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Cost-Effectiveness and Energy Impact of Phase Change Materials (PCMs) in Building Envelopes for Hot-Humid Regions: The Case of the UAE

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Abstract This study evaluates the technical performance and life-cycle economics of integrating phase change materials (PCMs) into residential building envelopes in the United Arab Emirates (UAE), a hot-humid climate with high cooling demand. Using DesignBuilder (EnergyPlus), a validated two-story base case was modeled, and a factorial analysis was run across envelope components (walls, roof, glazing), PCM placement (interior or exterior), and PCM thicknesses (3 cm and 5 cm) with a paraffin PCM at 47 ℃, followed by targeted tests at 31 ℃ and 55 ℃. Life-Cycle Cost (LCC) and Net Present Value (NPV) analyses were carried out using UAE-specific tariffs and market pricing, and sensitivity tests explored ultra-thin layers and unit-cost reductions. Results indicate that glazing-integrated PCM with a 5 cm layer melting at 55 ℃ yields the largest reduction in energy utilization intensity (EUI) (≈11% versus the base case). A 3 cm layer delivers nearly the same EUI reduction with ~40% less material, indicating that thickness has a small marginal effect on energy performance but a large effect on cost. Under current prices, payback for the 3 cm, 55 ℃ case approaches ~30 years; a 1 cm layer cuts payback to ~7 years with only ~1% difference in EUI reduction, and a 50% PCM price reduction (e.g., via local paraffin-based production) can shorten payback to ~4 years. These results offer guidance on where and how PCMs are most effective in UAE housing and identify cost as the primary adoption barrier, suggesting thinner layers and local manufacturing as feasible pathways to financial viability.

Keywords Phase Change Materials, Cost-Benefit Analysis, Building Energy Efficiency, Residential Buildings Performance, Energy Simulation

1. Introduction

Improving energy efficiency is crucial for tackling global energy usage and minimizing greenhouse gas emissions, which pose significant challenges to sustainable development [1]. Since buildings contribute to around 40% of global energy consumption, improving energy efficiency within this sector can greatly influence total consumption and emissions [2]. Within buildings, heating and cooling demands are particularly significant, with air conditioning alone consuming around 80% of the energy utilized for thermal comfort in warm climates. In regions with high temperatures, the need for energy-efficient solutions becomes even more pronounced, such as in the hot-humid conditions of the United Arab Emirates (UAE). To contextualize this need globally, energy demand for heating and cooling varies substantially depending on climate and regional conditions. For example, in the United States (U.S), air conditioning and space heating together account for more than half of the residential energy consumption [3]. Globally, heating and cooling typically account for approximately 30–50% of residential energy use, although this share can be considerably higher or lower depending on climatic conditions and building practices. As energy demand continues to rise alongside economic growth, the environmental implications become increasingly concerning. Therefore, adopting designs that are energy-efficient and improving the building envelope are crucial approaches to lowering energy usage and the related CO_2 emissions [4].

Given these global challenges, regions characterized by extreme climates face a particularly strong justification for adopting advanced and potentially higher-cost energy-efficiency measures, as the magnitude of energy savings can outweigh the initial investment. The hot-humid climate of the UAE, where summer temperatures often reach 48 ℃ and humidity in coastal cities like Sharjah, Dubai, and Abu Dhabi can climb to 90%, exacerbates urban heat problems. These urban areas are further affected by dense construction, heat-retentive building materials, and additional heat generated from air conditioning and vehicle traffic [2], which creates a heightened cooling need, which leads to an increase in energy consumption. The UAE ranks ninth globally for per capita electricity use at 12.5 MWh and eleventh for per capita energy consumption at 6.3 Mtoe [5]. Residential buildings contribute to over 37% of this energy consumption, whereas Sharjah has the highest electricity tariffs in this sector. In 2022, the electricity tariff in Sharjah ranged from 0.30 AED ($0.082) per kWh for consumption up to 2,000 kWh/month to 0.43 AED ($0.12) per kWh for usage exceeding 6,001 kWh/month, reflecting the high-cost burden on households [6].

In response to rising energy demands and growing environmental concerns, innovative solutions such as the use of Phase Change Materials (PCMs) have surfaced as a viable method for enhancing energy efficiency in buildings [7–10]. PCMs are a type of passive energy storage system that operates by changing phases without causing significant temperature changes [11–13]. Moreover, PCMs in the outer layers of buildings transition from a solid to a liquid state, absorbing and releasing latent heat during the processes of melting or solidifying within a defined temperature range [14,15]. When the temperature rises, PCM helps to slow down heat transfer by capturing some of the heat as it changes from solid to liquid. When temperatures fall, PCM reverts to its solid form and gives off the heat it absorbed in the liquid state, which minimizes heat loss through the building's envelope. This phase change characteristic aids in stabilizing indoor temperatures, decreasing cooling demands during off-peak times, and reducing heating requirements without altering the thermal properties of the building envelope [15–17]. As a result, PCMs possess a higher capacity for latent heat storage compared to conventional building materials such as bricks and concrete [4,18–20], storing as much as 20 times more energy per kilogram than masonry [14,21], which distinguishes them as a remarkable medium for thermal energy storage.

The performance of PCM is determined by its specifications, melting and solidification properties, and placement [2,22,23]. PCMs need to possess a high capacity for heat fusion, good thermal conductivity, and chemical stability, while also being non-toxic and non-corrosive and meeting fire-safety requirements or being appropriately encapsulated to mitigate flammability risks [17,24]. They must also be compatible with building envelope materials to avoid corrosion or degradation [17]. In hot climates, PCM with a low melting point may not regenerate for the next cycle at night [2]. Therefore, PCM’s melting point should correspond to the nighttime temperatures, ensuring that the solidus temperature is greater than the typical summer night temperature, which enables the PCM to emit heat and revert to its solid form [25]. According to Masood et al. [26], the melting temperature must exceed the highest temperature recorded at night. In a study conducted by Mahmoud et al. [27] on PCMs that are applied to the interior surfaces of lightweight building walls in Sharjah over a three-day period in June, it was observed that the PCM with a melting point of 31 ℃ performed better than the one with a melting point of 41 ℃.

