

Sequential optical modulation in smart glazing: A hierarchical thermochromic strategy for climate-adaptive building envelopes

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- A hierarchical thermochromic window sequentially regulates near-infrared (NIR) and visible light.
- Across 3,600+ global administrative units, 96% and 79% exceeded 30% cooling and total energy savings.
- Sequential switching balances cooling, heating, and lighting while keeping over-illumination below 10%.
- A vanadium dioxide (VO₂)-hydrogel prototype verified staged optical switching over 50 thermal cycles.

Sequential optical modulation in smart glazing: A hierarchical thermochromic strategy for climate-adaptive building envelopes

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Thermochromic glazing can passively regulate solar gains, but single-response systems often trade solar-heat rejection against daylight preservation. Here we propose a hierarchical response composite window that sequentially activates near-infrared (NIR) and visible-light modulation: a 28 °C VO₂ layer first limits NIR heat transmission, whereas a 40 °C hydrogel introduces stronger broadband attenuation only under intense solar thermal stress. Within a simulation-first, prototype-verified reverse-design framework, literature-derived optical spectra were implemented in Energy-Plus, validated against full-scale measurements (indoor-temperature RMSE = 0.45 °C), and assessed across more than 3600 global administrative units, 370 Chinese municipal-level units, and representative hot, mixed, and cold climates. Globally, 96% and 79% of valid units achieved cooling and total energy saving rates above 30%, respectively. In China, the composite window delivered mean cooling and total energy saving rates of 32.18% and 11.45%, with 84.1% of units exceeding 20% cooling savings. Matched-parameter controls further showed that sequencing improves the annual balance among cooling, heating, and lighting rather than maximizing cooling savings alone. It also suppressed over illumination to below 10% and improved useful daylight availability. Prototype spectra verified a VO₂-dominated NIR-first state followed by hydrogel-dominated broadband attenuation, while more than 50 thermal cycles confirmed short-term reversible operation. These results establish sequential thermochromic regulation as a climate-aware design principle for reconciling energy and daylighting demands in adaptive glazed façades.

INTRODUCTION

The building sector stands at the forefront of global decarbonization efforts, accounting for approximately 30% of global final energy consumption and nearly 40% of total CO₂ emissions.^{1,2} Within the building envelope, windows represent the most thermally vulnerable component, acting as the primary pathway for unwanted heat gain in summer and heat loss in winter.³ In modern commercial buildings, large-area transparent facades and curtain walls have become a defining architectural feature, amplifying this thermal vulnerability and placing enormous pressure on HVAC systems. While modern glazing technologies⁴ such as Low-E coatings and inert gas insulation have significantly improved static thermal insulation,^{5,6} they lack the adaptability to respond to dynamic environmental changes.⁷ Consequently, a substantial portion of building energy, particularly that consumed by heating, ventilation, and air conditioning (HVAC) systems, is used to counteract the thermal loads imposed by transparent facades. To address this, smart windows capable of dynamically modulating solar radiation transmission have emerged as a critical solution for next-generation green buildings. Among various dynamic technologies,^{8,9} thermochromic smart windows^{10,11} have garnered significant attention due to their passive, self-adaptive nature, which requires no external energy input or complex control systems.^{12–14} Recent studies have further extended VO₂-based thermochromism from solar-transmission control to temperature-adaptive long-wave radiative regulation.¹⁵

Currently, Vanadium Dioxide (VO₂) and hydrogels represent the two dominant classes of thermochromic materials, yet each suffers from intrinsic physical limitations when applied individually. VO₂ is a well-established near-infrared (NIR) modulating phase-change material^{16,17} that undergoes a

reversible metal-insulator transition at a critical temperature. Through doping strategies and multilayer engineering, its transition temperature can be reduced to near-ambient levels and its luminous transmittance (T_{lum}) improved.^{18–23} However, VO₂ primarily regulates the NIR spectrum; in hot climates with high solar altitude, the visible portion of the solar spectrum continues to contribute significantly to indoor heat gain, limiting its total energy-saving potential.²⁴ Conversely, thermochromic hydrogels^{25–27} utilize a hydrophilic-to-hydrophobic²⁸ transition to modulate light via scattering. Upon reaching their Lower Critical Solution Temperature (LCST),²⁹ hydrogels typically transition from transparent to opaque, blocking both heat and visible light indiscriminately.^{30,31} Recent efforts to incorporate nanoparticles or functional groups and enhance mechanical robustness have improved hydrogel performance, yet the fundamental “all-or-nothing” switching behavior persists, leading to excessive shading that forces occupants to rely on artificial lighting and compromises visual connection to the outdoors. The fundamental contradiction is clear. VO₂ provides insufficient total solar blocking (“under-shading”) while hydrogels sacrifice daylighting (“over-shading”).

To overcome these complementary limitations, we propose a “Hierarchical Response Composite Window” concept that integrates VO₂ and hydrogel layers into a single optical system to decouple the regulation of NIR and visible light.^{32,33} By leveraging the differential phase transition temperatures of the two materials, a sequential, relay-style modulation mechanism can be created. The VO₂ layer activates first at a lower temperature (e.g., 28 °C) to block invisible NIR heat while preserving daylighting, and the hydrogel layer activates at a higher threshold (e.g., 40 °C) to provide glare protection and deep solar blocking only under extreme conditions. This 12 °C temperature interval creates an intermediate NIR-modulating state, allowing the window to preserve daylight under moderate thermal stress and provide stronger visible and solar attenuation only when the window temperature rises further. Rather than fully resolving the energy–daylighting trade-off, the hierarchical design aims to mitigate the under-shading and over-shading limitations of single-response thermochromic smart windows. Related adaptive thermal-management studies have likewise shown that coordinating temperature-dependent emissivity, radiative behavior, and multifunctional composite structures with operating conditions can reduce seasonal mismatch and broaden functional adaptability.^{34–36}

Despite the theoretical promise, a critical gap remains in transitioning from material concepts to building applications. In the early stages of novel multilayer optical architecture development, comprehensive experimental data for large-area applications are inherently limited. A simulation-first approach can therefore quantify building-level performance potential and identify application-driven material targets before extensive device fabrication. The current research landscape is largely fragmented, material scientists focus on nanoscale synthesis while building physicists often rely on purely theoretical simulations without corresponding device-level demonstrations.³⁷ To bridge this gap, this study adopts a “simulation-first, prototype-verified” reverse design framework, as shown in Figure 1. In this framework, all building-energy simulations use optimized optical parameters extracted from peer-reviewed literature and representing advanced thermochromic materials, rather than the measured properties of the present laboratory prototype. Two complementary simulation sets were established. The literature-benchmark comparison evaluates three independently selected thermochromic technology routes at global, China-wide, and representative-climate scales, whereas

