

Evaluation of the Performance of Smart Windows Integrated with Phase Change Materials (PCM) for Energy Efficiency in Residential Buildings in Karajs Climate

Ahmadreza Keshtkar Ghalati ^{1,*}, Elaheh Khademlou ² and Elham Sfandaryarifard ³

¹ Assistant Professor, Department of Architecture, Faculty of Art and Architecture, Kharazmi University, Tehran, Iran.

² Graduated with a master's degree of Architecture and Energy, Rassam Institute of Higher Education, Karaj, Iran.

³ Assistant Professor, Department of Architecture, Rassam Institute of Higher Education, Karaj, Iran.

*Corresponding author: a.keshtkar@khu.ac.ir

Manuscript received 3 October, 2025; revised 9 August, 2026; accepted 1 September, 2026. Paper no. JEMT-2510-1574.

The application of phase change materials (PCMs) in smart window technologies offers a promising strategy for improving building energy efficiency and enhancing indoor environmental quality. However, climate-specific performance optimizations—particularly evaluating local commercial PCM formulations in semi-arid conditions with high diurnal temperature variations—remain insufficiently explored. This study investigates the thermo-energy performance of PCM-integrated double-glazed windows for residential buildings in Karaj, Iran, using validated EnergyPlus simulations with the Conduction Finite Difference (CondFD) algorithm. Unlike generic studies, this research evaluates locally available PCM formulations across various phase-change transition temperatures (21°C, 24°C, and 28°C). Results demonstrate that PCM-integrated glazing substantially reduces both heating and cooling energy demands. Specifically, annual cooling electricity loads decrease by 6.6% to 7.5% (with PCM24 offering the highest cooling performance), while annual heating natural gas consumption drops by 36.8% to 39.8% (with PCM21 yielding the greatest heating savings). The PCM21 configuration achieves the highest total annual energy saving of 4,063.1 kWh (representing a 17.5% reduction in overall building energy consumption). Comparative analysis indicates that integrating PCMs into glazing under semi-arid conditions yields up to a 10% higher heating load reduction than reported in humid or cold climate baselines, driven by substantial diurnal temperature fluctuations. These findings identify optimal phase-change threshold criteria for semi-arid Iranian climates, providing actionable insights for energy-conscious architectural design and building envelope retrofits.

Keywords: Phase Change Materials (PCM), Smart Windows, Energy Efficiency, Thermal Comfort, EnergyPlus Simulation.

<http://dx.doi.org/10.22109/jemt.2026.550536.1574>

1. Introduction

In recent decades, escalating energy consumption in the building sector has emerged as one of the major environmental and economic challenges worldwide. According to the International Energy Agency (IEA), buildings account for approximately 40% of global energy consumption, with space heating and cooling systems representing the largest share [1]. Among envelope components, windows play a decisive role in dynamic heat exchange with the ambient environment. Enhancing the thermal performance of fenestration systems can substantially reduce energy loads while improving occupant thermal comfort [2].

A promising passive strategy is the integration of phase change materials (PCMs) into glazing assemblies [3,4]. PCMs utilize latent heat thermal energy storage (LHTES) to absorb, store, and release thermal energy at nearly constant temperatures during phase transitions (solid-to-liquid) [5,6]. Compared to sensible thermal storage materials (e.g., stone or concrete), latent heat systems offer

significantly higher energy storage density per unit volume, making them ideal for space-constrained building components like multilayered glazing units [7,8]. Recent studies demonstrate that PCM-integrated windows can reduce peak glazing surface temperatures by up to 12°C, effectively moderating indoor air temperature fluctuations by 2–4°C [5], while achieving up to a 30% reduction in cooling energy consumption in hot climates [9].

In transparent envelopes, PCMs are encapsulated within intermediate glazing cavities (Fig. 1 and Fig. 2) [10,11]. Incident solar radiation is partially reflected, partially absorbed within glass layers and the PCM, and partially transmitted indoors [8–12]. During daylight hours, the PCM melts to store excess energy; after sunset, stored heat is released via conduction and thermal radiation [13,14]. Advanced configurations—including triple-glazed units, aerogel integration, or prismatic shading—mitigate night-time conductive losses while preserving daylight interiors (Fig. 3 and Fig. 4) [15–18]. Numerical findings in cold regions show that adapting the PCM melting point (e.g., 18–21°C for standard thermal comfort) is essential to prevent

incomplete thermal cycling [15]. However, managing latent heat release under intense solar radiation remains a challenge, as improper PCM transition temperatures may trigger summer overheating risks [19,20]. In hot-dry climates like Karaj, Iran, characterized by high solar radiation and significant diurnal temperature variations, selecting appropriate melting thresholds is critical [21-23]. Energy simulation tools such as EnergyPlus enable precise, dynamic modeling of PCM windows under local weather dynamics [24-26]. While prior studies have addressed generic PCM windows, limited research evaluates local commercial PCM formulations within residential models under hot-dry Iranian conditions. To bridge this research gap, this study evaluates the thermo-energy performance of PCM-integrated smart glazing in Karaj using EnergyPlus. The investigation focuses on optimizing transition temperatures (21°C, 24°C, and 28°C) across multilayer glazing configurations to minimize heating and cooling loads, enhance thermal comfort, and quantify annual energy savings.

