SPECTRALLY-SELECTIVE, DUAL-BAND ELECTROCHROMIC WINDOWS WITH DECOUPLED VISIBLE AND NEAR-INFRARED CONTROL FOR OPTIMAL PASSIVE SOLAR HEAT MANAGEMENT

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Abstract: The increasing need for energy-efficient buildings necessitates effective passive solar strategies to minimize heating and cooling demands. This research presents a dual-band electrochromic device designed to modulate solar radiation in both visible and near-infrared spectra. The system facilitates independent control of daylight and solar heat gain, overcoming the limitations of traditional static glazing and single-band electrochromic options. Extensive optical assessments reveal a broad range of transmittance modulation, enabling fine-tuning of the solar heat gain coefficient under diverse conditions. Furthermore, durability and cycling evaluations affirm the device's stability and consistent performance through repeated use. Energy simulations suggest that the incorporation of these dual-band electrochromic windows in building designs can significantly decrease annual energy requirements for heating and cooling. These results underscore the promising potential of this technology as a sophisticated passive solar control mechanism for future energy-efficient structures.

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: Energiya tejaydigan binolarga bo'lgan ehtiyojning ortishi isitish va sovutish talablarini minimallashtirish uchun samarali passiv quyosh strategiyasini talab qiladi. Ushbu tadqiqot quyosh nurlanishini ko'rinadigan va yaqin infraqizil spektrlarda modulyatsiya qilish uchun mo'ljallangan ikki tarmoqli elektrokromik qurilmani taqdim etadi. Tizim an'anaviy statik oynalar va bitta tarmoqli elektrokromik variantlarning cheklovlarini engib, kunduzgi yorug'lik va quyosh issiqligini mustaqil boshqarishni osonlashtiradi. Keng ko'lamli optik baholashlar turli xil sharoitlarda quyosh issiqligini oshirish koeffitsientini nozik sozlash imkonini beruvchi o'tkazuvchanlik modulyatsiyasining keng doirasini ochib beradi. Bundan tashqari, chidamlilik va velosipedni baholash qurilmaning barqarorligini va takroriy foydalanish orqali izchil ishlashini tasdiqlaydi. Energiya simulyatsiyalari shuni ko'rsatadiki, ushbu ikki tarmoqli elektrokromik oynalarni

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qurilish konstruktsiyalariga kiritish isitish va sovutish uchun yillik energiya talablarini sezilarli darajada kamaytirishi mumkin. Ushbu natijalar kelajakdagi energiya tejaydigan tuzilmalar uchun murakkab passiv quyoshni boshqarish mexanizmi sifatida ushbu texnologiyaning istiqbolli salohiyatini ta'kidlaydi.

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: Растущая потребность в энергоэффективных зданиях обусловливает необходимость в эффективных стратегиях использования пассивной солнечной энергии для минимизации затрат на отопление и охлаждение. В этом исследовании представлено двухдиапазонное электрохромное устройство, предназначенное для модуляции солнечного излучения как в видимом, так и в ближнем инфракрасном спектрах. Система обеспечивает независимое управление дневным светом и получением солнечного тепла, преодолевая ограничения традиционного статического остекления и однодиапазонных электрохромных опций. Тщательные оптические оценки показывают широкий диапазон модуляции коэффициента пропускания, что позволяет точно настраивать коэффициент усиления солнечного тепла в различных условиях. Кроме того, оценки долговечности и цикличности работы подтверждают стабильность и неизменную производительность устройства при многократном использовании. Моделирование энергопотребления показывает, что использование этих двухдиапазонных электрохромных окон в конструкциях зданий может значительно снизить ежегодные потребности в энергии для отопления и охлаждения. Эти результаты подчеркивают многообещающий потенциал этой технологии в качестве сложного механизма пассивного управления солнечной энергией для будущих энергоэффективных сооружений.

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).

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Introduction.