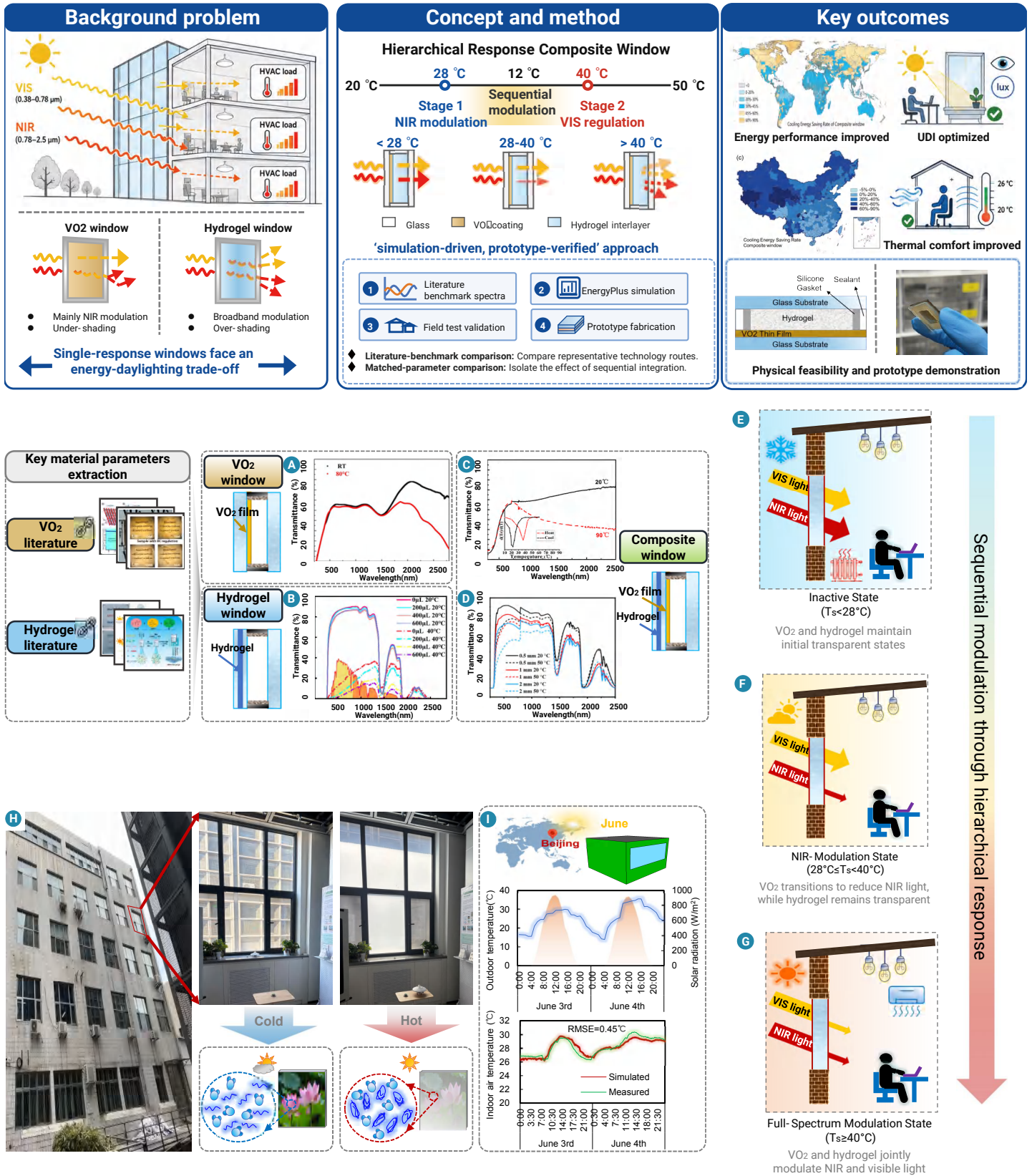


Figure 1. Research framework diagram. Literature datasets used to construct the thermochromic smart window models (lower) (A) Transmission spectra of the Mo–W co-doped VO₂ film used for the benchmark VO₂ window.³⁸ (B) Transmission spectra of hydrogel samples (W–VO₂ added 600 μL), used for the benchmark hydrogel window.³⁹ (C) Transmission spectra and transition parameters of VO₂ films at 20 °C and 90 °C, used in the hierarchical composite window and the matched VO₂ control.⁴⁰ (D) Transmission spectra of hydrogel samples (corresponding to a thickness of 2 mm), used in the hierarchical composite window and the matched hydrogel control.⁴¹ (E–G) Sequence modulation of VO₂–hydrogel composite window: (E) inactive state, (F) NIR-modulation state, (G) full-spectrum modulation state. Full-scale field measurements of the hydrogel-based thermochromic smart window. (H–I) Full-scale field measurements of the hydrogel-based thermochromic smart window: (H) Summer test-bed configuration showing the building site, the window's self-adaptive color change, and the sensor point. (I) Validated building simulation model and associated error analysis.

the matched-parameter comparison uses identical component datasets across Chinese municipalities to isolate the contribution of sequential inte-

gration. The thermochromic modelling framework is validated against full-scale field measurements of hydrogel-based thermochromic smart windows, with an indoor temperature RMSE of 0.45 °C. A composite prototype is subsequently fabricated to examine the physicochemical compatibility of the inorganic VO₂ film and thermoresponsive hydrogel and the feasibility of the laminated manufacturing process. Accordingly, the main contributions are to establish a sequential spectral-modulation concept, quantify its climate-dependent building-performance potential using literature-benchmark parameters, isolate the annual contribution of sequential integration through matched controls, and demonstrate the preliminary fabrication feasibility of the hierarchical composite architecture.

METHODOLOGY

Optical model construction based on literature benchmarks

The building-performance assessment was based on optical data reported for advanced thermochromic materials rather than on the optical properties of the current laboratory prototype. The prototype described in Section 4 was fabricated to examine physicochemical compatibility and assembly feasibility, whereas the literature data provide complete temperature-dependent spectra suitable for building simulation. Studies were screened for building-relevant transition temperatures, reliable spectra, and representative optical modulation. Figure 1A-D presents the four datasets selected from this survey, while the broader material screening is summarized in Tables S1 and S2.

The selected datasets serve two related purposes. The Mo-W co-doped VO₂ film and PNIPAM-based hydrogel define standalone literature benchmarks for representative single-response technologies. A second pair, comprising porous W-doped VO₂ with a lower transition temperature and an HPC/PVA hydrogel with a higher transition temperature, defines the hierarchical composite window. The same component pair is also used to construct matched-parameter single-response controls, allowing the effect of sequential integration to be assessed on a common material basis. The selection and configuration of these models are described in Sections 2.

Parameter acquisition for standalone literature-benchmark models.

The standalone VO₂ and hydrogel models represent two established single-response routes rather than the isolated components of the composite window. Within the literature survey described above, priority was given to datasets that combined a near-ambient transition temperature, complete temperature-dependent spectra, and strong optical performance as standalone glazing systems. These models provide a technology-level reference for comparing representative advanced VO₂ and hydrogel windows with the hierarchical composite under common building and climate conditions. Properties and selection of VO₂ and hydrogel materials are described in Supplementary Note 1.

For the benchmark VO₂ window model, we selected the Mo-W co-doped VO₂ film reported by Houimi et al.,³⁸ with the spectral data shown in Figure 1A and Table S1. Its transition temperature of 36.8 °C lies close to the operating range of building glazing. Furthermore, the nanostructured surface of Mo/V/W acted as a light-harvesting medium, reducing the reflectance arriving from the VO₂ surface and acting as an antireflecting layer. Compared with the properties of other VO₂ films in Table S1, the data of Mo-W co-doped VO₂ film have considerable NIR modulation ability (T_{sol} decreases from 52.5% to 40.1%, corresponding to a ΔT_{sol} of 12.43%) and maintain high T_{lum} of approximately 54.6%.

For the benchmark hydrogel window model, the PNIPAM-based nanoparticle hydrogel developed by Guan et al.³⁹ served as the data source, the spectral source used is shown in Figure 1B and Table S2. It responds at 32 °C and changes from a highly transparent state (T_{lum} = 86.8%, T_{sol} = 83.6%) to a strongly attenuating state (T_{lum} = 7.9%, T_{sol} = 2.4%), yielding a ΔT_{sol} of 81.2%. This dataset represents a strong broadband single-response route, although its large visible-light change can impose substantial daylighting penalties.

These two models and the hierarchical composite window constitute the literature-benchmark comparison used for the global, China-wide, and representative-climate analyses in Section 3.

Configuration of the hierarchical composite window model. The hierarchical composite model requires a pair of materials with clearly separated activation temperatures. Directly combining the standalone benchmarks, with transition temperatures of 36.8 °C for VO₂ and 32 °C for the hydrogel, would

create overlapping transition ranges and would not produce a stable intermediate NIR-modulating state. The composite model therefore uses a different material pair selected for complementary transition thresholds and spectral functions.

For the VO₂ component of the composite system, we used the porous W-doped VO₂ film reported by Hu et al.⁴⁰ (Tables S1 and Figure 1C). Its transition temperature is 28 °C. Across the measured states, T_{lum} changes only slightly from 44.6% to 45.7%, whereas T_{sol} decreases from 49.4% to 42.5%, corresponding to a ΔT_{sol} of 6.9%. The lower activation threshold allows NIR regulation to begin under moderate glazing temperatures while largely retaining visible transmission.

For the hydrogel component, we selected the HPC/PVA dual-network hydrogel reported by Feng et al.⁴¹ (see Table S2 and Figure 1D for specific parameters), which has a higher transition temperature of 40 °C. Its T_{lum} decreases from 71.3% to 49.6% and T_{sol} from 65.2% to 50.7%, corresponding to a ΔT_{sol} of 14.5%. The 12 °C separation between the two component thresholds creates an intermediate state in which the VO₂ layer is active while the hydrogel remains in its high-transmittance state.

The composite window adopts a layered design, with VO₂ coated on the outer glass pane facing the exterior and the hydrogel encapsulated between the glass layers. This configuration maximizes the material-specific modulation effects while maintaining structural integrity. By integrating these specific datasets (VO₂ at 28°C and Hydrogel at 40°C), the composite window model operates through a unique three-stage mechanism, as illustrated in Figure 1E-G:

Stage I (Transparent State, $T_s < 28^\circ\text{C}$): In cool environments, both functional layers remain in their low-temperature states. The window maintains maximum transparency to both visible and solar radiation, facilitating passive solar heating and unobstructed outdoor views.

