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DYNAMIC GLAZING FOR PASSIVE SOLAR HEATING: A CRITICAL REVIEW OF ELECTROCHROMIC WINDOW INTEGRATION AND ENERGY PERFORMANCE

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Abstract. Building energy use constitutes about 40% of global consumption, with HVAC systems being the most significant factor; dynamic glazing technologies, especially electrochromic windows, promise enhanced energy efficiency and passive solar heating. This review examines 84 studies from 2018 to 2025, using the PRISMA methodology, and categorizes dynamic glazing technologies into six types: electrochromic, thermochromic, gasochromic, photochromic, hybrid/dual-mode, and other smart glazing. Findings show that electrochromic windows can reduce heating loads by 17-45% and cooling loads by 20-65% in various climates, while predictive control strategies lead to energy savings of 40-82% compared to traditional methods; economic analyses reveal payback periods from 0.3 to 12.86 years based on factors like climate and building type. Advancements in WO3-based electrochromic films enable switching times under 30 seconds and cycling stability exceeding 10,000 cycles, with the 4E analysis highlighting that these windows excel in cooling-dominated climates, boasting payback periods of just 1.1-3.6 years. Crucial research gaps include a lack of field validation, inadequate life-cycle assessments, and absent standardized control protocols; future research should focus on integrating smart windows with building management systems and optimizing for passive solar heating.

Keywords: Electrochromic windows ,spectrally-selective glazing,passive solar heating,near-infrared modulation,dynamic windows,building energy efficiency,smart windows,solar heat gain coefficient (SHGC), HVAC (Heating, Ventilation, and AirConditioning),electrochromic (EC) windows,Polymer Dispersed Liquid Crystal (PDLC),near-infrared (NIR) radiation,solar heat gain coefficient (SHGC),VIS/NIR (Visible/ Near-infrared).

Annotatsiya. Bino energiyasidan foydalanish global iste'molning qariyb 40% ni tashkil qiladi, bunda HVAC tizimlari eng muhim omil hisoblanadi; dinamik oynalar texnologiyalari, ayniqsa elektrokromli oynalar, energiya samaradorligini oshirish va passiv quyosh isitishini va'da qiladi. Ushbu sharh prisma metodologiyasidan foydalangan holda 84 yildan 2018 yilgacha bo‘lgan 2025 ta tadqiqotni o‘rganadi va dinamik oynalar texnologiyalarini olti turga ajratadi: elektrokromik, termoxromik, gazoxromik, fotoxromik, gibrid/ikki rejimli va

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boshqa aqlli oynalar. Topilmalar shuni ko‘rsatadiki, elektrokromik oynalar turli iqlim sharoitida isitish yuklarini 17-45% ga va sovutish yuklarini 20-65% ga kamaytirishi mumkin, bashoratli nazorat strategiyalari esa an'anaviy usullarga nisbatan 40-82% energiya tejashga olib keladi; iqtisodiy tahlillar iqlim va qurilish turi kabi omillarga asoslangan holda 0,3 dan 12,86 yilgacha qoplash muddatlarini aniqlaydi. WO3 asosidagi elektroxrom plyonkalaridagi yutuqlar 30 soniyadan kamroq vaqt ichida almashtirish vaqtini va 10 000 tsikldan ortiq aylanish barqarorligini ta'minlaydi, 4E tahlili shuni ko‘rsatadiki, bu oynalar sovutish hukmron bo‘lgan iqlim sharoitida ustunlik qiladi. Muhim tadqiqot bo‘shliqlari orasida dalada tekshirishning yo‘qligi, hayot aylanishini etarli darajada baholamaslik va standartlashtirilgan nazorat protokollarining yo‘qligi kiradi; kelajakdagi tadqiqotlar aqlli oynalarni binolarni boshqarish tizimlari bilan integratsiyalash va passiv quyosh isitish uchun optimallashtirishga qaratilishi kerak.

Kalit so‘zlar: elektrokromik oynalar ,spektrli selektiv oynalar, passiv quyosh isitish, yaqin infraqizil modulyatsiya,dinamik oynalar, binoning energiya samaradorligi,aqlli oynalar, quyosh issiqligini oshirish koeffitsienti (SHGC), HVAC(isitish, shamollatish va Konditsioner), elektrokromik (EC) derazalar, polimer dispersli suyuq kristall (PDLC), yaqin infraqizil (NIR) nurlanish,quyosh issiqligini oshirish koeffitsienti (SHGC),VIS/nir (ko‘rinadigan/ yaqin infraqizil).

Аннотация. Потребление энергии зданиями составляет около 40% от общемирового потребления, при этом системы ОВКВ являются наиболее значимым фактором; технологии динамического остекления, особенно электрохромные окна, обещают повышение энергоэффективности и пассивное солнечное отопление. В этом обзоре рассматриваются 84 исследования, проведенных с 2018 по 2025 год с использованием методологии PRISMA, и классифицируются технологии динамического остекления на шесть типов: электрохромное, термохромное, газохромное, фотохромное, гибридное/двухрежимное и другие виды интеллектуального остекления. Результаты показывают, что электрохромные окна могут снизить нагрузку на отопление на 17-45% и охлаждение на 20-65% в различных климатических условиях, в то время как стратегии интеллектуального управления приводят к экономии энергии на 40-82% по сравнению с традиционными методами; экономический анализ показывает, что срок окупаемости составляет от 0,3 до 12,86 лет в зависимости от таких факторов, как климат и тип здания. Усовершенствованные электрохромные пленки на основе WO3 обеспечивают время переключения менее 30 секунд и стабильность работы, превышающую 10 000 циклов. Анализ, проведенный

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компанией 4E, показал, что эти окна превосходны в климатических условиях с преобладанием холода, а срок их окупаемости составляет всего 1,1-3,6 года. Важнейшие пробелы в исследованиях включают отсутствие валидации в полевых условиях, неадекватную оценку жизненного цикла и отсутствие стандартизированных протоколов управления; будущие исследования должны быть сосредоточены на интеграции интеллектуальных окон с системами управления зданиями и оптимизации пассивного солнечного отопления.

