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# IMPACT OF ENERGY EFFICIENT WINDOW SYSTEMS ON THE FINANCIAL REDUCTION OF ENERGY CONSUMPTION IN BUILDINGS

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**Abstract.** Windows constitute one of the most critical components of the building envelope because they significantly influence heat transfer, solar gains, daylight penetration, and, consequently, the overall energy performance of buildings. As global efforts toward decarbonization and sustainable construction intensify, the development and implementation of energy-efficient window technologies have become increasingly important. Recent advances in glazing materials, surface coatings, and adaptive technologies have created new opportunities to reduce energy consumption while improving indoor environmental quality and occupant comfort. The subject of this study is advanced energy-efficient window systems and their thermal and operational performance in contemporary buildings. The research focuses on innovative glazing technologies, including triple and vacuum glazing, transparent aerogel insulation, low-emissivity coatings and films, smart electrochromic and thermochromic glazing systems, and optimized framing materials. The purpose of the study is to assess the effectiveness of advanced window technologies in improving building energy efficiency, reducing thermal losses, and enhancing climate responsiveness. The study also seeks to identify the most economically and technically feasible solutions for both new construction and the retrofitting of existing buildings. The methodology of the research is based on a systematic review and comparative analysis of peer-reviewed scientific publications devoted to high-performance window technologies. The reviewed studies were evaluated according to several criteria, including thermal transmittance (U-value), solar control performance, adaptability to different climatic conditions, and applicability in building retrofit projects. A comparative approach was employed to identify the advantages and limitations of individual technologies and to examine their potential contribution to reducing building energy consumption. The findings indicate that vacuum glazing and aerogel-based transparent insulation systems demonstrate the lowest thermal transmittance values and provide superior thermal performance. Smart electrochromic glazing exhibits the highest level of adaptability and solar control efficiency in regions characterized by mixed climatic conditions. At the same time, low-emissivity coatings and films remain the most cost-effective and practically applicable solutions for improving the energy performance of existing buildings due to their relatively low installation costs and significant impact on reducing heat losses. The conclusions of the study suggest that advanced window technologies can reduce building energy consumption by approximately 15–45%, depending on climatic conditions, building characteristics, and selected technological solutions. The research also reveals a lack of integrated cross-technology assessment frameworks capable of simultaneously accounting for material performance, climate responsiveness, and building design parameters. The study concludes that the adoption of energy-efficient window systems should be considered a fundamental component of low-carbon building design and sustainable urban development strategies.

**Keywords:** Energy-efficient windows, building energy consumption, vacuum glazing, triple glazing, low-emissivity coatings, aerogel glazing, electrochromic smart windows, building envelope optimization, solar heat gain control, sustainable building design.

**JEL Classification:** Q40, Q48, D61, O33

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## 1. Introduction

The operational demand in the global building sector is mostly due to space heating, cooling, and mechanical ventilation. The building envelopes windows offer a paradox. Architecturally, they are attractive for providing daylight and people's view. Thermally, they are expensive because windows transfer heat at a faster rate than other materials. Standard glazing systems are especially bad in transmitting heat in cold climates and are worse in providing solar heat gains in warm climates. Exciting developments in material science and façade engineering, however, have changed this bleak picture in the last decade. Advanced triple glazing systems and vacuum glazing systems have, for the first time, provided high thermal resistance (Gunderson, Louie & Cort, 2024; Wakili et al., 2021) and low U-values (Peng, et al. 2024; Qiu, Yang & Dong, 2025) because vacuum systems have no convective heat transfer. Advanced spectral control systems provide low-emissivity (Low-E) laminated coatings to decrease radiative heat exchange (Moghaddam, et al. 2021; Nur-E-Alam et al., 2024).

Recent advancements in adaptive glazing, such as electrochromic and thermochromic glazing, have incorporated dynamic solar modulation capabilities (Teixeira et al., 2024; Wu et al., 2023). These technologies provide real-time management of solar heat gain and daylight control and may balance thermal performance and occupant experience. New materials, such as transparent aerogels, provide enhanced thermal insulative properties while offering good visible transmission (Carroll et al., 2022; Du, Wang & Li, 2024) (See Figure 1).

