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Technical Report

Critical Evaluation of Thermal Efficiency in Aerogel Glazing Systems for Energy-Saving Applications

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Abstract: Aerogels as a thermal superinsulation material possess a unique combination of properties, most notably low densities, and exceptionally low thermal conductivities, stemming from the high-volume fraction of air incorporated within their structure. Aerogel glazing systems have emerged as a promising solution to enhance the thermal performance of building envelopes while maintaining daylighting. With the notable reductions in production cost in recent years, the integration of aerogels has been observed in both new construction and retrofitting projects, signalling a shift towards more energy-efficient building designs. The use of aerogel in glazing systems leverages both monolithic and granular configurations within the glazing interspace, enhancing thermal resistance while preserving high visible transmittance. Silica aerogels are particularly noteworthy due to their transparency, extremely low thermal conductivity (0.010-0.013 W/mK), and low density, making them suitable for thermal insulation in buildings. Incorporating aerogels into composites or framing systems not only reduces the overall weight of the building envelope but also significantly increases thermal resistance, offering valuable solutions for energy-efficient retrofitting, including facade coverings and window panes.

Keywords: Aerogel Glazing, Energy Saving Windows, Thermal Superinsulation, Cost-Effective Retrofit

Introduction

Buildings still account for approximately 40% of global energy usage (Cuce, 2014). This is due to heat loss through the building envelope caused by insufficient thermal insulation properties of conventional materials used in floors, exterior walls, roofs, and windows. Windows, in particular, are viewed as the most sensitive building envelope components in terms of heat loss due to their somewhat high overall heat transfer coefficients (U-value). The fenestration market is still dominated by double-glazed windows where air or alternative inert gases like Argon are utilised between the panes (Cuce, 2018). However, in most cases, the U-value of windows take a value above 2.60 W/m^{2}K (Cuce, 2017), which is quite greater than those of insulated walls (0.15–0.4 W/m^{2}K) or insulated roofs (0.15-0.25 W/m^{2}K). Consequently, there is a growing interest in highly insulating materials, such as aerogels, for use in buildings to reduce energy consumption by reducing heat losses through the building envelope, notably windows (Khaled and Ghosh, 2023).

Aerogel is a low-density, nanostructured porous material with exceptionally low thermal conductivity (Cuce *et al.*, 2014b). This makes them promising candidates for a wide range of applications, including thermal insulation in buildings, as shown in Figure 1. Aerogels' capacity to considerably reduce heat losses has spurred substantial interest in incorporating them into window designs. Aerogel glazing can offer high g-values, which is very advantageous in cold climates because it has a considerable impact on how much energy is used annually for space heating. Aerogels can be incorporated into glazing systems in two ways: As solid aerogel and as granular aerogel in the glazing interspace to boost high thermal resistance while maintaining high visible

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transmittance (Moretti *et al*., 2019). The incorporation of aerogels into building components, such as windows and insulation panels, has shown promising results in improving energy efficiency (Cuce and Cuce, 2016). Aerogels' unique combination of properties, including their status as the lightest solid material and their semi-transparent nature, positions them as a key material in contemporary architectural design, notwithstanding their currently elevated cost (Abraham *et al*., 2023).

As shown in Figure 1, aerogel can be integrated into different components of the building envelope, including facades, windows, and insulation panels. Among these, glazing applications have been most extensively studied due to the simultaneous requirements for thermal resistance and light transmittance, while facade renders and roof insulation remain at an earlier stage of experimentation. This highlights that although aerogel is multifunctional, its market readiness differs across application areas. The fenestration industry offers a diverse array of products exhibiting significant variation in thermal, optical, acoustic, and economic performance characteristics (Carroll *et al*., 2022). The most common types of novel glazing systems as an alternative to conventional double-glazed windows are photovoltaic (PV) glazing (Cuce *et al.*, 2016), vacuum glazing (Cuce and Riffat, 2015), multilayer glazing (Zavala *et al*., 2025), low-e coated glazing (Zhang *et al*., 2025a), Phase Change Material (PCM) glazing (Zhang *et al*., 2025b), Transparent Insulation Material (TIM) glazing (Li and Wu, 2025) and pond glazing (Cuce and Cuce, 2017). Furthermore, cutting-edge technologies like chromogenic glazing (Teixeira *et al*., 2024), self-cleaning glazing (Cuce and Cuce, 2019), and light-guiding and shading glazing (Lu, 2024) are also available on the market. When the thermal performance assessment of glazing systems is discussed, the parameter that is commonly utilised in literature is the U-value. The U-value of a window measures how well it conducts heat. It indicates the rate at which heat transfers through the window, including the glass, frame, and any spacers. The U-value of single glazing is about 5 W/m^2K, whereas it is 1.6-3.0 W/m^2K for double glazing, depending on inert gas, 0.6-1.2 W/m^2K for triple glazing or low-e glass with gas fill and <0.8 W/m^2K for high-performance windows. An illustrative comparison of the most common glazing types in the market is shown in Figure 2.