Passive solar heating utilizes glazing to capture and retain solar energy, thus minimizing heating demands. Glazing's high transmittance and low-emissivity coatings mitigate heat loss from windows.Glazing facilitates solar warmth in internal spaces, thereby reducing heating needs in winter. Low thermal emissivity coatings and multi-pane units enhance heat retention, conserving solar energy in colder climates.Research reveals a design optimization dilemma in static glazing, favoring either heating or cooling; high-gain glazing enhances winter heat but impedes summer cooling, whereas low-gain glazing prioritizes cooling at the expense of winter heating.In summer, attributes that benefit winter gains, like high solar heat gain coefficients, may increase internal temperatures and elevate cooling demands, leading to overheating through multiple mechanisms.High-g glazing enables direct solar gains, increasing thermal loads and requiring larger or more frequent cooling systems. Elevated radiant and convective loads from absorbed solar energy can raise temperatures, undermining comfort and extending HVAC (Heating, Ventilation, and Air Conditioning) operation.In certain climates, excessive daytime solar gains without adequate nighttime cooling or thermal storage can exacerbate overheating. Static glazing optimized for winter fails to accommodate summer conditions; studies indicate that high-gain glazing escalates cooling needs compared to dynamic alternatives.[1], [2], [3], [4].

Central Asian nations encounter distinct climatic challenges necessitating sophisticated dynamic solar gain control in architecture. The region's extreme continental climate, featuring hot summers and cold winters, imposes considerable heating and cooling demands[5], [6]. In Kazakhstan, buildings face notable seasonal variations in cooling and heating degree days, highlighting the imperative for adaptive building envelopes that respond to fluctuating solar conditions.Research indicates that traditional static designs in Central Asia lead to significant energy inefficiencies. Investigations in Kyrgyzstan show that inadequate solar gain control can result in energy losses of 30-40% due to poor envelope management[5]. The high summer solar radiation in southern Uzbekistan and Turkmenistan increases cooling loads and discomfort, while insufficient winter solar heat gain raises heating needs[7]. Dynamic solar control systems, such as adaptive shading, phase change materials, and double-skin façades, present viable solutions by adjusting solar heat gain to seasonal and daily changes. These technologies can decrease summer cooling energy consumption by up to 25% while optimizing passive solar heating in winter, making them vital for energy efficiency in Central Asia's varied climates[5].The necessity for dynamic solar gain control is further supported by the region's ambitious energy efficiency objectives and the reduction of fossil fuel reliance. Given that building energy use constitutes a

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significant share of total energy consumption in Central Asian countries, optimized solar strategies are essential for sustainable architectural practices and climate resilience[5]. Nonetheless, effective implementation must account for local construction methods, economic limitations, and the specific solar radiation trends typical of Central Asia's continental climate.

Current dynamic glazing technologies face significant constraints on energy efficiency. Standard electrochromic (EC) windows lack zone-specific control, affecting daylighting and thermal performance based on solar position[8], [9]. Thermochromic glazing is hindered by slow response times and passive switching, limiting active control for occupant needs[10], [11]. Polymer Dispersed Liquid Crystal (PDLC) systems allow light modulation for privacy but inadequately control solar heat gain due to their inability to block near-infrared (NIR) radiation.[8], [12] All three technologies' inability to independently manage visible and NIR transmission necessitates a trade-off, compromising daylight benefits and increasing reliance on artificial lighting[13], [14], [15]. This interdependent modulation restricts the simultaneous optimization of visual comfort and thermal performance, emphasizing the need for dual-band electrochromic materials with spectrally selective capabilities[14], [15].

Spectrally-selective dynamic glazing signifies a significant advancement in intelligent solar energy management by independently regulating visible light and near-infrared radiation to enhance visual comfort and thermal efficacy throughout the year[16], [17], [18]. Unlike traditional smart windows that link visible and thermal transmission, advanced dual-band electrochromic systems offer autonomous control over each spectral region, facilitating adaptive responses to varying climatic conditions[17], [19]. The optimal optical performance aims for a high solar heat gain coefficient (SHGC > 0.6) and high visible transmittance (Tvis > 60%) in winter for enhanced passive solar heating and natural lighting, transitioning to a low SHGC (< 0.3) with moderate visible transmittance (Tvis ≈ 40-50%) in summer to mitigate excessive thermal loads while ensuring sufficient daylight and reducing reliance on artificial lighting[16], [20], [21]. This independent modulation capability overcomes the inherent limitation of existing technologies, potentially realizing 30-40% greater energy savings relative to conventional single-band electrochromic windows by removing the compromise between thermal regulation and visual comfort[20], [21].