Stage II (NIR-modulation State, $28^\circ\text{C} < T_s < 40^\circ\text{C}$): As the window temperature enters the intermediate range, the VO₂ layer undergoes its metal-insulator transition to block NIR heat, while the hydrogel layer remains transparent. This stage effectively resolves the “daylighting-thermal contradiction” inherent in traditional windows, rejecting heat without compromising visual comfort.

Stage III (Full-spectrum modulation State, $T_s > 40^\circ\text{C}$): Under conditions of extreme heat or intense solar radiation, the hydrogel layer activates, turning the window opaque. This final stage provides maximum glare protection and deep cooling load reduction, prioritizing thermal safety during peak load periods.

Because the literature-benchmark comparison changes both window architecture and material parameters, it cannot by itself determine whether the composite window's performance arises from sequential integration or from favorable component selection. The same 28 and 40 °C datasets are therefore used to construct the matched VO₂ control and matched hydrogel control described in previous section. Holding the component spectra, transition temperatures, double-glazing construction, and building assumptions constant isolates the annual contribution of the two-stage response relative to either component operating alone.

Field measurement validation. To ensure the reliability of the subsequent building energy simulations, we first conducted an empirical validation comparing field measurements with EnergyPlus simulation results (Figure 1H&I). Capitalizing on the large-scale manufacturability of hydrogel technologies, full-scale commercialized hydrogel smart windows were installed in a south-facing office within a multi-story building at Tsinghua University, Beijing. Real-world physical tests were carried out in June 2025 to monitor the indoor thermal environment under the passive adaptive coloration of the windows.

A corresponding twin model was constructed in EnergyPlus to replicate the physical geometry and boundary conditions of the test room, with the simulation driven by real-time local weather data measured concurrently during the experimental period. The thermochromic response and dynamic optical performance of thermochromic smart windows were simulated via the Window Material Glazing Group Thermochromic module embedded in EnergyPlus. This module allows users to set temperature dependent optical characteristics including transmittance reflectance and absorptance under multiple discrete predefined temperature bands. At every simulation time step the

EnergyPlus computation engine first calculates the instantaneous surface temperature of the glazing. The engine then interpolates corresponding optical property values from the preset temperature states based on the calculated surface temperature. This real time interpolation dynamically updates the glazing optical parameters to represent the instantaneous phase transition state of thermochromic materials. The adopted modeling accurately integrates the thermal optical switching effect of thermochromic glazing on solar heat gain and indoor daylight performance into whole energy simulations. As illustrated in Figure 1H&I, the simulated indoor average temperature trends exhibited high fidelity to the measured data, the Root Mean Square Error (RMSE) between the two datasets was calculated to be only 0.45°C, which validates that the EnergyPlus model can precisely capture the complex thermal dynamics of thermochromic smart windows. Consequently, this validated methodology provides a foundation for the extensive climate adaptability simulations of the proposed VO₂-hydrogel composite windows in the following sections. Detailed building parameters are provided in Supplementary Note 2.

Multi-scale simulation settings

To systematically evaluate the application potential of the VO₂ window, hydrogel window and proposed hierarchical response composite window, a comprehensive simulation framework was established using EnergyPlus and Python. The simulation settings encompass the building geometry, the reconstruction of optical models based on literature benchmarks, and the climatic typologies.

Building model. A standardized single-zone office model was developed to isolate the impact of window performance from other variables. The model dimensions were set to 8 m (depth) × 8 m (width) × 3.5 m (height), representing a typical perimeter office module. A fixed south-facing window-to-wall ratio (WWR) of 0.9 was used for the global and China-wide simulations to represent large-area glazed façades under a consistent geometric condition. For the representative-city analysis, the south-facing façade served as the primary variable interface, with the WWR sweeping from 0.1 to 1.0 in increments of 0.1 to investigate the correlation between fenestration area and thermochromic efficiency.

The opaque envelope (walls, roof, and floor) was configured to meet the local energy efficiency standards for each simulated climate zone, ensuring that the baseline thermal insulation aligns with regional requirements. Internal heat gains, including occupancy density, lighting loads, and equipment power densities, with specific schedules provided in Table S3.

Thermochromic smart window configuration. Five thermochromic smart-window models were assembled within a common double-glazing framework, with clear glazing serving as the reference. The thermochromic function was incorporated into the outer smart pane, followed by the argon gap and inner glass layer specified in Supplementary Note 3. Pane thicknesses, gas gaps, thermal transmittance, building geometry, WWR, internal-load schedules, HVAC settings, lighting control, and weather inputs were held consistent within each comparison. The low- and high-temperature spectra were imported through the EnergyPlus WindowMaterial:Glazing:SpectralData object.

The models formed two complementary analysis sets. The literature-benchmark comparison included the benchmark VO₂ window with a transition temperature of 36.8 °C, benchmark hydrogel window with a transition temperature of 32 °C, and the hierarchical composite window with sequential transitions at 28 and 40 °C. These models represent three advanced thermochromic technology routes and were evaluated at the global, China-wide, and representative-climate scales.

The matched-parameter comparison included the matched VO₂ control (28 °C), matched hydrogel control (40 °C), and the same hierarchical composite window (28/40 °C). The component spectra, transition temperatures, double-glazing construction, and building assumptions were held constant to isolate the contribution of sequential integration. The optical sources, transition temperatures, and simulation scopes of the five models are summarized in Table S4. The matched controls were evaluated across Chinese municipalities.

Climate selection. To comprehensively evaluate the climate adaptability of the hierarchical composite window, a three-tier multi-scale simulation frame-

work was designed. At the broadest scale, a global simulation encompassing over 3600 primary administrative regions worldwide was conducted to map the theoretical energy-saving potential across the full spectrum of global climatic conditions. At the national scale, China was selected as the primary testbed for broad climatic applicability analysis due to its vast territory covering all major ASHRAE climate zones, from the hot-humid south to the cold-arid north, making it an ideal proxy for evaluating climate-adaptive performance. Simulations were conducted for all Chinese municipalities. Finally, three representative cities: Abu Dhabi (ASHRAE Climate Zone 1B), Chicago (ASHRAE Climate Zone 5A), and Oslo (ASHRAE Climate Zone 6A) were selected for in-depth parametric discussions regarding the trade-offs between cooling, heating, and lighting energy consumption across a range of window-to-wall ratios (WWR = 0.1 to 1.0), as well as the dynamic optical response behavior and indoor environmental quality. Detailed climate parameters for simulation regions are provided in Figure 2 and Table S5 and S6.

Evaluation metrics. The simulation and performance evaluation framework was developed to comprehensively characterize the behavior of different thermochromic materials and configurations under varying conditions. The evaluation covers three dimensions: (1) energy performance, assessed in terms of annual cooling, heating, electric-lighting, and total energy savings; (2) daylighting quality, evaluated using Useful Daylight Illuminance (UDI) with thresholds of 500 and 2000 lux; and (3) thermal comfort, characterized by the annual probability density distribution of operative temperature.

Energy savings were calculated relative to the clear-glazing reference. In particular, the Cooling Energy Saving Rate (CESR) and Total Energy Saving Rate (TESR) were determined using Equations (1) & (2), respectively.

$$CESR_i = \frac{E_{cool,clear,i} - E_{cool,smart,i}}{E_{cool,clear,i}} \times 100\% \quad (1)$$

$$TESR_i = \frac{E_{total,clear,i} - E_{total,smart,i}}{E_{total,clear,i}} \times 100\% \quad (2)$$

where E_{cool} is the annual cooling energy use, and E_{total} is the sum of annual cooling, heating, and electric-lighting energy use. The subscripts "clear" and "smart" denote the clear-glazing reference and the evaluated thermochromic configuration, respectively. Positive CESR and TESR values indicate lower energy use than the clear-glazing reference.

RESULTS

Global performance of literature-benchmark technologies

To evaluate climate adaptability at the broadest spatial scale, the three literature-benchmark technologies were simulated for more than 3600 first-level administrative units worldwide. Each unit was represented by a city-specific EnergyPlus weather (EPW) file containing the local outdoor-temperature and solar-radiation conditions.