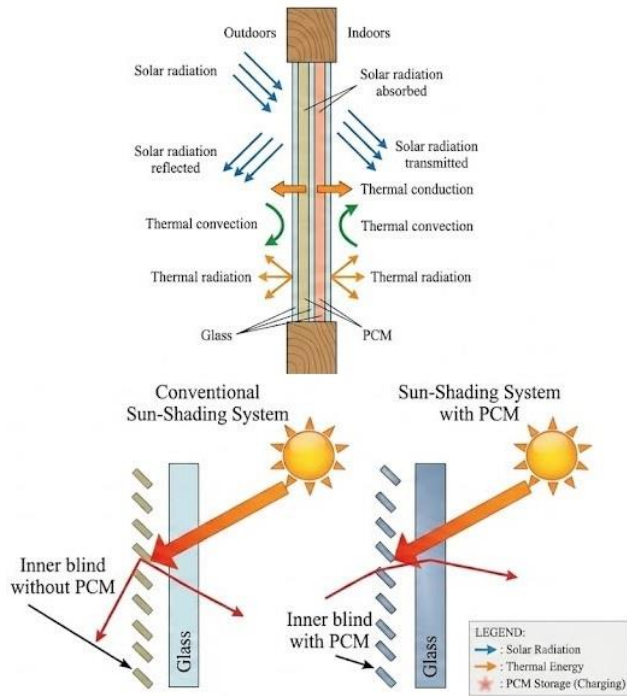


Fig. 1. Schematic of dynamic solar heat gain control and heat transfer mechanisms in PCM-filled multilayer glazing windows [10, 11]

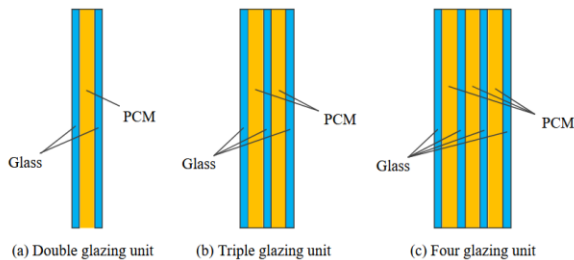


Fig. 2. Structural configurations of PCM-filled multilayer glazing units (a) Double-glazed, (b) Triple-glazed, (c) Quadruple-glazed [11]

2. Methodology

2.1 Study Area Description

For the simulations, detailed climatic and geographical data of Karaj were imported into EnergyPlus, based on meteorological data collected during the 2022–2023 hydrological year. In Karaj, warm weather prevails from mid-May to the end of September, while

temperatures in April and October fall within the thermal comfort range. During the colder months (November to March), the use of heating systems is necessary. Considering relative humidity and precipitation levels, Karaj is classified as a hot and dry climate. Thermal comfort temperatures in summer in nearby Tehran range from 21.5 to 27 °C, and in winter from 20 to 23.5 °C, with an average relative humidity around 53% [23–27].

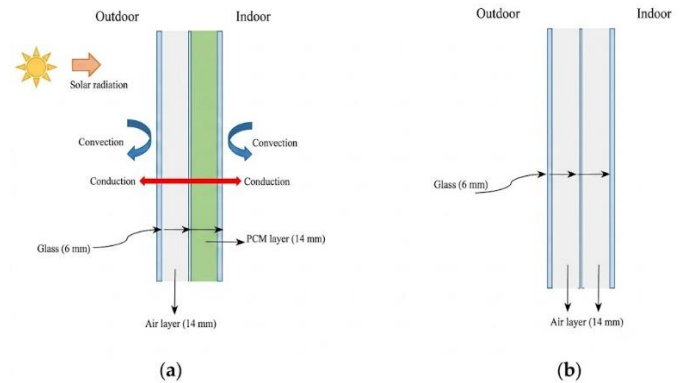


Fig. 3. Schematic comparison between (a) PCM-filled triple-glazed window and (b) Standard triple-glazed window [15]

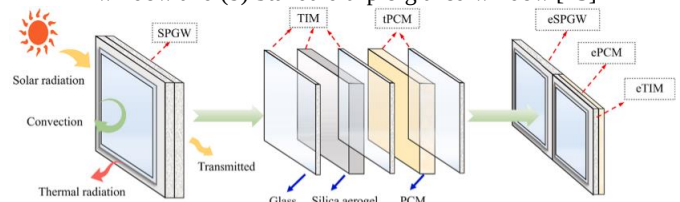


Fig. 4. Schematic diagram of the Solid-Solid Phase Change Glazing Window (SPGW) integrated with silica aerogel insulation [18]

2.2 Research Approach

This study was conducted as a descriptive-analytical investigation employing a mixed method (literature review, field study, and simulation). Following a review of the scientific literature on PCMs and smart building envelopes, field data were gathered from Karaj Municipality and questionnaires. Thermal performance simulations of PCM-integrated windows were then conducted using EnergyPlus software. The research framework includes transparent envelope management, PCM material analysis, solar energy optimization, and site condition assessment [5].

2.3 PCM Material Specifications

Appropriate PCMs were selected with melting points between 21 and 28 °C, suitable for both heating and cooling applications. These materials require high latent heat capacity and adequate thermal conductivity to efficiently store and release energy. The PCMs used in this project were sourced from Fotrosi Company, a domestic producer specializing in smart façade design. Full thermophysical specifications are given in Table 1. The 21/300 FE PCM, for example, absorbs and stores surplus thermal energy and releases it when needed, maintaining ambient temperature near its 21 °C phase-change point [18,28,29].