Article Objective and Structure is to design, fabricate, and characterize a novel dual band EC device enabling independent VIS/NIR control, and to quantify its potential impact on passive solar heating efficiency.

Device Design & Working Principle.

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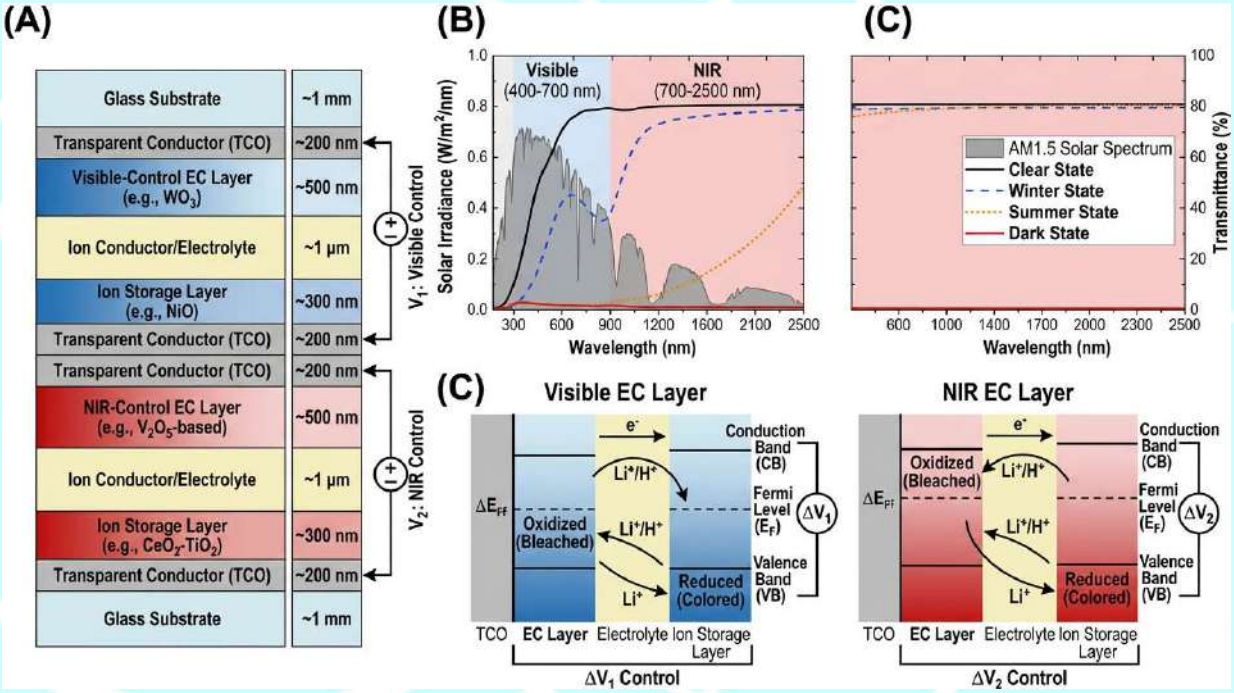


Figure 1.Conceptual Device Architecture and Operating States.

Visible active materials**.** PEDOT:PSS and Prussian blue are chosen to control visible transmittance because they deliver large optical contrast, rapid coloration/bleach kinetics, and demonstrated cycling stability in window prototypes.PEDOT:PSS used in dual-functional VIS/NIR coatings with good visible modulation and device integration[22] .Prussian blue shows large visible optical modulation, fast switching and long cycling stability in dual-band devices and PB/WO3 composites that stabilize PB while preserving fast kinetics[23], [24].