As shown in Figure 3A–C, the three technologies produced distinct cooling-energy patterns because their optical states were activated over different surface-temperature ranges. After the 36.8 °C transition of the benchmark VO₂ window, T_{sol} decreases from 52.5% to 40.1%, while T_{lum} remains at 54.6% in both states. This NIR-selective response preserves daylight, but the relatively high threshold limits the annual operating period, especially in mild climates. The benchmark hydrogel window switches at 32 °C from a highly transparent state (T_{lum} = 86.8%, T_{sol} = 83.6%) to strong broadband attenuation (T_{lum} = 7.9%, T_{sol} = 2.4%). This response provides effective solar rejection in tropical and subtropical climates, with 55% of the modeled units achieving CESR values above 30%, but frequent low-transmittance operation can increase electric-lighting demand and block useful winter solar gains. These penalties are reflected in the TESR map in Figure 3E. The benchmark VO₂ window avoids severe daylighting loss, but its selective regulation is insufficient to produce TESR values above 30% in more than 2% of the modeled units, as shown in Figure 3D.

The hierarchical composite window provides a two-stage response using the 28 °C VO₂ and 40 °C hydrogel component datasets. For the VO₂ component, T_{sol} decreases from 49.4% to 42.5%, while T_{lum} changes only slightly from 44.6% to 45.7%. For the hydrogel component, T_{sol} decreases from 65.2% to 50.7% and T_{lum} from 71.3% to 49.6%. The intermediate state therefore regulates near-infrared heat while retaining daylight, whereas the additional

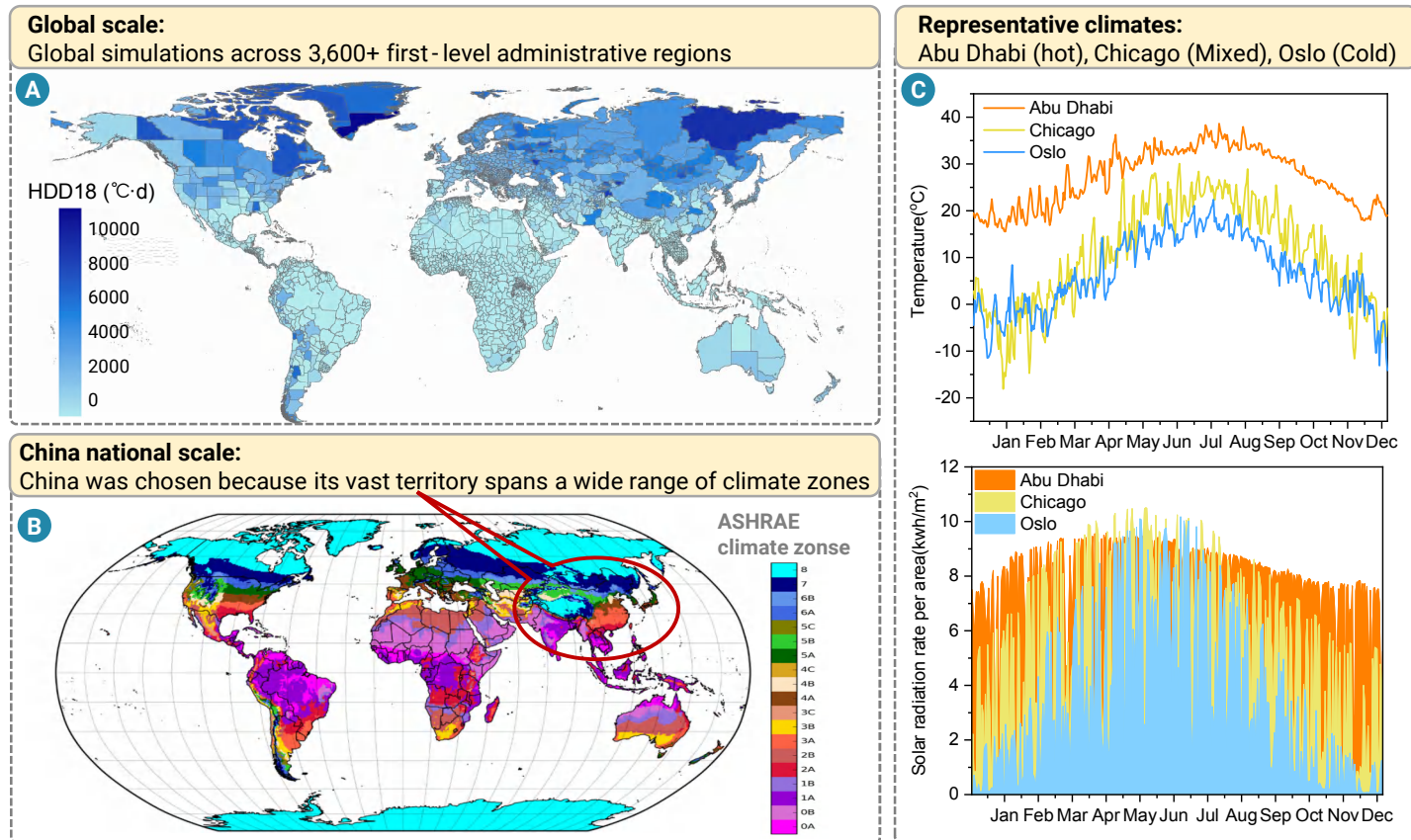


Figure 2. Meteorological conditions in different climate zones (A) Global HDD18 map illustrating regional climatic variability. (B) Distribution of ASHRAE climate zones showing the wide climatic span in China. (C) Outdoor air temperature and solar radiation trends for three representative cities.

broadband attenuation is introduced mainly during periods of stronger thermal stress. As shown in Figure 3C&F, 96% of the valid administrative units achieved CESR values above 30%, and 79% achieved TESR values above 30%. These percentages were calculated as the number of valid units exceeding the corresponding 30% threshold divided by the total number of valid simulated units. They represent unweighted shares of administrative units rather than fractions of global land area, population, or building stock. The broader spatial coverage indicates that sequential activation better reconciles solar-heat rejection with heating and daylighting demands across contrasting climates.

China-wide performance of literature-benchmark technologies

As shown in Figure 4, the China-wide analysis covered 370 mapped city-level administrative units using the EPW weather file assigned to each unit. The benchmark VO₂ and hydrogel windows represent independently selected single-response technology routes. The composite window achieved a mean CESR of 32.18%, and 311 units (84.1%) exceeded 20% cooling savings. By comparison, the benchmark VO₂ and hydrogel windows achieved mean CESR values of 24.40% and 14.54%, with 60.8% and 8.9% of the units exceeding 20%, respectively. The complete distributions, including median values and ranges, are summarized in Table S7.

The spatial contrast in Figure 4A–C reflects the interaction between local climate, glazing surface temperature, and optical-state duration. Relative cooling savings were generally higher in northern and northwestern China, including Qinghai, Gansu, Shanxi, Inner Mongolia, Ningxia, and Xinjiang, where strong solar exposure can drive the glazing above its transition threshold even though the annual cooling season is comparatively short. These percentage savings should therefore be interpreted together with the local baseline cooling demand. For the benchmark VO₂ window, the 36.8 °C threshold confines an NIR-selective decrease in T_{sol} from 52.5% to 40.1% mainly to the hottest hours, while T_{lum} remains at 54.6%. The benchmark hydrogel window activates at 32 °C and produces a much larger broadband

change. Its frequent near-opaque state reduces solar gain but raises electric-lighting demand and the associated internal heat, limiting net cooling savings. In the composite window, the 28 °C VO₂ component provides the first-stage NIR response (T_{sol} : 49.4% to 42.5%), whereas the 40 °C hydrogel component adds a later broadband response (T_{sol} : 65.2% to 50.7%; T_{lum} : 71.3% to 49.6%). This staged response extends the moderate-control period while reserving deeper shading for stronger thermal stress, explaining its broader 20–45% CESR distribution and its higher CESR than the benchmark VO₂ window in every mapped unit.

When cooling, heating, and lighting were combined, the spatial pattern shifted toward southern and eastern China and high-radiation mild climates such as Yunnan, as shown in Figure 4D–F. In these regions, the longer cooling season allows solar-heat rejection to outweigh the accompanying lighting and heating penalties. The composite window achieved the highest mean TESR of 11.45%, followed by 10.09% for the benchmark VO₂ window and 2.62% for the benchmark hydrogel window. TESR exceeded 10% in 69.5% of the mapped units for the composite window, compared with 64.9% and 1.6% for the two-benchmark single-response windows. The composite configuration ranked first in 268 units because the intermediate near-infrared state preserves more useful daylight than the hydrogel window while extending solar control beyond the shorter operating period of the benchmark VO₂ window. The benchmark VO₂ window remained preferable in some cold regions, where its higher transition temperature reduces activation during the heating season and better preserves beneficial winter solar gains.