Even with these advancements and materials, research still predominantly examines glazing systems in isolation from one another and often from a single climate or a single case, and intertechnology comparisons are still incomplete. Furthermore, assessments often neglect architectural considerations, such as window-to-wall ratios and edge thermal bridging, which are critical in determining overall energy performance (Liu et al., 2025; Zhang, Omer & Hu, 2025).

This paper therefore seeks to:

1. Systematically synthesize current research on advanced energy-efficient window systems.
2. Critically compare their quantified impacts on building energy consumption.
3. Identify methodological and analytical gaps in existing studies.
4. Propose an integrative comparative framework linking technology, climate, and architectural design.

The central argument advanced here is that optimal window performance cannot be determined solely by material-level thermal metrics. Instead, energy efficiency emerges from the interaction between glazing properties, climatic conditions, frame performance, and architectural configuration.

## 2. Literature Review

Innovation in window technologies shows growing Recognition that fenestration systems play a pivotal role in the energy performance of buildings. Research is moving on from standard double glazing towards more sophisticated multi-layer, vacuum insulating, spectral selectivity, and even smart glazing systems. There is more focus on the optimization of frames and the edge effects, as well as on design distribution parameters, e.g., the window to wall ratio, of the building's overall envelope. This critical synthesis seeks to review and integrate the literature in these seven related areas.

### 2.1 Advanced Multi-Pane and Triple Glazing Systems

In cold and temperate climates in particular, triple glazing has become a popular high-performance baseline solution. Triple-pane systems reduce convective and conductive heat transfer by adding an extra insulating cavity when compared to double glazing. However, because of edge losses and spacer effects, declared thermal transmittance (Ug-values) frequently deviates from measured performance, as Wakili et al. (2021) show. Thermal bridging at the perimeter can seriously compromise nominal insulation improvements, according to their comparison of measured and declared values. This result emphasizes how crucial it is to assess glazing systems as cohesive units as opposed to discrete glass layers.

Gunderson et al. (2024) carried out laboratory and field validation of thin triple-pane windows in residential buildings, building on these discoveries. Their research verified quantifiable decreases in the need for heating while preserving a suitable level of daylight transmission. Crucially, the authors also looked at cost-performance ratios, emphasizing the need to balance the financial viability of incremental insulation gains (Gunderson, Louie & Cort, 2024). The weight and installation issues with traditional triple glazing were addressed by the thin triple-pane arrangement, indicating that material optimization can lessen practical constraints.

When taken as a whole, these studies present triple glazing as a developed but still developing technology. However, when adding more pane layers results in weight and cost increases without corresponding decreases in U-values, diminishing returns become apparent. Interest in vacuum glazing solutions has increased as a result of this restriction.

### 2.2 Vacuum Glazing and Ultra-Low Thermal Transmittance Technologies

Because vacuum glazing (VIG) virtually eliminates convective heat transfer within the cavity, it represents a significant technological advancement. The