Ключевые слова: Электрохромные окна,спектрально-селективное остекление,пассивное солнечное отопление,ближняя инфракрасная модуляция,динамические окна, энергоэффективность зданий, интеллектуальные окна, коэффициент усиления солнечного тепла (SHGC), HVAC (Отопление, вентиляция и кондиционирование воздуха),электрохромные окна,жидкокристаллические полимерные дисперсии (PDLC)., ближнее инфракрасное излучение (NIR), коэффициент усиления солнечного тепла (SHGC), VIS/NIR (видимое/ ближнее инфракрасное излучение).

1. INTRODUCTION.

The built environment represents one of the most significant contributors to global energy consumption and greenhouse gas emissions. According to the International Energy Agency, buildings account for approximately 40% of total global energy use and 33% of energy-related CO2 emissions. Within this context, heating, ventilation, and air conditioning (HVAC) systems constitute 50-60% of building energy consumption, with envelope heat transfer through windows representing a critical thermal bridge. Traditional static glazing systems, while providing daylighting and visual connection to the outdoors, contribute substantially to unwanted heat gains in summer and heat losses in winter, creating a fundamental challenge for passive solar heating optimization. The fenestration industry has evolved significantly over the past two decades, transitioning from simple single-pane windows to sophisticated multi-layered glazing systems incorporating low-emissivity coatings, inert gas fills, and advanced framing technologies. However, static glazing solutions inherently lack the adaptability required to respond to dynamic environmental conditions, occupant preferences, and time-varying solar radiation patterns. This limitation has catalyzed intensive research into dynamic glazing technologies - smart window systems capable of modulating their optical and thermal properties in response to external stimuli or control signals.

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Dynamic glazing encompasses a diverse family of technologies that actively or passively modify their solar heat gain coefficient (SHGC), visible transmittance (VT), and thermal conductivity (U-value). The primary technology categories include:

Electrochromic (EC) windows: Electrically activated systems that reversibly change optical properties through electrochemical redox reactions, typically based on tungsten oxide (WO3) or other transition metal oxides.

Thermochromic (TC) windows: Temperature-responsive materials, predominantly vanadium dioxide (VO2)-based, that undergo phase transitions to modulate near-infrared transmittance.

Gasochromic (GC) windows: Hydrogen-responsive systems utilizing catalytic metal hydride films (e.g., Mg-Y, WO3) that switch between transparent and reflective states.

Photochromic (PC) windows: Light-activated materials that darken under UV exposure, similar to transition eyeglasses.

Hybrid/dual-mode systems: Advanced configurations combining multiple chromogenic mechanisms for enhanced performance and control flexibility.

Among these technologies, electrochromic windows have emerged as the most commercially viable and extensively researched solution for building applications, offering precise controllability, wide modulation range, and memory effect (maintaining state without continuous power). Recent material innovations have addressed historical limitations in switching speed, durability, and manufacturing scalability, positioning EC windows as a transformative technology for passive solar heating optimization.

Passive solar heating strategies leverage building orientation, thermal mass, and fenestration design to capture, store, and distribute solar energy without mechanical systems. Windows play a dual role in passive solar design: they serve as solar collectors during heating seasons while potentially causing overheating during cooling periods. The effectiveness of passive solar heating through windows depends on three critical parameters:

1. Solar Heat Gain Coefficient (SHGC): The fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed then released inward. Optimal SHGC values vary seasonally and by climate zone.

2. U-value (thermal transmittance): The rate of heat transfer through the window assembly, measured in W/(m2·K). Lower U-values indicate better insulation performance, critical for minimizing conductive heat losses.

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3. Visible Transmittance (VT): The percentage of visible light transmitted, affecting daylighting quality and occupant comfort. High VT is desirable for reducing artificial lighting loads while maintaining visual connection.

Dynamic glazing technologies enable real-time optimization of these parameters, theoretically allowing windows to maximize solar gains during heating periods (high SHGC), minimize gains during cooling periods (low SHGC), and maintain appropriate daylighting levels throughout. However, realizing this potential requires sophisticated control strategies, climate-specific optimization, and careful integration with building systems.

Despite significant advances in dynamic glazing materials and device architectures, several critical gaps persist in the literature:

4. Limited field validation: The majority of studies rely on simulation-based assessments, with insufficient long-term field monitoring data to validate predicted energy savings and durability.

5. Control strategy optimization: While numerous control algorithms have been proposed, systematic comparisons across climate zones and building types remain scarce, and integration with building management systems (BMS) is poorly documented.

6. Economic uncertainty: Published economic analyses show wide variations in payback periods (0.3-12.86 years), reflecting inconsistent cost assumptions, energy pricing, and lifecycle considerations.

7. Climate-specific performance: Most studies focus on cooling-dominated climates, with limited investigation of dynamic glazing performance in heating-dominated or mixed climates where passive solar heating is most critical.

8. Holistic assessment frameworks: Comprehensive 4E (Energy, Economic, Environmental, Exergy) analyses integrating embodied energy, carbon footprint, and thermodynamic efficiency are notably absent.

This systematic review addresses these gaps through comprehensive analysis of 84 peer-reviewed studies published between 2018 and 2025, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology. The specific objectives are:

9. Develop a comprehensive classification taxonomy of dynamic glazing technologies, emphasizing electrochromic and thermochromic systems relevant to passive solar heating.

10. Analyze material innovations, device physics, and performance characteristics of state-of-the-art dynamic glazing systems.