The g-value (also known as Solar Factor or Total Solar Energy Transmittance) of glazing systems refers to the total fraction of solar energy (direct and indirect) that enters through the glazing and contributes to indoor heating (Rosti *et al*., 2025). It includes direct solar transmittance, the part of solar radiation that directly passes through the glass, and secondary heat transfer, the part absorbed by the glass and re-emitted inward as longwave radiation. The g-value of single glazing is about 0.80-0.95, whereas it is 0.50-0.80 for double glazing, depending on coatings, 0.30-0.60 for triple glazing or low-e glass with gas fill and <0.50 for high-performance windows. Smart glazing technologies that are responsive to external stimuli have attracted considerable attention. These technologies can dynamically adapt their properties to control heat gain and light transmission. Smart glazing dynamically alters its optical and thermal characteristics to reduce reliance on mechanical air conditioning systems, particularly in hot regions, and to react to environmental changes (Feng and Ma, 2025a). Glazing systems with adjustable thermal and optical characteristics are required because improving only the glazing system's thermal transmittance is insufficient to lower its primary energy usage successfully after a certain point, and extra measures are required to efficiently prevent excessive solar radiation from entering the space (Abdelsamie *et al.*, 2025). Aerogel glazing has a solar transmittance of about 0.20-0.35 for a thickness of 15 mm for the basic monolithic silica aerogel created as part of the European projects. Table 1 illustrates the comparison of glazing technologies, including aerogel glazing, in terms of g-value. Aerogel glazing typically has a low g-value (~0.30 in real practice). This means less solar radiation enters the building, which is a disadvantage in cold climates, but beneficial in hot climates or south-facing façades with excessive solar gain. On the other hand, the U-value for aerogel glazing can be as low as 0.2 $W/m^2 \cdot K$, much lower than traditional glazing systems on the market. The exceptionally low thermal conductivity (~0.010-0.013 W/mK) of silica aerogel dramatically improves insulation, reducing heat loss. Aerogel glazing systems can be designed for different purposes with ultra-low U-value features, which is ideal for energy-efficient building envelopes (Gu and Ling, 2024).

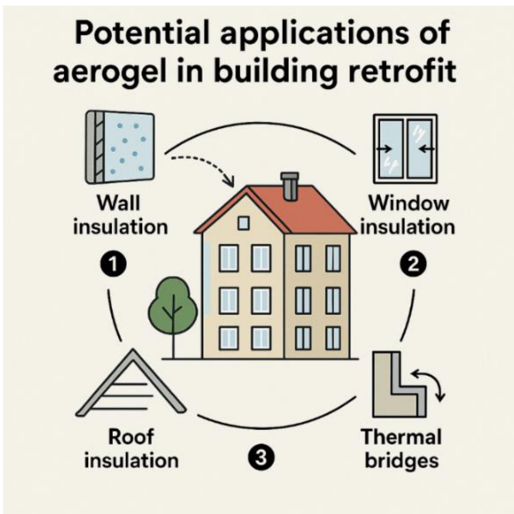

Fig. 1: Potential applications of aerogel in building retrofit

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Figure 2 and Table 1 collectively demonstrate the dual influence of U-values and g-values on glazing performance. While a low U-value reduces conductive heat losses, an excessively low g-value can diminish passive solar heating, which is disadvantageous in colder climates but beneficial in warmer regions. Aerogel glazing achieves an optimal balance by offering very low U-values with moderately reduced g-values, making it suitable for retrofitting in hot-arid or mixed climates, though less advantageous in high-latitude regions where solar gains are desirable.