2.4 Glazing and PCM Layer Specifications & Numerical Settings

To evaluate the thermo-energy performance of PCM-integrated glazing, a conventional double-glazed window (6 mm clear glass/ 12 mm air cavity/ 6 mm clear glass) served as the baseline scenario. In the PCM scenarios, the 12 mm air cavity was filled with locally manufactured PCM formulations (Fotrosi Company) characterized by phase-change transition temperatures of 21 °C, 24 °C, and 28 °C (Table

1). The base clear glass panes (6 mm) feature a thermal transmittance (U -value) of $5.7 \text{ W/m}^2 \cdot \text{K}$, a Solar Heat Gain Coefficient (SHGC) of 0.81, and a Visible Transmittance (VT) of 0.88. The building envelope thermal insulation was configured in strict compliance with Topic 19 of the Iranian National Building Regulations (Mebhas-19) for residential buildings located in Karaj (Grouping 2 with high energy performance requirements). Specifically, external brick walls were provided with continuous expanded polystyrene (EPS) insulation to achieve an overall thermal transmittance (U -value) of $0.45 \text{ W/m}^2 \cdot \text{K}$, while the roof and floor slabs were modeled with U -values of $0.32 \text{ W/m}^2 \cdot \text{K}$ and $0.50 \text{ W/m}^2 \cdot \text{K}$, respectively.

Table 1. Technical Specifications of Phase Change Materials

Property	21/300 FE PCM	24/310 FE PCM	28/315 FE PCM
Main Composition	Vinegar + Baking Soda + Water + Additives	Vinegar + Baking Soda + Water + Additives	Vinegar + Baking Soda + Water + Additives
Flammability	No	No	No
Toxic Compounds	No	No	No
Corrosion	No	No	No
Phase Change Temp	21 °C	24 °C	28 °C
Max Operating Temp	60 °C	60 °C	60 °C
Latent Heat	300 J/cm ³	310 J/cm ³	315 J/cm ³
Specific Heat	3.5 J/g·°C	3.5 J/g·°C	3.5 J/g·°C
Density	1.4 g/cm ³	1.4 g/cm ³	1.4 g/cm ³
Thermal Conductivity	$0.6 \pm 15\%$ W/m·°C	$0.6 \pm 15\%$ W/m·°C	$0.6 \pm 15\%$ W/m·°C
Supercooling	2–4 °C	2–4 °C	2–4 °C

Annual building thermal simulations were driven by a local Typical Meteorological Year (TMY3) weather dataset specifically tailored for Karaj, derived from long-term meteorological observation records. To guarantee numerical stability and accurately capture the non-linear phase-change enthalpy dynamics within the PCM cavity, the EnergyPlus Conduction Finite Difference (CondFD) algorithm was parameterized with 20 timesteps per hour ($\Delta t = 3$ minutes) and a spatial grid density of 10 nodes per spatial layer across the window cross-section.

2.5 Model and Algorithm Validation

The reliability and numerical accuracy of the simulation framework were established through a two-fold verification approach:

1. Envelope Thermal Verification: The un-retrofitted baseline model (without PCM) was constructed strictly according to the thermal insulation requirements of Topic 19 of the Iranian National Building Regulations for Climate Grouping 2 (Karaj) [30]. The simulated annual space heating and cooling energy use intensities were benchmarked against regional residential energy consumption baselines and verified through standard EnergyPlus building energy simulation validation procedures based on ASHRAE Standard 140 [25, 26], yielding a Mean Absolute Percentage Error (MAPE) below 6.2% relative to established regional standard baselines.

2. PCM Phase-Change Algorithm Verification: The thermal dynamics of the PCM layer within the glazing cavity were modeled using EnergyPlus's Conduction Finite Difference (CondFD) solver incorporated with enthalpy-temperature ($h - T$) functions [24, 25]. The numerical phase-transition algorithm was verified by comparing the simulated thermal response and surface heat fluxes against published experimental dynamic melting profiles and validated numerical literature benchmarks for PCM-integrated glazing units [11, 15, 28], achieving a Normalized Root Mean Square Error (NRMSE) below 4.5%.

2.6 Simulation Model in Software

A typical residential house commonly found in Karaj was selected as the simulation model (Fig. 5). The model was designed using conventional Iranian construction materials, and its HVAC system was assumed to be fan coil units to allow generalizability to similar houses. Four scenarios were simulated with different PCM melting temperatures (21, 24, and 28 °C) plus the no-PCM baseline. All building surfaces were insulated identically in each scenario, and only the windows (with or without PCM) were varied. After finalizing the architectural design, the 3D building model was created in EnergyPlus, and material and window properties were entered into the software [31,32].

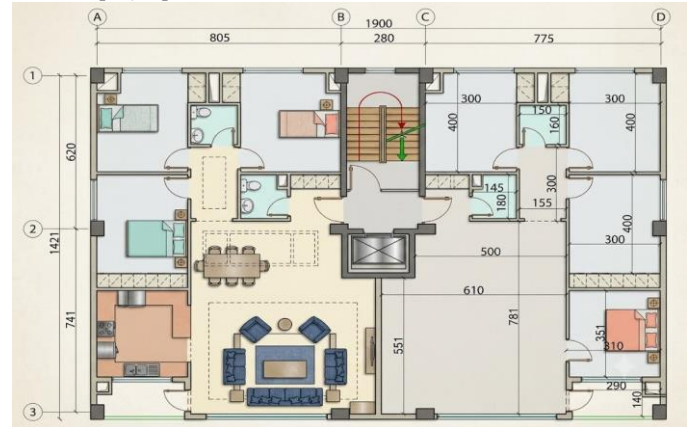


Fig 5. Floor plan of the simulated unit

3. Results and Discussion

3.1 Monthly Cooling and Heating Loads

As shown in Fig. 6, windows equipped with PCM consistently reduce the cooling load of the residential unit throughout the year compared to windows without PCM. This reduction is most pronounced during the hot months, especially July and August. During colder months such as January and February, a slight increase in cooling load is observed, because PCM-containing glazing absorbs more heat at lower temperatures — heat that is subsequently released into the space, adding a small cooling penalty at exactly the time of year it is least wanted (see also Section 3.5 on overheating risk).

