studied for various applications, including residential hot water tanks, building space heating and cooling, peak load shifting, solar energy applications, and seasonal storage [29]. Researchers have explored the integration and effectiveness of PCMs in buildings [23]. Passive technologies offer several methods for incorporating PCMs into construction materials,

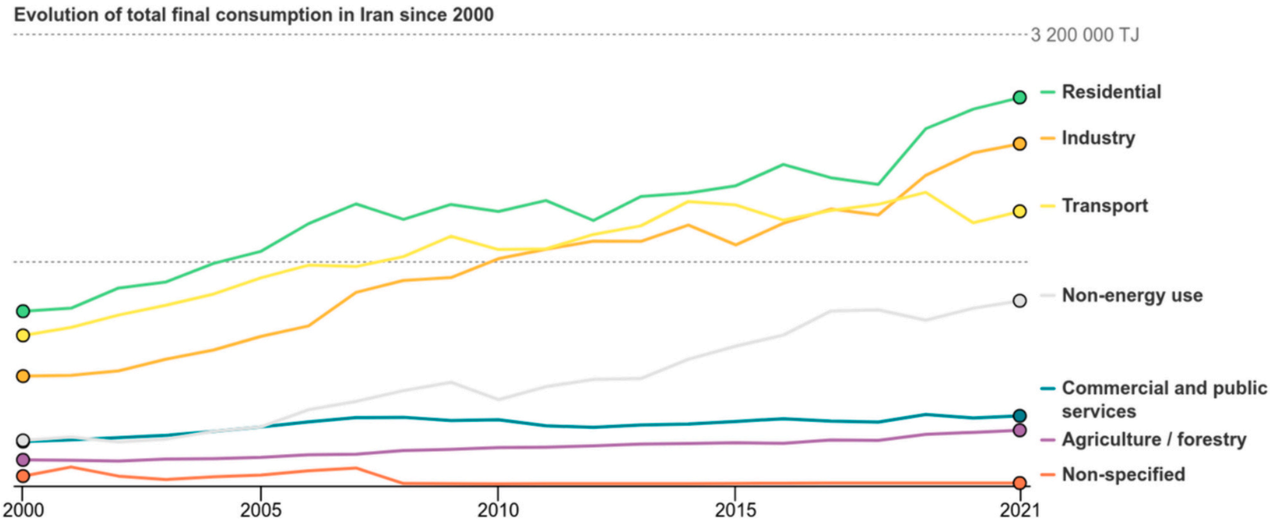


Fig. 1. Evolution of total final consumption (TFC) by sector, Iran 2000–2021. Source: IEA Data Services [8].

Table 1
Concepts for heating and cooling solutions.

Heating solutions	Cooling solutions
Solar collection: Gathering heat from the sun via the building exterior [9]	Solar control: Shielding a structure from direct solar rays [9].
Heat storage: T walls and floors store heat [9]	Ventilation: Replenishing fresh air and removing stale air [9].
Distribution of heat: Distributing heated air to various rooms that need to be heated [9]	Reduction of internal gains: Lowering heat generated by occupants, machinery, and artificial lighting [9].
Conserving heat: Keeping heat within the building [9]	Prevention of external gains: Dfending against unwanted heat transfer by penetration or conduction through the building envelope (particularly in hot climates) [9].
Thermal Energy Storage (TES): TES systems store excess thermal energy during periods of low demand and release it when needed. This can be achieved through various methods such as using insulated tanks of hot water or advanced materials with high heat retention properties [11]	Natural cooling: Enhancing natural ventilation by utilizing outside air (particularly in hot climates) [9].
Geothermal Heat Pumps: Utilizing the Earth's stable underground temperature, geothermal heat pumps transfer heat between the ground and the building. They are highly efficient and environmentally friendly, offering a sustainable alternative to traditional heating systems [12]	Evaporative Cooling Systems: Utilizing the principle of evaporative cooling, where water is evaporated to absorb heat from the surrounding air. Systems like evaporative coolers or swamp coolers can be integrated into buildings to provide energy-efficient cooling in dry climates without the high energy consumption associated with traditional air conditioning [13].
Radiant Floor Heating: This involves installing heating elements beneath the floor surface. The heat rises from the floor, creating a comfortable and even warmth in the living space. It's energy-efficient and eliminates the need for traditional radiators or forced-air systems [14]	Thermal Energy Storage for Cooling: Buildings can store cool energy during off-peak periods, such as at night, and release it during the day when cooling demands are higher. This method improves energy efficiency and reduces peak-load stress on power grids [11]
Artificial Intelligence in Thermostat Systems: Integrating AI into thermostat systems allows for more precise and personalized heating control. These systems can learn from user behavior, adapt to preferences, and optimize heating schedules based on factors like weather forecasts and occupancy patterns [15].	Green Roofs and Walls:Installing vegetation on rooftops and walls to help cool buildings by providing natural insulation and reducing the urban heat island effect. Plants absorb sunlight and release moisture through transpiration, creating a cooler microclimate around the building [16]
Phase Change Materials (PCMs): PCMs absorb and release thermal energy during the process of melting and solidifying. They can be incorporated into building materials such as walls or floors to store and release heat, helping to regulate indoor temperatures efficiently [17]	Passive Cooling Design: Designing buildings to naturally cool themselves without the need for mechanical systems. Strategies may include proper insulation, shading elements, and ventilation techniques to optimize airflow and reduce the reliance on active cooling [18]

such as immersion, direct incorporation, encapsulation, shape stabilization, and microencapsulation [23]. The storage systems in the building sector can be categorized as either active or passive solutions [31]. Zahir et al. [1] have highlighted the potential of PCMs for thermal energy storage in high-temperature regions as a means of achieving sustainable building solutions. Their study emphasizes the significance of appropriate PCM selection and recognizes gaps in research, particularly in the Middle East. This establishes the foundation for our inquiry, which aims to address the lack of scientific knowledge regarding PCM utilization in high-temperature environments. In addition, Saylam et al. [32] have suggested incorporating PCMs into pumice blocks, which are readily available in Turkey, to improve thermal mass. Their research demonstrates a potential increase of up to 6 % in thermal conductivity and 75 % in specific heat capacity. The study's primary objective was to examine the effects of PCM pumice blocks on time delays and temperature fluctuations, specifically in hot-humid climates, providing valuable insights. In a more recent study, Mukram et al. [33] introduced a new brick model integrating phase change materials (PCMs) into holes positioned closer to the outer wall. Their research emphasizes the importance of positioning the PCMs away from the heat source, resulting in a significant 32 % decrease in heat gain and a notable 1.2 °C reduction in room temperature. This spatial approach to PCM integration offers insights into optimizing passive cooling methods in building components. Passive TES systems aim to effectively utilize naturally occurring heat sources to maintain thermal stability in buildings and minimize the need for mechanical heating or cooling devices [34]. Conversely, active thermal energy storage (TES) systems improve the storage of thermal energy and provide a significant control over indoor environment. Active TES systems are commonly incorporated into buildings, while passive TES systems are embedded within building materials. These systems, suitable for both new construction and retrofitting, aim to enhance the efficiency of current installations, integrate strategies for shifting peak loads, and utilize renewable energy for space

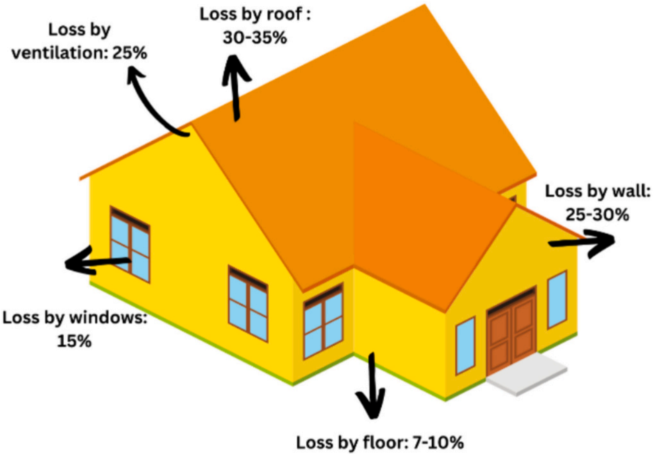


Fig. 3. Area of energy losses in building (inspired by [22,24]).

Table 2
Summary of heating, cooling, and hybrid PCM applications in buildings.

No	Technique used (cooling/heating/hybrid)	Passive or active	Reference
1	Hybrid (Transparent Thermal Insulation with PCM)	Passive	[36]
2	Hybrid (Microencapsulated PCM in Foam Concrete)	Passive	[37]
3	Heating (Activated Carbon-Based Shape-Stabilized PCM in Dry Floor Heating System)	Active	[38]
4	Hybrid (Photovoltaic Thermal Collector with PCM and Ground Source Heat Pump)	Active	[39]
5	Hybrid (PV/T System Cooled by Nano-PCM and Nanofluid)	Active	[40]
6	Cooling (PCM Enhanced Building Envelope)	Passive	[41]
7	Hybrid (PCM Integrated with CdTe Multi-Layer PV Ventilated Window System)	Passive	[42]
8	Cooling (Earth to Air Heat Exchanger with PCM)	Active	[3]
9	Hybrid (General PCM Applications in Buildings)	Passive/ Active	[43]
10	Heating (Microencapsulated PCM in Cementitious Materials)	Passive	[44]
11	Cooling (PCM Integrated Photovoltaic Systems)	Active	[45]
12	Hybrid (Photovoltaic-Thermal Heat Pump System with PCM)	Active	[46]
13	Hybrid (Solar PCM Systems for Indoor Heating/ Cooling)	Passive/ Active	[47]
14	Hybrid (Solar-Based Energy System with PCM)	Passive/ Active	[48]
15	Hybrid (Parabolic Trough Collector with PCM and Battery Bank)	Active	[49]

heating and/or cooling [23,35]. Table 2 presents a concise overview of the incorporation of TES in buildings, both in passive and active systems, as observed in recent studies.

As shown in Table 2, phase change materials (PCMs) have the potential to be used in buildings for a variety of purposes, including heating/cooling load management and power generation [50]. Table 2 also highlights recent PCM applications in buildings, both passive and active, which focus on PCM impregnation into building materials, PCM integration as a new layer within the building envelope (side walls, roof, and floor), positioning PCM-TES systems within the building, adding PCM to windows and sun protection systems, and incorporating PCMs into building equipment (air cooling, air heating, and ventilation systems). An alternative approach to incorporating PCM in building walls, which has been less explored, is its application as a thermal insulation material in wall structures [23]. Yang et al. [51] evaluated this concept, demonstrating how the combined benefits of PCM's storage capacity and polyurethane foams' insulation performance offer significant potential to increase building energy efficiency. Most PCM studies to date have concentrated solely on TES capacity [52], ignoring characteristics that make PCMs effective as thermal insulating materials, such as high heat transfer resistance and low thermal conductivity [23]. Further investigation is needed to explore the adaptation of this innovative thermal insulating material. Moreover, more studies are required to examine the effect of integrating PCM into buildings constructed with commonly used conventional materials on reducing heating and cooling loads.

Yaras et al. [53] investigated gypsum wallboards containing attapulgite (ATP) and 1-Dodecanol (DD) composite PCM, finding significant thermoregulatory benefits, reduced heating loads, and lower CO_2 emissions due to improved thermal regulation. Gencel et al. [54] developed cement mortars with bottom ash (BA) and Capric-Stearic (C-S) acid PCM, which enhanced thermal regulation and showed significant potential for energy savings and carbon emission reductions. Farahat et al. [55] examined wood fiber combined with stearic and capric acid PCM for building insulation, demonstrating substantial energy-saving potential across various climate regions, with notable cost savings and short payback periods. López-Sabirón et al. [56] analyzed the environmental impacts of incorporating PCMs into thermal energy storage (TES) systems using Life Cycle Assessment (LCA). Their study found that PCMs could effectively reduce carbon footprints by recovering waste thermal energy, though the specific PCM selection is crucial for maximizing environmental benefits. The energy crisis has become a critical issue in the building and construction industry, necessitating innovative solutions to reduce environmental impacts. This research partially addresses the gap in carbon reduction strategies within building energy management by focusing on PCMs. While previous studies have highlighted various energy-saving techniques, our study specifically demonstrates the potential of PCMs to lower CO_2 emissions by reducing energy consumption. Current low-cost approaches have limitations, highlighting the need for more sophisticated and sustainable alternatives. Our research explores the potential of PCMs to improve cooling and heating load management in buildings [57,58]. MATLAB was employed as the primary simulation tool for analyzing PCM integration within building envelopes due to its robust computational capabilities and versatility in handling complex mathematical models of thermal behavior. MATLAB enables precise modeling of PCM integration in building materials, allowing for detailed analysis of heat transfer, energy storage, and thermal performance under varying environmental conditions. Furthermore, MATLAB's extensive library of functions and toolboxes provides efficient solutions for simulating dynamic systems, which is essential for evaluating PCM's effectiveness in managing heating and cooling loads over time. Its scripting environment also allows for the customization and parameterization of simulations, enabling the tailoring of models to specific building designs and PCM configurations. However, while MATLAB offers powerful simulation capabilities, its computational demands may require adequate hardware resources to ensure efficient simulation runs.

Conducting the case study in a four-season region introduces an additional layer of complexity and relevance, highlighting the adaptability and effectiveness of PCM acress diverse climates. The reciprocal performance improvement of PCM is a standout feature, distinguishing it from conventional systems that often target a singular energy management objective. This characteristic enhances overall efficiency and better meets the complex demands of modern building structures. Furthermore, our research highlights the alignment of the proposed PCM integration platform with Sustainable Development Goal 7 (Affordable and Clean Energy), positioning PCM as not only a solution to the current energy crisis but also a strategic contributor to global sustainability objectives. Despite the substantial body of knowledge provided by previous studies, none have comprehensively investigated crucial aspects such as: economic assessments, thermodynamics and heat transfer analysis, sustainability evaluations, and innovations in Exergy analysis. The integration of Exergy analysis marks a significant step forward in this field. Unlike energy analysis, which focuses on measuring energy flows and transformations, Exergy analysis considers the quality and potential of energy by accounting for efficiency and irreversibilities. This method not only offers insights into how PCM systems manage heating and cooling loads but also provides a more thorough evaluation of their environmental sustainability and economic feasibility. By calculating the Exergy efficiency of buildings with PCM integration, we can identify areas for improving building performance and reducing resource consumptin. This gap in the existing literature highlights the need for a comprehensive examination that considers the economic viability of PCM integration, evaluates its sustainability impacts, and introduces Exergy analysis, a crucial aspect often overlooked in PCM research. Our study aims to fill this gap by providing a holistic view of PCM's potential, emphasizing its role in enhancing energy efficiency, supporting sustainable development, and offering a more nuanced understanding of its performance through Exergy analysis.