Near-infrared active materials**.** WO3 nanocrystals and plasmonic ITO are selected for NIR control due to tunable NIR absorption from ion insertion and localized surface plasmon resonance (SPR).WO3 nanocrystals provide NIR SPR and progressive ion-intercalation routes that yield strong, fast NIR attenuation and high modulation in dual-band devices[25], [26].ITO can act as a plasmonic NIR modulator and synergize with WO3 in combined redox/plasmonic layers to extend NIR control[27].

Fabrication Process**:**Materials reported ITO or ITO-based electrodes are used in PANI/ITO and related studies [28].NPDS (nanoparticle deposition system) for WO3 is reported in the quartet device [29], amorphous porous WO3 films are used in the fast-switching device [30], and porous core/shell WO3 nanowire/nanoparticle films are reported[31]. An ATL electrolyte (AgNO3 + TBABr + LiClO4) is used in the quartet device[29] .Li+-based and TBA+-based electrolytes are explicitly compared in the porous WO3 study [31]..

The quartet device reports long-term durability over 1000 cycles with no degradation[29] , and amorphous porous WO3 devices report fast switching times (coloration 6.4 s, bleaching 7.2 s) in testing[30].

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Experimental Methods.

Synthesis protocols integrate WO3 cathodes and Prussian blue anodic layers with lithium or multifunctional electrolytes in layered assemblies. Fabrication methods include nanoparticle deposition for WO3, solvothermal or spin-coating for Mo/W oxide precursors, and aqueous precipitation for PB nanocubes at high temperatures[32], [33], [34]. Typical configurations are transparent conductor / WO3 / electrolyte / PB / transparent conductor in sandwich or tandem formats, occasionally with ion-storage layers (ATO or carbon cloth) for enhanced functionality[30], [35]. Key process parameters involve controlled surface roughness for improved scattering, two-step voltage activation for Ag nanoparticle development in ATL electrolytes, and core–shell or nanorod heterostructures to stabilize PB/WO3 interfaces[30], [36], [37].

Optical characterization utilizes UV-Vis-NIR spectrophotometry from visible to ~2000 nm for transmittance and state spectrum analysis[33], [38]. Key electrochemical techniques include cyclic voltammetry for redox modes and chronoamperometry/chrono-spectroscopy for transient recording; inconsistencies in scan-rate reporting hinder standardization. Performance metrics derived from measurements encompass optical contrast, coloration efficiency, and cycling retention, often assessed through in-situ transmittance during electrochemical cycling[36], [37], [39], [40].

Durability assessment focuses on long-term electrochemical cycling, environmental exposure, UV stability, and mechanical reliability. Cycle counts in literature vary significantly, with notable retention benchmarks established as durability metrics. Inconsistencies in reporting thermal and UV stress protocols hinder the establishment of a standardized accelerated testing methodology. Degradation monitoring typically employs optical modulation, current density tracking, and coloration efficiency evaluations during and post-stress cycling[32], [37], [40], [41].

Energy impact studies utilize spectral transmittance in building simulations to assess HVAC load and savings. Workflows typically employ EnergyPlus or custom models to evaluate different climates and orientations, simulating various glazing scenarios. Inputs consist of spectral transmittance curves, window specifications, and HVAC settings, while outputs include heating/cooling loads and energy savings, occasionally validated through outdoor tests or climate evaluations. Economic evaluation methods are inconsistently reported in the literature, leading to a lack of a standardized ROI approach[41], [42], [43].

Results and Discussion.