Why Aerogel Glazing

Aerogel glazing represents a next-generation solution for enhancing the thermal and optical performance of building envelopes. Its unique combination of ultra-low U-value, low g-value, diffuse daylight transmission, and fire safety makes it particularly well-suited for use in energy-efficient facades, skylights, and retrofitted glazing applications (Tan *et al.*, 2025). As the construction industry continues to prioritise low-carbon and high-performance solutions, aerogel glazing is poised to play a key role in meeting both regulatory targets and occupant expectations in modern buildings. There are various reasons why aerogel is at the forefront compared to other alternatives as a multifunctional and thermal super insulation material.

Exceptional Thermal Insulation Performance

Aerogel glazing systems are emerging as one of the most promising technologies for achieving high thermal insulation in buildings. Silica aerogels possess an extremely low thermal conductivity ranging from 0.013 to 0.018 W/mK, making them one of the best-known solid insulating materials (Marof and Šiller, 2025). When integrated into glazing units, aerogels enable ultra-low U-values, sometimes as low as 0.2-0.5 W/m^2K. This performance is significantly superior to conventional double glazing ($U \approx 2.7$-3.3 W/m^2K) and even most triple glazing systems ($U \approx 1.0$-1.8 W/m^2K). This substantial reduction in thermal transmittance directly contributes to minimised heat loss in winter and improved thermal comfort throughout the year.

Controlled Solar Heat Gain and Low G-Value

In addition to its thermal insulation capacity, aerogel glazing offers excellent control over solar heat gain. With typical g-values in the range of 0.20 to 0.30, aerogel units effectively reduce the transmission of solar radiation into indoor spaces (Merli *et al.*, 2025). While this may limit passive solar heating potential in colder climates, it becomes highly advantageous in regions with high cooling loads or in buildings with large glazed facades exposed to direct sunlight. The reduction in solar gain not only contributes to occupant comfort but also decreases reliance on mechanical cooling systems, thus lowering energy demand during summer months.

Balanced Daylighting Through Diffuse Light Transmission

Unlike conventional glazing, which may allow direct light transmission and glare, aerogel-filled units offer high levels of diffuse light transmission. Translucent aerogel panels can transmit between 40 to 80% of visible light, depending on thickness and formulation (Gomaa *et al.* 2025). This diffused daylight eliminates harsh shadows and improves visual comfort, making aerogel glazing particularly effective in skylights, atriums, and facade systems where controlled natural lighting is essential. The soft illumination provided by aerogel contributes to occupant well-being while supporting daylight-based energy savings strategies.

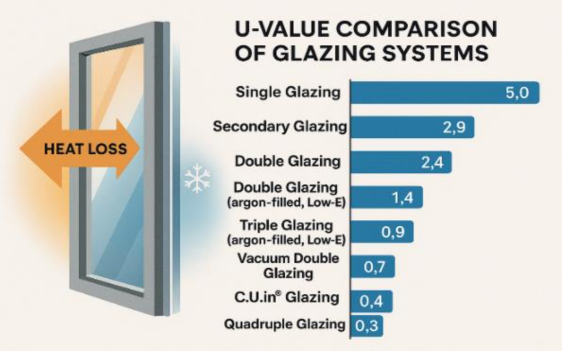

Fig. 2: Thermal insulation performance of different glazing products based on U-value

Table 1: Comparison of various glazing technologies in terms of g-value

Glazing type	Typical g-value range	Remarks
Single Glazing	0.80 – 0.90	Almost no solar control Maximum solar gain
Double Glazing	0.60 – 0.75	Varies depending on coatings and gas fill
Triple Glazing	0.50 – 0.65	More layers reduce solar gain
Low-E Glazing	0.30 – 0.60	Strong IR reflection, varies with coating
Vacuum Glazing	0.20 – 0.40	Lower heat and solar transfer
Aerogel Glazing	0.20 – 0.35	Aerogels absorb/diffuse sunlight Very low g-values
Pond Glazing	0.10 – 0.25	Water absorbs heat well
PV Glazing	0.10 – 0.30	Most solar energy is absorbed and converted to electricity
PCM Glazing	0.25 – 0.40	Absorbs and delays solar gain based on phase change
TIM Glazing	0.25 – 0.45	Transparent insulation materials allow light, resist heat flow

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Lightweight and Structurally Compatible

Another important advantage of aerogel glazing is its lightweight nature. Composed of over 90% air by volume, silica aerogel is significantly lighter than most conventional glass or composite materials Feng *et al.*, 2025b). This characteristic reduces the structural load on building facades and enables the use of slim-profile frames without compromising thermal performance. As a result, aerogel glazing can be easily integrated into curtain walls, retrofitted window systems, or bespoke architectural designs where weight is a constraint.