In the subsequent sections, Section 2 offers a detailed description of the materials and methods employed. Section 3 presents the simulation results, including thermodynamics and heat transfer analysis, economical assessment, and exergy analysis. The discussion includes a comparative analysis with other relevant studies. Ultimately, the conclusions of the present investigation are summarized in Section 4.

2. Material and methods

The purpose of this section is to outline the research methodology employed in this study. The methods used to address the research question are described in detail, including sampling, data collection, analysis, and implementation techniques. For this purpose, first a building with conventional walls is selected as the case study, and its related features are thoroughly examined using DesignBuilder simulation software [59]. Next, based on the case study and its locational features, a phase change material (PCM) is selected and assigned to the building's walls. This process is also carried out with an additional layer of nanofluids. Finally, the case study is simulated using the software, and the performance of the assigned PCM and nanofluids is analyzed, validated, and compared.

This study addresses the energy crisis in the building industry by proposing cost-effective strategies, focusing on the use of PCM for enhanced cooling and heating (Fig. 4). Using DesignBuilder simulations in a developing country case study, the research demonstrates a 6 % reduction in energy usage with PCM integration. The practical application in a four-season region highlights PCM's performance advantages over traditional systems, aligning with Sustainable Development Goal 7, promoting a more sustainable and energy-efficient built environment.

2.1. *Case study specifications*

The hotel examined in this study has 16 stories, 5 of which are below

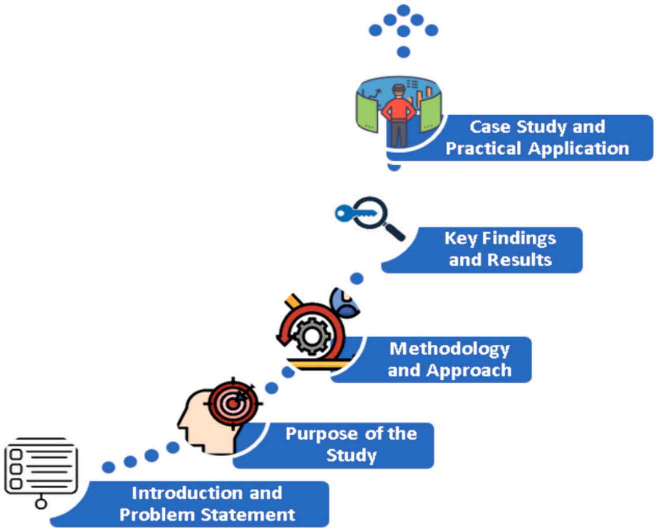


Fig. 4. Research roadmap of the present study.

ground level (basement) and 10 above ground (Fig. 5). The schematic floor layouts, along with the functions of different parts, are outlined in Appendix Figs. A.1-A.6. Additional features of the hotel's layout are provided in Table 3.

The external wall of the hotel, constructed with common masonry, is simulated using DesignBuilder software, as shown in Fig. 6. The wall comprises three layers of materials with different thicknesses: 3 cm of brick on the outermost layer, 15 cm of autoclaved aerated cement blocks (AAC blocks) in the middle layer, and 1.3 cm of plaster on the innermost layer. The values for the heat transfer coefficient and thermal mass, which are associated with the heat properties of the external wall without thermal insulation, are provided in Table 4.

Table 3
The height (meters) and area (square meters) of each floor of the building.

Floor level	Height (m)	Floor area (m^2)	Conditioned floor area (CFA) (m^2)
Basement (-5)	3.2	2010.3368	0
Basement (-4, -3, -2)	3.5	2010.3368	0
Basement (-1)	4.8	2010.3368	934.8
Ground floor	5.26	1800	726.5
First floor	6.24	1411	1073.6
2nd, 3rd, 4th, 5th, 6th, 7th and 8th 9th floor (right side)	3.5	569	312.7
2nd, 3rd, 4th, 5th, 6th, 7th and 8th 9th floor (left side)	3.5	559	311.1
10th floor (roof)	4	1075	768.8
Total	26	23,361.684	8494.1

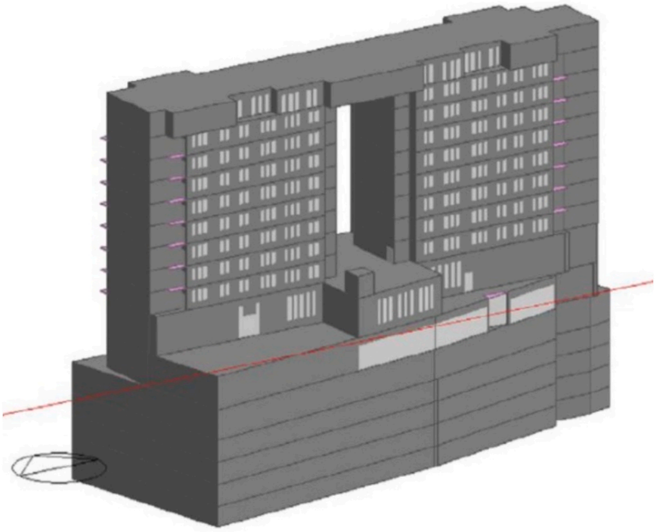


Fig. 5. Simulated 3D model of the building.

Fig. 6. Detail of external wall materials without PCMs or nanofluids.

Table 4
Heat properties of the external wall, interior wall, and roof without thermal insulation.

	Thickness (cm)	Heat transfer coefficient W/(m^2·K)	Thermal mass (J/K)	Materials
External wall	18.1	0.624	1.602	Brick- AAC Block-Plaster
Interior wall	15.2	0.598	1.674	AAC Block-Plaster
Roof	31.1	2.212	0.452	Asphalt-Concrete- Plaster

2.2. PCM and thermal nanofluids specification

As mentioned in the previous section, the phase change temperature is a critical factor in selecting a PCM. As a result, it is essential to first study the climate of Mashhad, where the chosen hotel is located. A PCM with a phase change temperature in an acceptable range that is close to room temperature should be used. If the phase change temperature is, for example, substantially higher or lower than 30 °C, the material may only be effective on a few particularly hot summer days or cold winter days. This would render the PCM practically useless for most of the year.

The second criterion for selecting the phase change material is its availability in the targeted location. If the material is not available locally, it would necessitate a redesign to incorporate an alternative solution.

The third consideration is the overall cost, including the price of the phase change material. To minimize expenses, the most cost-effective phase change material with the required thickness and compatibility with other parameters should be selected.

Another important factor is the density of the phase-change material. Since density and weight are inversely correlated, a lower-density material will reduce both the cost of structural design and the overall cost of the PCM. Additionally, other crucial features to consider include low thermal conductivity, corrosion resistance, fire resistance, and latent heat storage.

Considering the aforementioned factors and reviewing the relevant scientific literature, the RT18HC phase change material from paraffins, produced by Rubitherm Company, was chosen for this study. RT18HC is an organic, non-corrosive, flammable, affordable, widely available, and relatively low-density material. Its properties are detailed in Table 5 and illustrated in Fig. 7 [60].

The following are some further characteristics of this phase-change material and other products from the company with the RT prefix:

- High thermal energy storage capacity
- Fairly constant temperatures during heat storage and discharge.
- No supercooling or chemical reactions
- Long lifespan with stable performance in phase change cycles
- Available with a melting temperature range of −9 °C to 100 °C
- Reasonably priced (approximately $2 per unit weight for RT18HC, which is an impure paraffin wax.)

In this study, thermal nanofluids, which are more common in Iran and have multiple suppliers, are examined alongside phase change materials. These coatings act as a barrier to heat transfer, reducing thermal conductivity and minimizing heat loss or gain. Due to their nanoscale properties, they offer acceptable surface coverage and uniformity, which enhances overall thermal performance. They can be applied to various materials and substrates, including plaster, cement, and metal surfaces on external walls, facades, and roofs. The thermal characteristics of these thermal coatings are presented in Table 6 [61,62].

In this study, Junior Armor thermal nano-paints, produced by Nano Pars Company, were used. These paints have a final thickness of 1 mm on the wall and cover 1 square meter per kilogram of paint. This product is expected to have a durability of 10 years, with a price of approximately $7.2 per pound [63].

According to Fig. 8 and Fig. 9, a 2-cm layer of RT18HC and a 0.1-cm layer of nanopaint were applied to the building's external walls in this study. Additionally, the heat properties of the external walls, interior walls, and roof with a layer of RT18HC or nanopaint are shown in Table 7 and Table 8.

2.3. Simulation practice

Over the last few decades, PCM applications have been studied through two main approaches: experimental or numerical/ simulation methods [52]. From an economic perspective, simulations are often more desirable than experimental studies, as they are more cost-effective and have a shorter life cycle [52]. With advancements in computer technology, methods for estimating a building's energy requirements and energy flows have evolved from basic to highly complicated numerical methods [64], resulting in the development of over 200 simulation tools in recent years [65]. Therefore, there is a growing body of research on PCM applications in building thermal performance, including studies by [66–70]. In this study, the thermal impact of applying phase change materials and thermal nano-paints on the building envelope is explored by simulating a hotel in Mashhad, Iran, using DesignBuilder software. The general steps for energy simulation are summarized in Fig. 10.

Table 5
Thermodynamic properties.

Typical values	Amount	Unit (SI)
Melting range	17–19	° C
Freezing area	19–17	° C
Heat storage capacity ±7.5 %	260	kJ/kg
Specific heat capacity	2	kJ/kg·K
Fixed density (at 15 °C)	0.88	kg/l
Liquid density (at 25 °C)	0.77	kg/l]
Conductivity of heat	0.2	W/(m·K)
Volumetric expansion	12.5	%
The flash point	135	° C
Maximum of working temp.	50	° C

DesignBuilder, a building performance modeling software, offers a comprehensive range of features, including tools for energy simulation, HVAC system design, daylighting analysis, thermal comfort assessment, and renewable energy integration. In this research, five primary tasks were completed to effectively utilize DdesignBuilder: project setup, building geometry configuration, building property specification, HVAC system design, and energy simulation setup. All of these steps are further discussed in the following sections.

2.4. Project setup

In this step, the project settin gs were defined, including the project name, location, and units of measurement. To assign climatic characteristics to the weather folder, several options are available. In this research, weather data was extracted from both DesignBuilder's Built-in Weather Data and the Climate Consultant Application. Climate Consultant reads local climate data in EPW (Energy Plus Weather) format and displays various graphic charts of weather parameters, such as temperature, radiation range, sky cover range, wind velocity, and precipitation [71]. Figs. 11, 12, and 13 depict Mashad's climate data, derived from Climate Consultant. As shown in Fig. 11, February has the fewest sunlight hours, while July has the most. Fig. 12 shows that maximum temperatures occur between June and August, with the minimum in January. Additionally, the winter months experience greater temperature variation between day and night. Fig. 13 indicates that Mashhad's monthly average relative humidity ranges from 25 to 68 %. In addition to the climatic data from Climate Consultant, Table 10 presents the climatic characteristics assigned to the climate folder from Design Builder's library, which reflect the conditions of the project's location. According to the Köppen climate classification system, Mashhad falls under a Mediterranean climate (Csa), characterized by mild, wet winters and hot, dry summers.

2.5. Building geometry

This step involved constructing the building model, including its shape, dimensions, layouts, spaces, floors, walls, windows, roofs, and other components (Fig. 5). Additionally, the dimensions, orientations, and connections between the various building elements were defined (see Appendix A).

2.5.1. Building properties

In this step, suitable materials were assigned to the building elements from the software's materials library. The properties of walls, roofs, windows, and other surfaces, including heat transfer coefficient, thermal mass, and thickness, were defined (Table 4), (Table 9).

2.5.2. HVAC system design

HVAC system design involves configuring the HVAC system using the software's HVAC System Wizard or manual setup options, followed by connecting the selected system to different zones within the building model that have similar heating and cooling requirements. In this study, a 4-pipe fan coil with an air-cooled chiller powered by natural gas was considered. The system's coefficient of performance (COP), a metric for evaluating thermodynamic efficiency, is calculated from Eq. 1.

$$\text{Coefficient of performance } (COP) = Q/314W \tag{1}$$

Where:

- Q is the useful heat supplied or removed by the considered system (machine, BTU).

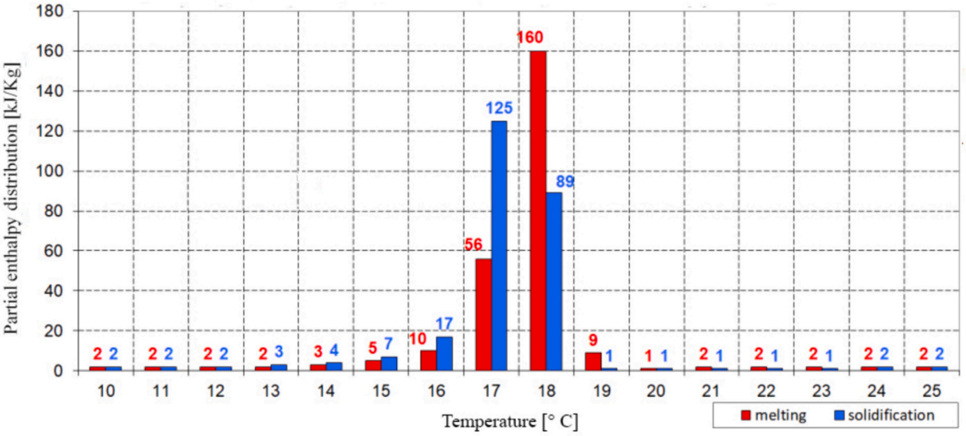


Fig. 7. RT18HC partial enthalpy distribution.

Table 6
Characteristics of thermal nanofluids.

	Specific thermal resistance (K·m/W)	Density (kg/m3)	Specific heat capacity (J/kg·K)
Thermal nanofluids	0.067	370	3500

- $W > 0$ is the network put into the considered system in one cycle(W, BTU).