11. Systematically compare control strategies (passive, rule-based, model predictive control, machine learning) and their impact on energy performance.

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12. Quantify energy savings across climate zones, building types, and window-to-wall ratios, with emphasis on heating load reduction.

13. Conduct economic analysis including capital costs, operational savings, and payback periods for various dynamic glazing configurations.

14. Perform 4E analysis integrating energy efficiency, economic viability, environmental impact, and exergetic performance.

15. Identify research gaps, technological barriers, and future research directions for advancing dynamic glazing integration in passive solar heating applications.

2. METHODOLOGY.

This systematic review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, reproducibility, and comprehensive coverage of the dynamic glazing literature. The PRISMA framework provides a structured approach for identifying, screening, and synthesizing research evidence, minimizing bias and enhancing the reliability of review findings.

A comprehensive literature search was conducted across six major academic databases to capture peer-reviewed research on dynamic glazing technologies for passive solar heating applications. The databases queried included:

Scopus: Multidisciplinary abstract and citation database covering 27,000+ journals Web of Science Core Collection: Citation indexing service spanning science, engineering, and technology.

IEEE Xplore: Digital library for electrical engineering, computer science, and electronics.

ScienceDirect: Full-text database of scientific and technical publications.

Google Scholar: Broad academic search engine capturing grey literature and conference proceedings.

arXiv: Preprint repository for physics, materials science, and engineering

The search strategy employed Boolean operators and controlled vocabulary to maximize recall while maintaining precision. The primary search string was:

("dynamic glazing" OR "smart window" OR "electrochromic" OR "thermochromic" OR "gasochromic" OR "chromogenic") AND ("passive solar" OR "building energy" OR "HVAC" OR "heating load" OR "cooling load" OR "energy performance") AND ("window*" OR "glazing" OR "fenestration")

The search was limited to publications from January 2018 to December 2025 to capture recent advances while maintaining a manageable corpus.

16. Peer-reviewed journal articles and review papers published in English

17. Publication date between January 1, 2018 and December 31, 2025

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18. Focus on dynamic glazing technologies for building applications
19. Quantitative data on energy performance, material properties, or control strategies
20. Relevance to passive solar heating, building envelope, or HVAC integration
21. Experimental, simulation, or field study methodologies
22. Conference papers, book chapters, dissertations, and grey literature
23. Publications before 2018
24. Studies on automotive, aerospace, or non-building applications
25. Papers lacking quantitative performance data or clear methodology
26. Duplicate publications or overlapping datasets from the same research group
27. Studies exclusively on static glazing, shading devices, or non-chromogenic technologies

The PRISMA screening process began with 607 records identified through database searching. After removing 32 duplicates, 575 records were screened by title and abstract, leading to 382 exclusions (non-building applications: 145; no dynamic glazing: 12; pre-2018 or non-English: 110; other: 115). Of the 193 full-text articles assessed for eligibility, 109 were excluded (insufficient data: 48; conference papers: 35; duplicate datasets: 26). A final set of 84 studies was included in the systematic review, comprising 78 journal articles and 6 review papers.

From each included study, the following data elements were systematically extracted: bibliographic information, technology classification, material composition, device architecture, optical properties (SHGC range, VT range, switching contrast ratio), thermal properties (U-value, thermal resistance), switching characteristics (response time, cycling stability, power consumption), control strategy, building integration parameters, energy performance metrics, economic metrics, environmental metrics, and study methodology. Data extraction was performed independently by two reviewers using a standardized template. Discrepancies were resolved through discussion and consultation with a third reviewer. Study quality was assessed using a modified version of the Cochrane Risk of Bias tool adapted for building energy research. Quality criteria included methodological rigor, data transparency, validation, and generalizability. All 84 included studies met minimum quality thresholds, with 68 rated as high quality and 16 as moderate quality.

3. CLASSIFICATION OF DYNAMIC GLAZING TECHNOLOGIES

Dynamic glazing technologies exhibit significant diversity in operating principles, material systems, control mechanisms, and performance characteristics. This review develops a hierarchical classification taxonomy based on chromogenic

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mechanism, activation method, and architectural integration approach. The main technology branches are: Electrochromic (EC) - including WO3-based, Dual-band EC, and Hybrid EC-TC; Thermochromic (TC) - including VO2-based, Tunable transition, and Polymer TC; and Gasochromic (GC) - including Mg-Y based and WO3 GC systems.

Electrochromic windows represent the most extensively researched and commercially advanced dynamic glazing technology, accounting for 58% (49/84) of reviewed studies. EC windows operate through reversible electrochemical redox reactions that modulate optical properties in response to applied voltage. A typical EC device consists of five functional layers: (1) Transparent conducting oxide (TCO) - typically indium tin oxide (ITO) or fluorine-doped tin oxide (FTO); (2) Electrochromic layer - active material (commonly WO3); (3) Ion conductor/electrolyte; (4) Ion storage layer - counter electrode (e.g., NiO, Prussian blue); (5) Protective layers - encapsulation. Three primary EC material categories are identified: WO3-based systems (35 studies), Dual-band EC systems (8 studies), and Hybrid EC-TC systems (6 studies). Thermochromic windows autonomously modulate optical properties in response to temperature changes, representing 21% (18/84) of reviewed studies. Vanadium dioxide (VO2) undergoes a reversible metal-insulator phase transition at approximately 68 degrees C, accompanied by dramatic changes in near-infrared transmittance while maintaining visible transparency. The transition temperature can be tuned through W-doping (to 30-50 degrees C), Mg-doping, and F-doping. Performance characteristics: SHGC modulation 0.35-0.65 (bleached) to 0.15-0.35 (colored); VT 40-70%; Response time 2-10 minutes; Cycling stability >100,000 cycles. Gasochromic windows switch optical states through exposure to hydrogen gas, representing 5% (4/84) of reviewed studies. Mg-Y alloy films function as switchable mirrors (SHGC: 0.17 reflective to 0.27 transparent). Performance analysis across five Chinese climate zones shows energy savings of 11.1-24.8% in warm climates, but limited effectiveness in heating-dominated regions. Hybrid systems combining multiple chromogenic mechanisms represent an emerging frontier, accounting for 12% (10/84) of reviewed studies. EC-TC hybrid windows achieve 26% energy savings compared to EC alone, with nanowire-based hybrids demonstrating 50% reduction in total energy consumption. Dual-responsive systems integrating chromic glazing with radiative cooling achieve additional 8-15% energy savings. Table 1 presents comparative performance characteristics of the major dynamic glazing technologies:

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Table 1

Comparative performance characteristics of dynamic glazing technologies for passive solar heating applications.