Fire Safety and Durability

Safety and longevity are also central to the appeal of aerogel-based glazing solutions. Silica aerogels are inherently non-combustible and remain stable at temperatures exceeding 500°C, offering superior fire resistance compared to many polymer-based insulation materials (Sun *et al.*, 2025). Additionally, aerogels are hydrophobic, UV-stable, and chemically inert, ensuring long-term performance in a wide range of environmental conditions. These properties make aerogel glazing suitable not only for residential and commercial buildings but also for specialised applications in industrial or heritage settings where fire safety and material stability are critical.

Compatibility With Sustainable Building Certifications

Aerogel glazing aligns well with the requirements of modern green building standards and energy efficiency certifications. Its ability to significantly reduce heat transfer and moderate solar gain supports compliance with Passive House, Net-Zero Energy Building (NZEB), and Nearly Zero-Energy Building (nZEB) performance criteria (Alassaf, 2024). Moreover, the daylighting benefits and material durability contribute to LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment's Environmental Assessment Method), and WELL rating systems under categories such as energy optimisation, indoor environmental quality, and material resource efficiency. An overview of why aerogel glazing is shown in Figure 3.

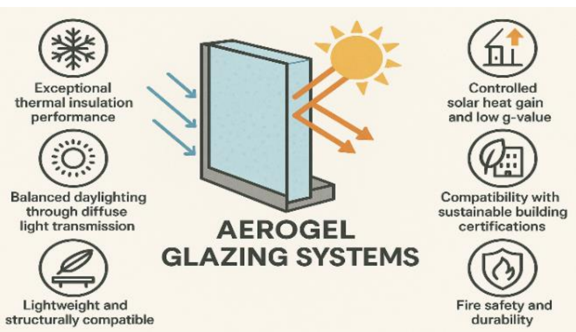

Fig. 3: Multifunctional benefits of aerogel glazing

Methodological Framework

This study follows a structured approach as a critical evaluation rather than presenting new experimental or analytical models. Relevant literature was systematically identified through databases such as Scopus Web of Science, and Science Direct by using keywords including “aerogel glazing,” “advanced glazing systems,” “retrofit insulation,” and “thermal superinsulation.” The search primarily focused on peer-reviewed journal articles, conference papers, and experimental studies published between 2005 and 2025 that reported quantitative performance values. From these studies, quantitative performance indicators including thermal conductivity, U-value, g-value, visible light transmittance, and acoustic insulation were extracted. Reported values were carefully compared across multiple sources, and when ranges were provided, representative values were selected to construct comparative tables. Simulation results cited in this manuscript are derived from published building performance analyses, which include clearly documented assumptions and boundary conditions in their original sources. Instead of replicating these simulations, the present study integrates and contrasts their outcomes in order to identify converging results and highlight inconsistencies where they exist. The methodological focus is thus not on reproducing laboratory measurements but on critically assessing their validity, limitations, and applicability across different climatic and operational contexts. Through this process, aerogel glazing is benchmarked against conventional and alternative glazing systems, and its techno-economic feasibility, long-term energy savings, and potential drawbacks are examined. This approach ensures that the manuscript provides not only a synthesis of available data but also an evaluative framework that addresses both strengths and limitations, consistent with its positioning as a critical evaluation.

Results and Discussion

Retrofit Applications of Aerogel Glazing and Thermal Insulation Performance

Aerogel glazing has emerged as a high-performance material in the retrofit of building envelopes, offering ultra-low thermal conductivity and high optical transparency. Recent studies have emphasised the unique advantages of silica aerogel when integrated into window systems for retrofitting purposes. For instance, silanised cellulose-based aerogels have demonstrated visible light transmittance exceeding 97% with thermal conductivities below 0.015 W/mK, outperforming traditional insulating materials (Zhao *et al.*, 2023). These aerogels can be incorporated into multilayer Insulating Glass Units (IGUs), preserving daylight autonomy while significantly reducing heating and

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cooling demands. Such characteristics make aerogel glazing particularly suited for heritage building retrofits where visual clarity and thermal comfort must be balanced (Ganobjak *et al.*, 2023).