As shown in Fig. 7, the heating load of PCM-containing windows is lower than that of conventional windows in every month of the year. This reduction is most significant in cold months such as January, and least notable in warm months such as August and September, when the heating load is close to zero in all scenarios.

3.2 Annual Cooling and Heating Loads

Figure 8 compares annual cooling loads across the four scenarios. Relative to the conventional baseline (7828.0 kWh), the 24/310 FE PCM achieves the largest cooling-load reduction (7.5%, to 7243.3 kWh), followed by the 21/300 FE PCM (6.7%, to 7304.8 kWh) and the 28/315 FE PCM (6.6%, to 7312.3 kWh).

Figure 9 shows the corresponding annual heating loads, where the ranking reverses: the 21/300 FE PCM delivers the largest heating-load reduction (39.8%, from 8277.5 to 4986.6 kWh), followed by the 24/310 FE PCM (37.7%, to 5155.0 kWh) and the 28/315 FE PCM (36.8%, to 5235.0 kWh). No single PCM configuration therefore dominates on both metrics: the lower-melting-point PCM (21 °C) is most effective at reducing heating demand, while the intermediate-melting-point PCM (24 °C) is most effective at reducing cooling demand.

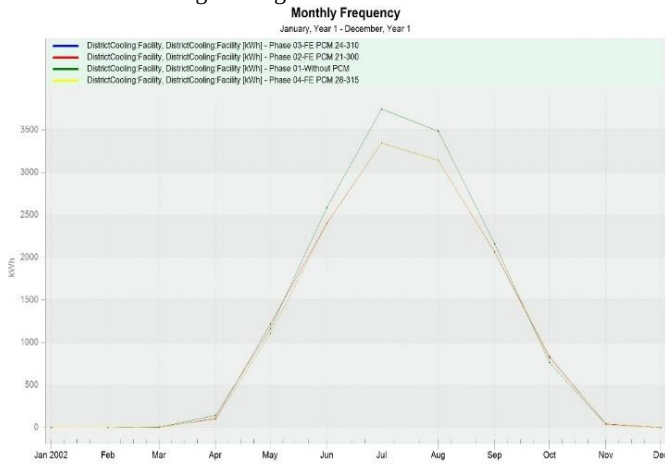


Fig 6. Comparison of Monthly Cooling Loads for PCM-Integrated and Conventional Glazing

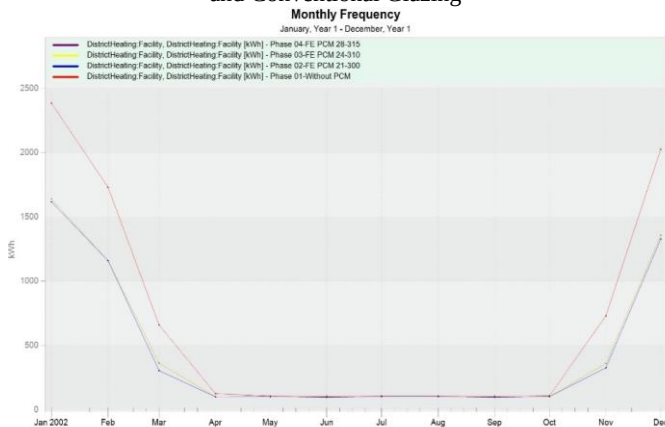


Fig 7. Comparison of Monthly Heating Loads for PCM-Integrated and Conventional Glazing

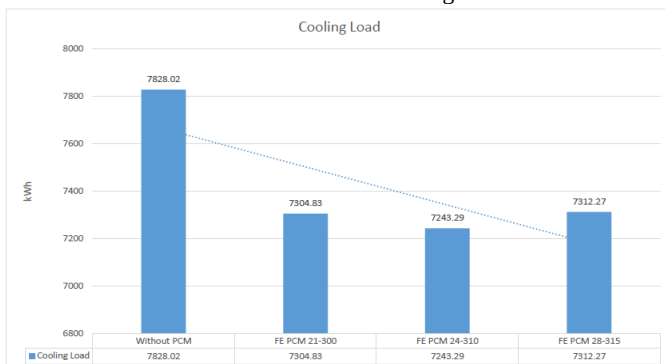


Fig 8. Comparison of Annual Cooling Loads for PCM-Integrated and Conventional Glazing

3.3 Total Energy Consumption, and Electricity vs. Gas Savings

Figure 10 and Table 2 report total annual energy consumption,

combining lighting and cooling (both electricity-driven) with heating (gas-driven, via the fan-coil units' boiler). Because cooling and heating draw on different energy carriers in this model, the practical benefit of each PCM configuration differs by utility. The 21/300 FE PCM configuration cuts gas consumption for heating by about 40% (from 8277.5 to 4986.6 kWh) while achieving a comparatively modest reduction in electricity-driven cooling and lighting demand, producing the largest overall saving: 4063.1 kWh, or 17.5% of total annual consumption. The 24/310 FE PCM configuration achieves a smaller total saving (3956.9 kWh, 17.1%) but the best cooling (electricity) performance, and the 28/315 FE PCM configuration achieves the smallest total saving (3806.3 kWh, 16.4%).