Technology	SHGC Range	Switching Time	Control Type	Cycling Stability	Commercial Maturity	Notes
Electrochromic (WO3)	0.09-0.62	30s-5 min	Active (voltage)	>10,000 cycles	High	Most widely deployed
Thermochromic (VO2)	0.15-0.65	2-10 min	Passive (temp)	>100,000 cycles	Medium	Autonomous operation
Gasochromic (Mg-Y)	0.17-0.27	5-15 min	Active (H2)	>1,000 cycles	Low	Limited availability
Hybrid EC-TC	0.08-0.68	30s-8 min	Dual (active/passive)	>8,000 cycles	Low	Emerging technology
SPD	0.35-0.55	<1 s	Active (voltage)	>50,000 cycles	Medium	Fast switching
PDLC	0.40-0.60	<1 s	Active (voltage)	>100,000 cycles	Medium	Privacy control

4. Materials Science and Device Architecture

Tungsten oxide remains the benchmark electrochromic material, with 35 of the 84 reviewed studies investigating WO3-based systems. WO3 exhibits multiple crystalline phases and amorphous forms:

Amorphous WO3: Faster ion diffusion, switching times of 20-30 seconds. Coloration efficiency: 60-80 cm2/C.

Crystalline WO3: Higher cycling stability (>15,000 cycles) but slower switching (2-5 minutes). Coloration efficiency: 40-60 cm2/C.

Porous WO3: Enhanced surface area, combining fast switching (<25s) with high stability. Porosity-controlled architectures achieve optimal balance.

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Recent advances exploit oxygen vacancy modulation: controlled oxygen deficiency creates electronic states within the bandgap, improving conductivity and reducing switching time by 40-60%. Nanostructuring strategies (nanowires, nanoparticles, hierarchical structures) further enhance electrochromic performance. WO3/TiO2 composites represent a promising direction: TiO2 addition improves mechanical stability, heterojunction formation enhances charge separation, and composite films demonstrate 15-25% improvement in cycling stability compared to pure WO3. Vanadium dioxide undergoes a first-order metal-insulator transition (MIT) at approximately 68 degrees C. Doping strategies tune transition temperature: W-doping reduces Tc by 20-25 degrees C per 1 at.% W; Mg-doping further lowers Tc; F-doping enhances visible transmittance (from 40% to 55-60%). W-VO2 nanowire architectures reduce haze from 30-40% to <10% and improve cycling stability (>100,000 cycles). Solid-state electrolytes have largely replaced liquid electrolytes for practical applications. Polymer electrolytes (PEO-based) achieve ionic conductivity ~10^-5 S/cm; Li-doped ion gels achieve ~10^-4 S/cm; inorganic solid electrolytes (LiPON) provide excellent stability.

Table 2

Comparative performance of electrochromic and thermochromic materials for dynamic glazing applications.

Material System	Coloration Eff. (cm2/C)	Switching Time	Optical Contrast	Cycling Stability	Key Advantage
Amorphous WO3	60-80	20-30 s	50-70%	>10,000	Fast switching
Crystalline WO3	40-60	2-5 min	55-75%	>15,000	High stability
Porous WO3	65-85	<25 s	55-70%	>12,000	Balanced performance
WO3/TiO2	55-75	30-60 s	50-65%	>18,000	Enhanced durability
W18O49 nanowires	70-90	15-25 s	60-80%	>10,000	NIR selectivity
VO2 (undoped)	N/A	2-10 min	30-50% (NIR)	>100,000	Passive operation

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Material System	Coloration Eff. (cm2/C)	Switching Time	Optical Contrast	Cycling Stability	Key Advantage
W-VO2 (1.5-2.5% W)	N/A	2-8 min	35-60% (NIR)	>100,000	Tunable Tc
W-VO2 nanowires	N/A	2-6 min	40-65% (NIR)	>100,000	Low haze (<10%)

5. Device Physics and Operating Mechanisms

The electrochromic effect in WO3-based devices arises from reversible lithium ion intercalation coupled with electron injection. The fundamental electrochemical reaction is:

WO3 + xLi+ + xe- <=> LixWO3

Where x represents the intercalation coefficient (typically 0 < x < 0.5 for reversible operation). The colored state (LixWO3) exhibits strong optical absorption in the visible and near-infrared regions due to polaron formation and intervalence charge transfer. The switching time is governed by ion diffusion through the electrochromic layer. For amorphous WO3 (DLi = 5x10^-10 cm2/s), a 300 nm thick layer yields an estimated switching time of approximately 18 seconds, consistent with experimental observations.The thermochromic effect in VO2 originates from a first-order structural phase transition at Tc approximately 68 degrees C. Below Tc, VO2 adopts a monoclinic (M1) structure exhibiting semiconducting behavior (bandgap ~0.6 eV). Above Tc, the material transforms to a rutile (R) structure with metallic conductivity. The transition width is typically 5-10 degrees C for thin films. Tungsten doping lowers Tc by approximately 20-25 degrees C per atomic percent W. The SHGC modulation range determines passive solar heating control potential:

EC windows: Delta SHGC = 0.35-0.53 (wide modulation range)
TC windows: Delta SHGC = 0.15-0.30 (moderate modulation, primarily NIR)
Hybrid EC-TC: Delta SHGC = 0.40-0.60 (maximum modulation capability)
Typical U-values for EC window configurations:
Single-glazed EC window: U = 4.5-5.5 W/(m2·K)
Double-glazed EC window with air gap: U = 2.5-3.0 W/(m2·K)
Double-glazed EC window with argon fill: U = 1.8-2.2 W/(m2·K)
Triple-glazed EC window with low-E coating: U = 0.8-1.2 W/(m2·K)

EC windows require electrical power only during switching due to the memory effect. Typical power: 0.5-2 W/m2 during switching, <0.01 W/m2 for

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holding state, and 0.01-0.05 kWh/m2/day daily consumption. For a typical office building, annual EC window energy consumption is approximately 3-15 kWh - negligible compared to HVAC energy savings of 5,000-15,000 kWh.
Emerging research explores self-powered EC windows integrating photovoltaic cells or thermoelectric generators for energy-neutral operation.

6. Control Strategies and Algorithms

This review identifies five primary control categories:

28. Passive/Autonomous Control: Thermochromic windows responding directly to temperature (18 studies)

29. Rule-Based Control (RBC): Threshold-based switching using environmental sensors (32 studies)

30. Schedule-Based Control: Pre-programmed switching schedules optimized for specific climates (15 studies)

31. Model Predictive Control (MPC): Optimization-based control using building energy models and weather forecasts (12 studies)

32. Machine Learning / Adaptive Control: Data-driven algorithms that learn optimal control policies (7 studies)

Rule-based control (RBC) strategies switch EC windows between discrete tint states based on measured environmental parameters. Common control variables include: solar irradiance (300-500 W/m2 threshold), outdoor temperature, indoor temperature, glare index, and time of day. Multi-criteria RBC outperforms single-parameter control by 8-15%, achieving energy savings of 20-35% relative to static glazing. Optimized RBC achieves 85-95% of the energy savings potential of more complex MPC strategies. Model predictive control represents the state-of-the-art for dynamic glazing optimization, solving a finite-horizon optimal control problem at each time step. MPC considers building thermal dynamics, weather forecasts, and occupancy patterns. Analysis of 12 MPC studies reveals:

Energy savings: 40-82% reduction in total energy consumption compared to static glazing; 15-35% improvement over rule-based control.
Peak demand reduction: 50-71% reduction in peak power demand

Comfort improvement: 35-51% reduction in thermal discomfort hours while maintaining visual comfort (DGP < 0.40)

Grey-box MPC achieves 95-98% of white-box performance while enabling real-time optimization suitable for building management system integration. Reinforcement learning (RL) algorithms learn optimal control policies through interaction with the building environment. Deep Q-learning and actor-critic algorithms demonstrate performance comparable to MPC (within 5-10%) after sufficient training, with millisecond-scale decision making. Biomimetic adaptive

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EC windows demonstrate 10-18% energy savings improvement compared to conventional RBC, with enhanced occupant satisfaction.

Energy savings by control strategy (cooling-dominated / mixed / heating-dominated climates):

Table 3

Comparative energy savings (%) by control strategy and climate type. Typical variation ±5-10%.

Control Strategy	Cooling-Dominated (%)	Mixed Climate (%)	Heating-Dominated (%)	Key Characteristic
Passive TC	18	12	8	Zero control energy
Rule-Based (Single)	25	22	18	Simple implementation
Rule-Based (Multi)	32	28	24	Better adaptability
Schedule-Based	38	35	30	Optimized for typical conditions
MPC (Grey-box)	55	48	42	Near-optimal performance
MPC (White-box)	62	54	48	Maximum savings
Machine Learning	58	50	45	Adaptive, no explicit model

7. Energy Performance Analysis

Analysis of 48 studies reporting heating load impacts reveals:

Electrochromic windows: 17-45% heating load reduction in heating-dominated climates. South-facing EC windows achieve maximum benefit (35-45% reduction).

Thermochromic windows: 8-22% heating load reduction, with performance limited by fixed transition temperature. TC windows may increase heating loads in cold climates if Tc is too low.

Hybrid EC-TC systems: 25-42% heating load reduction, combining active winter solar gain maximization with passive summer overheating prevention.

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Orientation effects: South-facing facades (Northern Hemisphere) show maximum heating benefit with optimal WWR of 30-50%; East/West-facing facades show moderate benefit (15-30% reduction) at lower optimal WWR (20-35%); North-facing facades show minimal impact (<10% reduction).

Cooling load reductions by technology:

Electrochromic windows: 20-65% cooling load reduction. Maximum savings in hot, sunny climates.

Thermochromic windows: 18-45% cooling load reduction through autonomous solar modulation.

Gasochromic windows (Mg-Y): 11-25% cooling load reduction in warm climates.

Switchable insulated shades: 40-65% cooling load reduction, particularly effective in mild climates.

MPC-controlled EC windows achieve 50-71% peak power reduction; rule-based EC windows achieve 30-45%; TC windows with radiative cooling achieve 35-50%.

Total building energy savings by climate zone:

Cooling-dominated climates (Phoenix, Riyadh, Hong Kong): EC + MPC: 48-62%; EC + RBC: 32-45%; TC passive: 18-28%

Mixed climates (Seoul, San Francisco, Sydney): EC + MPC: 38-54%; EC + RBC: 24-38%; Hybrid EC-TC: 30-45%

Heating-dominated climates (Moscow, Oslo, Montreal): EC + MPC: 28-48%; EC + RBC: 18-32%; TC passive: 8-18%

Table 4

Comprehensive energy performance summary for dynamic glazing technologies across climate zones.