2.5.3. *Energy simulation setup*

In this step, the energy simulation parameters, such as occupancy schedules, lighting schedules, HVAC operation schedules, equipment schedules, and other necessary input data for the analysis, were set up. These schedules define when and how these components operate or change their states over time.

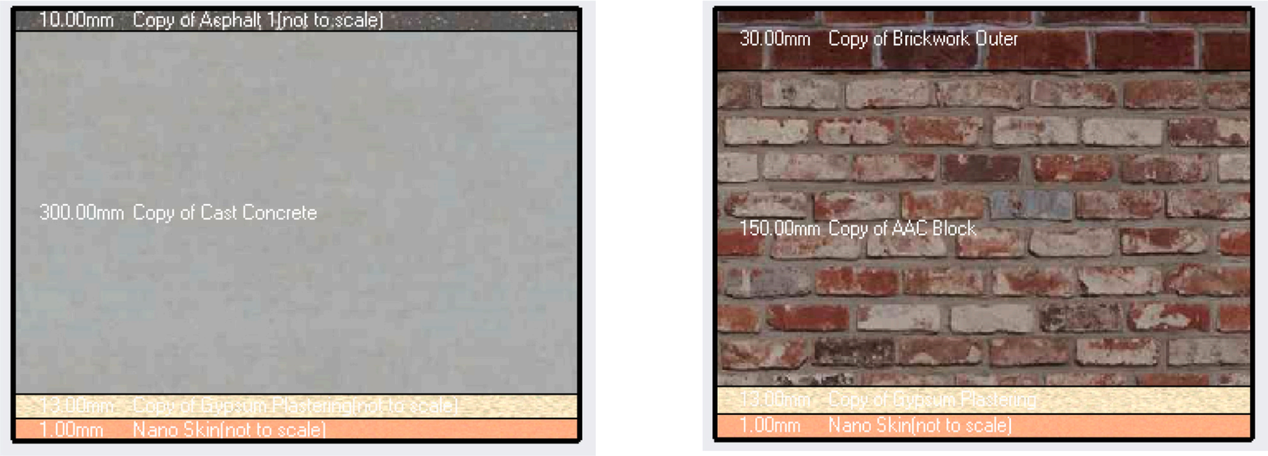
Activity or occupancy schedules involve assigning specific activities or operations to spaces within the building model. This process associates the intended use or function of a space with the corresponding activity or occupancy profile. Assigning activities helps in simulating energy performance, thermal comfort conditions, and optimizing the building design, HVAC systems, and other aspects based on expected activities in different areas. For this purpose, a custom activity or a predefined activity profile from DesignBuilder's library of typical activities and occupancy patterns can be selected. The assigned activity schedule for this research is shown in Table 11. Unconditioned locations, such as warehouses, elevators, stairwells, parking lots, etc., are not indicated in Table 11.

The information in Table 11 was meticulously gathered through a comprehensive process, beginning with a thorough survey during the case study phase. To ensure accuracy and reliability, the data underwent rigorous validation and double-checking, including consultations with principals to verify key details. Subsequently, the data was carefully categorized to align with the specific requirements of the simulation process. This categorization ensures the information is comprehensive and tailored to integrate seamlessly into the DesignBuilder modeling framework.Adjustments made during this process were essential for aligning the data with the simulation's detailed specifications. By adhering to the precise demands of the DesignBuilder modeling, the data in Table 11 is refined and optimized, ready to enhance the simulation's accuracy and reliability. The applied data relates to a real case study used in the present research, ensuring the values are actual data and calibrated within the simulation process.

This research analyzed the integration of PCM into the walls of a multi-floor structure to enhance energy efficiency. The focus on walls, rather than roofs, is due to the unique thermal dynamics of multi-floor designs, where the uppermost floor is most exposed to external conditions. This approach aims to optimize energy management by addressing

(a) *(b)*

Fig. 8. (a) Detail of the roof with PCM and (b) detail of external wall materials with PCM.



(a) *(b)*

Fig. 9. (a) Detail of the roof with a layer of nano paint and (b) detail of external wall materials with a layer of Nano paint.

Table 7
Heat properties of the external wall, interior wall, and roof with a layer of RT18HC.

	Thickness (cm)	Heat transfer coefficient W/(m^2·K)	Thermal mass (J/K)	Materials
External wall	20.1	0.565	1.769	Brick- AAC Block-PCM-Plaster
Interior wall	15.2	0.598	1.674	AAC Block- plaster
Roof	33.1	1.616	0.619	Asphalt- PCM-Concrete- Plaster

Table 8
Heat properties of the external wall, Interior wall, and roof with a layer of Nano paint.

	Thickness (cm)	Heat transfer coefficient W/(m^2·K)	Thermal mass (J/K)	Materials
External wall	18.2	0.619	1.617	Brick- AAC Block-PCM-Plaster
Interior wall	15.3	0.598	1.674	AAC Block- plaster
Roof	31.2	2.14	0.467	Asphalt- PCM-Concrete- Plaster

the nuanced thermal behavior of sequentially arranged floors. The finite difference algorithm within EnergyPlus was employed to simulate transient heat transfer and phase change processes. This numerical method discretizes the governing heat transfer equations over the PCM-enhanced building envelope, allowing effective approximation of spatial and temporal temperature derivatives. An optimal timestep, Δt, was carefully selected to balance computational efficiency and accuracy, ensuring the fidelity of the simulation results. This precise timestep selection is critical for accurately capturing the dynamic response of PCMs to temperature changes and phase transitions, providing reliable insights into their performance in building envelopes.

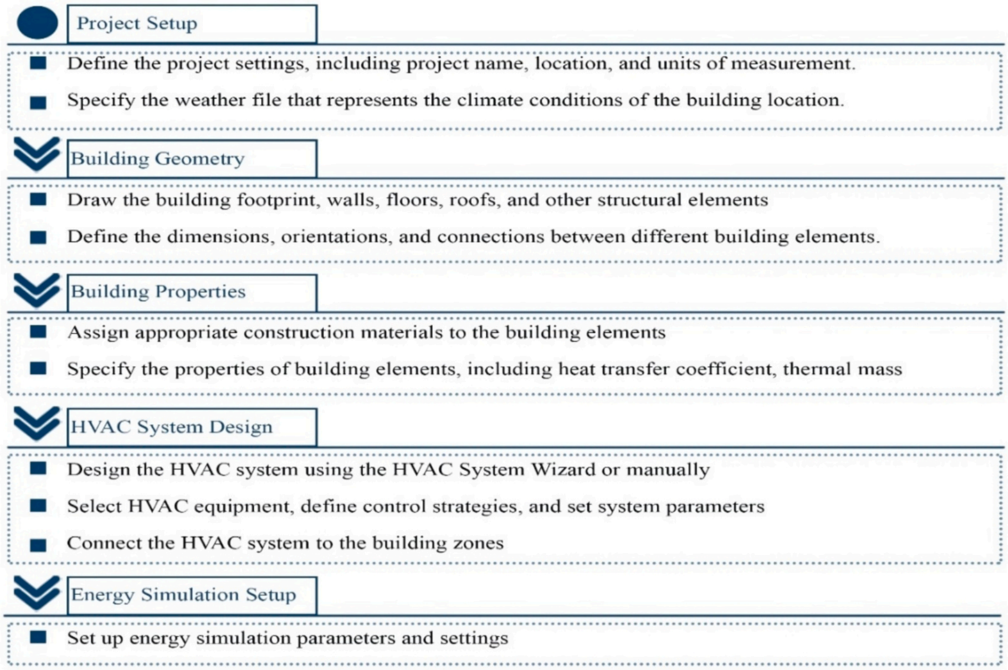
2.6. Thermodynamic assessment

This study involves the analysis of energy consumption in a building under three distinct thermal insulation scenarios : 1) without thermal insulation, 2) with PCMs, and 3) with nano paints. The data includes parameters such as building area, activity type, temperature, area per person, occupancy timing, appliances, and energy consumption results. The primary aim is to evaluate key aspects of thermodynamics, such as energy use intensity (EUI), potential energy savings, and the impact of PCMs on energy efficiency. Table 12 summarizes the mathematical formulas used to analyze these key thermodynamic features in the study [72,73].

2.7. Heat transfer analysis

To develop a comprehensive mathematical methodology for analyzing heat transfer in PCM for this research study, a structured approach is outlined in Table 13. This methodology is divided into sections covering problem formulation, numerical solution, and analysis. All programming and mathematical developments are conducted using MATLAB 2019b [74–76]. An enthalpy method is employed to handle the phase change in the simulation, updating the enthalpy based on the current temperature at each time step. The enthalpy determines the material's phase state — solid, liquid, or mushy (partially melted). Based on the phase, the temperature update is adjusted to accurately represent thermal behavior during the phase transition [76].

A finite element method is used to discretize both the spatial and temporal domains for analyzing heat transfer in the PCM and wall system. The spatial discretization step, Δx, and the time step, Δt, are selected based on stability criteria, such as the Courant-Friedrichs-Lewy (CFL) condition, to ensure numerical stability and accuracy [77]. The discretized equations are implemented in MATLAB, involving coding of the mathematical model to accurately represent the physical system. Once implemented, the numerical model is validated by comparing the results with analytical solutions or available experimental data to ensure accurate prediction of the thermal behavior of the PCM and wall system. After validation, parametric studies are conducted to investigate the effects of various parameters, including PCM thickness, ambient temperature, and initial temperature. These studies help assess the system's sensitivity to changes in key variables. In the context of heat transfer analysis involving a wall integrated with a PCM, "liquid in the wall" refers specifically to the state of the PCM within the wall structure. The PCM transitions between solid and liquid phases based on temperature changes. The wall material itself remains solid throughout, without undergoing any phase changes. The PCM embedded within the wall undergoes phase transitions—solidification or melting—as it absorbs or releases thermal energy, depending on whether its temperature is below or above its melting point. Thus, the term "liquid in the wall" pertains solely to the liquid state of the PCM within the wall [78]. The constants used in the simulation process are detailed in Table 14.



Project Setup

- Define the project settings, including project name, location, and units of measurement.
- Specify the weather file that represents the climate conditions of the building location.

Building Geometry

- Draw the building footprint, walls, floors, roofs, and other structural elements
- Define the dimensions, orientations, and connections between different building elements.

Building Properties

- Assign appropriate construction materials to the building elements
- Specify the properties of building elements, including heat transfer coefficient, thermal mass

HVAC System Design

- Design the HVAC system using the HVAC System Wizard or manually
- Select HVAC equipment, define control strategies, and set system parameters
- Connect the HVAC system to the building zones

Energy Simulation Setup

- Set up energy simulation parameters and settings

Fig. 10. General steps followed for energy simulation.

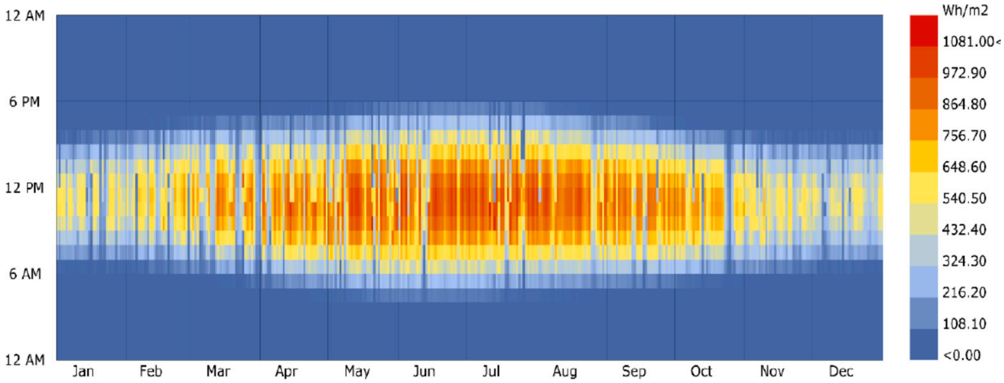


Fig. 11. Diurnal patterns of solar radiation of Mashhad, Iran.

3. Results and discussion

3.1. Simulation outcomes

After configuring all parameters and settings, the energy simulation process should be initiated and completed with the defined inputs and setups. The software will execute the calculations and generate results, including energy consumption, energy use intensity (EUI), operational costs, and other performance metrics, as explained in the following sections.

The software offers comprehensive reporting and visualization capabilities, enabling users to generate detailed reports, graphs, and visualizations of energy consumption. For this project, energy consumption is calculated over full year. However, the display settings are configured to show monthly consumption. To simulate the influence of phase change materials, the "General Solution" is set to "Finite Difference" mode, with all other options at default. Fig. 14 shows the energy consumption results obtained through this simulation for three different cases with and without thermal insulation.

The use of phase change materials, as shown in Fig. 14, reduces electricity consumption for cooling equipment, with July showing the greatest reduction. Additionally, in colder months, phase change materials decrease gas energy consumption for heating equipment, with peaks in January, February, and December (Figs. 15 and 16).

Although the use of thermal nanopaint coatings on external walls led to a reduction in energy consumption, the reduction was less significant compared to the use of phase-change materials. Additionally, the variation in electrical energy usage was minimal (Figs. 17 and 18).

To compare the energy efficiency of various buildings or to track the performance of a single building over time, Energy Use Intensity (EUI) is calculated. EUI expresses a building's energy use relative to its size by dividing the total energy consumed in one year by the total conditioned floor area of the building. This is used to calculate the EUI, which serves as a metric for comparing the building's gas energy efficiency in three situations: without thermal insulation, with PCMs, and with nanoparticles (Table 15).

Table 15 reveals that using phase-change materials and nano-paints reduced the energy use intensity by 5.6 % and 1.8 %, respectively. This indicates an improvement in building efficiency with the application of these materials in the building envelope.