Matched-parameter assessment of hierarchical integration

To test whether the advantage of the hierarchical composite window originates from sequential response rather than favorable material selection, the matched VO₂ control and matched hydrogel control were constructed using the same component spectra, transition temperatures, double-glazing construction, and building assumptions as the composite window. The matched VO₂ control activates only the 28 °C VO₂ response, while the

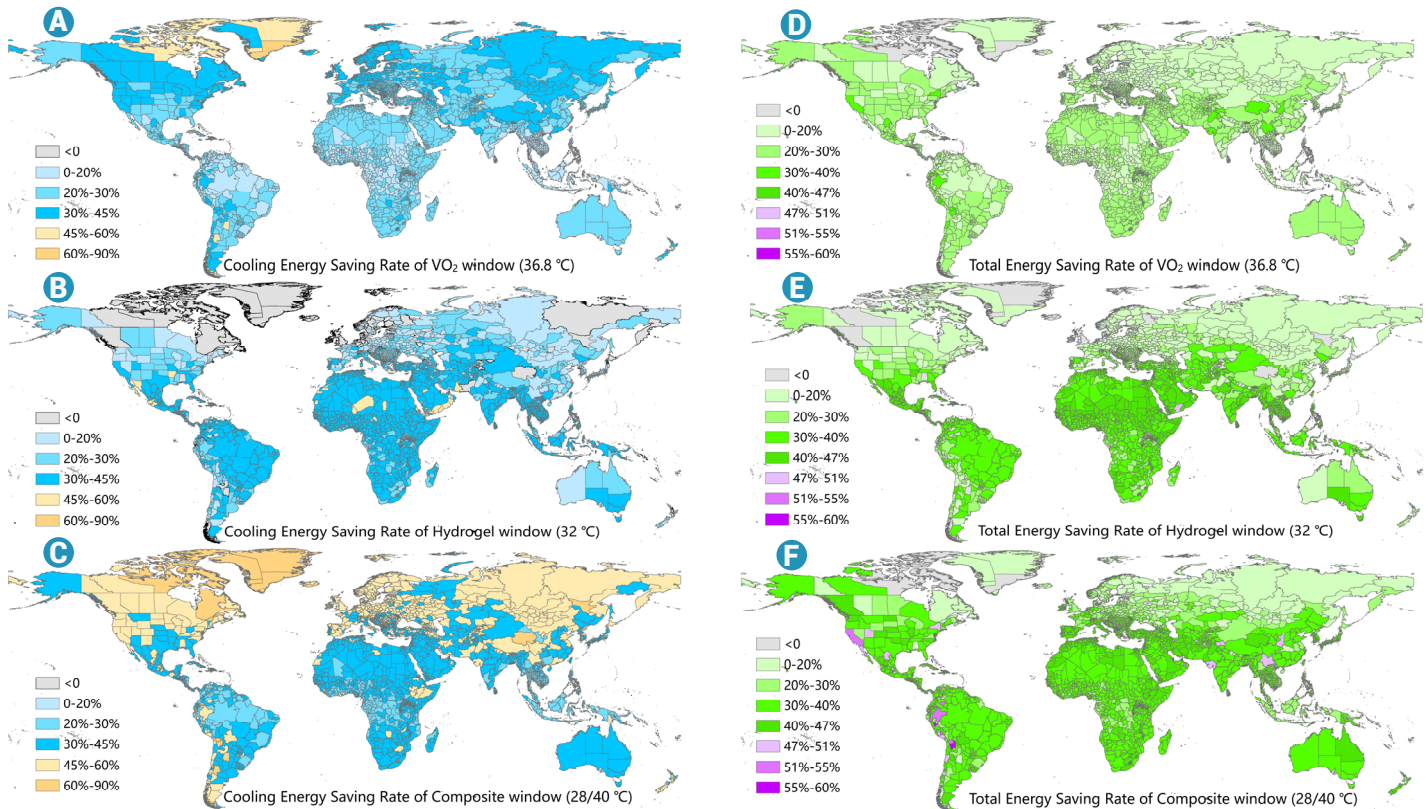


Figure 3. Global-scale evaluation of energy saving potential Spatial distribution of (A–C) annual Cooling Energy Saving Rate (CESR) and (D–F) annual Total Energy Saving Rate (TESR) for benchmark VO₂, benchmark hydrogel, and hierarchical composite windows across the globe relative to a clear window baseline.

matched hydrogel control activates only the 40 °C hydrogel response. The resulting China-wide distributions are shown in Figure S1.

As shown in Figure S1 A–C, the matched VO₂ and hydrogel controls achieved mean CESR values of 39.72% and 41.28%, respectively, and both exceeded 20% cooling savings in 99.2% of the mapped units. The composite window achieved a lower mean CESR of 32.18% and exceeded 20% in 84.1% of the units. The matched VO₂ control combines early activation at 28 °C with modest NIR-selective modulation; the matched hydrogel control activates at 40 °C and provides a stronger broadband change during the hottest surface-temperature conditions. The composite introduces both optical responses, but its high-temperature state also reduces daylight and increases electric-lighting use and associated internal heat. These effects offset part of the solar cooling benefit. Sequential integration therefore does not maximize cooling-energy savings in isolation.

The total-energy comparison shows a different outcome. As shown in Figure S1 D–F, the composite window achieved a mean TESR of 11.45%, compared with 9.27% for the matched VO₂ control and –0.69% for the matched hydrogel control. Positive total-energy savings occurred in 93.0%, 84.3%, and 57.6% of the mapped units, respectively. The composite outperformed the matched VO₂ control in 303 units and the matched hydrogel control in all 370 units. In northern heating-dominated regions, a single low-temperature response can block useful solar gains for too long, while broadband hydrogel switching can additionally increase lighting demand. In the composite window, the 40 °C hydrogel stage is mainly reserved for high-solar summer periods, adding stronger cooling control when it is most beneficial, while the intermediate state retains more daylight during moderate conditions. This sequencing reduces the negative TESR zones visible for the single-response controls and improves the annual balance among cooling, heating, and lighting. The matched-parameter results therefore confirm that the composite window's annual advantage is not solely attributable to the selection of more favorable material parameters.

Energy trade-offs in representative climates

Building energy consumption across different climate zones follows a

consistent pattern, as the WWR increases, total energy demand initially drops sharply before stabilizing (Figure 5). This trend underscores the critical trade-off between natural daylighting and artificial lighting; at higher WWRs, sufficient daylight reduces the energy penalty of indoor illumination.

According to Figure 5D, the relative energy-saving potential of the three thermochromic smart windows varies significantly by climate and WWR. In hot climates like Abu Dhabi, energy savings are negligible at low WWRs but increase markedly as the window area expands. The composite window outperforms the others at WWRs above 0.8, achieving a 17% saving rate at WWR 1.0, followed by the VO₂ window at 12% (Figure 5D). Conversely, hydrogel windows perform poorly in heat due to frequent opaque transitions. In the mixed climate of Chicago, energy savings are modest, only becoming apparent (3–5%) when WWR exceeds 0.8. In the cold climate of Oslo, where heating dominates, the VO₂ window is ineffective due to its low luminous transmittance (54.6%). Remarkably, the composite window performs worst in cold regions because its VO₂ component begins transitioning at a low 28°C, remaining in a gradual transition state up to 40°C. This prolonged opacity blocks beneficial passive solar heating. Consequently, the hydrogel window is the most viable option for cold climates.

Component-specific analysis reveals that composite windows offer the best cooling performance across all zones (Figure 5E), reaching energy-saving rates of 19% in hot zones and up to 62% in cold zones at WWR 1.0. However, at small WWRs (<0.3), all three thermochromic smart windows show negative cooling savings because the heat dissipated by necessary artificial lighting increases the cooling load. For heating (Figure 5F), hydrogel windows consistently deliver positive results in mixed and cold climates due to their high pre-transition transmittance. Regarding lighting (Figure 5G), all smart windows increase consumption compared to conventional glazing. The lighting penalty for hydrogel windows is most severe in hot climates, while composite windows exhibit the worst lighting performance in cold regions. In summary, composite windows are optimal for large-WWR buildings in hot and mixed zones due to superior cooling, while hydrogel windows are better suited for cold climates.