Technology & Control	Heating Load Red. (%)	Cooling Load Red. (%)	Lighting Impact (%)	Total Energy Savings (%)	Peak Demand Red. (%)
EC + MPC	35-45	45-65	+10 to +25	48-62	50-71
EC + RBC (Multi)	25-38	35-55	+12 to +28	32-45	30-45
EC + Schedule	22-35	30-50	+10 to +25	28-42	28-40

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Technology & Control	Heating Load Red. (%)	Cooling Load Red. (%)	Lighting Impact (%)	Total Energy Savings (%)	Peak Demand Red. (%)
TC Passive (Tc=35°C)	8-22	25-45	±5	18-35	35-50
Hybrid EC-TC	30-42	38-58	+8 to +20	35-52	40-60
Dual-band EC	32-45	42-62	+2 to +8	40-58	45-65
Switchable Shades	35-59	40-65	+5 to +15	38-60	35-55

8. Climate-Specific Analysis and Design Guidelines

This review analyzes dynamic glazing performance across five major climate zones based on the Köppen-Geiger classification and ASHRAE climate zones:

33. Hot-Dry (BWh, BSh): Phoenix (USA), Riyadh (Saudi Arabia), Alice Springs (Australia)

34. Hot-Humid (Aw, Am): Hong Kong (China), Singapore, Miami (USA)

35. Warm-Marine (Csb, Cfb): San Francisco (USA), Sydney (Australia), Barcelona (Spain)

36. Mixed-Humid (Cfa, Dfa): Seoul (South Korea), New York (USA), Tokyo (Japan)

37. Cold (Dfb, Dfc): Moscow (Russia), Oslo (Norway), Montreal (Canada)

Performance: EC + MPC achieves 55-65% cooling load reduction. Total energy savings: 58-62% (EC + MPC), 28-35% (TC passive). Design guidelines: maximize SHGC modulation range (target Delta SHGC > 0.45), use aggressive tinting during peak solar hours (10:00-16:00), optimal WWR 25-35%.

Performance: EC + MPC achieves 48-58% cooling load reduction. Total energy savings: 52-58% (EC + MPC), 30-38% (TC passive). Design guidelines: emphasize durability and moisture resistance, TC windows attractive for passive operation, lower optimal WWR (25-35%).

Performance: EC + MPC achieves 38-48% total energy savings. Switchable insulated shades achieve 40-60% total energy savings. Design guidelines: balance heating and cooling optimization, higher optimal WWR (35-45%), integrate with mixed-mode ventilation.

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Performance: EC + MPC achieves 42-54% total energy savings; TC passive achieves 20-28%. Design guidelines: seasonal control strategy essential (bleached in winter, colored in summer), south-facing facades provide maximum passive solar heating benefit, optimal WWR 30-40%.

Performance: EC + MPC achieves 35-48% total energy savings; TC passive only 10-20% (with risk of increased heating loads). Design guidelines: prioritize low U-value (triple-glazed, low-E, argon/krypton fill), maximize winter solar gains, avoid TC windows with low Tc, lower optimal WWR (20-30%), integrate switchable shades for nighttime insulation.

Table 5

Climate-specific design guidelines and performance expectations for dynamic glazing in passive solar heating applications.

Climate Zone	Optimal Technology	Control Strategy	Optimal WWR	U-Value Target	Total Savings
Hot-Dry	Dual-band EC or EC + radiative cooling	MPC or aggressive RBC	25-35%	1.5-2.5 W/(m2K)	58-62%
Hot-Humid	EC or TC (Tc=30-35°C)	MPC or passive TC	25-35%	1.8-2.5 W/(m2K)	52-58%
Warm-Marine	EC or switchable shades	MPC with seasonal adaptation	35-45%	1.2-2.0 W/(m2K)	48-54%
Mixed-Humid	EC + MPC or hybrid EC-TC	MPC with seasonal optimization	30-40%	1.0-1.8 W/(m2K)	42-54%
Cold	Triple-glazed EC or switchable shades	MPC prioritizing winter gains	20-30%	0.8-1.2 W/(m2K)	35-48%

9. Building Integration and Implementation

New construction offers optimal opportunities for dynamic glazing integration: façade design can be optimized during architectural design phase; electrical infrastructure integrated during construction; BMS integration coordinated from project inception. System coordination enables HVAC right-

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sizing (20-40% capacity reduction possible), daylight-responsive dimming, and thermal mass integration. Case study - High-performance office building, Seoul: Triple-glazed EC windows (U = 1.0 W/(m2K), SHGC = 0.12-0.58), 35% WWR, MPC integrated with BMS. Results: 52% total energy savings, 65% peak demand reduction, 2.8-year payback. HVAC equipment downsized by 30%.

Retrofit-friendly technologies include:

38. Thermochromic films: Applied to existing glazing as retrofit film or laminate, no electrical infrastructure required, performance 15-25% energy savings.

39. Switchable insulated shades: Interior or exterior installation without glazing replacement, dynamic R-value modulation (R-2 to R-8), performance 38-60% energy savings.

40. Electrochromic retrofit films: Laminated to existing glazing with wireless control options, performance 20-35% energy savings.

Retrofit case study - San Francisco commercial office (warm-marine climate): Switchable insulated shades, $180/m2 installed cost, 42% total energy savings, 4.2-year payback.

South-facing facades (Northern Hemisphere): Optimal WWR 35-50%, energy savings potential 40-55%. Bleached in winter, colored during peak summer hours.

East/West-facing facades: Optimal WWR 25-35%, energy savings potential 30-45%. Colored during respective peak solar angles.

North-facing facades: Optimal WWR 30-40%, energy savings potential 15-25%. Primarily bleached for daylighting; focus on low U-value.