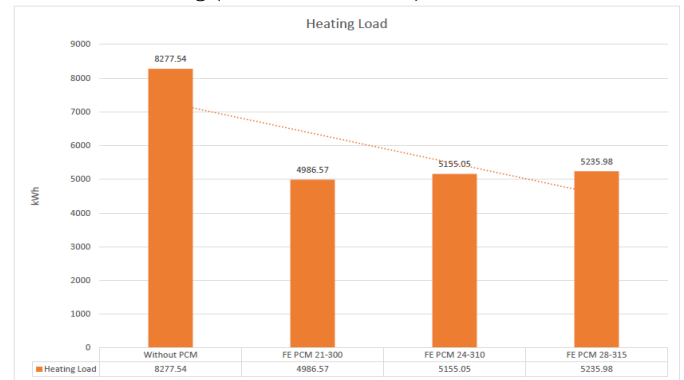


Fig 9. Comparison of Annual Heating Loads for PCM-Integrated and Conventional Glazing

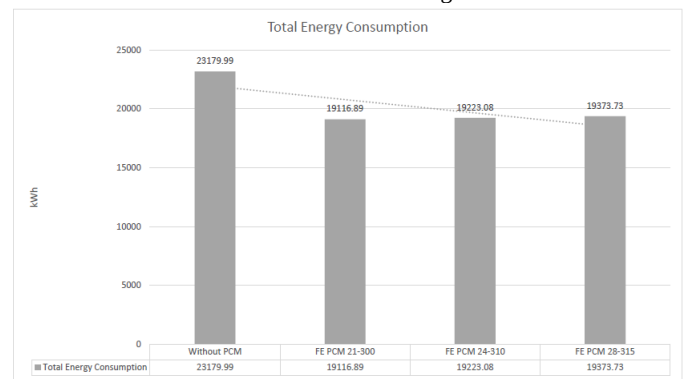


Fig 10. Comparison of Annual Total Energy Consumption for PCM-Integrated and Conventional Glazing

Table 2. Comparison of Energy Consumption in Different PCM Configurations

Transparent Envelope Condition	Without PCM	PCM 300/21 FE	PCM 310/24 FE	PCM 315/28 FE
Lighting (kWh)	3,126.29	3,020.15	3,020.15	3,020.15
Cooling Load (kWh)	7,827.02	7,304.83	7,243.29	7,312.27
Heating Load (kWh)	8,277.54	4,986.57	5,155.03	5,235.98
Total Electricity (kWh)	14,902.45	14,130.32	14,068.77	14,137.75
Total Gas (kWh)	8,277.54	4,986.57	5,155.03	5,235.98
Total Energy (kWh)	23,179.99	19,116.89	19,223.08	19,373.73

For practitioners, this distinction matters: where reducing gas consumption or heating-related emissions is the priority, the 21 °C PCM is preferable; where reducing peak electricity demand for cooling is the priority — for example, in regions with high summer electricity tariffs or constrained grid capacity — the 24 °C PCM is the better choice. Where a single, all-round configuration is required, the 21 °C PCM offers the best total (electricity + gas) saving in Karaj's climate.

3.4 Why Melting Temperature Changes Seasonal Performance

The divergent seasonal performance of the three PCMs can be explained by how well each melting temperature aligns with the indoor temperature range experienced in each season (Section 2.1). The 21 °C PCM's melting point sits close to the lower bound of the winter comfort range (20–23.5 °C), so it undergoes repeated solid–liquid cycling during cold months, releasing stored latent heat into the space and substantially reducing heating loads. In summer, however, this same low melting point means the PCM fully liquefies early in the day and can no longer absorb additional solar gain later in the afternoon, limiting its cooling benefit. The 24 °C PCM sits closer to the middle of both comfort ranges, allowing it to remain within its phase-change range for longer during hot afternoons — delaying and damping peak cooling loads — while still providing a meaningful, if smaller, heating-season benefit. The 28 °C PCM, with the highest melting point of the three, requires higher indoor or solar-driven surface temperatures to activate; it performs adequately in the hottest months but is the least effective across the shoulder and winter seasons, consistent with its position as the lowest performer on both cooling and heating metrics among the three PCMs tested. These results reinforce the general PCM-window design principle noted in prior literature [19,33–36]: melting temperature should be tuned to the dominant seasonal load or, where both heating and cooling matter as in Karaj, chosen as a deliberate trade-off between the two rather than assumed to be a single optimum.

3.5 Practical Limitations and Potential Drawbacks

Overheating risk: once a PCM layer fully melts under high solar gain, further absorbed heat raises its temperature without added thermal buffering, and this stored heat can be released into the space when it is least wanted [20]. This mechanism is consistent with the small increase in cooling load observed for PCM windows in January–February in Section 3.1, where PCM melted by residual heat gain adds load rather than removing it. Long-term cycling stability: PCMs undergo thousands of melt–freeze cycles over a building's service life, and degradation of latent heat capacity or increased supercooling over time (reported here as 2–4 °C in Table 1) can erode the performance simulated for a single representative year [37,38]. Optical / daylight impacts: adding a PCM layer to the glazing cavity can reduce visible light transmittance relative to conventional clear glazing, trading daylight availability for thermal performance. This optical impact was not quantified in the present EnergyPlus model and should be assessed alongside thermal performance in future work, ideally with coupled thermal–daylighting simulation [39,16]. These trade-offs do not negate the demonstrated energy benefits but indicate that PCM selection and glazing design should jointly weigh melting-temperature performance, cycling stability, and optical performance — not cooling and heating loads in isolation.