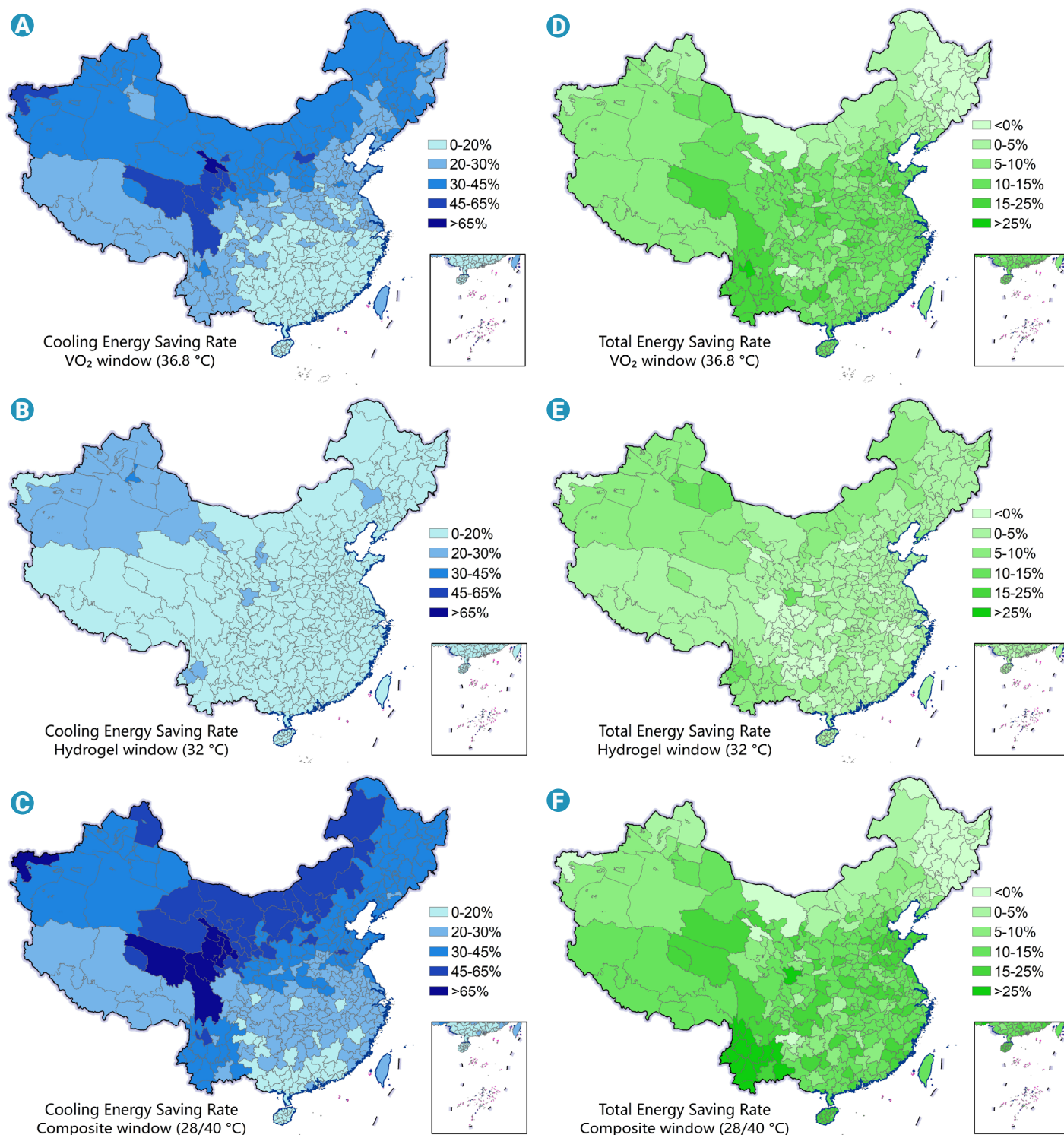


Figure 4. China-wide energy performance of the literature-benchmark thermochromic configurations Spatial distribution of (A–C) annual CESR and (D–F) annual TESR for benchmark VO₂, benchmark hydrogel, and hierarchical composite windows, relative to clear glazing. Hereafter, the benchmark VO₂ window, benchmark hydrogel window, and hierarchical composite window are referred to as the VO₂, hydrogel, and composite windows, respectively, unless otherwise specified.

Analysis of adaptive color-changing behavior

After a thorough investigation of the energy performance of various thermochromic smart windows, we have gained a comprehensive understanding of their macro-level performance. However, the energy-saving efficacy of smart windows fundamentally stems from the modulation properties of their materials. Understanding the dynamic optical response behavior is therefore essential for interpreting the energy performance results presented above. The coloration behavior of these materials not only influences the visual

appearance of the windows but also critically impacts their optical and thermal properties. In this section, we will delve into the coloration dynamics of these materials and explore potential pathways for optimizing performance.

The coloration state of VO₂ windows is driven by the glass surface temperature, which is jointly determined by the outdoor air temperature and solar radiation. A core advantage of this material is its ability to maintain a stable visible light transmittance before and after the phase transition. As illustrated in Figure 6A–C, in hot climates, the VO₂ window remains fully colored for 37%

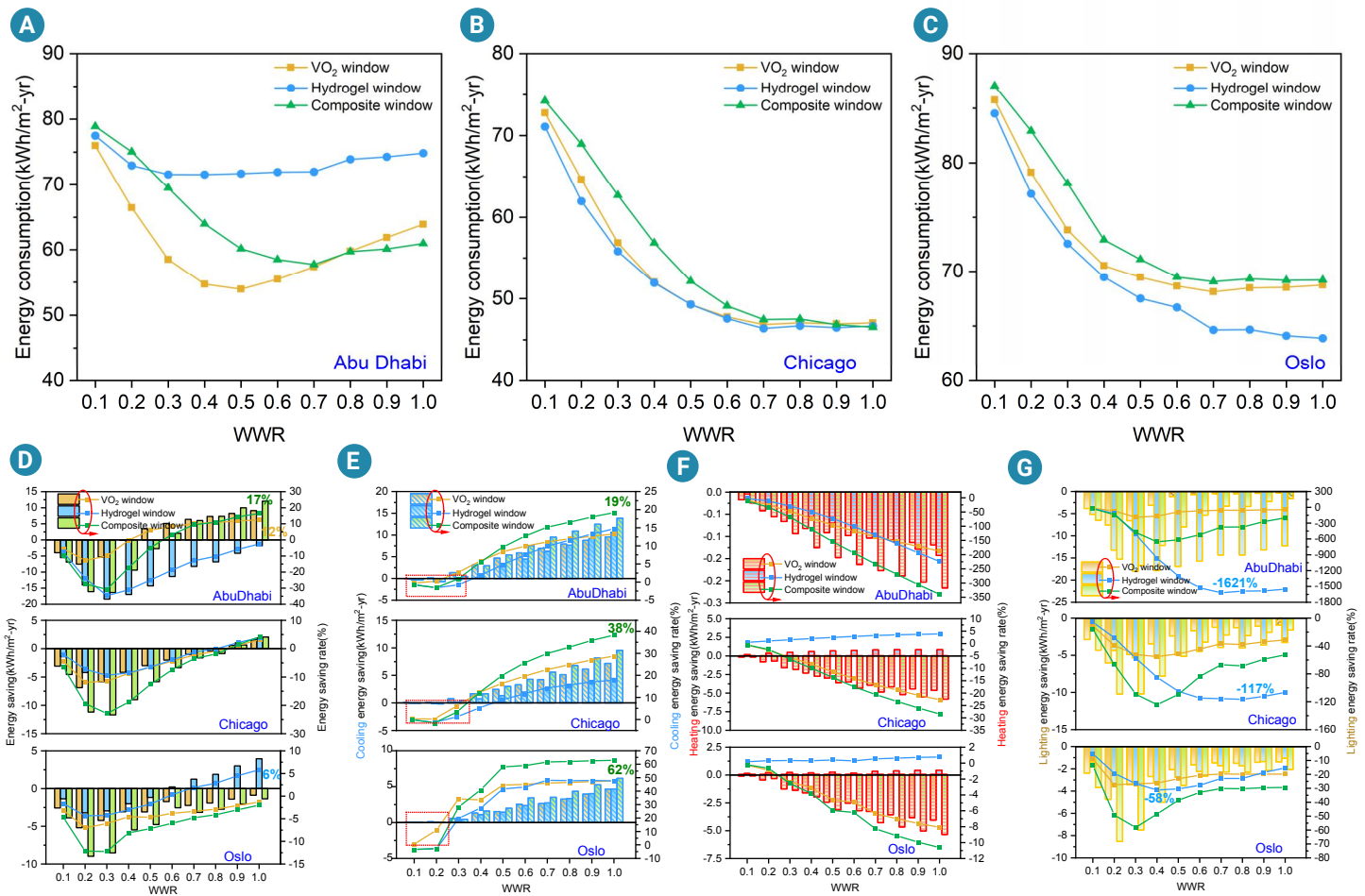


Figure 5. Annual trend chart of absolute total energy consumption of various types of windows (A) in hot climate (Abu Dhabi). (B) in mixed climate (Chicago). (C) in cold climate (Oslo). Energy-saving performance of different window types: (D) Total energy savings. (E) Cooling energy savings. (F) Heating energy savings, and (G) Lighting energy savings.

of the year to effectively modulate solar radiation. Conversely, in cold regions, the low ambient temperatures restrict the phase transition, leaving the window uncolored and transparent for 82% of the year. This intrinsic property allows VO₂ windows to efficiently block solar heat gain without significantly sacrificing natural daylighting.