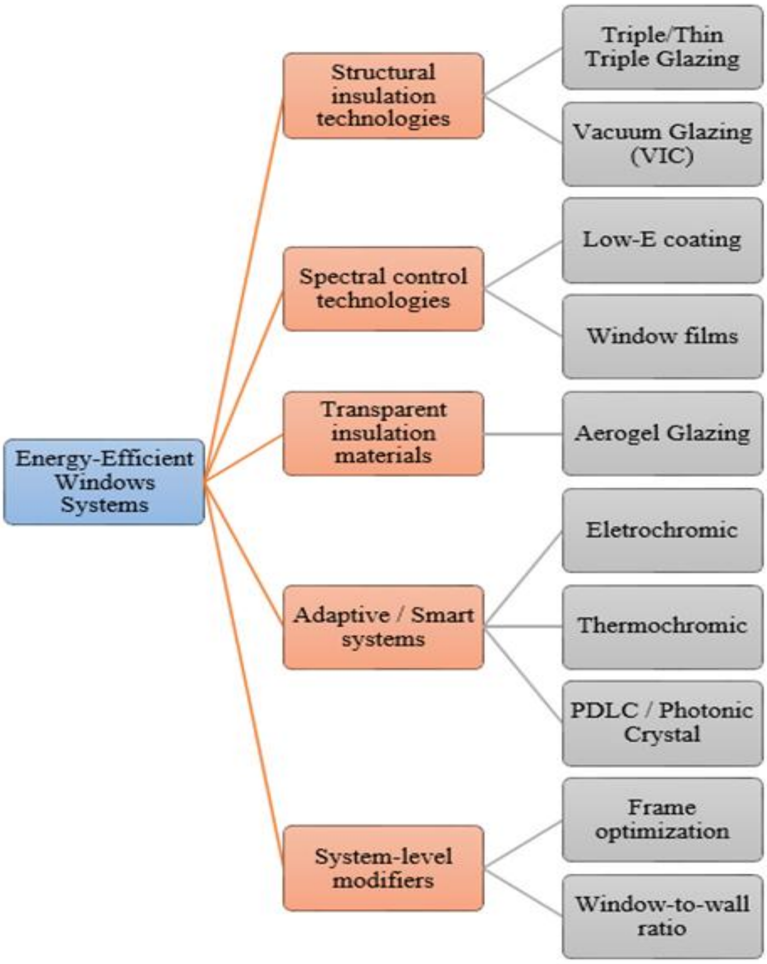

**Figure 1. Taxonomy of advanced energy-efficient window technologies and system-level modifiers synthesized from the reviewed literature**

*Source: author's development*

production, modeling, and assessment procedures for high-insulation vacuum glazing intended for low-carbon buildings are described by Peng et al. (2024). Their results show remarkably low U-values attained without excessive thickness, providing benefits in façade retrofits and new construction where space constraints are crucial.

This analysis is expanded upon by Qiu et al. (2025), who assess vacuum glazing in subtropical retrofit applications. Their study incorporates indoor thermal comfort assessment in addition to thermal metrics, showing that VIG lowers cooling loads and stabilizes indoor temperatures (Qiu, Yang & Dong, 2025). A larger trend in building science toward integrated environmental performance evaluation is reflected in this dual focus on energy performance and occupant comfort.

Vacuum glazing's main benefit is its capacity to outperform traditional multi-pane systems while preserving thin profiles. However, issues with cost, manufacturing complexity, long-term vacuum stability, and durability still need to be addressed. Therefore, even though VIG offers better insulation performance, its widespread adoption depends on technological advancement and lifecycle cost justification.

## 2.3 Low-Emissivity Coatings and Window Films: Spectral Control Strategies

Low-emissivity (Low-E) technologies use spectrally selective coatings to decrease long-wave radiative heat transfer. Low-E coatings change surface emissivity without significantly adding weight or thickness, in contrast to structural glazing modifications.

For retrofit applications, Nur-E-Alam et al. (2024) created laminated Low-E coated glass. Improved thermal performance without sacrificing optical clarity is indicated by their construction and physical performance analysis. The laminated structure increases its applicability in existing buildings and improves durability.

Low-E window films were examined by Moghaddam et al. (2021) as a potential retrofit for a historic stone building in a cold climate. Their findings show that while maintaining the architectural integrity of historic façades, films considerably lower heating demand. This finding is especially important in situations where replacing structural windows is not practical.

Huang et al. (2024) assessed how window films affected the indoor environment and the amount of electricity used by air conditioners. Their empirical findings support the climatic sensitivity of Low-E performance by demonstrating significant cooling energy reductions in warm climates. Additionally, when Low-E windows are paired with radiative roof systems, Jia et al. (2024) showed synergistic energy savings, indicating that envelope strategies work best in integrated configurations.

Therefore, Low-E technologies offer scalable and affordable solutions, particularly for retrofit markets. However, their static spectral characteristics restrict seasonal flexibility, resulting in trade-offs between summer solar control and winter heat retention.

### 2.4 Aerogel-Based Transparent Insulation Materials

Transparent aerogels have garnered interest because of their exceptionally low heat conductivity and ability to transmit light. Aerogel window designs with aesthetic integration that strike a balance between insulation performance and architectural appearance were proposed by Carroll et al. in 2022. The scholars have demonstrated how aerogels may be able to balance daylighting needs with thermal efficiency.

By creating energy-efficient windows made of transparent aerogels, Du et al. (2024) expanded on this idea. The microstructural features that allow for high insulation performance while preserving visible light transmission are highlighted in their work. Aerogel glazing diffuses daylight, which is significant because it lessens glare and may improve visual comfort (Du, Wang & Li, 2024).

Despite these benefits, problems with cost, large-scale production, moisture sensitivity, and mechanical strength still exist. Aerogel systems are a promising passive solution from a research standpoint that could either rival or supplement vacuum glazing technologies. There are still few comparative lifecycle analyses between vacuum and aerogel systems, which is a significant research gap.

