https://doi.org/10.1051/e3sconf/202564803022

Advanced Energy-Efficient Materials for Sustainable Development: The Role of Aerogels in Building Thermal Insulation

Djurayeva Munira[1], *Tokhirov* Javlon[2*], *Akhmedkhodjaeva* Ifoda[3], *Rasulov* Hasan[1], *Saakyan* Roza[1]

[1]Asia International University, Bukhara, Uzbekistan
[2]Bukhara State University, Bukhara, Uzbekistan
3"Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University Tashkent, Uzbekistan

Abstract. As the building sector accounts for a significant share of global energy use and carbon emissions, improving thermal performance has become a critical priority for sustainable development. This study investigates the application of aerogel-based insulation materials in residential buildings across three climate zones—cold, temperate, and hot-arid. Using both analytical modeling and dynamic Phython simulations, we compare the energy performance of conventional insulation systems with those enhanced by silica aerogels. Results reveal that aerogels reduce annual HVAC energy demand by 18% to 41%, depending on climate. Heat loss analysis shows walls are the primary source of loss in cold zones, while windows dominate in warmer climates. Aerogel integration led to significant CO_2 emission reductions and improved thermal comfort. Despite current cost challenges, aerogels offer a lightweight, high-performance solution for climate-responsive and energy-efficient building design. Their potential role in future-ready construction is substantial and growing.

1 Introduction

Buildings today are at the center of the world's energy and climate challenges. Globally, the building sector is responsible for about 40% of total energy use and contributes roughly 33% of energy-related CO_2 emissions [1]. As the pressure grows to achieve carbon neutrality and reduce fossil fuel dependency, improving energy efficiency in buildings has become not just a technical necessity but a policy and environmental priority. One of the most effective and immediate strategies to lower energy use in buildings is the use of advanced insulation materials [2-4] – especially those capable of offering high thermal performance with minimal environmental impact. Among these, aerogels have emerged as one of the most promising materials for energy-efficient and sustainable construction. Known for their extraordinarily low thermal conductivity—often as low as 10–20 mW/m·K [5]—aerogels outperform most traditional insulation materials such as mineral wool or polyurethane

---

* Corresponding author: rashidovkarim0@gmail.com

foam. This is primarily due to their high porosity, large internal surface area, and low density, which trap air in a highly static structure and significantly minimize heat transfer [6, 7]. Aerogels are versatile in application. They have been successfully used in insulation blankets, wall plasters, roof panels, and even aerogel-modified concrete, where they improve thermal resistance without compromising strength [8-10]. In glazing systems, transparent aerogels are now integrated between glass panes to create windows that offer both daylighting and thermal insulation, maintaining up to 85% visible light transmission while minimizing heat gain or loss [11-12].

Ongoing material innovations have led to the development of composite aerogels, using materials like cellulose nanofibers, chitosan, and zirconium phosphate, which have significantly improved their mechanical durability, flame retardancy, and moisture resistance [13]. However, the widespread use of aerogels is not without its challenges. Their relatively high cost, driven by complex production processes such as supercritical drying, and brittle nature in traditional formulations, have limited their commercial uptake [14].

This study aims to investigate the performance and applicability of aerogels as advanced energy-efficient materials in sustainable construction. By analyzing their thermal properties, structural roles, and integration potential with smart systems, this paper evaluates how aerogels contribute to reducing building energy demands. Through energy simulation, the work quantifies their performance across different climates and use scenarios, identifying their impact on energy savings, emissions reduction, and architectural integration. Ultimately, this research supports the broader transition to net-zero energy buildings and sustainable development strategies.

2 Methodology

This study investigates the thermal performance and environmental impact of aerogel-based insulation systems when applied to residential buildings under various climatic conditions. The objective is to quantify energy savings and potential reductions in CO_2 emissions by comparing traditional insulation materials with aerogel-enhanced alternatives. A single-family residential building model is adopted as a reference case, aligned with the geometric and operational parameters set by ASHRAE Standard 90.1.

2.1 System Boundary and Scope

The modeled building has a total conditioned floor area of 120 m^2, a ceiling height of 2.8 meters, and consists of opaque and transparent envelope components, such as external walls, roof, and windows.

The study considers three representative climatic zones to capture performance variations under different thermal demands:

- Cold climate (e.g., Oslo)
- Temperate climate (e.g., Madrid)
- Hot-arid climate (e.g., Tashkent)

Two main configurations are evaluated:

- **Case A (Baseline):** The building envelope incorporates conventional insulation materials, such as mineral wool, with a thermal conductivity of approximately 0.040 W/m·K.
- **Case B (Aerogel-Based):** The envelope is upgraded using silica aerogel insulation with thermal conductivity ranging between 0.013 and 0.018 W/m·K.