The energy simulation results for megacities like Mashhad underscore the significant benefits of incorporating advanced technologies to

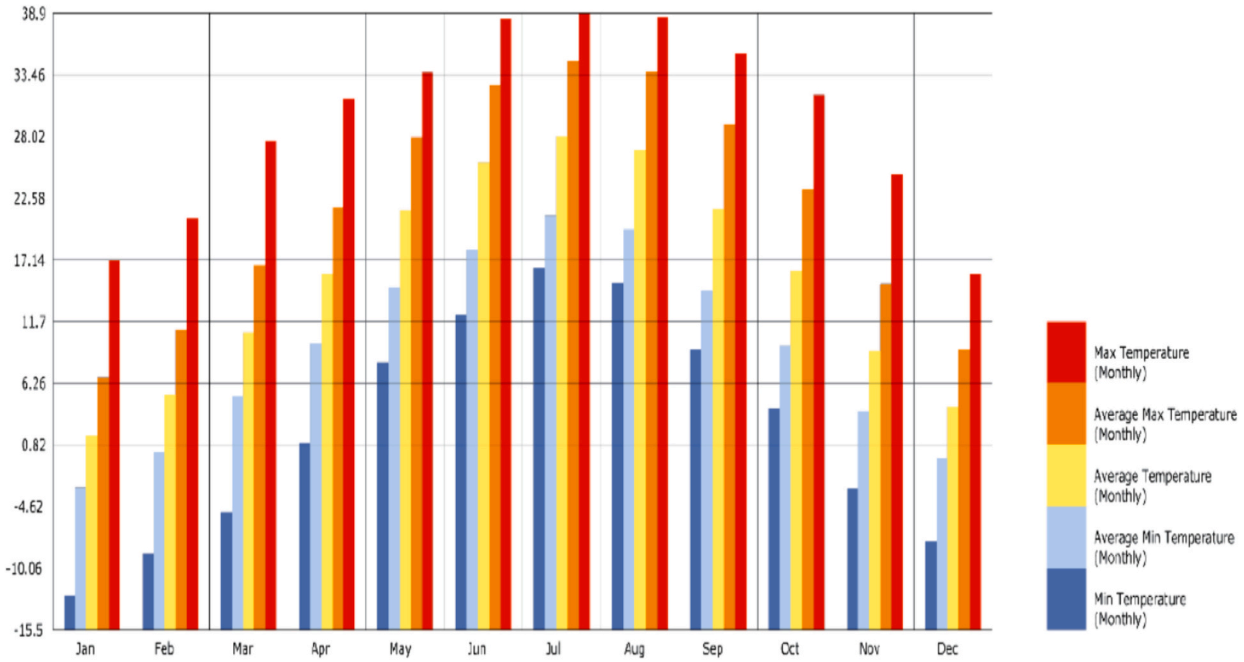


Fig. 12. Monthly average temperatures over a year in Mashhad, Iran.

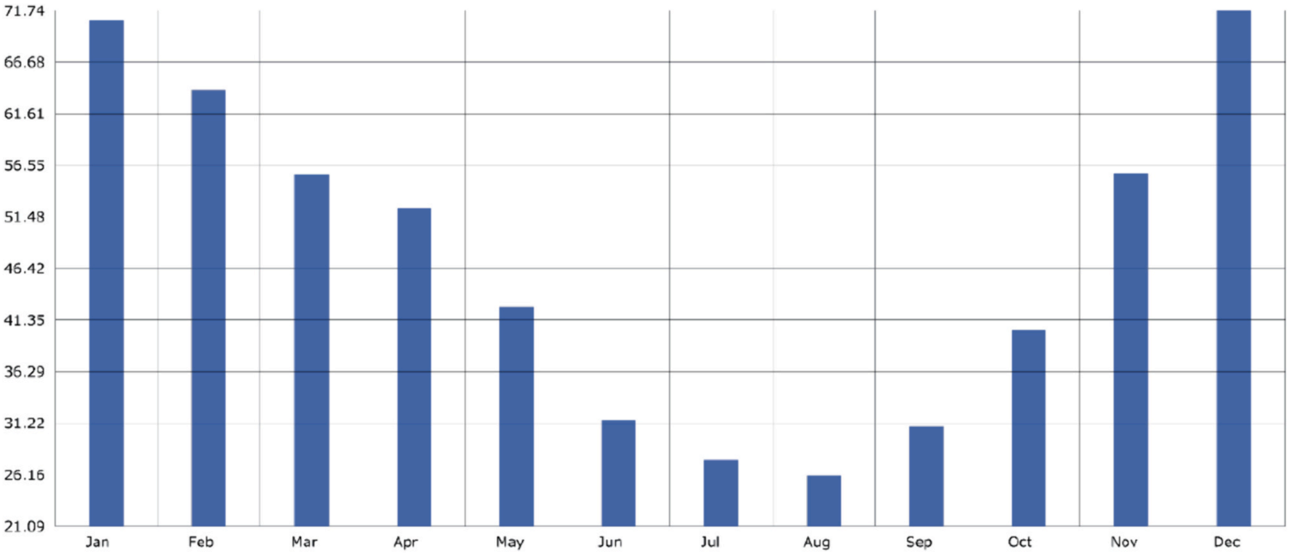


Fig. 13. Monthly average relative humidity of Mashhad, Iran.

Table 9
Heat properties of openings.

	Thickness (cm)	Heat transfer coefficient W/(m^2·K)	Materials
Door	2.54	3.3	wood
Window	7	1.5	Double glazed Low-E glass Argon

improve building energy efficiency. Detailed reporting and visualization features provide a comprehensive understanding of energy consumption patterns. The monthly breakdown of energy use facilitates nuanced analyses, which are crucial for addressing the dynamic energy demands in megacities. Notably, the simulation's use of the Finite Difference method to model PCMs demonstrates the software's versatility in capturing the impact of innovative materials on energy consumption. Fig. 14 vividly depicts a substantial reduction in electricity consumption during peak cooling periods and a corresponding decline in gas usage during colder months with the use of PCMs. Meanwhile, the examination of nano-paint coatings in Figs. 17 and 18 presents an alternative approach to energy efficiency. Although nano-paints contribute to a reduction in energy consumption, the impact is less pronounced compared to PCMs.. This underscores the importance of selecting materials suited to specific climate conditions and building requirements, considering the trade-offs between effectiveness and cost.

The quantitative comparison of building efficiency in Table 15, through EUI calculations, reinforces the positive impact of alternative materials. The data shows a 5.6 % reduction in EUI with PCMs and a 1.8 % reduction with nanopaints, highlighting their promising role in enhancing building performance. These results emphasizes the significance of exploring alternative materials in the construction industry to

Table 10
Assignment of climatic traits to the climate folder from the Design Builder's library.

General	
City name: MASHHAD	
Country	IRAN
Source	ASSHRAE/ ITMY
WMO	407,450
ASHRAE climate zone	2B
Koppen classification	Bwh
Latitude (°)	36.27
Longitude (°)	59.63
Elevation (m)	999.0
Standard pressure (kPa)	89.9
Time and daylight saving	
Time zone	(GMT +03:30) Tehran
Beginning of winter	Oct
Winter's End	Mar
Beginning of summer	Apr
Summer's End	Sep
Energy codes	
Legislative region	IRAN
Heating 99.6 %	
Outside design temp. (°C)	−9.1
Wind velocity (m/s)	9.2
Direction of the wind (°)	0.0
Heating 99 %	
Outside design temperature (°C)	−6.1
Wind speed (m/s)	7.7

achieve sustainable and energy-efficient structures, especially in megacities with high energy demands.

Zhan et al. [79] explored energy-efficient alternatives using PCMs in building envelope applications. Their hierarchical review covers simulation tools, classification, integration technologies, and the benefits and drawbacks of widespread PCM adoption. The review identifies a gap in understanding occupant intervention, especially in ventilation, and urge future research to focus on hydrothermal and optical performance, sustainable materials, visual comfort, and moveable PCM-based interventions. Liu et al. [80] investigated the impact of a novel PCM-integrated composite concrete on building envelopes across different climates. Their results highlights the effectiveness of PCM concrete in regulating indoor temperatures and emphasize the need to select appropriate PCMs based on specific climatic conditions. Erdogmus et al. [81] introduced an innovative solution for the management and disposal of water treatment sludge (WTS) by integrating it with PCM in foam concrete. Their study demonstrates that WTS/PCM foam concrete composites can reduce heating/cooling loads, provide energy savings, and lower carbon emissions. Zhussupbekov et al. [82] explored machine learning techniques for forecasting energy demand in PCM-integrated residential buildings within the Mediterranean climate region. Their study proposes a model for predicting energy consumption and identifies key design parameters, with Support Vector Machines (SVM) and Artificial Neural Networks (ANN) emerging as more reliable prediction methods. Collectively, these studies highlight diverse approaches and innovations in leveraging advanced technologies, alternative materials, and predictive models to enhance building energy efficiency. As megacities continue to grow, integration of these technologies becomes crucial for addressing energy-related challenges and promoting environmentally conscious urban development.

Table 12
Summary of key features of thermodynamic analysis in this study.

Key features	Mathematical formula
Energy Use Intensity (EUI)	$\text{EUI} = \frac{\text{Energy Consumption}}{\text{Total Conditioned Area}}$
Percentage Energy Savings Calculation	$\text{Energy Savings} = 1\text{-}\frac{\text{Energy Consumption with Insulation}}{\text{Energy Consumption without Insulation}}$
Energy Storage Potential of PCM	$\text{Energy Storage Potential} = \frac{\text{Desnity} \times \text{Thickness} \times \text{Latent Heat of Fusion}}{1000}$
Temperature Variation Analysis	$\Delta\text{Temperature} = \text{Current Temperature} - \text{Mean Temperature}$
Activity Energy Impact	$\text{Activity Energy} = \text{Area per Person} \times \text{Area}$

Table 11
Activity assignment of different parts of the building.

	Function	Num	Area (m^2)	Activity	Temperature (°C)		Area per person (m^2)	Timing	others
					Cold	Warm			
1	Lobby	1	196.4	Walking	23	20	0.2147	Full-time	–
2	Reception	1	48.5	Walking	23	20	0.1046	Full-time	Computer Fax Telephone
3	Empty space	1	202.3	Walking	23	20	0.18	Full-time	–
4	Corridor	20	3138	Walking	23	20	0.12	Full-time	–
5	Entrance	4	152	Walking	25	20	0.49	Full-time	–
6	Elevator halls	3	33	Standing	25	20	0.18	Full-time	–
7	Pool	1	183	Exercising	32	28	0.12	Part-time	–
8	Massaging	1	27	Relaxing	32	28	0.14	Part-time	–
9	Coffee shop	2	213	Drinking/eating	25	23	0.18	Part-time	Appliances
10	Restaurant	2	1004	Drinking/eating	21	17	0.33	Part-time	Appliances
11	Kitchen	3	176	Cooking	21	17	0.21	Part-time	Appliances oven
12	Prayer room	1	38	Exercising	25	20	0.11	Part-time	–
13	Commercial	7	997	Shopping	24	20	0.43	Part-time	Computer
14	office	3	726	Walking/seating	24	22	0.11	Part-time	Computer Fax Telephone
15	Food Warehouse	2	64	Storing	23	23	0.02	Full-time	Appliances
16	Housekeeping	16	236	Preparation	25	20	0.05	Full-time	Appliances
17	Laundry	2	103	Washing	24	18	0.12	Full-time	Appliances
18	Restroom	2	99	Relaxing	25	20	0.11	Part-time	–
19	Pantry	1	13	Food preparation	21	17	0.21	Full-time	Appliances oven
20	Suit	88	907	Seating	25	21	0.09	Part-time	Appliances
21	Room	88	857	Relaxing	25	20	0.05	Part-time	Appliances
22	Restaurant's Lobby	1	62.37	Walking	23	20	0.48	Full-time	–

Table 13
Heat transfer mathematical logics in this study (inspired by [74–76].

<table>
<tr><th>Concept</th><th>Formula</th></tr>
<tr><td>Heat conduction equation in the wall</td><td>
<table>
<tr><th></th><th>Construction Cost (USD)</th><th>Gas Energy Saving (kWh)</th><th>Electricity Energy Saving (kWh)</th><th>Gas Cost Saving (USD)</th><th>Electricity Cost Saving (USD)</th><th>Total Cost Saving (USD)</th></tr>
<tr><td>RT18HC</td><td>467,918</td><td>85,066</td><td>29,377</td><td>153.3</td><td>87.2</td><td>240.5</td></tr>
<tr><td>Nanopaint</td><td>123,384</td><td>27,466</td><td>4,925</td><td>17.4</td><td>86</td><td>103.4</td></tr>
</table>
$\frac{\partial T_w}{\partial t} = \alpha_w \frac{\partial^2 T_w}{\partial x^2}$
where T_w is the temperature in the wall, α_w is the thermal diffusivity of the wall material, and x is the spatial coordinate.</td></tr>
<tr><td>Heat conduction equation in the PCM</td><td>$\frac{\partial T_{PCM}}{\partial t} = \alpha_{PCM} \frac{\partial^2 T_{PCM}}{\partial x^2} + \frac{L}{\rho_{PCM} c_{PCM}} \frac{\partial f}{\partial t}$
where T_{pcm} is the temperature in the PCM, α_{pcm} is the thermal diffusivity of the PCM, L is the latent heat of fusion, ρ_{pcm} is the density of the PCM, c_{pcm} is the specific heat capacity, and f is the liquid fraction.</td></tr>
<tr><td>Discretized equations for heat conduction</td><td>$T_w^{n+1}(i) = T_w^n(i) + \alpha_w \Delta t \frac{T_w^n(i+1) - 2T_w^n(i) + T_w^n(i-1)}{(\Delta x)^2}$</td></tr>
<tr><td>Discretized equations for heat conduction in the PCM</td><td>$T_{PCM}^{n+1}(i) = T_{PCM}^n(i) + \alpha_{PCM} \Delta t \frac{T_{PCM}^n(i+1) - 2T_{PCM}^n(i) + T_{PCM}^n(i-1)}{(\Delta x)^2} + \frac{L}{c_{PCM} \rho_{PCM}} \left(\frac{\partial f}{\partial t}\right)$</td></tr>
<tr><td>Initial and boundary conditions</td><td>$T(x,0) = T_{Initial} T(0,t) = T_{Ambient} \rightarrow (\text{At x} = 0, \text{exterior surface}) \frac{\partial T}{\partial x} = 0 \rightarrow \text{At x} = \text{L, interior surface}$
Defined based on the specific scenario of the simulation.</td></tr>
</table>

Table 14
The constant values and assumptions in the heat transfer process simulation.