Elnajjar [24] examined the cyclic PCM performance in bricks in June and concluded that choosing the appropriate melting temperature for PCM requires a minimum evaluation period of seven days. While a one-day assessment indicated that a PCM with a 27 ℃ melting point could provide energy savings, the week-long analysis revealed that a PCM with a melting temperature of 47 ℃ was more effective because its solidus temperature exceeds the nighttime temperature, in contrast to the other PCMs studied. According to Piselli et al. [28], in Abu Dhabi’s hot desert climate, the optimal reduction of roof heat gain was attained when PCMs melted at roughly 35 ℃ for roofs with cool membranes and 55 ℃ for roofs with dark membranes. The study was conducted during the hottest summer months, June and July. While these studies did not investigate the use of PCM during other times of the year, Al-Yasiri et al. [18] assessed the performance of paraffin wax PCM (40-44 ℃ melting temperature) in Iraq from May to October. They discovered that the selected PCM decreased energy use and increased interior comfort, especially in May, August, and September. However, PCM’s effectiveness decreased in October due to lower outdoor air temperatures. This study demonstrates that a certain type of PCM with a certain melting/solidus temperature may not maintain its effectiveness all year long [18]. This reduction in effectiveness outside peak summer conditions does not imply the absence of benefits throughout the year, but rather highlights that PCM performance is climate- and season-dependent, with the greatest impact occurring during periods of high cooling demand. Thus, one of the main limitations of these studies is that their analyses were confined to selected months rather than accounting for full-year performance.

Furthermore, PCM performance depends on selecting the appropriate type of PCM. There are three categories: organic PCMs, which comprise paraffin waxes, fatty acids, and materials derived from biological sources; inorganic PCMs, which consist of salt hydrates and metallics; and eutectic PCMs, which are mixtures of organic and inorganic materials [29]. Organic PCMs are the most used for building applications, with paraffin wax being the most popular type employed [15,22,30]. The choice of PCM is influenced by the regional climate, as different types perform better in specific environments [15,31]. In hot climates, PCM with an elevated phase change temperature is better at capturing heat and reducing indoor temperatures. Paraffin waxes can absorb valuable amounts of thermal energy during the phase transition process and maintain their thermophysical characteristics over multiple thermal cycles, making them ideal for hot climates. This durability also makes paraffin waxes more cost-effective when compared to other PCMs, which may degrade over time [17].

Building on the significance of choosing the right type of PCM, the strategic positioning and integration of PCMs within different building elements also play an essential role in maximizing their energy-saving potential. Integrating PCMs into walls is the most popular measure [31]. Hasan et al. [25] studied the cooling effectiveness of PCM (RT-42) in insulated concrete wall blocks in the UAE's hot climate, finding that PCM layers adjacent to indoor spaces outperformed those near the outdoors, and mechanical ventilation was recommended to improve PCM regeneration in such conditions. Sedaghat et al. [4] investigated PCMs in portable cabins in Kuwait, demonstrating up to 20% annual energy savings with PCM at 24 ℃ on interior walls. However, more research was needed for other months and exterior applications, as the study did not investigate the exterior side of the wall. Furthermore, additional research on full-scale buildings is required. Beyond wall integration, PCMs can also be applied in glazing to reduce solar transmittance [2]. However, if the PCM is not adequately encapsulated, it could lead to leakage [15]. The study by Shaik et al. [32] compared organic-based PCMs to traditional double-glazing units during the summer in India, investigating thermal analysis, natural daylighting, carbon emission reductions, operating costs, cost savings, and payback time. The findings showed that PCMs with melting points of 30 ℃ and 35 ℃ successfully minimized heat gains, lowered operating expenses, decreased carbon emissions, and shortened payback periods. Besides walls and glazing, the application of PCMs has also been investigated in various building elements, including window shades, shutters, ceilings/roofs, and floors [24]. Experimental tests and numerical analysis by Piselli et al. [28] showed that the effectiveness of PCMs in reducing roof temperatures and heat flux varies based on the melting point of the PCMs, climate conditions, and the thermal-optical properties of the roofing materials.

Building envelope orientation to the sun also plays a role in the effectiveness of PCM integration [22]. Liu et al. [33] explored how PCM influences energy usage when incorporated into lightweight walls oriented towards the four cardinal directions (east, south, west, and north). The study discovered that the best arrangement and melting temperature of the PCM for these walls vary based on their orientation. Saafi et al. [31] examined PCMs in Tunisian buildings and discovered that only west-oriented walls provided long-term savings, with a 30-year payback period. However, this study did not consider the integration of PCMs in other building envelope elements, such as roofs and glazing. Fateh et al. [34] found that employing PCMs in building applications can reduce heat loads by up to 75 percent, though their impact is limited in north-facing walls due to lower solar radiation. In a later study [35], they observed that PCMs applied to south-facing walls could achieve significant energy savings of 70% to 90% during peak summer months, demonstrating their effectiveness for passive cooling. These results emphasize the significance of strategically placing PCM, considering its orientation, even though the studies did not encompass other elements of the building envelope.

Besides increasing energy efficiency, PCM utilization in building envelopes has been shown to be cost-effective. Studies like Saafi et al. [31] and Shaik et al. [32] investigate the cost-effectiveness of PCM integration in walls and glazing, respectively. Abd El-Raheim et al. [36] examined the economic feasibility of wall-integrated PCMs with different melting points in Egypt, while Lingfan et al. [37] conducted a 10-year economic feasibility study of PCM integration in walls. Imafidon et al. [38] examined the energy-saving benefits of incorporating a PCM layer into wall assemblies in prefabricated retrofit panels across various climates, concluding that upgrading existing structures with PCM provided substantial energy and financial savings. It should be noted that reported cost-effectiveness and acceptable payback periods in these studies are inherently context-dependent and influenced by local investment conditions, including electricity tariffs, financing structures, interest rates, and technology lifetime. However, these studies primarily focused on individual building components rather than assessing the comparative economic feasibility of PCM placement across different parts of the building envelope.