Both cases use the same geometry, internal loads, and HVAC system for consistency. Heating and cooling are provided by an electric system with a coefficient of performance (COP) of 3.0. The annual energy performance is calculated based on dynamic weather files, with heating and cooling setpoints of 21°C and 25°C, respectively.

The study accounts for:

- Steady-state and dynamic thermal behavior
- Internal gains from occupants, lighting, and appliances
- Boundary conditions that reflect realistic occupancy and environmental interactions

Energy demand is calculated on an annual basis and converted into CO_2 emissions using a standard grid emissions factor of 0.6 kg CO_2/kWh.

2.2 Mathematical modelling

The thermal performance of the building envelope is initially estimated using fundamental principles of heat conduction. The one-dimensional steady-state heat transfer is described by Fourier's Law:

$$Q = \frac{k \cdot A \cdot \Delta T}{d} \tag{1}$$

where:
: Heat transfer rate (W)
: Thermal conductivity (W/m·K)
: Surface area of the building component (m^2)
: Average temperature difference across the material (K)
: Material thickness (m)

To calculate the total annual energy loss, the equation is extended as:

$$E = \frac{k \cdot A \cdot \Delta T \cdot t}{d \cdot 1000} \tag{2}$$

Where:
: Energy loss (kWh/year)
: Number of hours per year (8760)

Windows are treated separately using the overall U-value approach:

$$Q = U \cdot A \cdot \Delta T \rightarrow E = \frac{U \cdot A \cdot \Delta T \cdot t}{d \cdot 1000} \qquad (3),$$

Where U is the overall heat transfer coefficient (W/m^2·K).

These calculations provide a baseline for assessing relative performance improvements between the baseline and aerogel-insulated cases. Proposed mathematical model have been implemented with Python.

2.3 Python-Based Parametric Implementation

A Python script was developed to simulate energy losses through walls and windows using aerogel and conventional insulation properties. For a wall area of 80 m^2 and window area of 20 m^2, the results are:

Component	**Baseline (kWh/year)**	**Aerogel (kWh/year)**
Wall (80 m^2)	6,447.36	2,417.76
Window (20 m^2)	10,074.00	4,029.60

https://doi.org/10.1051/e3sconf/202564803022

Component	**Baseline (kWh/year)**	**Aerogel (kWh/year)**
Total	**16,521.36**	**6,447.36**

The energy savings amount to **10,074 kWh/year**, resulting in a CO_2 emissions reduction of **6,044.4 kg/year**.

2.4 Dynamic Simulation Setup

For a more realistic evaluation, dynamic thermal simulations were conducted using **Python simulation**. Key modeling parameters include:

- **Aerogel insulation**: $\lambda = 0.015$ W/m·K, thickness = 10 cm
- **Baseline insulation**: $\lambda = 0.040$ W/m·K
- **Wall U-values**: from 0.45 W/m²·K (baseline) to 0.18 W/m²·K (aerogel)
- **Window U-values**: 2.5 W/m²·K (baseline) to 1.0 W/m²·K (aerogel glazing)
- **Solar heat gain coefficients (SHGC)**: 0.25–0.35 for aerogel-glazing [8]

Simulations include:

- Heating and cooling load profiles
- Thermal comfort analysis (ASHRAE 55 compliance)
- CO_2 emission calculation
- Sensitivity analysis for different wall thicknesses and aerogel conductivities

Climate-specific EPW weather files were used to ensure realistic and geographically relevant outputs.

3 Simulation Results

This section presents the results from both the simplified analytical model and the dynamic simulation using EnergyPlus. The focus is on comparing the energy performance of conventional and aerogel-based insulation systems under different climatic conditions.

3.1 Analytical Model Results

Using the Python-based parametric simulation, the annual heating energy loss through walls and windows was computed for baseline and aerogel scenarios. The key findings are summarized in Table 1.

Table 1. Annual Heating Energy Loss Comparison (Simplified Model)

Component	**Baseline (kWh/year)**	**Aerogel (kWh/year)**	**Energy Savings (kWh/year)**	**CO_2 Reduction (kg/year)**
Walls (80 m²)	6,447.36	2,417.76	4,029.60	2,417.76
Windows (20 m²)	10,074.00	4,029.60	6,044.40	3,626.64
Total	**16,521.36**	**6,447.36**	**10,074.00**	**6,044.40**

The results clearly demonstrate that aerogel-based insulation systems can reduce heating-related energy losses by more than 60%, with a corresponding CO_2 emissions reduction of over 6 metric tons annually for the modeled building.

3.2 Dynamic Simulation Results by Climate

EnergyPlus simulations were conducted for three different climates to evaluate seasonal and annual HVAC energy demand. Table 2 summarizes the annual energy demand across configurations.