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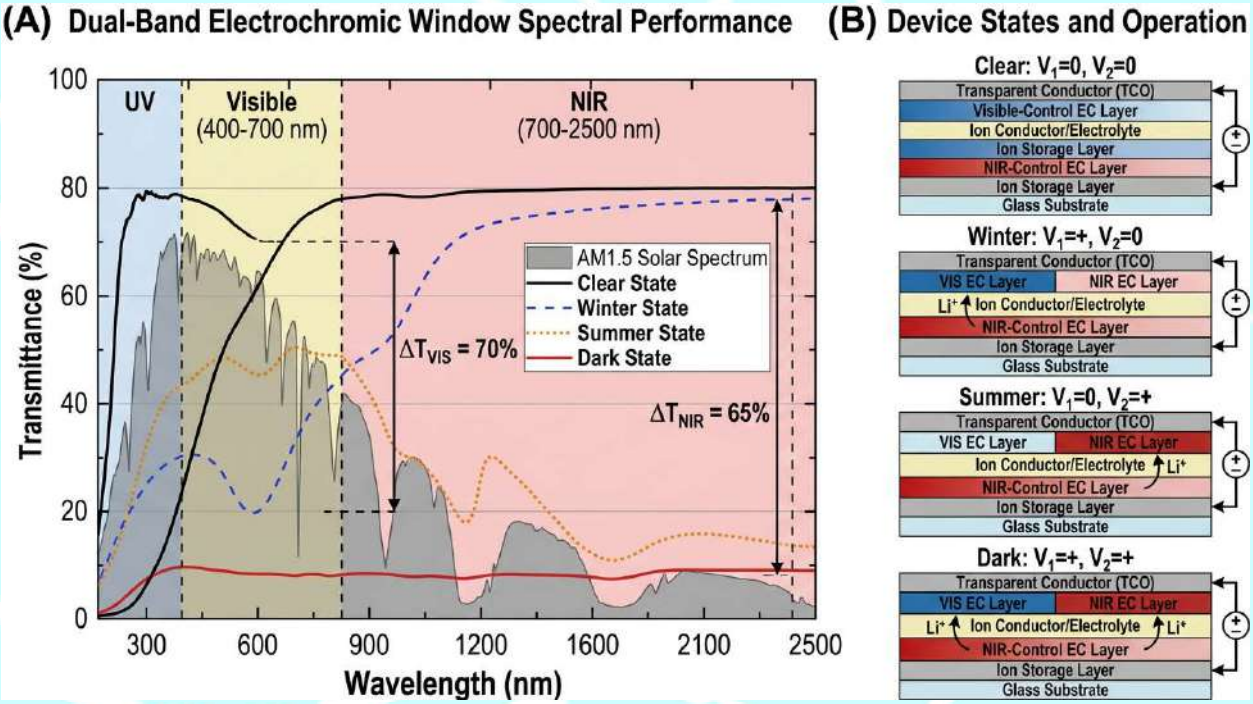