Unlike low-threshold materials, the phase transition of high-threshold windows is characterized by an abrupt switch between fully transparent and fully colored states. As shown in Figure 6 D-F, even on humid and overcast days with low solar radiation in hot climates, outdoor temperatures exceeding 30°C can trigger a complete coloration. Consequently, the hydrogel window operates in a low-transmittance state for up to 56% of the year. While this frequent and severe shading effectively insulates the building, it inevitably exacerbates the energy demand for indoor artificial lighting. In mixed and cold climates, however, the hydrogel predominantly maintains an uncolored state.

The hierarchical composite window integrates the distinct thermal response advantages of both layers to establish a hierarchical, multi-stage optical modulation mechanism. As depicted in Figure 6 G-I, the low-threshold VO₂ layer activates first at 28°C to filter near-infrared heat, followed by the high-threshold hydrogel layer, which activates at 40°C to regulate visible light. In hot regions, the VO₂ layer rarely remains uncolored, and the hydrogel layer provides deep shading for nearly half of the time. As the climate transitions to colder conditions, the activation frequency of the hydrogel drops significantly, and the system relies primarily on the VO₂ layer for mild thermal regulation. This sequential response strategy grants the composite window exceptional global adaptability across diverse and complex climatic conditions.

Analysis of the light environment

Useful Daylight Illuminance (UDI) is used to evaluate daylighting quality, where illuminance levels below 500 lux indicate insufficient daylight, 500-2000 lux represent the effective range, and values above 2000 lux correspond to excessive daylight. According to Figure 6J-L, the daylighting performance of VO₂ windows varies significantly across different climate zones. As the WWR ratio increases to 0.7, the proportion of effective daylighting rises substantially and then tends to stabilize. This window type performs best in hot climates, achieving a maximum effective daylighting rate of 63%. However, due to its limited dynamic modulation of visible light, excessive daylighting and potential glare become unavoidable when the window-to-wall ratio exceeds 0.6.

As illustrated in Figure 6M-O, hydrogel windows are highly prone to causing a severe lack of basic indoor daylighting. In hot regions, frequent and intense phase transitions ensure that even at large window-to-wall ratios, the proportion of insufficient daylighting remains as high as 70%, with effective daylighting reaching only about 18%. Consequently, the indoor environment relies heavily on artificial lighting. Conversely, in colder cities, the reduced frequency of hydrogel phase transitions allows the proportion of insufficient daylighting to fall to around 40%. This highlights the inherent trade-off of hydrogel windows in hot climates, where their strong ability to block solar heat radiation and intense light comes at the severe expense of natural daylighting potential.

As shown in Figure 6P-R, the hierarchical composite window substantially optimizes the overall daylighting quality through its hierarchical and sequential response mechanism. This synergistic modulation successfully suppresses the proportion of excessive daylighting to below 10% across all evaluated climate zones, almost entirely eliminating the threat of over-illumi-

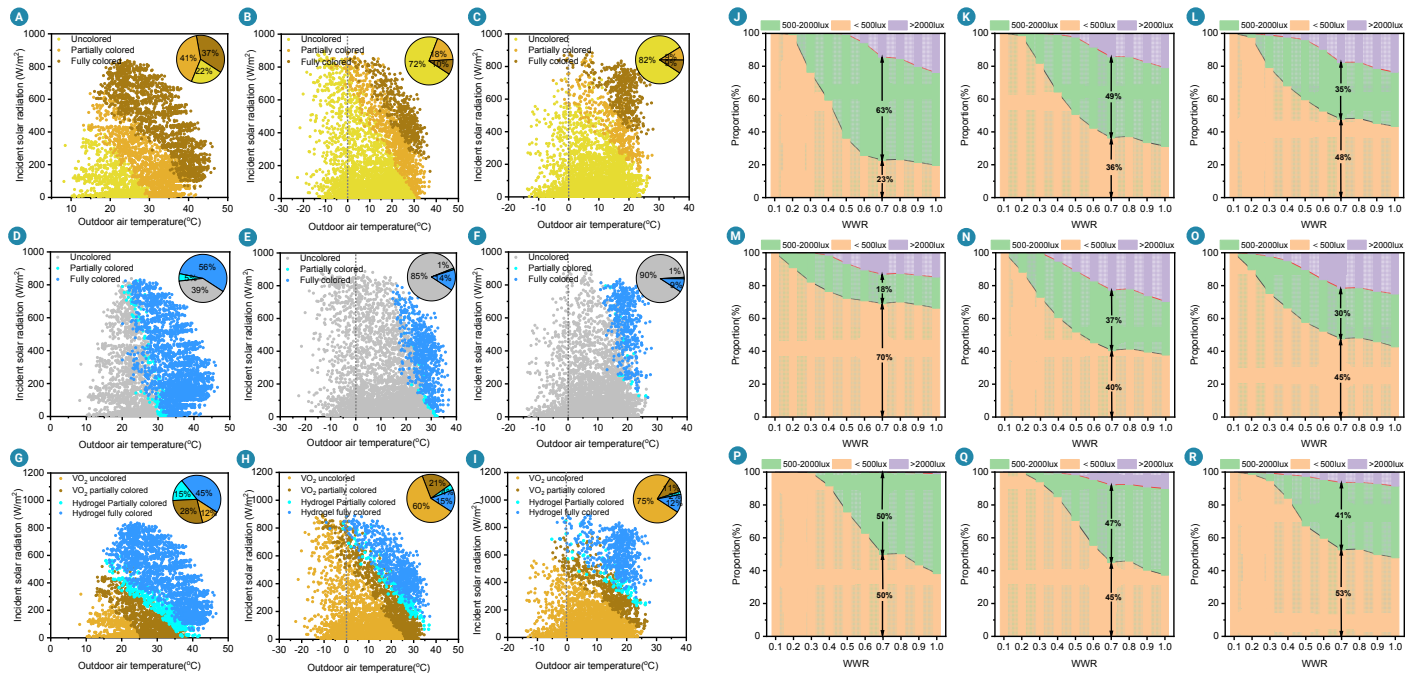


Figure 6. Coloring conditions and annual occurrence of tinting states for three thermochromic smart windows in representative climates, and proportion of indoor illuminance ranges at different WWRs for three thermochromic smart windows in representative climates VO₂ window in (A&J) Abu Dhabi, (B&K) Chicago, (C&L) Oslo. Hydrogel window in (D&M) Abu Dhabi, (E&N) Chicago, (F&O) Oslo. Composite window in (G&P) Abu Dhabi, (H&Q) Chicago, (I&R) Oslo.