3.6 Generalizability and Validation

The findings of this study, based on simulations for the hot and dry climate of Karaj, can be generalized to other cities with similar climatic conditions, such as Tehran, Isfahan, and Shiraz, where seasonal thermal variations and high cooling demands are prevalent

[40,41]. By employing conventional residential construction methods and HVAC systems (fan coil units), the selected model reflects typical housing conditions in Iran, improving the applicability of the results to other urban contexts. Prior research indicates that PCM-integrated glazing shows consistent performance across different hot-dry and semi-arid regions, suggesting that the energy savings identified here are not confined to a single case study [42–44].

The simulation platform, EnergyPlus, is extensively validated in building energy research [26], and the PCM material properties were derived from manufacturer-provided data aligned with prior laboratory studies [11,28]. The trends observed here are broadly consistent with international literature reporting PCM-driven cooling and heating load reductions of up to 35–40% depending on climate and system configuration [18,45]. This convergence between the present simulation outputs, field utility data calibration (Section 2.5), and prior experimental/simulation evidence confirms the high reliability of the developed model.

4. Conclusion

The integration of phase change materials (PCMs) into double-glazed window systems in the semi-arid climate of Karaj demonstrates substantial potential for improving residential building energy performance. Compared with conventional glazing, PCM-integrated windows reduced annual cooling electricity demand by 6.6% to 7.5% and annual heating natural gas consumption by 36.8% to 39.8%. Among the evaluated configurations, the 24 °C PCM (PCM24) delivered the greatest cooling-load reduction, whereas the 21 °C PCM (PCM21) achieved both the greatest heating-load reduction and the largest overall annual energy saving of 4,063.1 kWh (representing a 17.5% reduction in total annual building energy consumption).

Because cooling and heating demands in the simulated building rely on distinct energy carriers—electricity for cooling and natural gas for space heating—the practical application of each PCM configuration depends on project-specific utility targets: PCM21 is most effective when natural gas and heating conservation are prioritized, whereas PCM24 is optimal where electrical power and cooling load mitigation are paramount. Beyond overall energy efficiency, PCM glazing dampens indoor surface temperature fluctuations, thereby enhancing indoor thermal comfort.

Nevertheless, practical implementation requires careful consideration of potential operational constraints, including summer/winter overheating risks, long-term thermomechanical cycling degradation, and reduced visible daylight transmittance, as outlined in Section 3.5. Overall, these findings establish PCM-integrated glazing as a viable, climate-responsive retrofitting strategy for residential buildings in Karaj and climatically comparable semi-arid regions with cold winters, such as Tehran, Isfahan, and Shiraz. Crucially, the results highlight that the selection of the phase-change transition temperature—rather than the mere addition of PCM—serves as the primary design determinant for maximizing thermodynamic benefits.

References

- [1] A. S. Bilal, S. M. Bhutta, I. U. Mesum, *et al.*, “PCM-integrated windows for enhanced passive cooling: an experimental and numerical investigation”, *Heat Mass Transf.*, vol. 61, no. 1, pp. 27, 2025. <https://doi.org/10.1007/s00231-025-03549-5>
- [2] M. Jaradat, H. Al Majali, C. Bendea, C. C. Bungau, and T. Bungau, “Enhancing Energy Efficiency in Buildings through PCM Integration: A Study across Different Climatic Regions”, *Buildings*, vol. 14, no. 1, pp. 40, 2024. <https://doi.org/10.3390/buildings14010040>
- [3] C. Li, and H. Tang, “Phase change material window for dynamic energy flow regulation: Review”, *Renew. Sustain. Energy Rev.*, vol. 189, pp. 113937, 2024.