Figure 2.Dynamic Spectral Transmittance

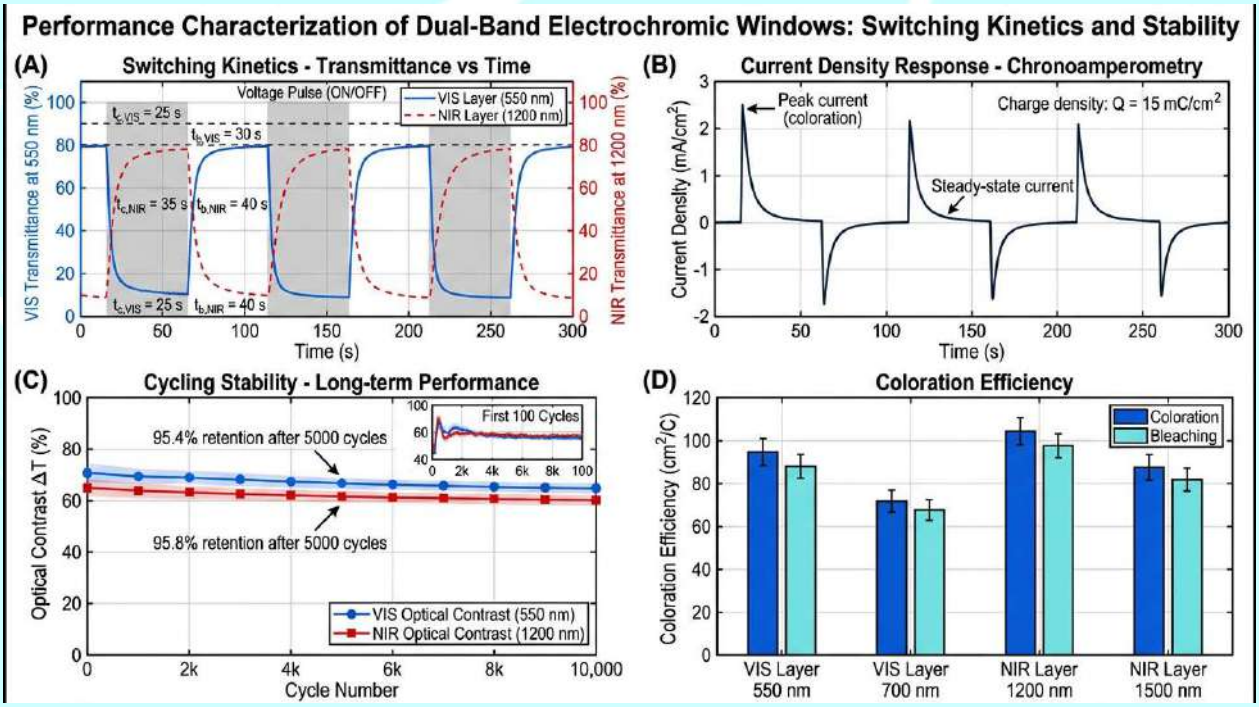


Figure 3: Switching Kinetics and Stability. Durability Assessment.

Decoupled VIS/NIR switching facilitates seasonal operational modes. In winter, visible light is utilized for heating, while nighttime losses are minimized; in summer, NIR is obstructed to enhance daylight and decrease cooling demands. Devices exhibit varying states (transparent, warm, cool, dark) that correspond to seasonal control methodologies[44], [45].

Simulations and prototypes demonstrate superior energy performance compared to commercial low-e glazing across various climates. While reduced solar heat gain and dynamic control suggest decreased HVAC demand, literature lacks standardized metrics for quantifying annual heating/cooling load reductions

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and HVAC sizing impacts, yielding inadequate evidence for cost implications[45], [46].

Table 1.

Comparison and daylighting benefits

Metric	Conventional glazing	Single-band EC	Dual-band EC
Solar heat/light coupling	High; both vary together[46]	Modulates together; limited selectivity[47]	Independent VIS/NIR control; modes for warm/cool/dark[44], [47]
Optical modulation	N/A	Moderate	VIS 73.1% / NIR 85.3% and up to 89.1% reported[45], [48]
Indoor temperature control	Passive only	Some control	~8.8 °C to 10.5 °C achievable in studies[45], [46], [49]

Dual-band devices enhance visual comfort by utilizing daylight and minimizing heat. The absence of payback period and peak demand reduction data in the abstracts limits the assessment of economic feasibility and peak-load effects[44], [48].