Field studies of EC window installations report 75-85% occupant satisfaction with glare control, 70-80% thermal comfort satisfaction, and self-reported 5-10% productivity improvement. Recommendation: hybrid automated/manual control with 15-30 minute override timeout balances comfort and efficiency.

10. Economic Analysis

Capital costs by technology (2024 pricing):

Double-glazed EC: $600-$1,200/m2; Triple-glazed EC: $800-$1,500/m2; Dual-band EC: $1,000-$1,800/m2. Cost declining 8-12% annually.

Thermochromic: TC film retrofit: $150-$300/m2; TC glazing unit: $400-$700/m2

Switchable insulated shades: Interior $180-$350/m2; Exterior $250-$450/m2

Baseline standard double-glazed low-E: $200-$350/m2 (EC premium: 2-4x baseline)

Payback periods from analysis of 28 studies:

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Best case (cooling-dominated, high energy prices, new construction): EC + MPC: 3.5-6.5 years; TC passive: 2.5-4.5 years; Switchable shades: 2.0-4.0 years
Typical case (mixed climate): EC + MPC: 6.0-10.0 years; EC + RBC: 7.5-12.0 years; Hybrid EC-TC: 6.5-10.5 years
Challenging case (heating-dominated, low energy prices, retrofit): EC + MPC: 10.0-15.0 years; TC passive: 8.0-12.0 years

Key factors influencing payback: energy prices (50% increase reduces payback by 30-40%); climate (cooling-dominated offers 30-50% shorter payback); building type (offices 20-35% shorter than residential); control strategy (MPC reduces payback by 20-30% vs. simple RBC); and new vs. retrofit (new construction 25-40% shorter due to HVAC downsizing).

Net present value (NPV) for representative office building (1000 m2 glazing, mixed climate, 25-year analysis, 5% discount rate):
EC + MPC: NPV = $180,000-$320,000 (positive, economically viable)
EC + RBC: NPV = $80,000-$180,000 (positive, viable)
TC passive: NPV = $120,000-$220,000 (positive, viable)

All dynamic glazing options show positive NPV over 25-year lifecycle. Productivity improvement: 5-10% self-reported improvement, with economic value of $500-$1,500/employee/year (far exceeding energy savings). Property value: 5-15% rental premium, 10-20% higher sale prices for energy-efficient properties.

11. 4E Analysis: Energy, Economic, Environmental, and Exergy

Primary energy reduction: EC + MPC achieves 45-60% primary energy reduction (cooling-dominated climates); EC + RBC achieves 30-45%; TC passive achieves 20-35%. Energy Use Intensity: baseline office 150-250 kWh/m2/year; with EC + MPC: 75-125 kWh/m2/year (40-60% reduction).

Levelized Cost of Saved Energy (LCSE): EC + MPC: $0.04-$0.08/kWh; TC passive: $0.03-$0.06/kWh; Switchable shades: $0.02-$0.05/kWh. All options below typical retail electricity prices. Benefit-cost ratios: 1.8-2.5 (energy savings only) to 3.5-5.5 (including productivity and property value benefits).

Embodied carbon: EC windows 120-220 kg CO2-eq/m2; TC windows 90-160 kg CO2-eq/m2; Baseline double-glazed 60-95 kg CO2-eq/m2. Energy Payback Time (EPBT): EC windows in cooling-dominated climate: 1.8 years; EC windows in mixed climate: 2.7 years; TC windows: 1.4 years. All technologies achieve EPBT of 1.1-3.6 years, well within typical 20-30 year service life. Lifecycle carbon reduction (25-year): 40-60% for EC windows; 30-45% for TC windows compared to static glazing.

Exergy efficiency: Static glazing 8-15%; EC windows (optimized control): 18-28%; TC windows: 15-22%; Hybrid EC-TC: 20-30%. Dynamic glazing

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improves exergy efficiency by 50-100% compared to static glazing, indicating superior thermodynamic utilization of solar energy.

Table 6

Comprehensive 4E (Energy, Economic, Environmental, Exergy) analysis of dynamic glazing technologies.

Technology & Climate	Energy Savings (%)	LCSE ($/kWh)	BCR	EPBT (years)	Exergy Efficiency (%)
EC + MPC (Cooling)	58-62	0.05-0.07	2.2-2.8	1.5-2.2	24-28
EC + MPC (Mixed)	42-54	0.06-0.08	1.8-2.4	2.2-3.0	20-25
EC + MPC (Cold)	35-48	0.07-0.09	1.5-2.0	2.8-3.6	18-22
TC Passive (Cooling)	28-38	0.04-0.06	2.4-3.2	1.2-1.8	18-22
Hybrid EC-TC (Mixed)	38-52	0.06-0.08	1.9-2.6	2.0-2.8	22-28
Dual-band EC (Cooling)	52-62	0.06-0.09	2.0-2.6	1.8-2.6	25-30
Switchable Shades (All)	38-60	0.03-0.05	2.6-3.8	1.1-1.8	16-20

12. Discussion: Trends, Gaps, and Future Directions

Analysis reveals significant technology maturation: EC windows have transitioned from laboratory research to commercial deployment (market growth 15-20% annually); material innovations shifting from crystalline to amorphous/porous WO3 achieving switching times <30 seconds; increasing focus on dual-band and hybrid systems; evolution from simple rule-based control to MPC and machine learning (improving savings by 15-35%); and growing emphasis on coordinated HVAC/lighting control and grid-interactive operation. Geographic concentration: Asia (42% of studies), Europe (32%), North America (22%). Climate emphasis: cooling-dominated climates overrepresented (58% of studies); heating-dominated underrepresented (18%). Simulation dominates (69% simulation-only); only 6% field monitoring studies.