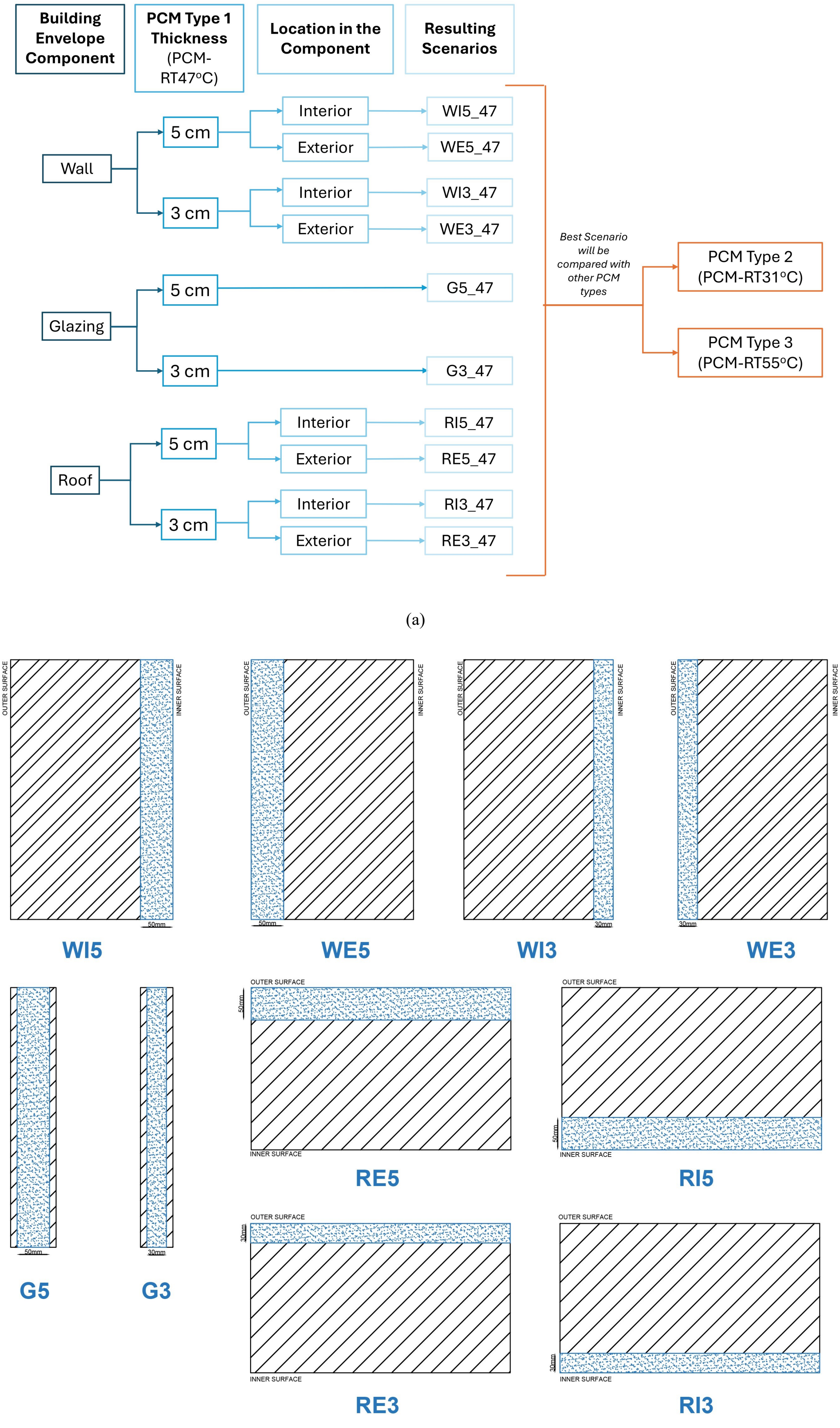
Building on this gap, it is essential to examine how technologies such as PCMs can be adapted to local conditions, particularly in regions like the UAE, where extreme temperatures drive some of the highest energy demands in the world. PCM technology shows promise in reducing cooling energy requirements and associated costs, offering a context-specific approach to address the UAE's unique climatic challenges [39]. While the incorporation of PCM in residential structures has been thoroughly examined, there is still a significant lack of understanding regarding its long-term cost-efficiency, especially when utilized in various envelope elements in hot-humid climates. Existing studies typically isolate individual elements such as walls or glazing, overlooking comparative economic evaluations that consider placement, thickness, and thermal properties in tandem. Furthermore, the lack of region-specific economic analyses, particularly in Gulf countries where residential electricity tariffs are often subsidized and follow tiered pricing structures, limits the applicability of global findings to the UAE context, as reflected in the tariff structure adopted in this study. To date, no cost-benefit analysis of PCM studies has been conducted that explores the economic feasibility across different building envelope components, orientations, and PCM locations within the envelope. Furthermore, existing research presents conflicting findings regarding the optimal placement of PCMs in building envelopes for energy savings in hot regions, further complicating the development of best practices. Some studies advocate for external installation [17,18], while others suggest that internal placement is more effective [25], depending on factors such as the cooling strategy, ventilation approach, and system operation. Conflicting findings exist regarding the optimal PCM melting point for hot climates, with studies recommending values ranging from 31 ℃ to 55 ℃. This inconsistency underscores the need for a systematic evaluation of PCM effectiveness in hot-humid regions. Given these inconsistencies, a comprehensive analysis is needed to establish more definitive guidelines on PCM's cost-effectiveness in UAE residential buildings. This study provides the first combined thermal and economic assessment of PCM integration in the UAE context by using energy simulations together with LCC and NPV analyses. Unlike prior research that focused only on thermal benefits or on single envelope components, this work evaluates PCM performance under different thicknesses, placements, and melting points in a hot-humid climate. In addition, a novel sensitivity analysis introduces ultra-thin PCM layers and explores the potential of local PCM production to reduce costs, offering practical insights for Gulf countries with similar energy conditions. The research aim is to assess the short and long-term financial implications of PCM integration in residential buildings. This aim is achieved through the following objectives:

- To quantify the energy savings achieved by integrating PCMs into various building envelope components, using simulation-based analysis.
- To determine the initial installation costs and operational savings associated with PCM integration in residential buildings of hot-humid climates.
- To evaluate the overall cost-effectiveness of PCM integration by comparing LCC and NPV analysis across different design parameters.

2. Materials and Methods

This study employs a mixed-method approach, incorporating energy simulations and cost-benefit analysis alongside a literature review to evaluate the practicality of integrating PCM into building envelopes. The qualitative component involved synthesizing existing research in the literature to uncover insights into the benefits, challenges, and best practices associated with PCM use in building envelopes. On the quantitative side, energy simulations and cost-benefit analysis were conducted utilizing a factorial approach, where design solutions were derived by varying one or more parameters while keeping others constant. This approach allowed for the assessment of the impact of specific parameters on design objectives, with a focus on three main factors: the building component (roof, wall, or glazing), the location of the PCM within the component (interior side or exterior side), and the PCM thickness (5cm or 3cm). In all glazing-related scenarios, PCM is not intended to replace transparent glass elements. Instead, it is considered as an encapsulated, thermal storage layer integrated within a multi-layer glazing system or associated assemblies, consistent with PCM-glazing configurations reported in the literature [40–42]. Optical properties and light transmission were therefore not considered; this study focuses on the thermal and economic performance of PCM integration. However, according to a review paper by Hafnaoui et al. [15], the transparency of paraffin wax PCM in glazing can range from transparent to translucent, depending on the PCM's state: it is transparent in the liquid state and translucent in the solid state. The PCM thickness of 5 cm follows recommendations from Hasan et al. [25], who determined this value based on solar heat gain during typical summer conditions in the UAE. A thickness of 3 cm was also chosen as a thinner alternative to 5 cm to evaluate its practicality in reducing material usage and costs while still providing measurable thermal regulation benefits.

The factorial analysis resulted in 10 scenarios, as shown in Figure 1. Each scenario was denoted by three letters: the first indicated the envelope component, the second the PCM thickness, and the third the PCM location within the component. With the validated base case established, a factorial study systematically evaluated the effects of PCM integration under different conditions by varying key parameters. The PCM type employed in this factorial study was PCM-RT47, a paraffin-based material with a 41-48 ℃ melting point that had been shown to perform well in the UAE climate [24,43].