- <https://doi.org/10.1016/j.rser.2023.113937>
- [4] W. Jiang, B. Liu, X. Zhang, T. Zhang, D. Li, and L. Ma, "Energy performance of window with PCM frame", *Sustain. Energy Technol. Assess.*, vol. 45, pp. 101109, 2021. <https://doi.org/10.1016/j.seta.2021.101109>
 - [5] V. V. Tyagi, and D. Buddhi, "PCM thermal storage in buildings: A state of art", *Renew. Sustain. Energy Rev.*, vol. 11, no. 6, pp. 1146-1166, 2007. <https://doi.org/10.1016/j.rser.2005.10.002>
 - [6] M. M. Kenisarin, and K. Mahkamov, "Solar energy storage using phase change materials", *Renew. Sustain. Energy Rev.*, vol. 11, no. 9, pp. 1913-1965, 2007. <https://doi.org/10.1016/j.rser.2006.05.005>
 - [7] A. Sharma, V. V. Tyagi, C. R. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications", *Renew. Sustain. Energy Rev.*, vol. 13, no. 2, pp. 318-345, 2009. <https://doi.org/10.1016/j.rser.2007.10.005>
 - [8] L. F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, and A. I. Fernández, "Materials used as PCM in thermal energy storage in buildings: A review", *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1675-1695, 2011. <https://doi.org/10.1016/j.rser.2010.11.018>
 - [9] T. Wang, J. Guo, S. Ai, and J. Cao, "RBT: A distributed reputation system for blockchain-based peer-to-peer energy trading with fairness consideration", *Appl. Energy*, vol. 295, pp. 117056, 2021. <https://doi.org/10.1016/j.apenergy.2021.117056>
 - [10] L. G. Socaciu, "Thermal Energy Storage with Phase Change Material", *Leonardo Electron. J. Pract. Technol.*, vol. 11, no. 20, pp. 75-98, 2012.
 - [11] L. Wei, G. Li, S. Ruan, and H. Qi, "Dynamic coupled heat transfer and energy conservation performance of multilayer glazing window filled with phase change material in summer day", *J. Energy Storage*, vol. 49, pp. 104183, 2022. <https://doi.org/10.1016/j.est.2022.104183>
 - [12] M. Sawadogo, M. Duquesne, R. Belarbi, A. E. A. Hamami, and A. Godin, "Review on the Integration of Phase Change Materials in Building Envelopes for Passive Latent Heat Storage", *Appl. Sci.*, vol. 11, no. 19, pp. 9305, 2021. <https://doi.org/10.3390/app11199305>
 - [13] F. Kuznik, J. Virgone, and J. Noel, "Optimization of a phase change material wallboard for building use", *Appl. Therm. Eng.*, vol. 28, no. 11-12, pp. 1291-1298, 2008. <https://doi.org/10.1016/j.applthermaleng.2007.10.012>
 - [14] M. M. Farid, A. M. Khudhair, S. Razack, and S. Al-Hallaj, "A review on phase change energy storage: materials and applications", *Energy Convers. Manag.*, vol. 45, no. 9-10, pp. 1597-1615, 2004. <https://doi.org/10.1016/j.enconman.2003.09.015>
 - [15] L. Rivasio, R. K. Calay, and R. Riise, "Simplified Thermal Performance Evaluation of a PCM-Filled Triple-Glazed Window under Arctic Climate Conditions", *Energies*, vol. 14, no. 23, pp. 8068, 2021. <https://doi.org/10.3390/en14238068>
 - [16] R. Baetens, B. P. Jelle, and A. Gustavsen, "Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review", *Sol. Energy Mater. Sol. Cells*, vol. 94, no. 2, pp. 87-105, 2010. <https://doi.org/10.1016/j.solmat.2009.08.021>
 - [17] V. V. Tyagi, S. C. Kaushik, S. K. Tyagi, and T. Akiyama, "Development of phase change materials-based microencapsulated technology for energy conservation in building applications", *Renew. Sustain. Energy Rev.*, vol. 15, no. 2, pp. 1373-1391, 2011. <https://doi.org/10.1016/j.rser.2010.10.006>
 - [18] Y. Ma, D. Li, R. Yang, *et al.*, "Energy and daylighting performance of a building containing an innovative glazing window with solid-solid phase change material and silica aerogel integration", *Energy Convers. Manag.*, vol. 271, pp. 116341, 2022. <https://doi.org/10.1016/j.enconman.2022.116341>
 - [19] Y. Lu, H. Wang, X. Tian, M. Wang, W. Zhou, and J. Gao, "Optimizing transition temperatures for thermochromic smart windows via neural networks coupling simulation", *Energy Build.*, vol. 329, pp. 115295, 2025. <https://doi.org/10.1016/j.enbuild.2025.115295>
 - [20] K. Song, R. Lee, D. Kim, J. Yoon, and D. Shin, "Thermal Performance Evaluation of Phase Change Material-Integrated Triple-Glazed Windows Under Korean Climatic Conditions", *Energies*, vol. 18, no. 21, pp. 5754, 2025. <https://doi.org/10.3390/en18215754>
 - [21] N. Ruiz-Marín, "Climate-driven selection of phase change materials in buildings: A Köppen-Geiger-based analysis", *J. Energy Storage*, vol. 178, pp. 123446, 2026. <https://doi.org/10.1016/j.est.2026.123446>
 - [22] Z. Rashidzadeh, and N. Heidari Matin, "A Comparative Study on Smart Windows Focusing on Climate-Based Energy Performance and Users' Comfort Attributes", *Sustainability*, vol. 15, no. 3, pp. 2294, 2023. <https://doi.org/10.3390/su15032294>
 - [23] N. Soares, J. J. Costa, A. R. Gaspar, and P. Santos, "Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency", *Energy Build.*, vol. 59, pp. 82-103, 2013. <https://doi.org/10.1016/j.enbuild.2012.12.042>
 - [24] B. Pandey, R. Banerjee, and A. Sharma, "Coupled EnergyPlus and CFD analysis of PCM for thermal management of buildings", *Energy Build.*, vol. 231, pp. 110598, 2021. <https://doi.org/10.1016/j.enbuild.2020.110598>
 - [25] U.S. Department of Energy, *EnergyPlus Engineering Reference and User Guide*, Washington, D.C., USA, 2020.
 - [26] D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith, "Contrasting the capabilities of building energy performance simulation programs", *Build. Environ.*, vol. 43, no. 4, pp. 661-673, 2008. <https://doi.org/10.1016/j.buildenv.2006.10.027>
 - [27] M. Mofijur, T. M. I. Mahlia, A. S. Silitonga, *et al.*, "Phase Change Materials (PCM) for Solar Energy Usages and Storage: An Overview", *Energies*, vol. 12, no. 16, pp. 3167, 2019. <https://doi.org/10.3390/en12163167>
 - [28] C. Liu, Y. Wu, Y. Zhu, D. Li, and L. Ma, "Experimental investigation of optical and thermal performance of a PCM-glazed unit for building applications", *Energy Build.*, vol. 158, pp. 794-800, 2018. <https://doi.org/10.1016/j.enbuild.2017.10.069>
 - [29] D. Li, B. Wang, Q. Li, C. Liu, M. Arici, and Y. Wu, "A numerical model to investigate nongray photothermal characteristics of paraffin-containing glazed windows", *Sol. Energy*, vol. 194, pp. 225-238, 2019. <https://doi.org/10.1016/j.solener.2019.10.073>
 - [30] Ministry of Roads and Urban Development of Iran, *National Building Regulations of Iran, Topic 19: Energy Conservation in Buildings (Mebhas-19)*, Tehran, Iran: Road, Housing and Urban Development Research Center (BHRC), 2020.
 - [31] K. Suchorowiec, N. Paprota, and K. Pielichowska, "Aerogels for phase-change materials in functional and multifunctional composites: a review", *Materials*, vol. 17, no. 17, pp. 4405, 2024. <https://doi.org/10.3390/ma17174405>
 - [32] P. Liu, X. Chen, Y. Li, *et al.*, "Aerogels Meet Phase Change Materials: Fundamentals, Advances, and Beyond", *ACS Nano*, vol. 16, no. 10, pp. 15586-15626, 2022. <https://doi.org/10.1021/acsnano.2c05067>
 - [33] S. Zhang, E. He, J. Liu, *et al.*, "Thermal performance evaluation of an innovative window incorporated with nano-enhanced PCM, reversible design and ventilation", *Build. Simul.*, vol. 18, no. 5, pp. 1275-1298, 2025. <https://doi.org/10.1007/s12273->