In practical retrofit scenarios, recent research has provided robust evidence of the benefits of aerogel glazing systems in hot-arid climates. Mohamed *et al.* (2023) demonstrated through combined field measurements and building energy simulations in Aswan that aerogel-filled glazing systems can reduce indoor air temperatures by 0.3–1.9°C compared to conventional glazing and achieve up to 26.3% reductions in annual cooling energy demand, with payback periods as low as 4.1 years. Their results further indicated that building orientation and courtyard aspect ratio significantly influence the effectiveness of aerogel glazing, with south-facing façades and elongated courtyard geometries offering the greatest savings. Similarly, (Abdelrady *et al*., 2021) investigated nanogel glazing integrated into residential buildings in New Aswan City. Their findings showed that the use of aerogel-filled double glazing achieved approximately 11% annual energy savings compared to clear glass windows, while more advanced multilayer nanogel glazing systems reduced energy consumption by up to 26%. When combined with insulated walls using polystyrene foam, the integrated retrofit strategy yielded a total improvement of 47.6% in energy efficiency. Together, these studies confirm that aerogel glazing not only enhances thermal comfort and reduces reliance on mechanical cooling but also provides attractive payback periods and scalable solutions for energy-efficient building retrofits in hot-arid regions. Beyond windows, aerogel-based insulation materials have been used in retrofit applications such as renders and composite boards, leading to life-cycle energy savings of €60/m^2 over a 30-year span (Haugbak and Talic, 2021). These findings underscore aerogel's potential to transform energy performance while maintaining aesthetic and functional integrity. A critical evaluation of these results, however, indicates that the reported benefits are strongly dependent on climatic conditions, façade orientation, and material costs. Whilst aerogel glazing provides substantial improvements in thermal resistance, its relatively low g-value can limit passive solar heating in cold climates, and its high production cost remains a barrier for widespread adoption. These aspects highlight that aerogel glazing is not a universally optimal solution, but rather a context-dependent technology whose advantages must be weighed against economic and environmental constraints. A brief summary of aerogel glazing as a retrofit solution in terms of different performance metrics is given in Table 2.

Cost Assessment of Aerogel Glazing

Aerogel glazing is at the central to modern architectural interests (Dicka *et al.*, 2024). However, compared to the conventional glazing systems and other novel alternative fenestration products in the market, cost still remains a challenge for aerogel glazing (Cuce *et al.*, 2014a). The total cost of aerogel glazing systems includes material cost, manufacturing and processing cost, installation cost and transportation cost. Aerogel itself is an expensive material, costing around €150-€400/m^2 depending on the type (monolithic vs granular), thickness, and source. Specialised fabrication techniques, including vacuum sealing and lamination, are required in addition to production costs. It requires skilled labour and careful handling due to the fragility and custom dimensions of the units. Aerogel panels are lightweight but fragile, increasing logistics costs due to protective packaging requirements.

Table 2: Comparison of aerogel glazing with conventional glazing as a retrofit solution in terms of different performance metrics

Performance Metric	Before Retrofit (Typical Glazing)	After Retrofit (Aerogel Glazing)	Source
Thermal Conductivity (W/mK)	0.7–1.0	0.013–0.020	(Buratti *et al*., 2017; Jelle *et al.,* 2010)
U-Value (W/m^{2}K)	2.6–3.0	0.3–0.5	(Jelle *et al.*, 2010; Baetens *et al*., 2010)
Solar Heat Gain Coefficient (g-value)	0.6–0.7	0.2–0.4	(Buratti *et al*., 2017; Reim *et al*., 2005)
Visible Light Transmittance (%)	70–90	5.8–37.3	(Leung *et al*., 2020)
Cooling Load Reduction (%)	—	Up to 8.5%	(Leung *et al*., 2020)
Annual Energy Savings (%)	—	20-45% (climate-dependent)	(Buratti and Moretti, 2012)
Sound Reduction (dB)	28–34	31–37	(Cotana *et al*., 2014)

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Cost components and the estimated cost range of aerogel glazing are shown in Table 3. To assess competitiveness, aerogel glazing is compared to other glazing systems in Table 4 in terms of cost and thermal performance.