(a)

(b)

Figure 1. (a) Factorial study scenarios, (b) details of the scenarios

Table 1. PCM type specification [43]

Specification	RT31	RT47	RT55
Melting Point (℃)	29–34 (main peak at 31)	41–48 (main peak at 47)	51–57 (main peak at 55)
Heat Storage Capacity (kJ/kg)	165	160	170
Density (kg/l)	0.83 (solid) 0.76 (liquid)	0.88 (solid) 0.77 (liquid)	0.88 (solid) 0.77 (liquid)
Specific Heat Capacity (kJ/kg·K)	2 kJ/kg·K	2 kJ/kg·K	2 kJ/kg·K
Thermal Conductivity	0.2 W/(m·K)	0.2 W/(m·K)	0.2 W/(m·K)

Subsequently, the most cost-effective scenario identified from the factorial study was compared with two alternative PCMs with different melting points to evaluate the impact of melting point selection on economic feasibility. The chosen melting points, 31 ℃ (PCM-RT31) and 55 ℃ (PCM-RT55), were selected to represent one below and one above the primary melting point value of 47 ℃ (PCM-RT47), the specifications of which are outlined in Table 1.

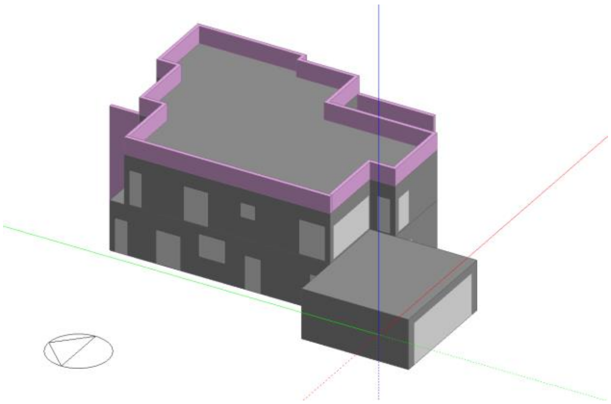


Figure 2. Base Case 3D model

2.1. Base Case Specifications

The base case was an uninsulated two-story villa modeled in DesignBuilder, chosen to reflect typical residential construction in the UAE and ensure a realistic assessment of PCM's impact, as shown in Figure 2. The architectural design of the residential building was adapted from a paper by Taleb [44], which describes a typical two-story villa in Dubai, UAE, a location similar in climate to that of Sharjah. This reference was used solely as a design precedent to ensure that the building geometry and layout are representative of the regional residential typologies found in the UAE. The base case's construction specifications, demonstrated in Table 2, were adapted from Al-Alili et al. [45] and Friess et al. [46], both of which report envelope and HVAC characteristics typical of UAE residential buildings. This approach ensured that the base case served as a valid reference for evaluating PCM's performance under local climatic conditions. Furthermore, the villa's characteristics, such as the lack of insulation and the use of single-panel glazing, allowed for an accurate evaluation of the PCM's effect. The base-case energy performance was further validated using reference [46], which reports the corresponding energy use intensity (EUI).

The simulations were conducted using weather data corresponding to a latitude of 24.43 °N and a longitude of 54.65 ° E, representing typical climatic conditions in the UAE. An infiltration rate of 0.7 air changes per hour (ACH) was assumed under natural conditions. This value represents a moderately leaky residential envelope and is consistent with reported infiltration ranges for residential buildings in hot climates, where measured or inferred natural infiltration commonly ranges from approximately 0.5 to above 1.0 ACH [47–49]. UAE-focused studies further indicate that infiltration is non-negligible and that improvements in envelope airtightness led to measurable reductions in energy demand [50].

Occupancy schedules, internal gains, and plug-load densities were defined using DesignBuilder default residential templates and assigned according to space function (e.g., living areas, bedrooms, sanitary spaces, and circulation zones). These templates represent standard residential usage patterns and are commonly applied in building energy simulation studies when detailed monitored data are unavailable. This approach ensures consistency across all simulated cases, allowing the relative impact of PCM integration to be evaluated independently of occupancy-related variability. Lighting in the base case was modeled using incandescent fixtures, and indoor thermal conditions were controlled using a cooling setpoint temperature of 22 ℃ during occupied periods. Lastly, electricity consumption was supplied from the grid using the residential electricity tariffs summarized in Table 3.

Table 2. Base case specification (adapted from [46,45])

Parameters	**Specifications**
Num. of Floors	2
Total Gross Area	213 m^2
Floor Height	3 m
External Wall	15 mm mortar (outer surface) 200 mm concrete block 20 mm gypsum plaster (Total wall U-value: 1.589W/m^2-K)
Roof	2 mm bitumen 200 mm concrete slab (Total roof U-value: 1.475W/m^2-K)
Fenestration	Single glazing, operable, metal-framed windows SHGC = 0.8
Infiltration	0.7 ac/h
HVAC	Split system Electricity from grid (kWh prices in Table 3) Cooling setpoint: 22ºCCooling system seasonal CoP = 4.25
DHW	Instantaneous hot water only Electricity from grid
Lighting	Incandescent
Occupancy and Electricity (Plug Loads)	Zone-level schedules and densities assigned using DesignBuilder default residential templates according to space.

Table 3. Electricity Tariff in Sharjah, UAE [6]

Energy Consumption Rate (kWh)	Electricity Tariff in Sharjah (fils/KWh)
1-2,000	30.0
2,001 - 4,000	33.0
4,001 - 6,000	37.0
6,001+	43.0

2.2. Model Validation

The energy consumption of the base scenario was modeled and simulated using DesignBuilder, leading to an energy utilization of 190.07 kWh/m^2per year. This value was validated against the study by Friess et al. [46], who reported a measured (billed) energy utilization index (EUI) of 194 kWh/$m^2$for a residential villa in Dubai. Thus, the deviation between this study and ref [43] is 2.05%, which falls within the acceptable range. The comparison is considered appropriate given the close alignment in climatic conditions, construction typology, and occupancy patterns between both cases. EUI is calculated as:

$$EUI = \frac{Total\ Annual\ Electricity\ (kWh)}{Total\ Gross\ Area\ (m^2)} \quad \text{(Equation 1)}$$

2.3. Phase Change Material (PCM) Modelling on DesignBuilder

In building envelope applications, PCMs are implemented in encapsulated or shape-stabilized forms to prevent leakage and ensure compatibility with construction materials, which is widely recognized as standard practice in the literature [41,42,51]. Accordingly, the PCM considered in this study represents a building-integrated encapsulated PCM system, consistent with commercially available PCM products used in walls, roofs, and glazing-related assemblies. While the specific encapsulation technology is not explicitly modeled, this approach aligns with prior simulation-based and techno-economic studies that evaluate PCM performance at the building scale without resolving encapsulation details [40,52].