Constant/parameter	Description	Value
PCM melting point	Melting point of the PCM (°C)	25
PCM heat capacity solid	Specific heat capacity of PCM in solid state (J/kg·K*)	2000
PCM heat capacity liquid	Specific heat capacity of PCM in liquid state (J/kg·K)	2500
PCM latent heat	Latent heat of fusion of PCM (J/kg**)	200,000
PCM density	Density of PCM (kg/m^3)	880
PCM thickness	Thickness of PCM layer (meters)	0.01
Wall thickness	Thickness of the wall (meters)	0.2
Wall conductivity	Thermal conductivity of the wall material (W/m·K)	0.72
Ambient temperature	Ambient temperature (°C)	15
Initial temperature	Initial temperature of PCM (°C)	20
Time step	Time step for simulation (seconds)	3600
Total time	Total simulation time (seconds)	86,400
Grid size	Size of the 3D grid for discretization	10

[*] The unit denotes the amount of heat required to change the temperature of a unit mass of a substance by one degree Kelvin.

[**] The unit denotes thermal mass representing the ability of a body to store thermal energy.

3.2. Economical assessments

Although DesignBuilder concentrates on simulating and analyzing building performance rather than performing in-depth cost calculations, it nonetheless has a cost module to evaluate the economic impact of building designs. With the help of this module, users can incorporate life-cycle analysis into the primary energy analysis model and compute construction costs, utility costs, and other expenditures.

In this research, the cost of the phase-change materials estimated by DesignBuilder is \$ 467, 918 based on the total weight of materials used in the building. This estimation assumes a cost of \$2 per kilogram for the RT18HC phase- change material. For Nano paints, the same procedure was followed as illustrated in Table 16. Subsequently, the initial investment required for incorporating phase-change materials and nanopaint is calculated, followed by an assessment of the economic justification for their use in the building. For this purpose, after determining the amount of gas and electrical energy saved, the annual utility cost savings from energy efficiency should be calculated based on the applicable energy carrier tarrifs (Table 17).

In the next phase, the payback period is determined by calculating the time required to recoup the intial cost through annual revenue or savings. This revenue is first calculated from the investor's perspective using (Table 17) domestic energy carrier pricing and then from a national perspective using (Table 18) energy carrier export rates. Naturally, these rates are adjusted for annual inflation (Eq. 2).

$$\text{Total Income} = \text{Annual Income}^*(1 + 1.05^n) \tag{2}$$

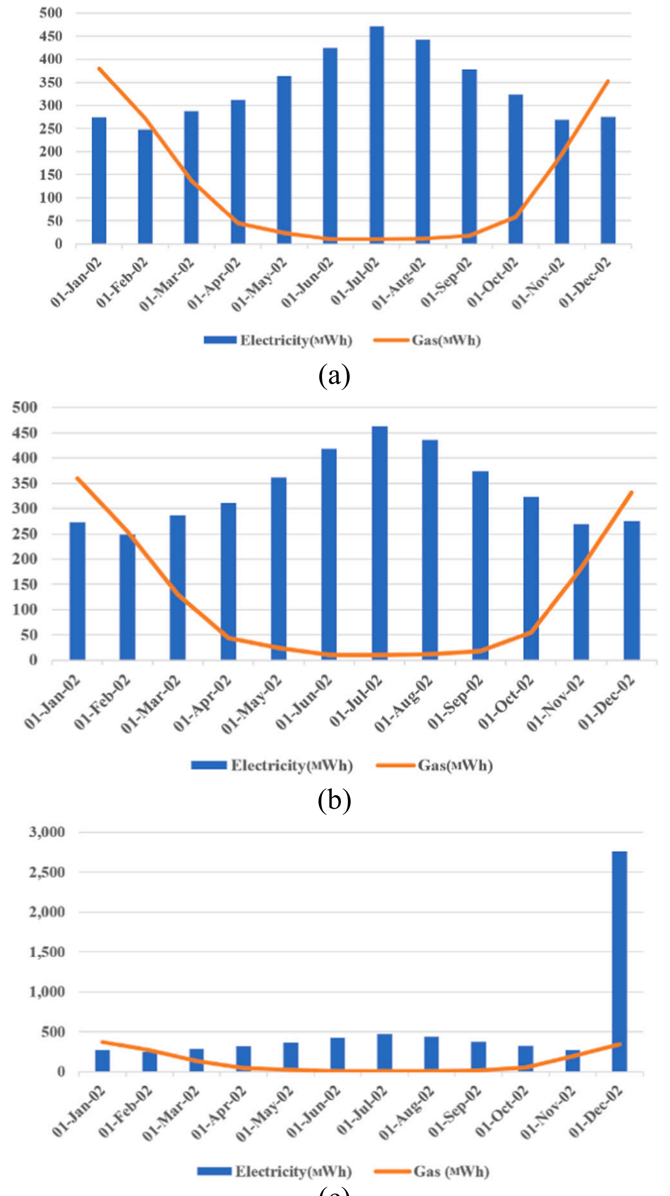
Where:

- n: Time unit (year)
- 1.05: Annual energy price inflation rate increase of 5 %.

To estimate the annual revenue from a national perspective, the total reduction in energy consumption for each scenario is calculated. The annual income is then determined based on the rate of \$0.06 per kilowatt of exported energy carriers (Table 18).

The application of PCM as a thermal insulation material and its role as a passive system in building envelopes has been studied through simulated models. The findings on energy consumption and the costs of using insulating coatings indicate that phase change materials are 3.8 % more energy efficient than nanopaints. However, they initially cost approximately four times as much as nanopaints and take an additional four years to return the initial investment. Additionally, given that the materials used in this study are more expensive than energy carriers, particularly at domestic rates in Iran, it takes a considerable amount of time to break even on the initial costs, making the use of these materials economically unjustifiable. In other words, the low cost of energy in Iran serves as a reason for not adopting phase-change materials and nanopaints in this study.

In the pursuit of enhancing building energy efficiency, the integration of PCMs and nanopaints has been examined through rigorous analyses, with a particular emphasis on economic considerations. DesignBuilder, renowned for its ability to simulate building performance, offers a dedicated cost module to assess the financial implications of adopting innovative building materials. This research provides a detailed examination of the economic aspects associated with PCM utilization. Specifically, the construction costs for RT18HC PCM and nanopaints are estimated at \$467,918 and \$123,384, respectively. This study also explores the initial investment required for incorporating these materials and assesses the annual utility cost savings, factoring in the identified reduction is gas and electricity consumption. Determining



(a)

(b)

(c)

Fig. 14. Energy consumption outputs of the simulation based on electricity and gas resources (MWh) as per (a) external wall without thermal insulation, (b) external wall with a layer of RT18HC, and (c) external wall with a layer of Nano paint.

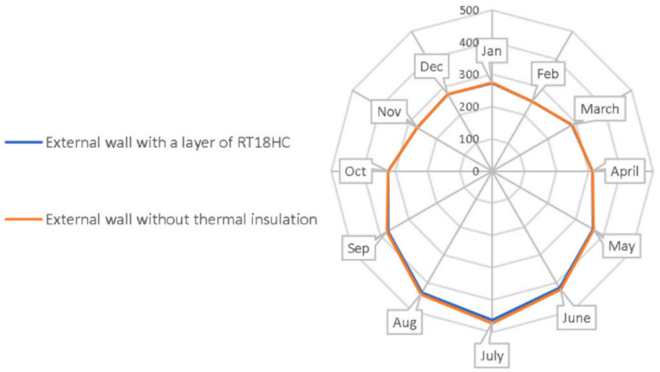


Fig. 15. Yearly electrical energy consumption utilizing phase-change materials.

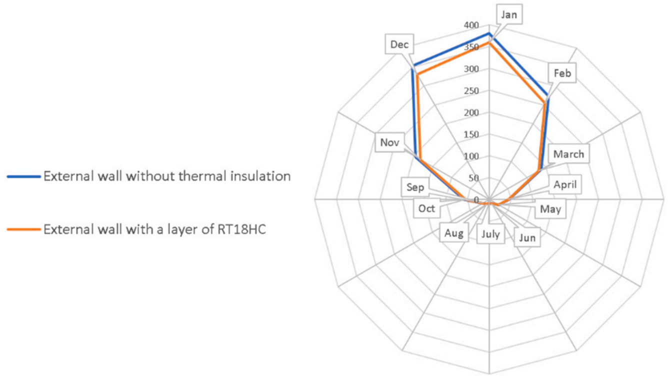


Fig. 16. Yearly gas energy consumption utilizing phase-change materials.

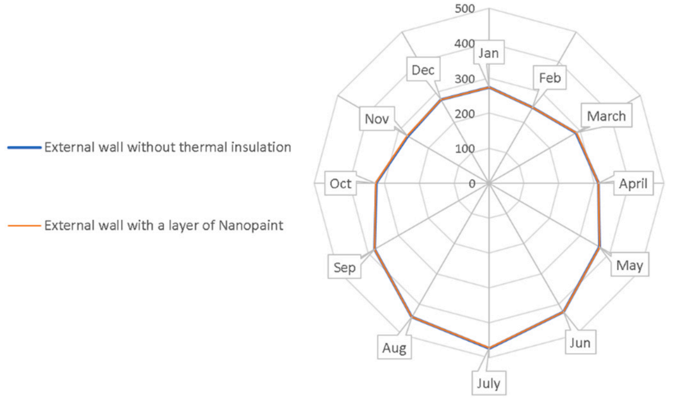


Fig. 17. Electrical energy consumption throughout the year using Nano paints.

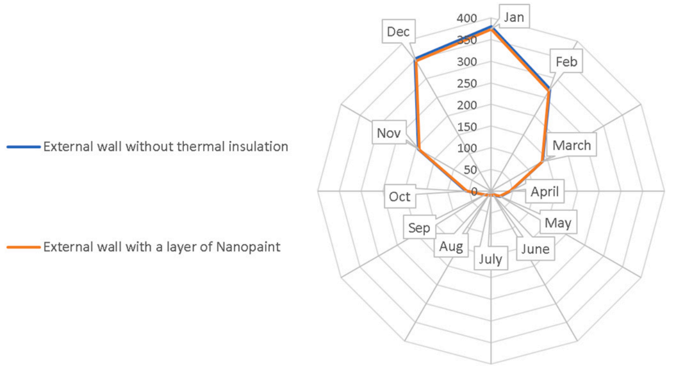


Fig. 18. Gas energy consumption throughout the year using Nano paints.

Table 15
Energy Use Intensity in different scenarios.

	Without thermal insulation	With PCMs	With nano paints
Energy consumption (gas)	1,515,197	1,430,131	1,487,731
Total conditioned floor area	8494.1	8494.1	8494.1
Energy Use Intensity (EUI)	178.38	168.36	175.14

the payback period, which represents the time required to recover the initial investment through annual savings, is a critical phase of this economic analysis. From an investor's perspective, the payback period

Table 16
Economic justification of utilizing RT18HC and Nano paints in the building.

	Construction cost (USD)	Gas energy saving (kWh)	Electricity energy saving (kWh)	Gas cost saving (USD)	Electricity cost saving (USD)	Total cost saving (USD)
RT18HC	467,918	85,066	29,377	153.3	87.2	240.5
Nanopaint	123,384	27,466	4925	17.4	86	103.4

*The exchange rate used in this study was 250,000 Iranian Rials per US Dollar.

** The annual cost of energy carriers has been calculated according to the natural gas tariff table of 2019 provided by Iran's National Gas Company. This tariff varies according to the cold and hot months of the year.

*** The electricity consumption cost is based on the electricity tariff and its general conditions announced by Tawanir Company (IRAN Power Generation Transmission & Distribution Company) and is calculated according to the climate and hot and cold months.

Table 17
Payback period as seen from the perspective of the investor.

	Initial cost (USD)	Total annual income (savings) (USD)	Payback period (Year)
RT18HC	467,918	240.5	94.1
Nanopaint	123,384	103.4	84

Table 18
Payback period from a societal perspective.

	Initial cost (USD)	Energy saving (kWh)	Total annual income (savings) (USD)	Payback period (Year)
RT18HC	467,918	114,443	6866	31.5
Nanopaint	123,384	32,391	1352	35.2

for RT18HC PCM is projected at 94.1 years, while nanopaints exhibit a shorter payback period of 84 years. These projections take into account factors such as energy carrier pricing, inflation, and exchange rates. Comparisons with other studies further enrich the discussion. Agarwal and Prabhakar (2023) analyzed the integration of PCMs in clay bricks to optimize thermal comfort and reduce energy consumption. Their economic analysis reveals varying cost savings and payback periods depending on PCM positions and thicknesses, with economic infeasibility identified in Jaipur's climatic conditions [83]. Hou et al. (2023) explored the impact of PCM thermal parameters on energy demand and economic benefits, highlighting the importance of analyzing all thermal parameters and their interactions to understand how they affect economic outcomes [84]. Gao et al. (2023) introduced the concept of thermal energy storage (TES) using PCMs in solar heating systems. Their economic evaluation involves designing a TES unit with different horizontal metal foam filling ratios, revealing that gradient microstructures contribute to the phase transition process, and identifying optimal filling ratios and payback periods [85]. Safarzadeh et al. (2023) addressed the shortcomings of common PCMs, focusing on improving energy and exergy performance through an air–PCM heat exchanger. The economic analysis, conducted under cold climate conditions, underscores the significance of nano-PCM concentrations in reducing charging and discharging periods, ultimately influencing the return on investment [86]. Collectively, these studies offer a nuanced exploration of the economic viability of PCM and nanopaint applications in building design, considering factors such as construction costs, energy savings, payback periods, and regional climatic conditions. This findings contribute valuable insights for decision-makers in the realm of sustainable building technologies.

3.3. Sustainability assessment

The following MATLAB algorithm simulates and compares the reversed sustainability indices of three building insulation scenarios: Without Thermal Insulation, With PCMs, and With Nanopoints. The primary goal is to assess the impact of temperature sensitivity on the sustainability indices for each scenario. The model defines constants, including the total conditioned floor area, temperature data, and hypothetical energy use intensities (EUI) for each insulation scenario. Temperature sensitivity coefficients are specified for the scenarios Without Thermal Insulation, With PCMs, and With Nanopoints. The reversed sustainability indices are calculated using a function that incorporates temperature effects, and the results are visualized through heat maps, allowing for a comparative analysis of sustainability indices across the three scenarios [87].