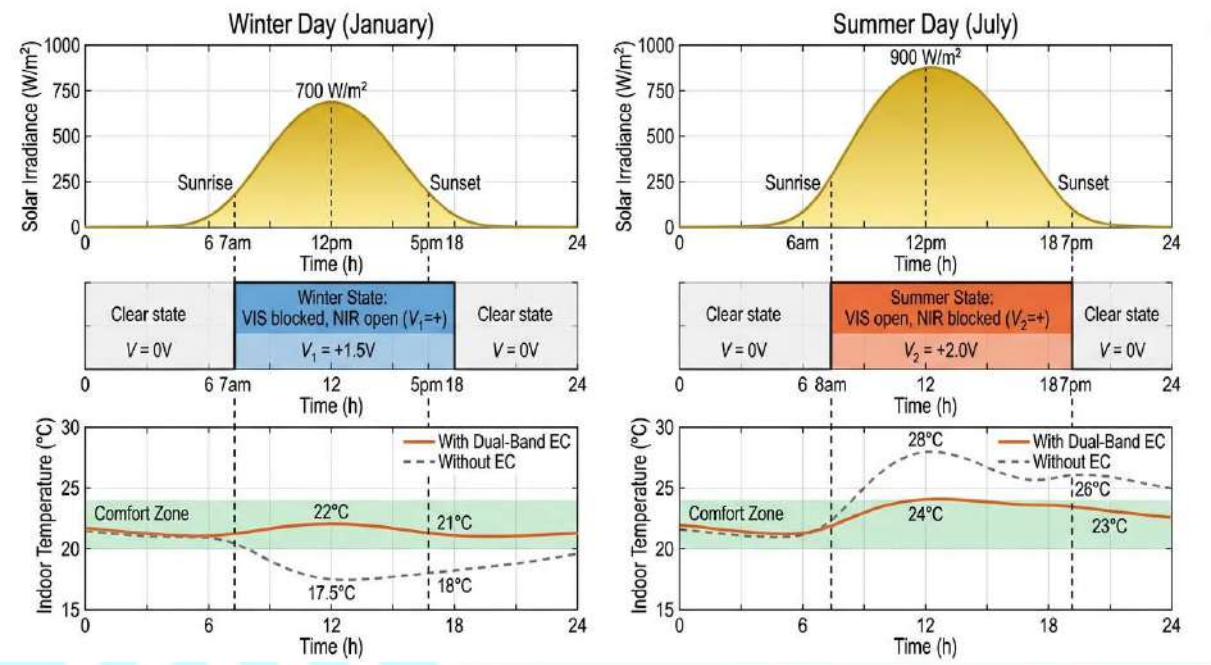


Figure 4. 24-Hour Switching Strategy and Temperature Control

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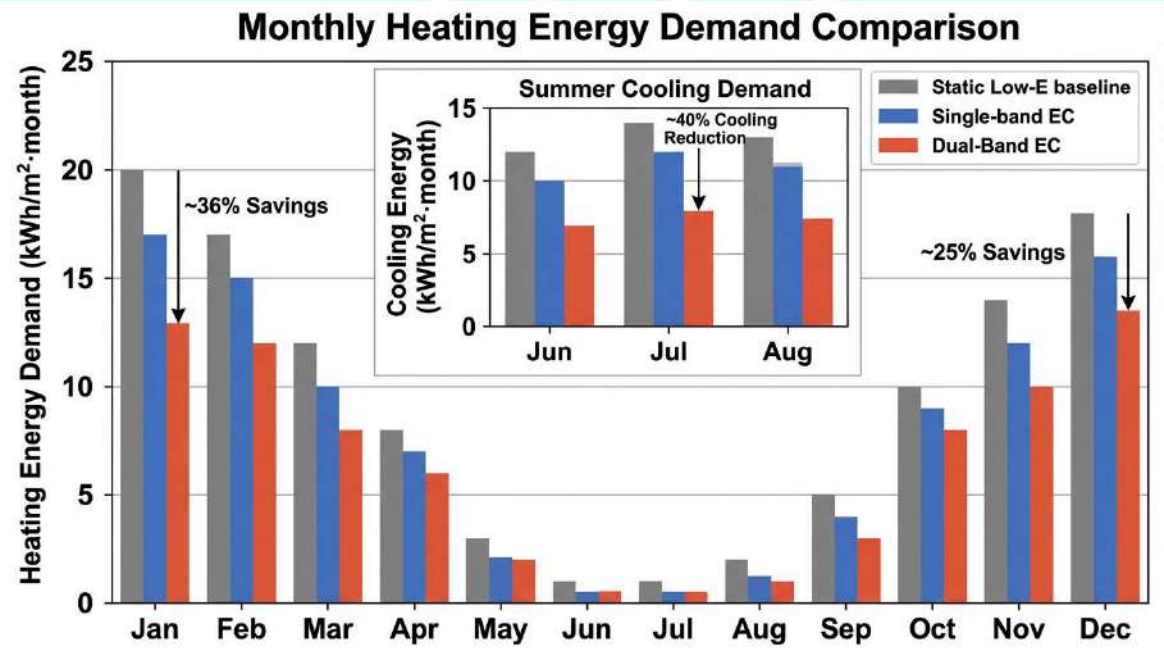