The PCM was defined by enabling the “Phase change material” option within the material properties in DesignBuilder and implemented using the enthalpy-temperature approach with hysteresis. Thermophysical properties taken from [43] (Table 1) were inputted for each PCM type in the liquid and solid states, including specific heat, density, and thermal conductivity. Moreover, latent heat, as well as melting and freezing curves, were identified by plugging in the peak melting and freezing temperatures. This approach captures the dynamic heat-storage and release behavior of PCMs with different phase-change temperatures. This approach is a common practice found in the literature [53,54].

2.4. Energy Simulation and Cost-Benefit Analysis

Energy simulations were conducted for each of the 10 scenarios using Design Builder software, which operated on the Energy Plus engine. These simulations measured energy consumption to calculate annual operational energy savings, using the formula:

$$\begin{aligned}&Annual\ operational\ energy\ savings\ (S)\\&= (Base\ case\ energy\ consumption\\&-\ PCM\ scenario\ energy\ consumption)\\&x\ Energy\ cost\ per\ unit\end{aligned} \quad \text{(Equation 2)}$$

The annual operational energy savings were then used to calculate the Net Present Value (NPV) in Equation 5. The cost-effectiveness of PCM integration was evaluated using Life Cycle Cost (LCC) and Net Present Value (NPV) analysis. LCC accounted for costs over the PCM’s lifespan, which is considered to be 35 years [37,55], while NPV provided a more accurate estimation of payback, incorporating the time value of money [56,57]. The LCC was calculated using the following formula:

$$LCC = C_{PCM} + PWF \times EC \quad \text{(Equation 3)}$$

Where C_{PCM} represents the initial cost of PCM employment, which includes the material and its installation costs. The installation cost, estimated at 25–35% of the PCM material cost, was included in the total cost calculation [57]. EC denotes the annual energy expenditure needed to ensure indoor comfort, which was calculated based on the electricity rates in Sharjah, UAE (see Table 3). PWF (Present Worth Factor) is defined as:

$$PWF = \frac{1-(1+r)^{-N}}{r} \quad \text{(Equation 4)}$$

Where r represents the discount rate, considered to be 4.35% [58], and N denotes the lifetime, considering the PCM’s average service life to be 35 years [37,55].

In prior research [36,37], the payback period was often calculated using a simple payback period (SPP), which ignored the time value of money and underestimated the actual investment payback time. This study, however, evaluated the PCM application using the Net Present Value (NPV), which incorporated the time value of money. The NPV was calculated as:

$$NPV = \frac{S_t}{(1+r)^t} - C_{pcm} \quad \text{(Equation 5)}$$

Where S (calculated from Equation 2) represents the annual savings at time t, r is the discount rate, and C_{PCM} is the initial cost of PCM installation. NPV provides a more accurate estimation of the payback period by accounting for the time value of money, addressing limitations of simpler payback methods. It is commonly utilized in technoeconomic analysis to give a more realistic representation of energy management practices [55].

A sensitivity analysis was conducted to assess how variations in PCM quantity and price impact cost-effectiveness. This approach accounted for fluctuations in material costs and potential changes in energy savings, providing a more robust economic evaluation.

3. Results and Discussion

3.1. Energy Simulation Results

The results of the simulations indicated that integrating PCMs with different scenarios reduces energy demand relative to the base case (BC) model. Among the tested scenarios, PCM-RT47 (47℃ melting point) reduced Energy Utilization Intensity (EUI) and cooling electricity demand. As shown in Table 4, the glazing-integrated PCM scenario (G5_47) demonstrated the highest EUI reduction, achieving approximately a 10% decrease compared to the base case. Nsaif et al. [59] reported that PCM-glazing combinations delay peak heat loads and enhance thermal comfort, reinforcing the performance observed in the G5_47 scenario. On the other hand, reducing PCM thickness from 5 cm to 3 cm (G5_47 vs. G3_47) yielded only a 0.4% reduction in energy savings, indicating that a thinner PCM layer offers nearly identical thermal performance at a lower cost. This suggests that even with a thinner PCM layer, energy savings can still be accomplished, making G3_47 a potentially more cost-effective alternative. Across walls, glazing, and roofs, reducing PCM thickness from 5 cm to 3 cm led to only a 1% reduction in energy savings. However, it resulted in a 40% decrease in material costs, making it a significantly more cost-effective option. This aligns with Sedaghat et al.’s [4] findings, which indicate that PCM thickness does not significantly impact energy performance; it’s more about the placement of PCM that makes a change. It should be noted that the material costs considered in this analysis correspond to encapsulated PCM systems used in building applications, and therefore, reductions in PCM thickness directly translate into proportional reductions in encapsulated system costs, which governs the observed improvement in cost-effectiveness and recovery time. This approach aligns with findings from previous studies in the literature [52,60].

In the simulated scenarios, interior PCM placement in walls resulted in moderate energy savings, showing a 3.5% improvement over the base case. However, for roofs, exterior PCM placement was more effective, likely due to direct solar exposure and heat accumulation on the roof surface. This suggests that PCM placement should be optimized based on surface solar exposure and heat transfer dynamics. Overall, the analysis identified glazing as the most effective component for PCM integration, delivering the best energy savings performance compared to walls and roofs. Glazing surfaces receive the highest levels of solar radiation, making them a major contributor to indoor heat gain [61]. Integrating PCMs into glazing helps absorb and store excess heat, reducing cooling demand and improving energy efficiency [62]. This finding aligns with passive cooling strategies that treat glazing as a critical element for reducing heat ingress while maintaining daylighting benefits [63]. In practical applications, PCM–glazing solutions are implemented as multi-layer systems in which encapsulated or shape-stabilized PCM layers are integrated within glazing cavities or composite assemblies rather than replacing transparent glass elements [40,41,42]. These additional layers introduce structural and cost considerations; however, such effects are reflected in the PCM market prices adopted in this study rather than explicitly modeled at the component level.

The analysis of varying PCM melting points (31 ℃ and 55 ℃) in glazing scenarios, as shown in Table 5, further highlighted the sensitivity of energy performance to PCM temperature thresholds. The G5_55 scenario, with a greater melting point, accomplished a slightly greater decrease in EUI than the glazing-integrated PCM with a 47 ℃ melting point, representing an 11% decrease compared to the base case. Additionally, the G5_31 and G5_47 scenarios showcased similar performance trends, though their energy reductions were slightly less pronounced compared to G5_55. These findings emphasize the significance of optimizing PCM melting points for climate-specific applications, especially in hot-humid regions like the UAE. A higher melting point allows the PCM to absorb and store heat efficiently during peak hours, delaying heat transfer and providing greater thermal stability throughout the hottest parts of the day [64]. RT 55 becomes fully solid at around 51 ℃ (Table 1); therefore, full daily regeneration requires nighttime PCM temperatures well below this level. In the simulated model, it was found that in the UAE summer (July), the external and internal glazing surface temperatures dropped below 30 ℃ during the night, providing a temperature difference of more than 25 K relative to the PCM phase-change temperature. Unlike RT 31 PCM, which fully solidifies at around 29 ℃, warm nocturnal conditions and low air movement hinder full re-solidification on nights when surface temperatures are above 29 ℃ (Table 1). For RT 55, the large temperature drop allows the RT55 layer to fully regenerate every night. Consequently, the PCM recovers its full latent storage capacity for the following day.