The developed program aims to investigate how different insulation scenarios affect the reversed sustainability indices of a building, considering temperature sensitivity. The sustainability indices are calculated based on hypothetical energy use intensities, while temperature data is used to simulate the effects of temperature on the building's energy performance. The goal is to provide insights into which insulation scenario demonstrates higher sustainability under varying temperature conditions. The reversed sustainability index for each scenario is calculated using the Eq. 3 [88].

$$\text{Sustainability index} = 1/(\text{baseEUI} + \text{temperatureAdjustment}) \tag{3}$$

here: based EUI is the hypothetical energy use intensity for the scenario, temperatureAdjustment is the product of the temperature sensitivity coefficient (β) and the difference between the temperature data and a reference temperature (T_{base}). The analysis output includes three heat maps representing the reversed sustainability indices for the scenarios Without Thermal Insulation, With PCMs, and With Nano paints (Fig. 19). In this hypothetical scenario, the sustainability index for the PCM scenario is reported to be higher than the other two scenarios due to its lower energy use intensity under various temperature conditions. The heat maps provide a visual representation of the sustainability indices, aiding in the comparison of insulation scenarios and their sensitivity to temperature variations.

3.4. Exergy analysis

The presented algorithm analyzes and compare the exergy performance of three distinct building thermal management scenarios: Without Thermal Insulation, With PCMs, and With Nanopaints. Exergy, which measures the available work in a system, is calculated based on monthly mean temperatures and entropy values, taking into account gas energy consumption, total conditioned floor area, and energy use intensity for each scenario. The goal is to evaluate the impact of different thermal management strategies on the exergy efficiency of a building over a 12-month period. By incorporating monthly mean temperatures and entropy calculations, the algorithm calculates the exergy for each scenario and visually presents its variations across the months. The exergy values serve as a metric to compare the efficiency of each scenario in utilizing energy for building conditioning purposes [89].

The exergy (E) for each scenario is calculated using the formula E = Energy Consumption - T0 * Entropy, where Energy Consumption refers to the gas energy consumption for each scenario, T0 is the reference temperature in Kelvin, and Entropy represents the actual entropy values based on monthly mean temperatures. These calculations are performed

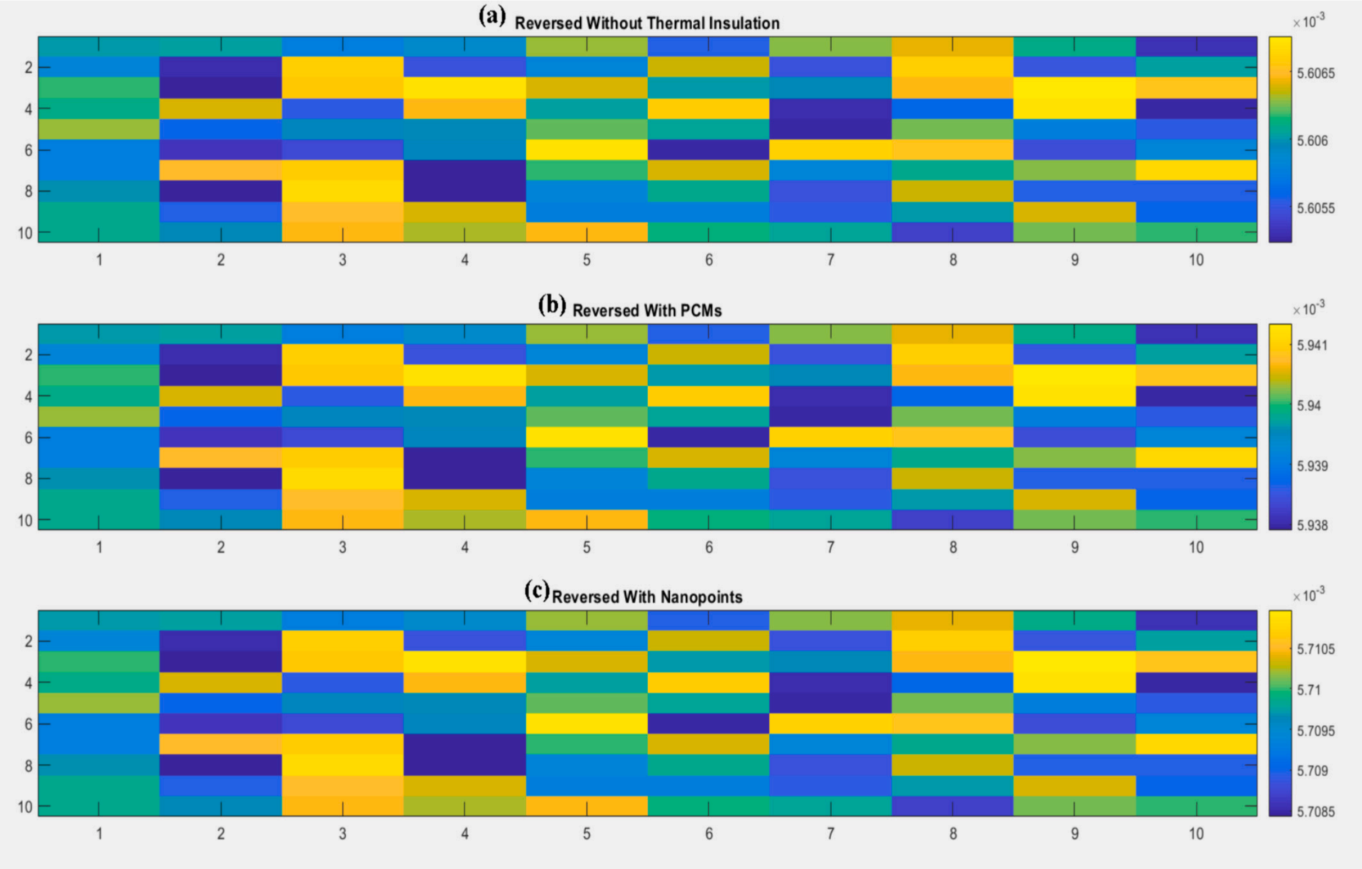


Fig. 19. The sustainability index changes in different temperatures as per (a) Without Thermal Insulation, (b) With PCMs, and (c) With Nano paints.

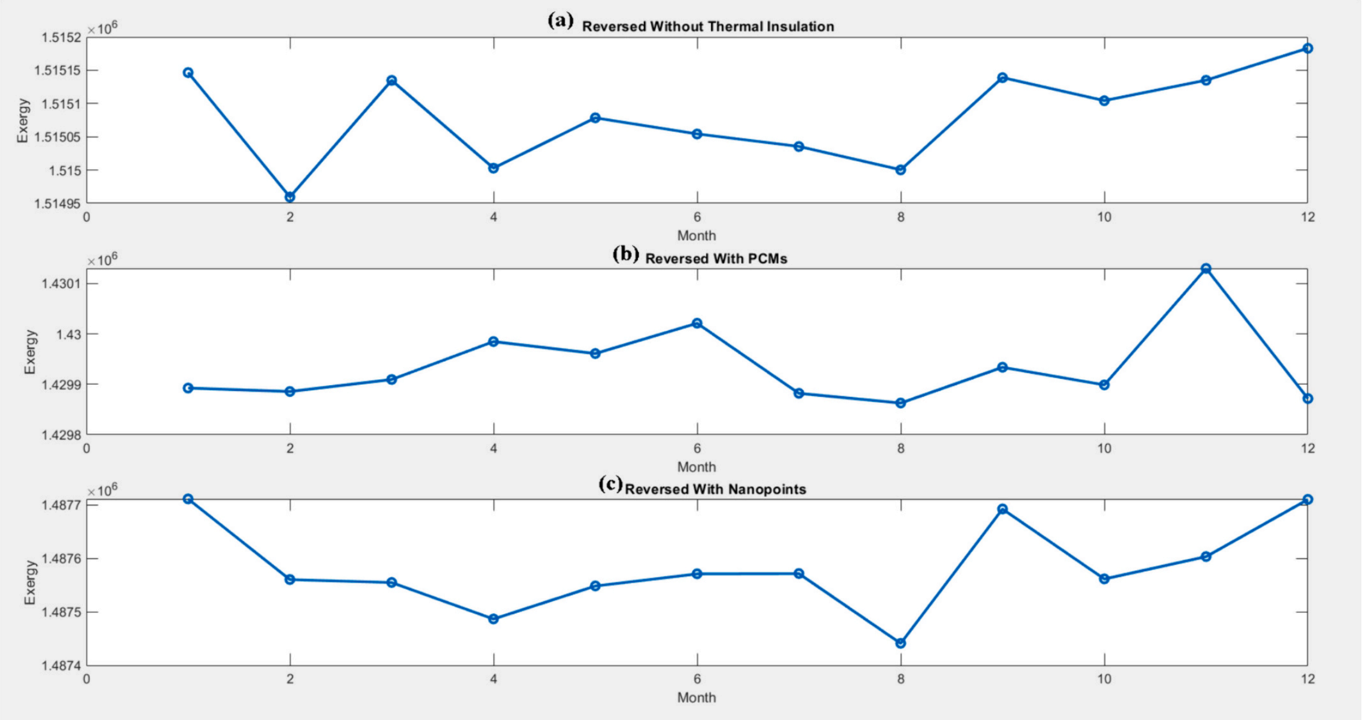


Fig. 20. The exergy fluctuations in different temperatures as per (a) Without Thermal Insulation, (b) With PCMs, and (c) With Nano paints.

over 12 months, accounting for variations in temperature and entropy for each month [90].

The analysis output reveals the exergy values for each scenario over the 12-month period (Fig. 20). In this case, the PCM scenario demonstrates lower exergy limitations compared to the scenarios without thermal insulation and with nanopaints. This outcome suggests that the PCM scenario is the most efficient in terms of exergy, due to its lower energy use intensity across different temperature variations. Therefore, from an exergy perspective, the PCM scenario proves to be the superior choice among the three thermal management strategies. The visual representation of exergy variations over the months provides a comprehensive understanding of the performance of each scenario.

3.5. *Thermodynamic assessment*

According to Fig. 21 (a and b), it is evident that, from a thermodynamic perspective, PCM offers the most favorable energy savings, energy consumption breakdown, and EUI index compared to the other conditions. Specifically, PCM demonstrates the highest energy savings and the lowest energy consumption, making it the most thermodynamically efficient option among the evaluated scenarios, which include conditions without PCM and with nanopaint. Therefore, PCM exhibits the highest thermodynamic performance.

Furthermore, Fig. 21 (c) reveals that land use in areas such as shopping, dining/drinking, and walking spaces significantly impacts energy consumption. This is primarily due to their high energy demand per person per unit area, requiring substantial energy inputs and contributing to the overall energy consumption metrics.

According to Fig. 21 (d), the analysis shows that PCMs have the greatest impact on temperature variations in rooms designated for exercise and relaxation. These rooms exhibit a significant increase in temperature stability, with variations up to 8 °C. This indicates that PCMs are particularly effective in environments where physical activity or relaxation occurs, likely due to the higher metabolic heat production during exercising and the need for thermal comfort during relaxation. In contrast, the minimum impact of PCMs is observed in rooms used for drinking/eating, cooking, and food preparation, with temperature variations reduced by around −4 °C. This suggests that in these areas, the presence of PCMs results in a slight improvement in temperature stability. Several factors could contribute to this. For instance, cooking areas generate substantial amounts of heat from ovens and stovetops, which may overshadow the thermal regulation capabilities of PCMs. Similarly, in drinking or dining areas, intermittent occupancy and varying heat loads can reduce the effectiveness of PCMs in maintaining stable temperatures. This differential impact highlights the importance of strategically placing PCMs in buildings to optimize their thermal regulation benefits. In rooms where consistent thermal comfort is essential, such as exercise and relaxation areas, PCMs can play a crucial role in mitigating temperature fluctuations, enhancing comfort, and potentially reducing energy consumption for heating and cooling. Conversely, in areas with more dynamic thermal conditions, such as kitchens and dining spaces, alternative or supplementary thermal management strategies might be necessary to achieve optimal temperature control.

3.6. *Heat transfer assessment*

The heat transfer model simulates the thermal dynamics of a PCM integrated into a wall structure. Key parameters, including the PCM melting point, heat capacities (in both solid and liquid states), latent heat of fusion, density, and thickness are defined to accurately capture heat transfer phenomena. The simulation calculates how heat flux influences temperature changes within the PCM over time, as represented in a 3D grid in Fig. 22.

Through iterative calculations, the model determines heat conduction across the wall, affecting the PCM's temperature distribution and phase transitions. This visualization of heat flux changes offers insights into how thermal energy transfers through the system, impacting the PCM's phase states—solidification, melting, or a transition. By adjusting simulation parameters, the model enables an analysis of how factors

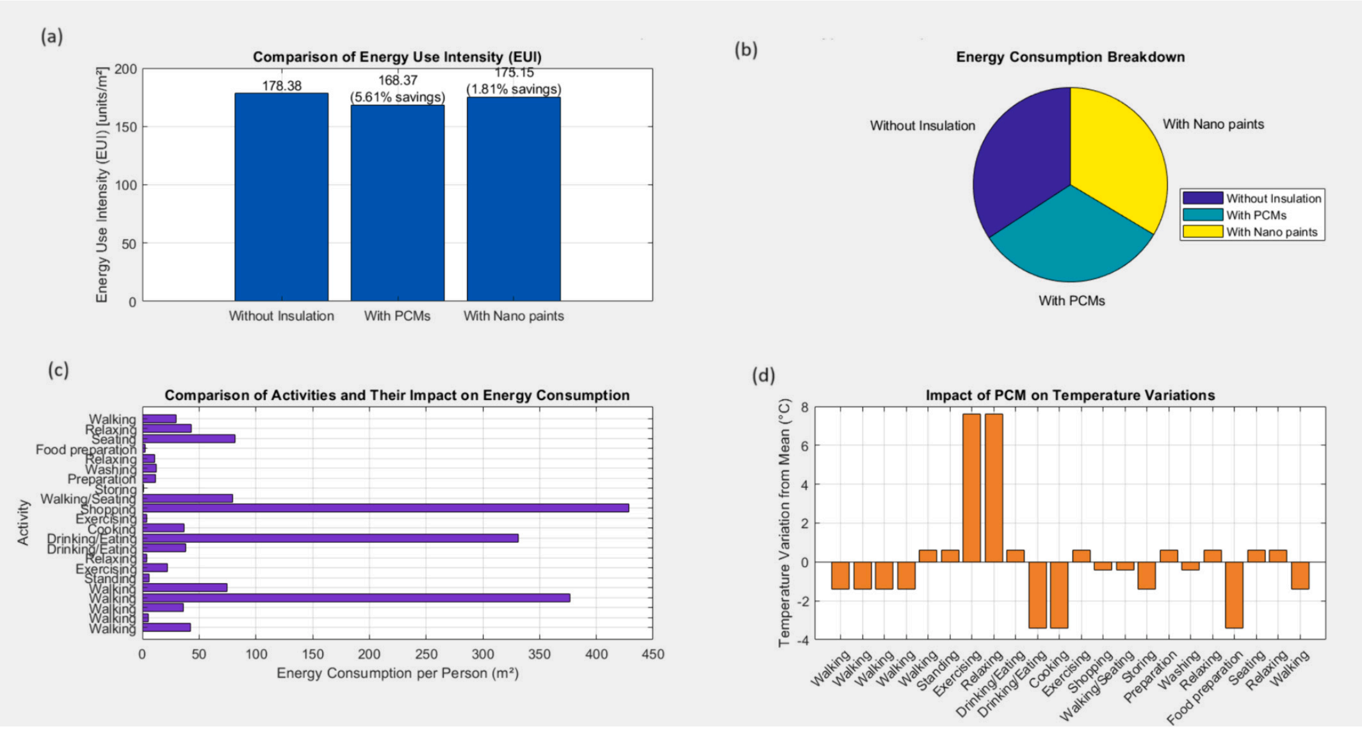


Fig. 21. The outcomes of thermodynamic assessment of PCM/Nano-paints application in this study (a) comparison of EUI, (b) Energy consumption Breakdown, (c) Comparison of activities and their impact on energy consumption, and (d) Impact of PCM on temperature variations.