### 2.5 Smart and Adaptive Glazing Technologies

Variable solar transmittance is introduced by dynamic glazing technologies via photonic, thermochromic, or electrochromic mechanisms. Smart windows, in contrast to static Low-E systems, can modify optical characteristics in response to control inputs or environmental stimuli.

The development of thermochromic and electrochromic materials from laboratory materials research to building-scale applications is thoroughly reviewed by Wu et al. (2023). Their analysis highlights how electrochromic technologies are becoming more sophisticated, especially in commercial office buildings (Wu et al., 2023).

In a simulation-based assessment of electrochromic glazing in an office space, Teixeira et al. (2024) showed improvements in indoor comfort and decreases in cooling demand. Yeh et al. (2025) evaluated the impact of electrochromic film on indoor environmental quality and confirmed advantages in terms of thermal and visual conditions.

Ghosh (2023) studied the combination of switchable transparency and insulation in vacuum-integrated switchable polymer dispersed liquid crystal (PDLC) glazing. A growing trend toward multipurpose window systems is reflected in this hybridization.

A novel smart window that uses photonic crystal structures for spectral control was proposed by Zaky and Aly (2022). By introducing nanostructured materials with selective wavelength manipulation capabilities, their work pushes the conceptual limits of smart glazing (Zaky & Aly, 2022).

Although adaptive glazing offers seasonal flexibility and possible energy savings, there are obstacles due to system complexity, control requirements, and higher initial costs (Lee et al., 2023). Performance benchmarking is further complicated by the paucity of studies that directly compare smart glazing with high-performance static alternatives under uniform conditions.

### 2.6 Frame Materials, Edge Effects, and Thermal Bridging

Optimal window performance is not guaranteed by glazing upgrades alone. A thorough analysis of window frame materials in China was carried out by Wang et al. (2024), with a focus on material selection, cavity insulation, and geometry optimization. According to their findings, overall window U-values can be greatly impacted by frame conductivity (Wang et al., 2024).

The effect of edge heat loss on triple-glazed units was further emphasized by Wakili et al. (2021). Gains from advanced glazing technologies may be offset by thermal bridging at spacers and frames. Frame-glass interactions must therefore be taken into account when evaluating windows holistically.

In comparison to glazing innovations, this field is still relatively understudied, indicating a research imbalance that favors glass technologies over supporting structural components.

### 2.7 Architectural Configuration and Window-to-Wall Ratio

The parameters of façade design are inextricably linked to window performance. The seasonal effects of window-to-wall ratio (WWR) and glazing combinations in office buildings were examined by Liu et al. (2025). According to their findings, the ideal WWR varies depending on the season and climate, and too much glazing increases heat gains and losses.

According to Zhang et al.'s (2025) investigation into window size modification in residential buildings in the UK, dimensional changes can have a substantial impact on annual energy consumption. The usefulness of multi-criteria decision frameworks was demonstrated by Lee et al. (2023), who used hierarchical energy simulation to optimize window glass design in South Korean office buildings.

Gomaa et al. (2025) highlighted climate-specific performance variation in a comparative study of advanced glazing technologies in Jeddah City. Their results support the idea that geographic context and glazing selection are inextricably linked.

Together, these studies show that material characteristics and architectural design interact to produce window system efficiency.

**Synthesis and Identified Gaps**

The literature demonstrates rapid technological advancement across multiple domains: structural insulation (triple and vacuum glazing), spectral control (Low-E coatings), passive insulation (aerogels), and dynamic modulation (electrochromic systems). This is especially visible in the discussion of the dominant heat transfer mechanisms (Table 1).

However, research fragmentation persists. Most studies focus on single technologies within localized contexts, limiting cross-technology comparability.

Three major gaps are evident:

1. Lack of standardized comparative modeling across technologies under identical climatic conditions.
2. Limited lifecycle cost and durability assessments.
3. Insufficient integration of glazing performance with frame optimization and façade design variables.

Addressing these gaps requires integrative analytical frameworks capable of synthesizing material science, climate modeling, and architectural design considerations.

## 3. Methodology

This study synthesizes and critically assesses twenty peer-reviewed publications on advanced energy-efficient window technologies using a structured qualitative meta-analytical design. The methodological framework was created to maintain analytical rigor while guaranteeing systematic comparison across diverse studies.