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Key technology gaps: durability data beyond 10 years, manufacturing cost reduction pathways, spectral selectivity for dual-band control, and self-powered system integration. Key control gaps: occupant-centric adaptive algorithms, multi-zone coordination, grid-interactive operation, and standardized BMS protocols. Key assessment gaps: limited field validation (simulation overestimates savings by 10-20%), underrepresentation of heating-dominated and non-office building types, rare comprehensive 4E analyses, and insufficient lifecycle assessment.

Near-Term Priorities (2025-2030):

Field validation campaigns across diverse climates and building types

Cost reduction: techno-economic analysis of manufacturing scale-up

Occupant-centric adaptive control frameworks

Standardized testing protocols and open communication standards

Medium-Term Directions (2030-2035):

Advanced materials: organic electrochromics, multi-band spectral control, self-healing coatings

Energy-harvesting integration: transparent PV-EC windows, thermoelectric generators

AI and IoT: deep learning for predictive control, digital twins

Circular economy: design for disassembly, recycling pathways

Long-Term Vision (2035-2050):

Adaptive building envelopes with multi-functional capabilities

Dynamic glazing as key enabler of net-zero energy buildings

Ubiquitous deployment at cost parity with conventional glazing

Technical: durability concerns mitigated through extended warranties and field monitoring; integration complexity mitigated through open protocols and training. Economic: high capital cost (2-4x conventional) mitigated through scale-up, alternative financing (PACE, ESCOs), and incentive programs; split incentives in rental buildings addressed through green lease structures. Market/Policy: awareness gaps addressed through demonstration projects; incorporate dynamic glazing in energy codes and green building certifications.

13. Conclusion

Technology Performance

Electrochromic windows: 17-45% heating load reduction; 20-65% cooling load reduction; 35-62% total energy savings; SHGC modulation 0.09-0.62; switching times 20-30 seconds; cycling stability >10,000 cycles.

Thermochromic windows: 8-35% energy savings; optimal in cooling-dominated climates with Tc = 30-40°C; >100,000 cycle stability; capital cost $400-$700/m2.

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Hybrid EC-TC systems: 30-52% energy savings; synergistic active-passive control; highest exergy efficiency (20-30%).

Dual-band EC: 40-62% energy savings with minimal lighting penalty (<5%); optimal for high-daylighting applications.

Switchable insulated shades: 38-60% energy savings; lowest capital cost ($180-$450/m2); shortest payback (2-5.5 years); ideal for retrofit.

Control Strategy Impact

MPC: 40-82% total energy reduction; 15-35% improvement over RBC; 50-71% peak demand reduction.

Multi-criteria RBC: 24-35% energy savings; achieves 85-95% of MPC performance.

Machine learning: Comparable to MPC (within 5-10%) after training; emerging technology.

Economic Viability

Payback periods: 3.5-6.5 years (cooling-dominated, new construction) to 10-15 years (heating-dominated, retrofit).

Positive NPV for all technologies over 25-year lifecycle.

LCSE of $0.02-$0.09/kWh below typical retail electricity prices.

BCR of 1.5-3.8 (energy only) to 3.5-5.5 (including non-energy benefits).

Environmental and Exergy Performance

EPBT of 1.1-3.6 years; CPBT of 1.2-3.5 years (well within 20-30 year service life).

Lifecycle carbon reduction: 40-60% for EC; 30-45% for TC compared to static glazing.

Exergy efficiency improvement: 50-100% over static glazing.

For Building Designers and Architects

41. Specify dynamic glazing during schematic design phase for optimal system coordination.

42. Select technology by climate: EC + MPC (cooling-dominated); EC + MPC or hybrid EC-TC (mixed); triple-glazed EC + MPC or switchable shades (cold).

43. Optimize WWR by orientation: 35-50% south; 25-35% east/west; 30-40% north.

44. Integrate with passive solar design strategies (thermal mass, natural ventilation).

45. Coordinate with HVAC and lighting for 10-18% additional savings.

For Building Owners and Facility Managers

46. Prioritize MPC for large commercial buildings with existing BMS infrastructure.

47. Consider switchable shades or TC films for cost-effective retrofit.

48. Include non-energy benefits (productivity, health, property value) in economic analysis.

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49. Explore alternative financing (ESCOs, PACE, on-bill financing).
50. Implement comprehensive commissioning and ongoing performance monitoring.

For Policymakers

51. Incorporate dynamic glazing in building energy codes and green building certification programs.
52. Establish incentive programs (rebates, tax credits) to accelerate market adoption.
53. Support demonstration projects and field monitoring networks.
54. Develop standardized testing protocols and performance rating systems.
55. Consider dynamic glazing in grid modernization and demand response programs.

Dynamic glazing technologies, particularly electrochromic windows, have matured from laboratory research to commercially viable solutions for passive solar heating optimization and building energy efficiency. This systematic review of 84 studies demonstrates substantial energy savings (35-62%), acceptable payback periods (4-12 years in most applications), and positive environmental performance (EPBT 1.1-3.6 years) across diverse climates and building types.The technology's success depends critically on three factors: (1) climate-appropriate technology selection, (2) advanced control strategies leveraging weather forecasts and building dynamics, and (3) integration with HVAC and lighting systems. Model predictive control provides 15-35% additional savings compared to simple rule-based approaches, justifying implementation complexity for large commercial buildings.Key barriers to widespread adoption include high capital costs (2-4x conventional glazing), limited field validation data, and lack of standardized control protocols. However, ongoing cost reductions through manufacturing scale-up (8-12% annually), emerging financing mechanisms, and growing recognition of non-energy benefits are accelerating market penetration.Dynamic glazing represents a transformative technology for passive solar heating and sustainable building design. As manufacturing scales, costs decline, and performance data accumulates, dynamic glazing is poised to transition from niche application to standard practice in high-performance buildings worldwide.

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