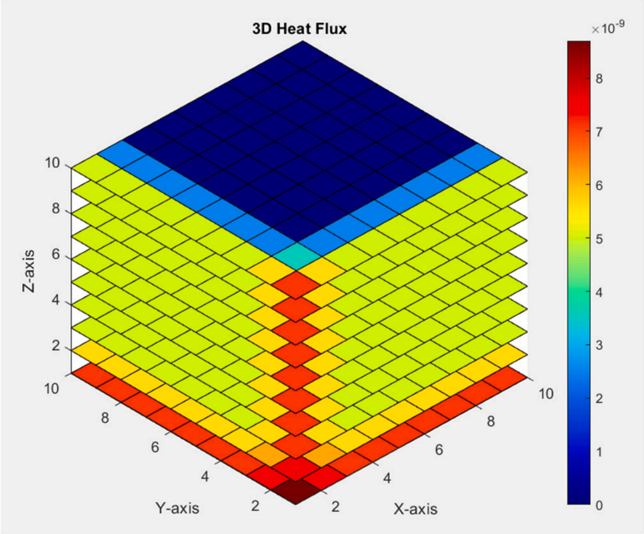


Fig. 22. The 3D view of heat flux distribution in the PCM covered the wall in this study.

such as wall conductivity and initial temperatures influence heat flux dynamics and PCM behavior. This is crucial for optimizing energy storage systems and enhancing thermal management strategies in practical applications.

The simulations illustrate the thermal behavior of a PCM integrated into a wall structure, where dimensions are crucial in understanding heat flux dynamics. For instance, in a wall element measuring 10 cm × 10 cm × 10 cm, the simulation reveals that as distance from the point of contact with the heat source increases, the heat flux predictably decreases, in accordance with fundamental principles of heat transfer in physics. Heat flux, defined as the rate of heat energy transfer per unit area, diminishes with distance from the heat source due to several key factors. Firstly, the PCM's thermal conductivity influences how effectively heat is transmitted through its structure. In the simulation, the material's thermal properties, such as density and specific heat capacities in both solid and liquid states, directly affect the heat's propagation and storage within the PCM [91]. Moreover, the thickness of the PCM layer and the wall itself play significant roles in moderating heat transfer. A thicker wall, for instance, can serve as a thermal insulator, slowing heat conduction and reducing heat flux across its breadth. Conversely, a thinner wall or PCM layer facilitates quicker heat transfer, resulting in higher heat flux values nearthe heat source [92].

3.7. Research discussion

Phase change materials (PCMs) have become prominent as passive components within building envelopes, significantly enhancing thermal performance. In a study by Saffari et al. [93], the focus was on identifying the optimal PCM peak melting temperature to improve the energy efficiency of residential structures across cooling, heating, and annual heating and cooling energy consumption. The research Employed an optimization methodology based on simulations using EnergyPlus and GenOpt, targeting Tehran, a city with Köppen climate classification similar to that of our research, along with other climatic parameters from the Köppen-Geiger classification.

Saffari et al. [93] found that utilizing a PCM with a 20 °C melting point for both heating and cooling purposes in Tehran resulted in energy savings of approximately 2 %, reducing the total annual energy demand for heating and cooling by about 922 kWh. This investigation reinforces the importance of selecting PCMs based on their melting temperature to significantly enhance energy efficiency, advancing our comprehension of the potential benefits of PCM integration within buildings located in similar climates.

Similarly, Hasan et al. [94] conducted an empirical exploration demonstrating that using PCMs as thermal insulation materials within building walls and ceilings effectively improves thermal performance, enhances thermal comfort, and reduces cooling loads during the summer. The study utilized a paraffin wax layer with a melting point of 44 °C within an experimental chamber as a thermal insulation medium. It was fond that adopting a 1 cm thick PCM layer for all walls was the most efficient approach, resulting in daily electricity cost savings of $1.35 per cubic meter of building space. This research underscores the significance of PCM thickness and placement in insulation applications, particularly in achieving substantial cost savings for larger structures.

Building on previous research, Vukadinovi et al. [64] investigated the impact of PCM type and placement within walls on annual heating and cooling energy consumption at five locations in Serbia. The study evaluated three potential PCM placements: beneath the outer wall layer, within the middle of the wall, and beneath the inner wall portion. The most efficient configuration demonstrated a 2.37% reduction in energy consumption, with mid-wall PCM placement proving most effective across all locations. The essential role of phase change materials (PCMs) in enhancing energy efficiency and thermal comfort within building structures is well-established in existing literature. Zahir et al. [1] similarly emphasized the importance of selecting PCM materials based on their melting temperature, aligning with our study's focus on optimizing PCM characteristics for energy management in buildings. Their findings in Tehran, a key Middle Eastern city, resembling our research context, underscored substantial energy savings of approximately 2 % by utilizing PCMs with a 20 °C melting point. This reinforces the significant potential of PCM integration, guided by optimal melting temperatures, to reduce annual energy demand for heating and cooling.

Mukram et al. [33] presented a unique perspective on integrating PCMs into brick walls, demonstrating the effect of PCM positioning on heat flux reduction. Their study complements our focus on PCM placement within building envelopes, achieving a maximum heat gain reduction of 32 % when PCMs were placed away from the outer wall. This aligns with our objective of optimizing PCM integration to reduce heat transfer and showcase the potential for significant energy savings in buildings. Similarly, Saylam et al. [32] explored PCM-enhanced pumice blocks, offering valuable parallels to our study's consideration of PCM in building materials. Their findings on improved thermal conductivity and specific heat capacity resonate with our emphasis on understanding the impact of PCM thickness and orientation in building envelopes. The economic considerations in their study also provide a valuable reference for our cost-benefit analysis, as both studies share a common objective of enhancing thermal performance and reducing energy consumption.

In alignment with earlier studies, Sovetova et al. [95] employed numerical analysis to examine climatic factors, particularly in hot desert climates, by integrating PCMs into building envelopes (walls and roofs) with localized design characteristics. Evaluating thirteen distinct PCMs, this investigation assessed thermal performance and energy efficiency in residential structures integrated with PCMs, using EnergyPlus across eight different cities within the hot desert climate zone. The results showed that top-performing PCMs could mitigate temperature fluctuations and reduce temperatures by up to 2.04 °C. The reduction in energy consumption ranged from 17.97 to 34.26 %, depending on the structure's location, surface area, and thickness and type of the PCM layer.

In a separate numerical study conducted within the same geographic area as the present research, the heat transfer characteristics of conventional building walls -composed of plaster (2 cm), clay brick (15 cm), and cement (3 cm)- were compared with thirteen different PCMs. The study also examined two distinct PCM positions within the wall (proximal to the interior and exterior). Outcomes indicated that PCM's phase-change enthalpy and melting temperature were pivotal factors influencing wall performance. PCMs with lower thermal conductivity, greater latent heat of phase-change, and phase-change temperatures closer to room temperature, effectively limited heat transfer to the interior. Notably, Enerciel 22 achieved the most substantial heat transfer reduction, ranging from 15.6 to 47.6 %, while CaCl2. 6H2O exhibited the least reduction (2–7.8 %). It is also noteworthy that doubling the PCM thickness did not consistently result in a proportional reduction in heat transmission [96].

In a related study, the applicability of nine PCMs (PCM19 to PCM27) in a subarctic climate was assessed from both economic and environmental perspectives. Utilizing metrics such as maximum temperature reduction (MTR), discomfort hours, and average temperature fluctuation reduction (ATFR), the study revealed that integrating PCMs into residential buildings offered significant benefits in terms of ATFR, especially during warm seasons. The results indicated potential yearly energy savings of up to 10,000 kWh for the subarctic region, with economic and environmental payback periods ranging from 16 to 32 years and an estimated annual CO2 savings of 4817 kg. This study underscores the potential of PCM utilization to enhance the thermal and energy performance of buildings, even in subarctic climates [97].

In line with evolving trends, Kharbouch et al. [98] investigated the use of PCMs to enhance the thermal performance of building envelopes for cooling purposes in Morocco, a city characterized by its warm to hot summers. This comprehensive study combined both numerical and experimental approaches to analyze various properties of PCMs, focusing on their peak phase change temperatures. Additionally, the study explored different PCM layer placement within wall and roof structures, employing two distinct configurations. Outcomes indicated that optimizing the phase change temperature was critical for enhancing the thermal performance of PCM-enhanced wall and roof systems. Among the findings, the east facade exhibited the most favorable conditions, while the roof demonstrated the least optimal performance.

The findings of the aforementioned studies align with our research in demonstrating the potential of PCM application as insulation materials to enhance thermal performance and reduce energy consumption in building envelopes, with minor changes in some cases. Our findings regarding the financial benefits of phase change materials (PCMs) diverge from previous research in this field. While earlier studies highlight the multifaceted advantages of PCMs, including significant energy savings and cost reductions, making them a promising solution for improving building efficiency and sustainability, our research presents contrasting results. In this research, the cost-benefit analysis indicated only marginal cost savings, unlike the substantial economic advantages reported in previous research. These discrepancies may be attributed to Iran's low energy cost in comparison to other countries. This is despite the potential for a reduced payback period and a more reasonable use of phase-changing materials in Iran due to increases in the price of the dollar, improved availability of phase-changing materials, and a subsequent decrease in their pricing.

The structure of the sustainability plan for implementing PCM applications in buildings is demonstrated in Fig. 23. Implementing PCMs in buildings requires a methodical approach to enhance energy efficiency and comfort while reducing environmental impact. Initially, clear objectives must be defined to pinpoint where PCM integration can best achieve goals such as energy savings, improved thermal comfort, and reduced greenhouse gas emissions [55]. A thorough feasibility assessment then evaluates building characteristics, such as insulation levels and HVAC systems, to determine PCM suitability. The selection of appropriate PCMs depends on factors such as melting temperatures, thermal conductivity, and compatibility with existing building materials, ensuring both functional effectiveness and environmental responsibility [99]. Developing a robust integration strategy involves close collaboration with architects and engineers. Utilizing energy modeling software allows for precise simulation of PCM performance, optimizing their placement within building envelopes or HVAC systems for maximum efficiency [100].

Effective implementation planning is crucial and involves coordinated procurement of PCM products and engagement with experienced contractors familiar with installation requirements. Once installed, continuous performance monitoring is essential. Baseline measurements establish initial energy consumption and comfort parameters, while ongoing monitoring tracks energy savings, indoor temperature fluctuations, and PCM performance over time [101]. Regular evaluation and adjustment based on monitoring data ensure that PCM systems align with the initial goals. Fine-tuning PCM settings further optimizes energy efficiency and enhances occupant comfort, reinforcing the sustainability benefits [100].

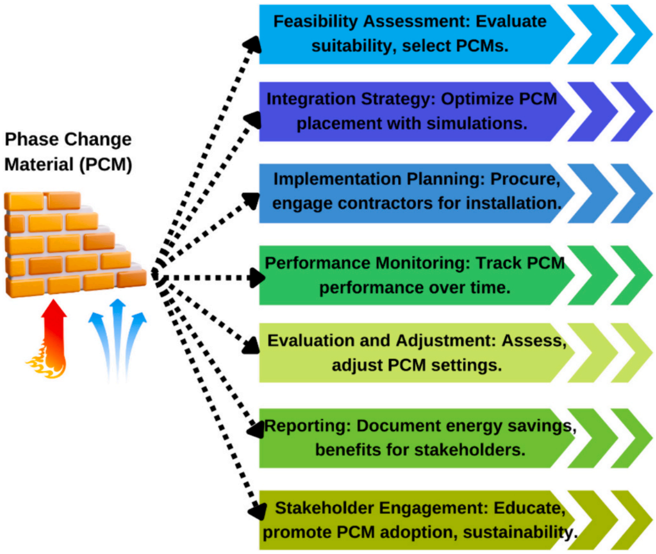


Fig. 23. The schematic plan of sustainability policy implementation of PCM solution in energy management of buildings as managerial insight in this study.

Comprehensive reporting and documentation of outcomes are crucial for stakeholders. This includes detailed analysis of energy savings, thermal comfort improvements, and other relevant metrics, enabling informed decision-making and demonstrating the tangible benefits of PCM integration [102]. Lastly, effective stakeholder engagement is essential. Internally, educating building occupants and management about PCM benefits fosters support and encourages sustainable behaviors. Externally, sharing successes and lessons learned with industry peers, policymakers, and the broader community promotes wider adoption of PCM technology and sustainable building practices [55].

Furthermore, an economic assessment of the model can be discussed. The goal of this economic analysis, conducted using MATLAB, is to calculate and visualize the cumulative cost savings over 40 year for two different technologies, RT18HC and nano paints, considering a discount rate. This approach facilitates a comparison of the long-term financial benefits of each technology.

The program assumes that cost savings occur annually and are discounted at a constant rate of 5 % per year. The cumulative discounted savings for each year are calculated using Eq. 4 [103].

$$\textit{Cumulative Savings}_t = \sum_{i=0}^{t-1} \frac{\textit{Annual Savings}}{(1+\textit{Discount Rate})^i} \tag{4}$$

where t is the number of years, and i ranges from 0 to $t-1$.