Firstly, all of the chosen studies were divided into six technological domains: (1) low-emissivity coatings and films; (2) vacuum glazing systems; (3) aerogel-based transparent insulation; (4) triple and multi-pane glazing; (5) smart and adaptive glazing technologies; and (6) frame optimization and façade configuration strategies. Thematic structuring and cross-technology comparison were made possible by this classification.

Secondly, we focused on the key performance indicators found in the literature review. Thermal transmittance (U-value), solar heat gain coefficient (SHGC), reported percentage reductions in heating and cooling energy demand, indoor environmental quality indicators, and, when available, cost-performance metrics were among were found to be the most important KPI mentioned in the previous studies. Climate context, building typology, and simulation versus empirical validation approaches received special attention.

Thirdly, to assess technology performance across climate zones (cold, temperate, subtropical, and hot-arid), a comparative analytical matrix was built. This made it possible to identify patterns of performance convergence and divergence under different environmental circumstances (Figure 2).

Additionally, a critical evaluation of the methodological constraints in the reviewed literature was carried out. The analysis showed that the research design was fragmented and that there were few standardized cross-technology comparisons under the same boundary conditions.

This study's main contribution is to synthesize scattered findings into an integrative evaluation framework that connects architectural variables like window-to-wall ratio, material performance, climatic sensitivity, and retrofit applicability. The methodology offers an organized foundation for evidence-based window system selection in sustainable building design, going beyond isolated case studies.

## 4. Findings

To enhance cross-technology comparability, the key findings of the meta-analysis are synthesized in Table 2.

Table 1

**Comparative reduction of dominant heat transfer mechanisms across advanced glazing technologies**

| Technology | Conduction | Convection | Radiation | Solar Gain Control |
|---|---|---|---|---|
| **Triple glazing** | ↓↓ | ↓ | ↓ | ↓↓ |
| **Vacuum glazing** | ↓↓↓ | ↓↓↓ | ↓ | ↓↓ |
| **Low-E** | – | – | ↓↓↓ | ↓ |
| **Aerogel** | ↓↓↓ | ↓↓ | ↓ | Diffused |
| **Electrochromic** | – | – | ↓ | ↓↓↓ |