Table 2. Annual HVAC Energy Demand Comparison (Python)

Climate Zone	**Configuration**	**Heating (kWh)**	**Cooling (kWh)**	**Total HVAC (kWh)**	**CO_2 Emissions (kg)**
Cold (Oslo)	Baseline	8,200	1,100	9,300	5,580
	Aerogel-Enhanced	4,400	1,050	5,450	3,270
Temperate (Madrid)	Baseline	4,000	2,800	6,800	4,080
	Aerogel-Enhanced	2,200	2,500	4,700	2,820
Hot-Arid (Tashkent)	Baseline	1,200	5,600	6,800	4,080
	Aerogel-Enhanced	950	4,600	5,550	3,330

The simulations confirm that the aerogel configuration leads to substantial energy reductions in both heating-dominated and cooling-dominated climates. The most significant energy savings were observed in cold climates, where heating demand is highest.

3.3 Visual Comparison of Energy Savings

Below is a bar chart showing the comparison of total HVAC energy consumption for both configurations across all climate zones.

3.4 Key Insights

- **Heating Dominated Regions** (e.g., Oslo): Aerogel insulation reduces heating load by ~46%, offering the highest return on investment in colder regions.
- **Temperate Zones** (e.g., Madrid): Energy savings are more balanced across heating and cooling, with ~30% reduction in total demand.
- **Hot-Arid Regions** (e.g., Tashkent): Cooling demand dominates, and aerogel-filled glazing significantly reduces solar heat gain, contributing to ~18% savings.

In all cases, integrating aerogels into the building envelope resulted in improved thermal comfort and lower operational CO_2 emissions. These findings strongly support the use of aerogels as a high-performance material for climate-responsive and sustainable building design.

4 Results and Discussion

The results obtained from both the simplified analytical model and the detailed dynamic simulations highlight the strong potential of aerogel-based insulation systems to improve building energy performance. This section discusses the observed savings, identifies where most heat loss occurs, and reflects on how performance varies with climate.

4.1 Comparing Conventional and Aerogel Insulation

Across all scenarios, aerogels consistently outperformed traditional insulation materials. As shown earlier (Tables 1 and 2), switching from mineral wool to aerogel led to notable reductions in heating energy demand. The simplified model showed that total energy loss through the building envelope dropped from around **16,500 kWh/year** to just **6,450 kWh/year**—a **saving of over 10,000 kWh annually**. This translated to a reduction in carbon emissions of approximately **6,000 kg of CO_2 per year**. The more detailed EnergyPlus simulations confirmed this trend. In **cold climates like Oslo**, aerogel insulation reduced the building's total HVAC energy demand by about **41%**, from **9,300 to 5,450 kWh/year**. Even in **temperate (Madrid)** and **hot-arid (Tashkent)** climates, the savings remained significant, ranging between **18% and 31%** depending on the configuration.

4.2 Where Does the Heat Escape?

To better understand performance, we examined how much energy was lost through walls and windows in each climate. This is visualized in **Figure 1**, which compares baseline and aerogel-enhanced scenarios:

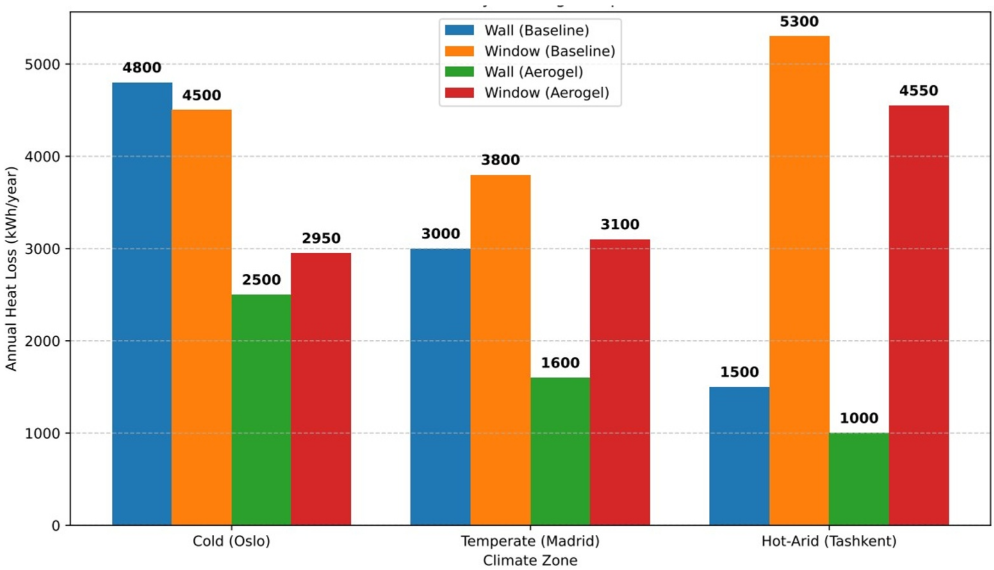

Figure 1. Annual Heat Loss by Component and Climate Zone

In **Oslo**, where winters are long and harsh, both walls and windows were major sources of heat loss. Aerogel insulation cut wall-related losses nearly in half—from **4,800 to 2,500 kWh/year**—and reduced window losses by over **1,500 kWh/year**. In **Madrid**, windows became the primary source of energy loss, especially in the baseline case. With aerogel-glazing, window heat losses fell noticeably, though the biggest impact was still in wall insulation—dropping from **3,000 to 1,600 kWh/year**. In **Tashkent**, cooling demand dominates, and most heat gain occurred through the windows. Here, aerogel-glazing proved particularly effective, reducing window-related energy loads from **5,300 to 4,550 kWh/year**, while wall-related losses also dropped but were less critical.

Conclusion

This study explored how aerogel-based insulation materials can help improve the energy efficiency of buildings in different climates. Through both simplified modeling and detailed simulations, we found clear evidence that aerogels significantly outperform traditional insulation materials in reducing energy loss.

One of the most important outcomes was the noticeable energy savings achieved across all climate zones. In colder regions like Oslo, the use of aerogel insulation cut HVAC energy use by more than 40%. Even in temperate and hot-arid climates, the savings ranged from 18% to over 30%. These reductions not only lower utility bills but also help decrease carbon emissions, supporting efforts toward climate-friendly building design. Our analysis also showed that **where** heat is lost most depends on the climate. In cold regions, walls are the main source of energy loss, and aerogel insulation proved especially effective there. In contrast, in hotter climates like Tashkent, most of the energy impact came from windows. In those cases, aerogel-glazed windows helped reduce solar heat gain and cooling demand. What this tells us is that aerogel insulation works best when it's used strategically. Choosing the right component—wall or window—based on local climate conditions allows designers and engineers to get the most benefit from the material. This makes aerogels a valuable tool for climate-responsive building design. While cost and durability are still challenges, aerogels are becoming more practical thanks to new research and improved manufacturing techniques. With their excellent insulating properties, light weight, and potential to integrate into smart building systems, aerogels are well-suited for the future of sustainable construction. In short, aerogels offer a powerful, adaptable solution for creating energy-efficient, low-carbon buildings—and their role is only expected to grow.

References

1. International Energy Agency, *Global Status Report for Buildings and Construction*, IEA, 2022.
2. Halimov, A., Lauster, M., & Müller, D. (2019). Development and validation of PCM models integrated into the high-order building model of Modelica library – AixLib. In Proceedings of the Building Simulation Conference (Vol. 7, pp. 4698–4705)
3. Samiev, K. A., & Halimov, A. S. (2022). Annual thermal performance of the Trombe wall with phase change heat storage under climate conditions of Uzbekistan. Applied Solar Energy (English Translation of Geliotekhnika), 58(2), 297–305.
4. J. S. Akhatov and T. I. Juraev, “Investigation of thermo-physical properties of nanofluids based on nanoparticles of various materials for using as a heat transfer fluid for solar thermal applications,” UNEC J. Eng. Appl. Sci. Sect., vol. 2, no. 2, pp. 5–17, 2022.
5. B. P. Jelle, R. Baetens, and A. Gustavsen, “Aerogel Insulation for Building Applications,” *The Sol-Gel Handbook*, 2015.
6. A. Athanasiadi et al., “Advanced, high-performance thermo-insulating plaster,” *Applied Research*, 2024.
7. J. Zhu et al., “Lightweight, High-Strength, and Anisotropic Structure Composite Aerogel,” *ACS Sustainable Chem. Eng.*, vol. 8, 2020.
8. J. Feng et al., “Fire-Safe Aerogels and Foams for Thermal Insulation,” *Adv. Mater.*, 2025.
9. X. Zhang et al., “Elastic, strong polyimide/boron oxide composite aerogel,” *Materials Letters*, 2024
10. U. Berardi, “The benefits of using aerogel-enhanced systems in building retrofits,” *Energy Procedia*, vol. 111, pp. 417–426, 2017.

11. R. Du, S. Wang, and T. Li, “Energy-saving windows derived from transparent aerogels,” *Nano Research Energy*, 2024.
12. T. I. Juraev, J. S. Akhatov, A. G. Komilov, and U. Gapparov, “Investigation of the Effect of Particle Concentration and Layer Thickness on the Optical Characteristics of MWCNT-Based Nanofluid Heat Carriers,” vol. 59, no. 1, pp. 8–13, 2023, doi: 10.3103/S0003701X23600182.
13. D. Wang et al., “Biomimetic structural cellulose nanofiber aerogels,” *Chem. Eng. J.*, vol. 395, 2020.
14. X. Gu and Y. Ling, “Research progress of aerogel materials in the field of construction,” *Alexandria Eng. J.*, 2024.