The total annual cost savings are assumed to remain constant over the years, with a discount rate fixed at 5 % and the analysis spans 0 to 40 years. Initial data for the calculations include total cost savings of $240.5 per year for RT18HC and $103.4 per year for nano-paints.

The results of this analysis are demonstrated in Fig. 24. According to the scheme, over a period of 40 years, the cumulative savings of RT18HC are significantly higher than those of nano-paints. Specifically, the cumulative savings for RT18HC are approximately double those of nano-paints. This difference is due to the higher annual savings associated

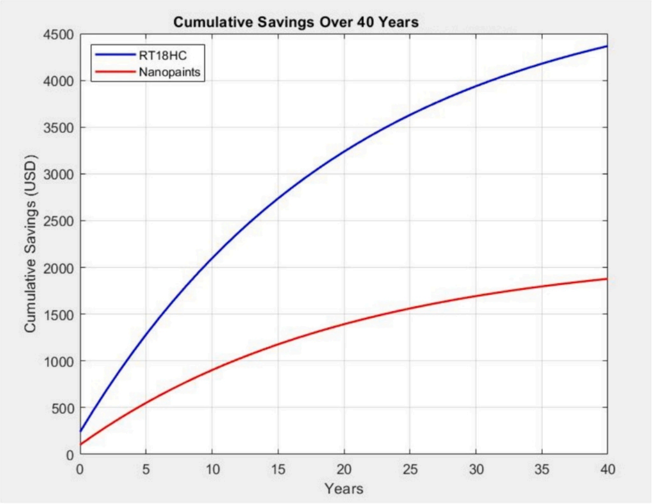


Fig. 24. The financial process diagram of RT18HC and Nanopaints during 40 years.

with RT18HC, which, when compounded over four decades with a 5 % discount rate, results in substantially larger total savings. The plot visually illustrates how savings for RT18HC grow more rapidly compared to nano-paints, reinforcing the financial advantage of investing in RT18HC over the long term. This analysis highlights the importance of considering long-term financial benefits and the impact of discounting when evaluating investment options.

As explored in various studies, this study shows incorporating PCMs into building structures is a promising technique for enhancing energy efficiency and thermal comfort [104]. The use of PCMs in the construction industry addresses the challenges posed by energy consumption and increasing thermal comfort within buildings [105]. The thermal performance of PCMs has been extensively studied, with a focus on cooling/heating load reduction, energy savings, and overall thermal comfort improvements [104]. The sustainability of phase-change materials emphasizes their crucial role in saving energy and reducing greenhouse gas emissions, underscoring their importance in environmentally conscious construction practices [106]. This study also explored the connection between PCMs, energy efficiency, and combating energy poverty by highlighting their potential to reduce costs and achieve energy savings in buildings [107]. It demonstrated that, with appropriate design considerations, PCMs can significantly contribute to both cost reduction and energy efficiency, offering a viable solution for sustainable construction practices [106]. Recent advancements in incorporating PCMs into building materials further emphasize their role in addressing energy consumption concerns, showcasing ongoing efforts to optimize their integration for maximum impact [108]. The strengths of this study lie in its detailed approach to addressing the energy crisis in the building sector. By focusing on PCMs for cooling and heating management and conducting thorough analyses, it offers practical solutions, especially for developing countries. The use of Design-Builder simulations ensures the findings are applicable in real-world settings. while a 6 % reduction in energy usage may seem modest, it aligns with green building goals and highlights the importance of diversified strategies for sustainability. PCMs also save energy by absorbing and releasing latent heat during phase changes, stabilizing indoor temperatures and reducing reliance on mechanical heating and cooling systems. They are particularly effective in regions with significant temperature fluctuations and buildings with varying thermal loads. Our case study in a four-season region highlights PCM's dual role in managing both cooling and heating demands. The effectiveness of PCMs is influenced by factors such as insulation, building orientation, and occupancy patterns. Future research could explore different climates and building types to expand upon these findings. Choosing the right PCM is crucial for maximizing energy savings, with considering factors such as melting point, latent heat capacity, and compatibility with building materials. Additionally, our study compared PCM performance with nano-paints, which serve as a complementary method for enhancing energy performance. A deeper investigation into the challenges of implementing PCMs in various contexts and further comparisons with alternative strategies could strengthen the study's recommendations and broaden its applicability.

4. Conclusions

Energy management in the construction industry is regarded as one of the most strategic tools for building resilience against the emerging crisis of energy resources. Simultaneously, the utilization of phase-change materials offers a stable pathway toward achieving sustainable development goals. The primary objective of this research was to evaluate the performance of nanoparticles and PCMs in optimizing heating and cooling energy in buildings through simulation approaches. The final investigations have demonstrated that, when considering both investment and operation costs along with the comparative performance efficiency of the examined materials, PCMs are more suitable for achieving the aforementioned purposes. On the other hand, the efficiency of PCMs in reducing energy consumption is highly dependent on various environmental aspects, including building conditions, climate context, PCM properties, phase change temperature, placement within the envelope, the orientation of the PCM-integrated external walls (north, south, west, and east), and PCM thickness. These parameters can also be further investigated in future research. Also, the present study suggests that laboratory tests on all types of PCMs with green compounds in the construction industry could be an important part of ongoing research. Additionally, examining air conditioning and air purification indicators in buildings with new coatings would be valuable. Note that the current study primarily utilized simulation-based approaches to assess the potential of PCM integration for managing heating and cooling loads in buildings. While calibration and experimental validation are important for enhancing the accuracy of simulation models, they were beyond the scope of this study due mainly to significant financial support required for experimental tests in real-world conditions. However, future research could benefit from conducting experimental tests for calibration purposes to refine the PCM model and improve simulation accuracy.

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CRediT authorship contribution statement

Mojtaba Mousazadeh Aghoei: Writing – original draft, Conceptualization. **Atieh Astanbous:** Writing – original draft, Validation, Conceptualization. **Reza Yeganeh Khaksar:** Supervision, Methodology, Formal analysis. **Reza Moezzi:** Writing – review & editing, Validation, Resources. **Kourosh Behzadian:** Writing – review & editing, Supervision, Investigation. **Andres Annuk:** Writing – review & editing, Validation, Supervision. **Mohammad Gheibi:** Writing – review & editing, Visualization, Software, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the proofreading step, the authors used ChatGPT for improving the readability and language of the manuscript.

Declaration of competing interest

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

Data availability

The data that support the findings of this study are available on request from the corresponding author.

Appendix A

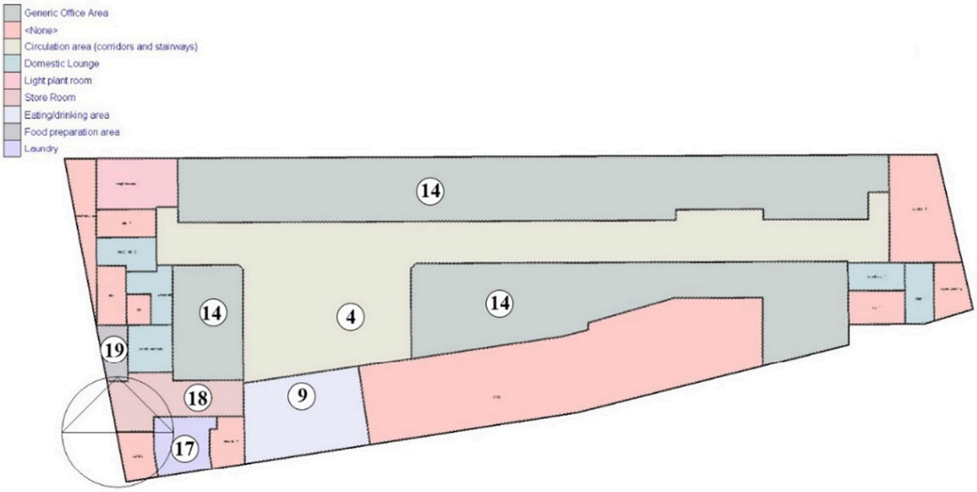

Fig. A.1. Basement(-1) floor plan.

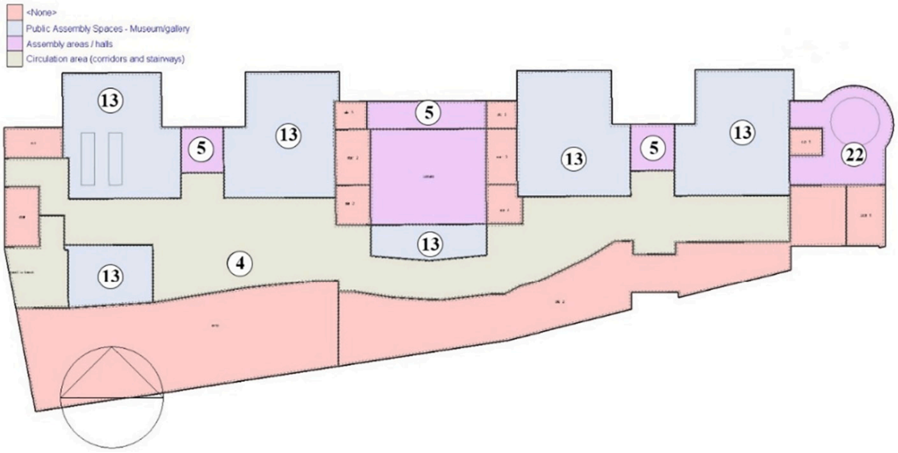

Fig. A.2. Ground floor plan.

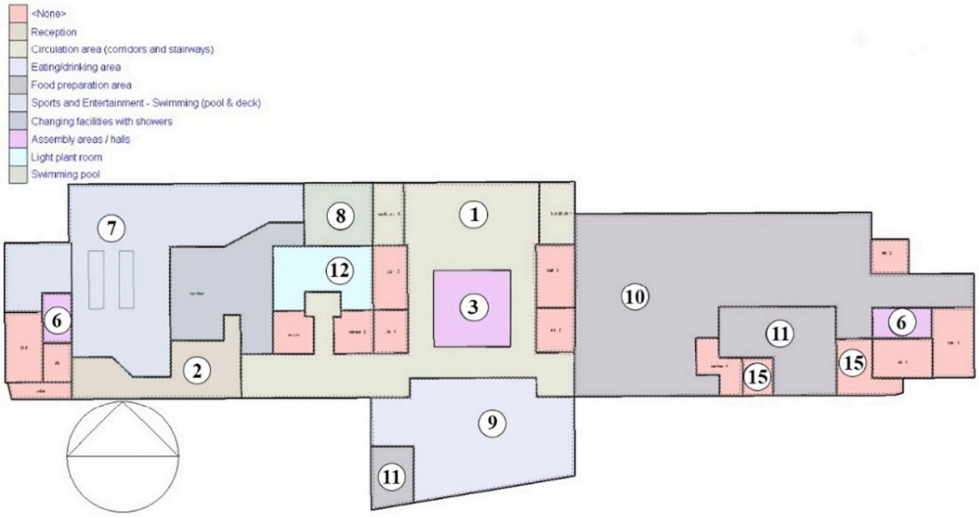

Fig. A.3. 1st floor plan.

Fig. A.4. 2nd - 9th floor plan (east).

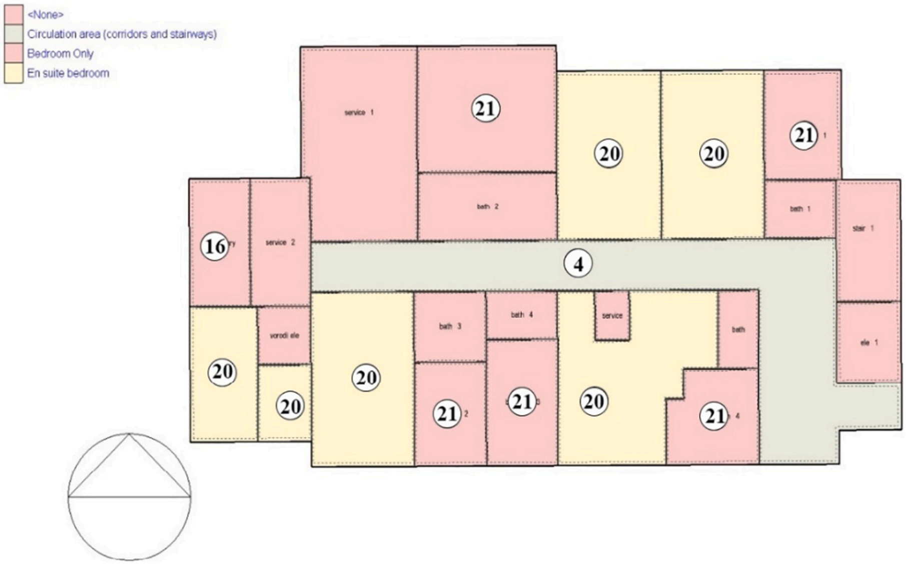

Fig. A.5. 2nd - 9th floor plan (west).

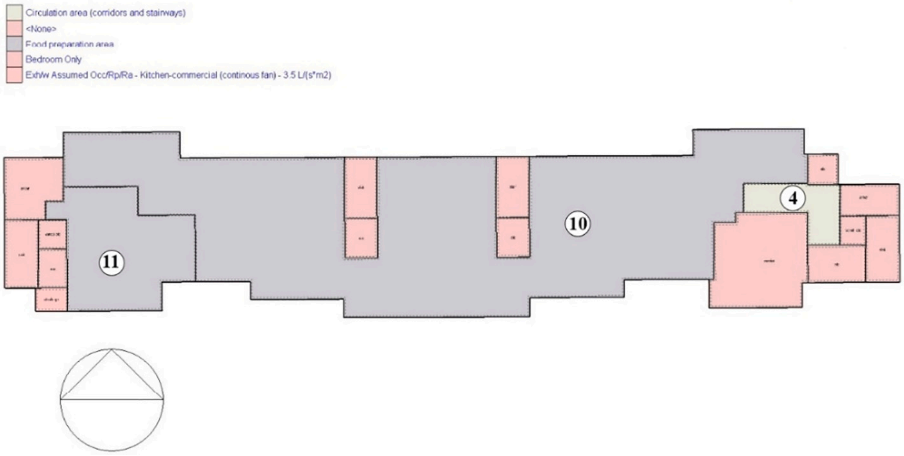

Fig. A.6. 10th floor plan.

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