Aerogel is an eco-friendly and non-combustible thermal superinsulation solution, as shown in Figure 4, for highly efficient building envelopes. Furthermore, Fig. 4 and Table 4 underline the main barrier to large-scale adoption of aerogel glazing: Its high initial cost compared to conventional alternatives. However, policy instruments such as EU directives on nZEB and national retrofit incentive schemes are expected to accelerate market uptake by offsetting upfront investment through subsidies and tax credits. Thus, while cost currently limits real-world implementation, alignment with regulatory frameworks and carbon reduction targets may enhance the economic attractiveness of aerogel glazing in practice. Although the initial cost of aerogel glazing is significantly higher, its potential to reduce heating and cooling energy demand can lead to long-term savings. For example, in cold climates, building simulations show that aerogel glazing can reduce annual heating demand by 15-25% compared to triple glazing, translating into notable energy cost reductions over a 30-50 year lifespan. A simplified lifecycle cost analysis shows that the payback period of aerogel glazing is about 8-15 years, depending on climate zone and energy prices. In addition, CO_2 savings is up to 50 kg CO_2/m^2/year for buildings replacing standard double glazing. Currently, limited production volumes keep aerogel glazing costs high. However, ongoing R&D efforts, improved manufacturing methods, and government incentives for nZEB are expected to reduce costs. Pilot programs in EU-funded demonstration projects show up to 30% cost reductions when aerogel glazing is used at scale.

Limitations and Challenges of Aerogel Glazing

Despite their remarkable thermal and optical properties, aerogel glazing systems face several challenges that constrain their large-scale adoption. One of the main drawbacks is optical haze, particularly in granular aerogels, which reduces visual clarity and may compromise daylighting quality in highly transparent applications. Fragility is another concern, since aerogel materials are mechanically brittle and require special handling and protective encapsulation during manufacturing and installation. This adds to both processing complexity and cost. Moreover, the long-term durability of aerogels remains under investigation; although hydrophobic treatments enhance moisture resistance, issues such as dust accumulation, UV exposure, and potential shrinkage over decades can impair performance. Another key barrier is economic feasibility. Even though costs are expected to decline with mass production and technological improvements, aerogel glazing is still considerably more expensive than conventional and even some advanced glazing systems, limiting its current market penetration. Finally, manufacturing scale-up poses technical and logistical challenges, as producing large, defect-free aerogel panels with consistent optical and mechanical properties is not yet fully standardised. Addressing these limitations through material innovation, encapsulation strategies, and cost reduction efforts will be essential for mainstream integration of aerogel glazing in energy-efficient building designs.

Fig. 4: Non-combustible and eco-friendly feature of aerogel

Table 3: Cost assessment of aerogel glazing

Cost Component	Estimated Range (€/m^2)
Aerogel Material	150 – 400
Processing & Assembly	60 – 120
Installation	20 – 50
Packaging & Delivery	10 – 30
Total	240 – 600

Table 4: Cost comparison of aerogel glazing with alternative glazing systems

Glazing Type	U-value (W/m^{2}K)	Solar heat gain (g-value)	Cost (€/m^2)
Single Glazing	~5.0	~0.85	20 – 40
Double Glazing	~2.7 – 3.0	~0.65	50 – 100
Low-E Double Glazing	~1.1 – 1.6	~0.5 – 0.7	70 – 130
Vacuum Glazing	~0.6 – 0.8	~0.3 – 0.5	200 – 350
Aerogel Glazing	~0.3 – 0.5	~0.2 – 0.4	240 – 600

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Conclusion

Aerogel glazing systems represent a significant advancement in high-performance building envelope technologies, offering a unique combination of exceptional thermal insulation, optical transparency, and environmental durability. The consistently reported ultra-low thermal conductivity and U-values of aerogel glazing, as evidenced in earlier sections, underpin its ability to minimise heat loss through windows and significantly improve energy efficiency in both new constructions and retrofits. Unlike conventional glazing, aerogel-integrated units provide high visible light transmittance with a remarkably low solar heat gain coefficient (g-value), ensuring a balance between daylighting and solar control. In addition to their energy-saving potential, aerogel glazing contributes to enhanced occupant comfort, reduced HVAC loads, and long-term sustainability by meeting the performance criteria of green building certifications. Despite challenges related to cost, optical clarity, and large-scale manufacturability, continuous innovations in aerogel synthesis and encapsulation techniques are gradually addressing these limitations. Aerogel glazing systems stand out as a transformative solution in the pursuit of low-carbon, thermally resilient, and daylight-optimised building designs. Their adoption is poised to grow, particularly in climate-conscious architecture and retrofitting strategies aimed at meeting stringent energy efficiency targets.

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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