Table 4. Energy results of scenarios with PCM with a melting point of 47 Cº

Scenarios	BC	WI5_47	WE5_47	WI3_47	WE3_47	G5_47	G3_47	RI5_47	RE5_47	RI3_47	RE3_47
Room Electricity (kWh/m^2)	10.99	10.99	10.99	10.99	10.99	10.99	10.99	10.99	10.99	10.99	10.99
Lighting (kWh/m^2)	85.94	85.97	85.97	85.96	85.96	85.94	85.94	85.94	85.94	85.94	85.93
Cooling (Electricity) (kWh/m^2)	75.46	69.03	72.12	69.09	70.98	55.94	56.66	71.51	70.06	70.00	70.76
DHW (Electricity) (kWh/m^2)	17.67	17.72	17.77	17.70	17.70	17.70	17.70	17.67	17.67	17.67	17.67
Total Electricity (kWh)	58330	55260	56190	55720	56290	52340	52560	57120	56680	56660	56890
EUI (kWh/m^2)	190.07	183.72	186.81	183.74	185.64	170.55	171.27	186.11	184.67	185.61	185.37

Table 5. Energy performance comparison of the best 47°C PCM scenarios with variations at 31°C and 55°C melting points

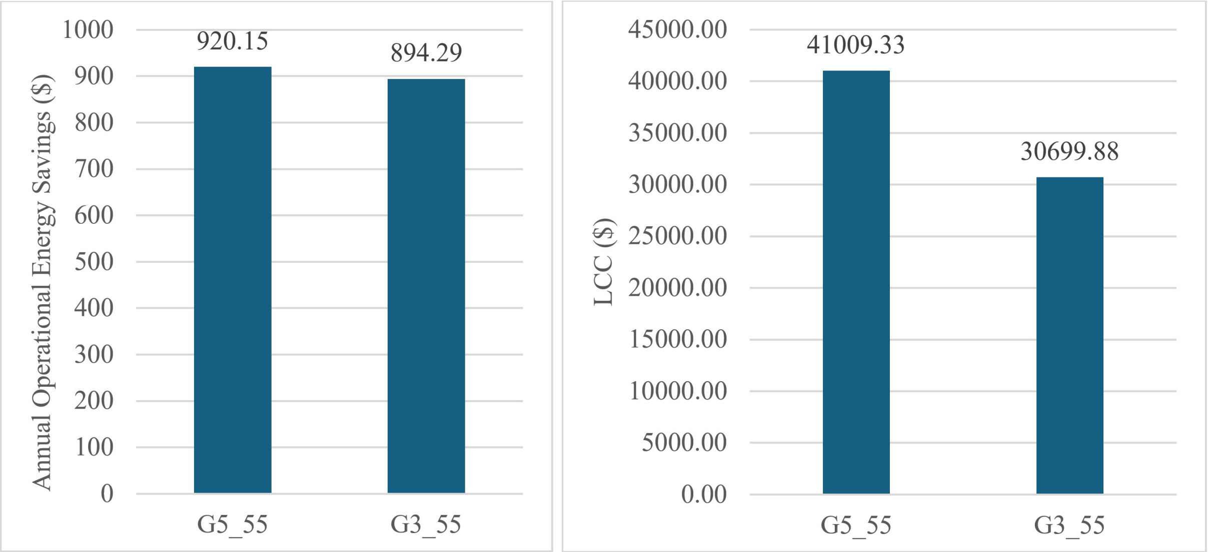
Scenarios	BC	G5_47	G3_47	G5_31	G3_31	G5_55	G3_55
Room Electricity (kWh/m^2)	10.99	10.99	10.99	10.99	10.99	10.99	10.99
Lighting (kWh/m^2)	85.94	85.94	85.94	85.94	85.94	85.94	85.94
Cooling (Electricity) (kWh/m^2)	75.46	55.94	56.66	57.09	57.38	54.55	55.38
DHW (Electricity) (kWh/m^2)	17.67	17.70	17.70	17.67	17.70	17.70	17.70
Total Electricity (kWh)	58330	52340	52560	52700	52790	51920	52170
EUI (kWh/m^2)	190.07	170.55	171.27	171.70	171.99	169.15	169.99

3.2. Cost-Benefit Analysis

Based on the energy simulation results, the economic analysis focused on the top-performing scenarios, G5_55 and G3_55, which accomplished the greatest energy savings. Both scenarios utilized PCM in glazing with a melting point of 55 ℃ but differed in thickness: 5 cm for G5_55 and 3 cm for G3_55. The annual operational energy savings (Equation 2) were $920.15 for G5_55 and $894.29 for G3_55, a minimal difference of approximately $25 or 2.8% (Figure 3a). This indicates that PCM thickness has little impact on energy cost savings but significantly affects the initial PCM cost. Consultations with contractors in the UAE revealed an average PCM price of $6.35/kg, which includes material, delivery, and installation costs. The required PCM mass for each scenario was calculated based on volume and material density (as shown in Table 1), with 0.88 kg/L used for RT55. Installation costs were estimated at 25–35% of material costs as per market feedback. The cost of 3 cm PCM was found to be 60% of the cost of 5 cm PCM. Consequently, the thinner PCM layer in G3_55 offered better cost-effectiveness, with a 40% reduction in material usage compared to G5_55. However, the NPV analysis revealed a 30-year payback period for G3_55, with an LCC of $30,699.88 over PCM's 35-year lifespan (Figure 3b). This long payback period suggests that, under current PCM pricing, the investment is not financially viable in the UAE, where electricity costs are relatively low. These findings align with Saafi et al. [31], who observed a similar 30-year payback period for PCM in Tunisian buildings. Given PCM's 35-year operational lifespan, this extended payback period highlights its lack of cost-effectiveness in the UAE, primarily due to high PCM costs relative to the country's low electricity prices. As noted by Souayfane et al. [57], PCM is most effective in regions with high energy costs, where energy savings justify the initial capital investment. These findings suggest that cost, not performance, is the primary constraint to PCM adoption in hot-humid regions. Local production of paraffin wax-based PCMs in the UAE could significantly reduce costs and improve market viability. Government incentives, subsidies, or demonstration projects could further support deployment in residential buildings.