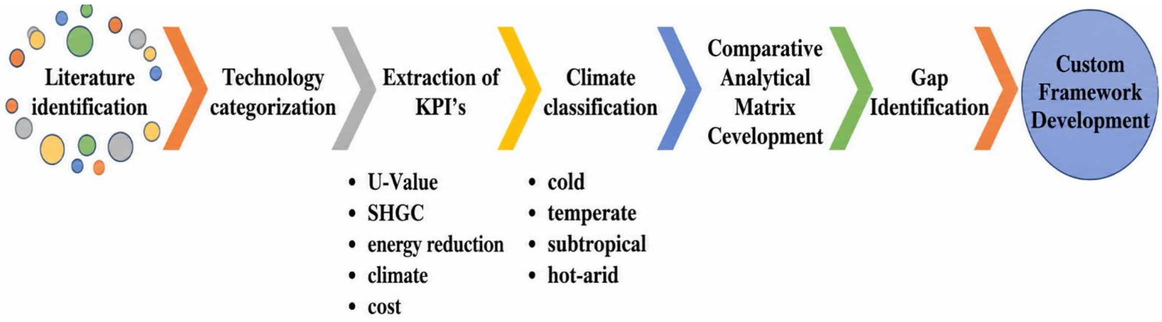

**Figure 2. Structured methodological workflow for cross-technology comparative synthesis**

*Source: author's development*

Table 2

**Comparative Performance of Energy-Efficient Window Technologies**

| Technology Type | Primary Performance Mechanism | Optimal Climate Context | Reported Energy Reduction Range* | Key Advantages | Key Limitations | Representative Sources |
|---|---|---|---|---|---|---|
| Triple / Thin Triple Glazing | Reduced conductive and convective heat transfer | Cold, temperate | 20–35% (heating-dominated cases) | Mature technology, validated performance, moderate cost | Increased weight, diminishing returns, edge losses | Wakili et al. (2021); Gunderson et al. (2024) |
| Vacuum Glazing (VIG) | Near-elimination of convection; ultra-low U-value | Cold, extreme climates | 30–45% | Very low U-values, thin profile | High cost, manufacturing complexity | Peng et al. (2024); Qiu et al. (2025) |
| Low-E Coatings / Films | Reduced long-wave radiation; SHGC control | Cold, warm, retrofit contexts | 15–30% | Cost-effective retrofit solution, scalable | Static performance (limited adaptability) | Moghaddam et al. (2021); Nur-E-Alam et al. (2024); Huang et al. (2024) |
| Aerogel Glazing | Ultra-low thermal conductivity; light diffusion | Cold, temperate | 25–40% (modeled scenarios) | High insulation + glare reduction | Cost, durability, commercialization barriers | Carroll et al. (2022); Du et al. (2024) |
| Electrochromic / Smart Glazing | Dynamic solar modulation; adaptive SHGC | Mixed, hot climates | 20–40% (cooling-dominated) | Seasonal adaptability, comfort improvement | Higher capital cost, control complexity | Teixeira et al. (2024); Yeh et al. (2025); Wu et al. (2023) |
| Window Films (Retrofit) | Solar control and emissivity reduction | Warm, retrofit applications | 15–25% | Minimal structural intervention | Limited insulation improvement | Moghaddam et al. (2021); Huang et al. (2024) |

The table consolidates performance characteristics, climatic suitability, reported energy reduction ranges, and implementation considerations derived from the reviewed studies.

The comparative analysis shows that no single technology can maximize energy efficiency in all situations; instead, performance depends on configuration and climate. Ultra-low U-values are crucial for reducing conductive heat loss in heating-dominated climates. Because vacuum glazing virtually eliminates convective transfer, it consistently exhibits the strongest heating reduction potential (Peng, et al. 2024). Theoretical performance gains are reduced by edge losses in advanced triple-pane systems, which offer significant but relatively modest improvements (Wakili et al., 2021).

Solar heat gain management becomes equally important in mixed or cooling-dominated climates. While dynamic electrochromic systems outperform static alternatives by modifying solar transmittance seasonally (Teixeira et al., 2024), static Low-E systems consistently reduce cooling energy demand (Nur-E-Alam et al., 2024). Smart glazing's ability to adapt is especially useful in regions with significant seasonal variability.

With its passive high insulation and lack of mechanical complexity, aerogel glazing occupies an intermediate position (Carroll et al., 2022). However, there are still financial barriers to its widespread implementation.

Crucially, a number of studies show that architectural design parameters like window-to-wall ratio can either amplify or counteract material-level improvements (Liu et al., 2025; Zhang, Omer & Hu, 2025). Therefore, energy savings of 15% to more than 40% result from integrated system design rather than just technology.

**Figure 3. Relative performance positioning of advanced window technologies across insulation and solar modulation dimensions**

*Source: author's development*

## 5. Discussion

The comparative synthesis of advanced window technologies shows that system adaptability, solar exposure, façade design, and climatic demand interact to produce energy efficiency results that are not solely based on material performance. Together, the reviewed studies demonstrate that dynamic modulation, solar heat gain control, and thermal transmittance reduction are three interrelated but separate performance mechanisms.

Reducing radiative and conductive heat transfer is still the main tactic in climates where heating is predominant. Vacuum glazing systems exhibit significant reductions in heating demand and consistently achieve the lowest U-values (Peng, et al. 2024 Qiu, Yang & Dong, 2025). Their thin profile makes them even more suitable for use in retrofit situations where façade depth is limited. However, the disparity between declared and measured values noted by Wakili et al. (2021) suggests that whole-unit integration and edge detailing play a major role in performance gains. This implies that in order to achieve the full theoretical benefits, technological advancements at the glass level must be matched by comparable advancements in spacer design and frame conductivity.

Because of their well-established manufacturing base and balanced cost-performance ratio, triple and thin triple-pane glazing systems (Gunderson, Louie & Cort, 2024) are still very relevant. They are a scalable solution that can consistently improve residential applications, even though their insulation potential falls short of vacuum glazing. From the standpoint of systems, they fall somewhere between ultra-high-performance vacuum systems and traditional glazing.