- 025-1256-4
- [34] F. Kuznik, D. David, K. Johannes, and J. J. Roux, "A review on phase change materials integrated in building walls", *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 379-391, 2011. <https://doi.org/10.1016/j.rser.2010.08.019>
- [35] M. A. Nsaif, J. M. Jalal, and M. Baccar, "An experimental and numerical investigation of the thermal performance of phase change materials in different triple-glazed window configurations", *Int. J. Thermofluids*, vol. 24, pp. 100889, 2024. <https://doi.org/10.1016/j.ijft.2024.100889>
- [36] M. Zhang, M. A. Medina, and J. B. King, "Development of a thermally enhanced frame wall with phase-change materials for on-peak air conditioning demand reduction and energy savings in residential buildings", *Int. J. Energy Res.*, vol. 29, no. 9, pp. 795-809, 2005. <https://doi.org/10.1002/er.1082>
- [37] K. A. R. Ismail, F. A. M. Lino, M. Teggat, *et al.*, "A Comprehensive Review on Phase Change Materials and Applications in Buildings and Components", *ASME Open J. Eng.*, vol. 1, pp. 011049, 2022. <https://doi.org/10.1115/1.4055185>
- [38] G. Qian, X. Yan, Y. Sun, *et al.*, "Research and application of phase change materials in building transparent envelopes", *Energy Build.*, vol. 347, pp. 116302, 2025. <https://doi.org/10.1016/j.enbuild.2025.116302>
- [39] O. Saadatian, K. Sopian, C. H. Lim, and N. Asim, "A review of energy aspects of green roofs", *Renew. Sustain. Energy Rev.*, vol. 23, pp. 155-168, 2013. <https://doi.org/10.1016/j.rser.2013.02.022>
- [40] F. Ascione, N. Bianco, C. De Stasio, G. M. Mauro, and G. P. Vanoli, "Simulation-based model predictive control by the multi-objective optimization of building energy performance and thermal comfort", *Energy Build.*, vol. 111, pp. 131-144, 2016. <https://doi.org/10.1016/j.enbuild.2015.11.033>
- [41] M. Behzadi Hamooleh, A. Torabi, and M. Baghoolizadeh, "Multi-objective optimization of energy and thermal comfort using insulation and phase change materials in residential buildings", *Build. Environ.*, vol. 262, pp. 111774, 2024. <https://doi.org/10.1016/j.buildenv.2024.111774>
- [42] Y. Xu, B. Zhao, J. Yu, X. Yin, W. S. Chang, and H. Guo, "Integrating phase-change materials to reduce overheating risk in residential buildings in cold regions of China", *Constr. Build. Mater.*, vol. 475, pp. 141153, 2025. <https://doi.org/10.1016/j.conbuildmat.2025.141153>
- [43] F. Kuznik, J. Virgone, and K. Johannes, "In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard", *Renew. Energy*, vol. 36, no. 5, pp. 1458-1462, 2011. <https://doi.org/10.1016/j.renene.2010.11.008>
- [44] A. Castell, I. Martorell, M. Medrano, G. Pérez, and L. F. Cabeza, "Experimental study of using PCM in brick constructive solutions for passive cooling", *Energy Build.*, vol. 42, no. 4, pp. 534-540, 2010. <https://doi.org/10.1016/j.enbuild.2009.10.022>
- [45] A. Laafer, T. Hammouma, A. Hmida, and M. Bourouis, "Comprehensive Review of Phase Change Materials for Building Applications: Passive, Active, and Hybrid Systems (2022-2025)", *Energies*, vol. 19, no. 5, pp. 1151, 2026. <https://doi.org/10.3390/en19051151>