3.3. Sensitivity Analysis

To explore the potential for more economically feasible PCM integration, a sensitivity analysis was conducted on two parameters: PCM thickness and PCM unit price. This allowed for a deeper understanding of how variations in material quantity and cost influence payback period and life cycle cost outcomes. In this study, the PCM unit price used in the sensitivity analysis corresponds to building-integrated, encapsulated PCM products rather than raw PCM material. To determine the economic feasibility threshold, the sensitivity analysis evaluated how the quantity and price of PCM affect its cost-effectiveness. To assess the quantity threshold, the analysis tested the energy performance of a 1 cm PCM thickness, which resulted in an EUI of 171.76 kWh/m². As shown in Figure 4, decreasing the PCM thickness to 1 cm while maintaining a melting point of 55 ℃ led to slightly higher energy consumption than the G3_55 scenario (3 cm thickness), with an increase of approximately 1%, but a 10% decrease relative to the base case (BC). However, the cost of using 1 cm of PCM was reduced by 66.67% compared to 3 cm and by 80% compared to 5 cm. Consequently, reducing PCM thickness to 1 cm improved cost-effectiveness, lowering the payback period to 7 years, which is well within PCM's 35-year lifespan. Moreover, the LCC of using PCM of 1cm thickness is $19,877.99, a 51.5% reduction compared to the LCC of the 5cm PCM and a 26.4% reduction compared to that of the 3cm PCM (see also Figure 3).



(a) (b)

Figure 3. (a) The annual operational energy savings and (b) LCC calculated for the scenarios tested for cost-effectiveness (G5_55 and G3_55)

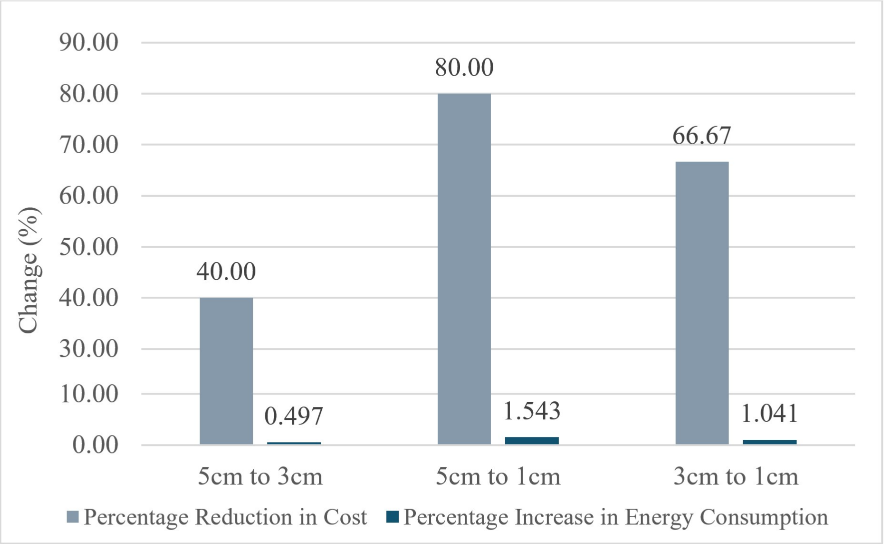


Figure 4. Comparative analysis of cost reduction and energy consumption increase across the three PCM thicknesses

These findings demonstrate that optimizing PCM thickness is not merely a technical adjustment but a key strategy for improving economic feasibility. The fact that a 1 cm PCM layer provides nearly the same thermal performance at a significantly lower cost suggests a practical solution for real-world applications. This suggests that thinner PCM layers could provide an economically viable option for passive cooling in hot-humid climates. This opens the door for architects and developers to consider PCM integration without prohibitive upfront investments. Moreover, if cost reductions can be achieved through local manufacturing or bulk adoption, thin PCM layers may become a cost-effective standard for passive cooling in hot-humid climates such as the UAE.

A 50% reduction in PCM price lowers the payback period for G3_55 to 11 years. For 1 cm PCM, it further shortens to just 4 years, making it highly cost-effective within PCM's lifespan—an 86.67% improvement over the initial 30-year period as outlined in Section 3.2, making both scenarios much more feasible within the material's 35-year operational lifespan. This raises a critical question about the cost of paraffin wax-based PCM in the UAE, given the country's substantial oil reserves [65]. As a petroleum by-product, paraffin wax should theoretically be more affordable in this region. It is derived from oil waste through the petroleum refining process and consists primarily of saturated hydrocarbons. Typically considered a low-cost material, paraffin wax can be further processed into high-value products, including PCMs [66,67]. This suggests that local PCM production could reduce costs, rendering it a more viable option for UAE energy-efficient building applications.

The feasibility of integrating PCM layers into standard commercial glazing systems depends on several factors, including the PCM's thermal storage capacity, thickness, and encapsulation method. While a 1 cm PCM layer is likely to be more easily integrated into existing glazing configurations due to minimal impact on the overall thickness, a 3 cm layer may require adjustments in the glazing unit's structure to accommodate the additional material. In practice, commercial systems may need to incorporate specialized designs to maintain performance and durability, especially for PCM layers with higher thicknesses.

These findings indicate an opportunity for policy and industry alignment. As paraffin wax is a petroleum by-product, its availability in the UAE should, in theory, allow for lower PCM costs through domestic manufacturing. Establishing local production facilities could dramatically reduce material prices, decrease payback periods, and make PCM-based strategies more financially attractive for residential buildings. Moreover, government-led incentives, such as subsidies, public-private partnerships, or demonstration projects, could further accelerate adoption by offsetting upfront costs. Integrating PCM technologies into national energy efficiency policies may offer a practical pathway to reduce cooling demand and enhance sustainability in the building sector.

4. Limitations and Future Directions

Although this study offers a valuable understanding of PCM cost-effectiveness in building construction, some limitations must be acknowledged. First, the study did not account for visual comfort related to PCM usage in glazing, which could influence occupant well-being. Additionally, the limited availability of PCM contractors in the UAE, due to the technology's limited market adoption, posed a challenge in obtaining a more accurate PCM cost. Encapsulation design and shell material selection were not explicitly modeled in this study and represent additional practical design variables that may influence cost, durability, and constructability. Instead, current market prices of encapsulated PCM products were used as an aggregated proxy in the economic analysis, consistent with approaches reported in the literature [40,52]. Future work should explicitly evaluate specific encapsulation technologies (e.g., macro- or micro-encapsulated PCM systems) and their associated costs and thicknesses to further refine feasibility assessments.

Another limitation was the study's focus on residential buildings, which have continuous occupancy patterns. Buildings with intermittent occupancy, such as offices and schools, may benefit even more from PCM’s thermal regulation, leading to greater energy savings and cost reductions. Finally, this study focused on Sharjah, where electricity tariffs are relatively high compared to other Emirates. Since lower tariffs in other regions may affect PCM cost-effectiveness, future studies should consider a broader UAE-wide analysis.