Performance priorities shift to controlling solar heat gains in cooling-dominated or mixed climates. Because they require little structural intervention, low-emissivity coatings and films (Huang et al., 2024; Moghaddam, et al. 2021; Nur-E-Alam et al., 2024) offer consistent reductions in cooling energy demand and are especially beneficial in retrofit scenarios. However, seasonal trade-offs result from their static spectral properties, as solar gains that are advantageous in the winter may be undesiredly limited.

By adding flexibility, dynamic glazing technologies overcome this constraint. Teixeira et al. (2024) and Yeh et al. (2025) evaluated electrochromic systems that show quantifiable cooling reductions while maintaining indoor environmental quality and daylight access. The growing maturity of thermochromic and electrochromic materials in building-scale implementation is further highlighted by Wu et al. (2023). Because fixed optical properties cannot simultaneously optimize performance year-round in climates with significant seasonal variability, these systems are particularly beneficial. However, lifecycle-oriented evaluation is required due to their higher capital costs and control requirements.

Low thermal conductivity and light diffusion are combined to create a passive high-insulation strategy in aerogel-based glazing systems (Carroll et al., 2022; Du, Wang & Li, 2024). Aerogels improve insulation without the need for mechanical control mechanisms, in contrast to electrochromic systems. Durability concerns and commercialization difficulties, however, continue to be limiting factors. When passive insulation is the main goal, their role seems most promising in cold or stable temperate climates.

Architectural arrangement is crucial, even more so than material choice. Research by Zhang et al. (2025) and Liu et al. (2025) shows that glazing size and window-to-wall ratio considerably mediate annual energy outcomes. Material performance is extremely sensitive to façade design because larger glazed areas magnify both gains and losses. In a similar vein, Lee et al. (2023) demonstrate how hierarchical simulation-based optimization improves alignment between building function and glazing type. These results support the need to evaluate window efficiency at the façade-system level rather than just at the component level.

Frame materials and edge effects are another factor to take into account. While Wakili et al. (2021) show measurable edge heat losses even in advanced glazing units, Wang et al. (2024) stress that frame geometry and conductivity significantly affect overall performance. As a result, glazing improvements that disregard frame optimization may result in lower returns.

When considered collectively, the research indicates that a structured evaluation logic incorporating four key variables is beneficial for window system selection:

1. Climatic dominance (heating, cooling, or mixed demand)
2. Required performance mechanism (insulation, solar control, or adaptive modulation)
3. Retrofit feasibility and construction constraints
4. Façade configuration parameters, particularly window-to-wall ratio

Table 3 proposes a simplified decision matrix, created by the author of this paper and derived from these variables. Its name is the Kovalskyi Climate-Responsive Window Selection Framework.

The Kovalskyi Climate-Responsive Window Selection Framework arranges the available data into a climate-responsive selection framework rather than offering a general solution. It represents the conclusion that window technologies ought to be assessed as context-dependent tactics incorporated into comprehensive building design rather than as rival options in isolation.

By matching material performance to architectural design and environmental requirements, this method converts technological advancement into quantifiable decreases in building energy consumption.

## 6. Conclusion

One of the most important ways to lower the operational building energy demand is through energy-efficient window systems. While Low-E coatings offer useful retrofit options, vacuum and aerogel technologies provide outstanding thermal insulation. Adaptive solar modulation is made possible by smart electrochromic systems, which are especially well-suited to mixed climates.

However, frame design, mitigation of thermal bridging, and architectural configuration must all be considered when evaluating glazing performance. The study shows that in order to select the best technology, integrated assessment frameworks are required.

Depending on the system type and climate, energy savings of 15% to 45% are possible. Standardized comparative modeling and long-term lifecycle analysis should be given top priority in future research to support evidence-based sustainable building design implementation.

Table 3
**The Kovalskyi Climate-Responsive Window Selection Framework**

| Climate Profile | Primary Energy Demand | Recommended Performance Strategy | Preferred Technology Category |
|---|---|---|---|
| **Cold / Heating-Dominated** | Heat loss reduction | Ultra-low U-value insulation | Vacuum glazing; advanced triple glazing |
| **Temperate** | Balanced heating and cooling | Insulation + moderate solar control | Triple glazing with Low-E coatings; aerogel systems |
| **Hot / Cooling-Dominated** | Solar heat gain reduction | SHGC minimization | Low-E glazing; solar control films |
| **Mixed / High Seasonal Variation** | Variable heating and cooling | Adaptive solar modulation | Electrochromic / smart glazing systems |

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