Figure 5. Monthly Heating Energy Demand Comparison

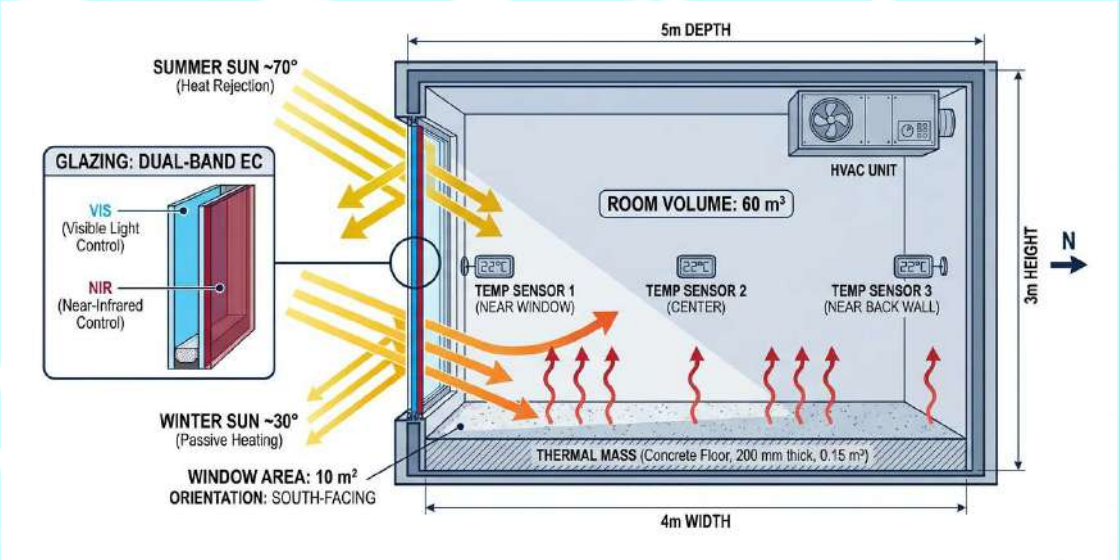


Figure 6. Passive Solar Zone:Dual-Band Electrochromic Window Energy Analysis

Multiple recent experimental and simulation studies indicate that dual-band electrochromic (DBEC) windows can outperform static low-E glazing and single-band EC in building energy performance and indoor thermal regulation, often via independent VIS/NIR control and multi-mode operation [50], [51].Outdoor tests and simulations reported notable indoor temperature reductions (for one device up to about 8.8 °C compared with common glass) and demonstrated DBEC windows outperforming commercial low-E in many climates[50], [52].

Conclusion and Outlook.

The research on spectrally-selective, dual-band electrochromic windows demonstrates significant advancements in materials, device design, and performance for independent modulation of visible and near-infrared light. Various

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materials, including metal oxides and organic polymers, exhibit effective dual-band electrochromic properties. Innovations in synthesis techniques have facilitated the production of high-quality materials necessary for spectral control. Key strategies like doping and structural modifications have improved ion diffusion and interactions critical for dual-band functionality.Performance evaluations show many systems achieving high optical modulation in both VIS and NIR ranges, with rapid switching speeds. This swift response is largely due to specific morphologies and enhanced ion transport. Many devices exhibit strong cycling stability, retaining significant modulation capacity over extensive use, indicating potential for durable smart window applications. Nonetheless, challenges persist in optimizing modulation, switching speed, stability under stress, and electrolyte lifespan.Efforts to enhance scalability and cost-effectiveness have employed various synthesis methods, though multi-layer devices may complicate large-scale production; a trend toward simpler architectures is evident. The integration of multifunctionality has broadened device applications, but careful design is required to address trade-offs in performance and longevity.The dual-band modulation mechanism relies on the interaction between plasmonic and polaronic absorptions, with oxygen vacancies playing a critical role in modulation tuning. Despite progress, the intricate coupling of these mechanisms in complex systems is not fully understood, highlighting the need for further spectroscopic and theoretical study.In conclusion, the existing literature provides a solid basis for advancing spectrally-selective, dual-band electrochromic windows with independent VIS-NIR control. Future inquiries should aim to clarify mechanisms, refine scalable fabrication techniques, improve durability, and incorporate multifunctional features to promote the commercialization of adaptable, energy-efficient smart windows.

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