Another limitation is that while the study included glazing as one of the envelope components for PCM integration, it did not account for the impact on daylighting or visual comfort. Unlike walls and roofs, glazing exhibits both thermal and optical functions, and integrating PCM into windows may affect natural lighting conditions. However, the comparison across walls, roofs, and glazing was conducted solely from an energy and economic perspective, under a uniform simulation framework. Future studies should include a visual performance analysis to provide a more comprehensive evaluation of PCM integration in transparent envelope elements. Moreover, a limitation of this study is that the industrial feasibility of local paraffin production in the UAE was not fully explored. While local production holds promise for reducing costs and improving PCM availability, a detailed feasibility analysis would be valuable to assess its technical, economic, and logistical aspects. Future directions could concentrate on evaluating the practical implications of local production to further enhance PCM cost-effectiveness and accessibility in the UAE market.

Ultimately, future research should focus on conducting comparative cost-effective analysis of PCM against other energy-efficient systems, considering regional electricity tariffs for a more comprehensive economic evaluation. Additionally, testing different PCM thicknesses would optimize its thermal performance and economic feasibility across diverse building types and climate conditions. Research should also explore integrating PCM with complementary technologies such as HVAC and solar systems, assessing the combined impact on energy cost savings and lifecycle costs. Expanding research to include non-residential buildings, such as offices and schools, would clarify how PCM cost-effectiveness varies based on occupancy patterns and operational schedules. Future research should also explore alternative PCM materials, such as bio-based PCMs, which offer renewable and environmentally friendly solutions, or salt-hydrate PCMs, known for their higher thermal conductivity. Assessing these materials in UAE-specific conditions could uncover more sustainable and cost-effective options. This approach could uncover materials with better thermal conductivity, reduced environmental impact, and lower costs, advancing wider implementation in the construction sector.

The high availability of raw materials in the UAE [65] presents an opportunity for local PCM production, reducing import-related expenses and lowering overall costs. Capitalizing on this resource could significantly boost PCM adoption in energy-efficient construction, supporting both economic and environmental sustainability goals. Addressing pricing challenges through local production strategies or government incentives may make PCM more accessible. Future research could also explore innovative methods to enhance PCM affordability in the UAE and similar climates, ensuring its long-term viability in sustainable construction.

5. Conclusions

This current study assessed the energy and economic impacts of integrating PCMs into residential building envelopes in the UAE's hot-humid climate. The study focused on determining the most effective PCM placement, thickness, and melting point to achieve maximum energy savings while ensuring cost-effectiveness. A mixed-methods approach was employed, combining literature review, energy simulations, and cost-benefit analysis. Using a factorial design, 10 PCM integration scenarios were tested by varying envelope components (walls, roof, glazing), PCM placement (interior or exterior), and PCM thickness (3 cm or 5 cm). Additionally, different PCM melting points of 31℃, 47℃, and 55℃ were evaluated to establish their effect on thermal performance and energy savings. The DesignBuilder simulation software, run with the EnergyPlus engine, provided detailed energy performance data, while LCC and NPV analyses were conducted to assess financial feasibility based on UAE-specific electricity tariffs.

The results indicated that integrating PCM into glazing surfaces yielded the highest energy savings, reducing energy utilization intensity (EUI) by up to 11% relative to the base case. This performance was attributed to the high solar radiation exposure of glazing components, making them ideal for passive cooling. Additionally, increasing PCM thickness from 3 cm to 5 cm produced only a marginal improvement in energy savings, suggesting that thinner PCM layers could achieve similar thermal performance while significantly reducing material costs. Among the tested PCM melting points, a higher melting point of 55℃ performed best under the UAE's extreme heat conditions, delaying heat transfer and stabilizing indoor temperatures during peak heat hours.

Despite the promising energy savings, the cost-benefit analysis revealed that PCM integration remains economically challenging because of high initial costs and relatively low electricity tariffs in the UAE. The G3_55 scenario, featuring a layer of 3cm thick PCM with a melting point of 55 ℃, emerged as the most cost-effective configuration, offering a 30-year payback period with a 40% reduction in material costs compared to a 5 cm PCM layer. A sensitivity analysis further demonstrated that reducing PCM thickness to 1 cm shortened the payback period to just 7 years, highlighting the potential for more practical PCM applications if material quantity is reduced. Furthermore, a 50% reduction in PCM prices could lower the payback period to as little as 4 years, emphasizing the importance of local PCM production to reduce costs through petroleum by-products widely available in the UAE.

This research provides the first combined thermal and economic evaluation of PCMs as a thermal energy storage strategy for residential buildings in the UAE, accounting for both energy savings and lifecycle economics under hot-humid conditions. By comparing multiple envelope components (walls, roofs, and glazing) and introducing a novel sensitivity analysis with ultra-thin PCM layers and cost-reduction scenarios through local production, this work establishes regionally specific pathways for PCM feasibility that have not been explored in prior studies. The findings align directly with the scope of sustainable energy research by demonstrating how thermal energy storage can reduce cooling demand, support energy efficiency, and contribute to sustainable development goals in Gulf countries. They also provide actionable guidance for architects, policymakers, and the construction industry on PCM adoption, while highlighting the role of economic mechanisms such as subsidies and local manufacturing in accelerating deployment.

Future studies should expand beyond residential buildings to include offices and schools, assess alternative PCM types with improved thermal conductivity, and investigate incorporation with complementary energy-saving technologies to maximize the combined impact on energy storage and conservation.

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.

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Credit Authorship Contribution Statement

Ameera Ghanim: Writing – review & editing, Writing – original draft, Conceptualization, Visualization, Methodology, Investigation, Formal Analysis, Software, Validation. **Aya Elshabshiri:** Writing – review & editing, Writing – original draft, Conceptualization, Visualization, Methodology, Investigation, Formal Analysis, Software, Validation. **Shouib Nouh Ma'bdeh:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Emad Mushtaha:** Writing – review & editing. **Vittorino Belpoliti:** Writing – review & editing**.** **Aseel Hussien**: Writing – review & editing

Abbreviations

AED	United Arab Emirates Dirham

BC	Base Case
CoP	Coefficient of Performance
DHW	Domestic Hot Water
EUI	Energy Utilization Intensity
HVAC	Heating, Ventilation, and Air Conditioning
kWh	Kilowatt-hour
LCC	Life Cycle Cost
Mtoe	Million Tons of Oil Equivalent
MWh	Megawatt-hour
NPV	Net Present Value
PCM	Phase Change Material
PWF	Present Worth Factor
SHGC	Solar Heat Gain Coefficient
SPP	Simple Payback Period
UAE	United Arab Emirates
W/m ^{2}K	Watts per square meter per Kelvin

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