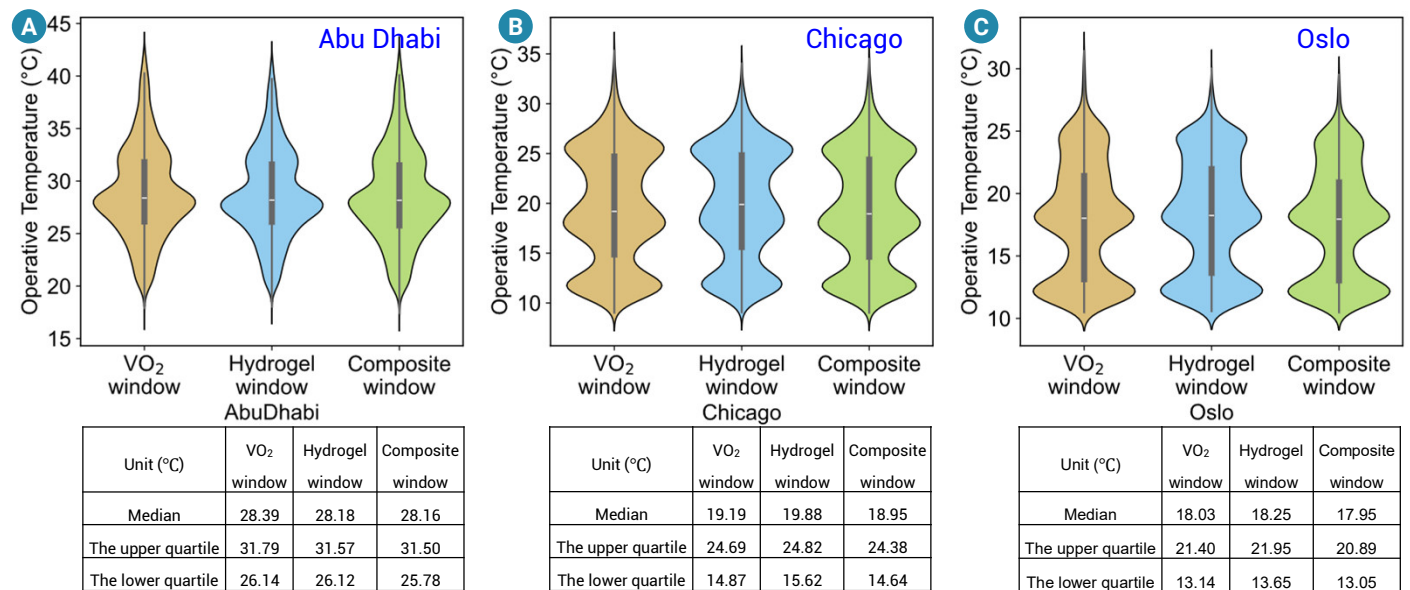


Figure 7. Violin plot of the annual operating temperature probability density distribution (A) Abu Dhabi, (B) Chicago, (C) Oslo.

nation in hot regions. In a cross-climate comparison, the composite window maintains high levels of effective daylighting in mixed and cold climates at 47% and 41%, respectively, demonstrating a comprehensive performance that surpasses the standalone window types. This configuration successfully achieves an ideal balance between restricting intense direct sunlight and ensuring sufficient illumination, exhibiting exceptional adaptability across diverse and complex climate zones.

Analysis of the thermal environment

Based on an 8m×8m×3.5m building model with a 0.8 south-facing window-to-wall ratio, a comprehensive analysis of annual operative temperature probability density distributions elucidates the coupling between thermochromic smart-window modulation mechanisms and climate adaptability

(Figure 7). Driven by a sequential phase transition mechanism featuring VO₂ at 28°C and hydrogel at 40°C, the composite window demonstrates superior thermal robustness across diverse climatic zones. It consistently maintains the lowest median and quartile operative temperatures, fundamentally mitigating the risk of indoor thermal runaway.

Nevertheless, intrinsic phase transition dynamics dictate significant regional performance divergence. In cooling-dominated climate (Abu Dhabi), the standalone hydrogel window induces regulatory lag and exacerbates indoor warming due to its elevated triggering threshold and highly transparent initial state. Conversely, in the heating-dominated environment of Oslo, the high transmittance of the hydrogel window translates into advantageous passive solar heating. Under severe cold conditions, the composite window inevitably induces an over-shading effect constrained by its low initial solar

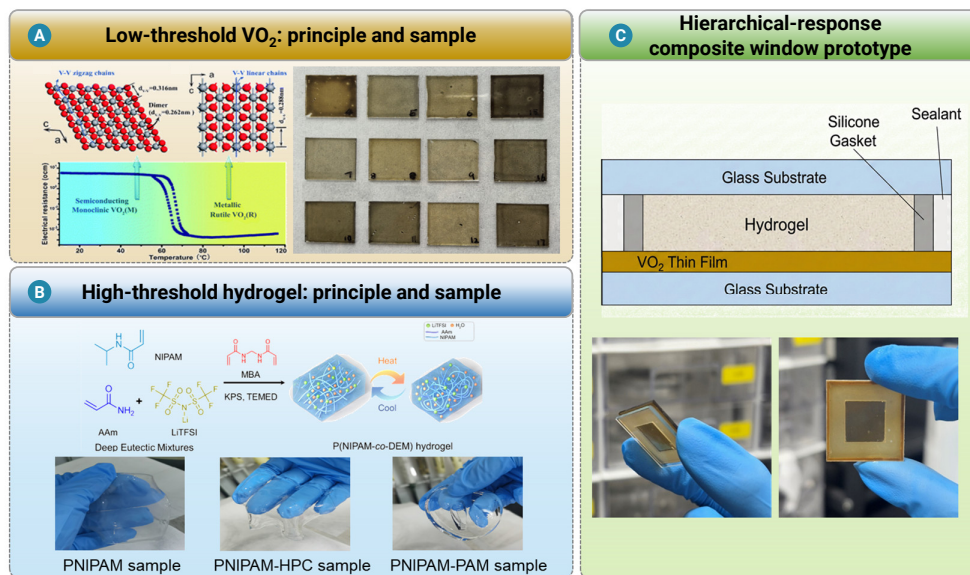


Figure 8. Schematic illustration of window prototypes (A) Principle⁴² and samples we prepared by spin coating method of VO₂ with low-threshold phase transition. (B) Microscopic mechanism²⁸ and three hydrogel samples we prepared. (C) The structural diagram and samples of the fabricated composite window.

To directly verify that the intended sequential optical response is retained after device assembly, the direct transmittance spectrum of the composite-window prototype was measured at 20, 35, and 50 °C (Figure S11 and Table S9). From 20 to 35 °C, T_{lum} changed only from 42.13% to 41.82%, while the transmittance over 1000–1300 nm decreased from 56.20% to 50.76%. The much larger near-infrared change, with little visible-light loss, identifies a VO₂-dominated intermediate state while the hydrogel remains largely transparent. At 50 °C, T_{lum} , T_{sol} , and T_{NIR} in 1000–1300

transmittance, thereby excessively suppressing the indoor operative temperature.

Physical feasibility and prototype demonstration. To close the loop of the “simulation-first” framework and demonstrate that the proposed hierarchical architecture is not merely a theoretical construct, we fabricated the individual functional layers and assembled a composite window prototype (Figure 8). Beyond the initial fabrication assessment, reversible hot-plate switching and long-term ambient storage were examined to provide a preliminary evaluation of device-level stability. This section focuses on demonstrating physical realizability and interfacial compatibility, rather than reporting optimized material properties.

Fabrication of hierarchical functional layers

VO₂ film preparation and characterization. As shown in the Figure 8A, a sol-gel assisted spin-coating strategy with dual ascorbic-acid (AA) reduction and silane coupling agent (KH550) grafting was employed to suppress the severe nanoparticle aggregation typically induced by W-doping.⁴³ Dynamic Light Scattering (DLS) characterization confirmed a dramatic transition from micron-scale agglomeration (~1330 nm) in unmodified samples to sub-micron uniform dispersion (~385 nm) in the dual-modified system, yielding films with balanced luminous transmittance and thermochromic response. Detailed synthesis protocols and parametric optimization data are provided in Supplementary Note 5.

Hydrogel preparation and characterization. a series of PNIPAM-based hydrogels were synthesized via in situ free radical polymerization, incorporating hydroxypropyl cellulose (HPC) or acrylamide (AM) as secondary components to form semi-interpenetrating (PNIPAM-HPC) and copolymerized (PNIPAM-PAM) networks (Figure 8B). The introduction of secondary components significantly enhanced environmental tolerance and mechanical robustness. DSC analysis revealed freezing point depressions to −14.45 °C (PNIPAM-HPC) and −16.14 °C (PNIPAM-PAM), while tensile testing showed Young's modulus surging from 1.67 kPa (pure PNIPAM) to 9.39 kPa (PNIPAM-HPC) and 14.28 kPa (PNIPAM-PAM), attributed to extensive intra- and inter-molecular hydrogen bonding. Detailed synthesis procedures are provided in Supplementary Note 6.

Composite window prototype

Building upon the individual layer optimization, a laminated composite window prototype was assembled using two transparent glass substrates with dimensions of 25 × 25 × 1 mm (Figure 8C). The low-threshold-coated (VO₂) glass served as the bottom substrate, a pristine glass slide as the cover, and a silicone spacer defined the hydrogel chamber. The high-threshold hydrogel precursor solution was injected and cured in situ, effectively encapsulating the liquid phase between the rigid glass layers. Detailed geometry and assembly procedures are provided in Supplementary Note 7.

ively. This broadband attenuation is dominated by hydrogel phase separation and light scattering. The assembled-device spectra therefore verify the qualitative three-state response.

During repeated hot-plate heating and cooling, the encapsulated hydrogel retained reversible transparent-to-hazy switching for more than 50 cycles, with no visible leakage, edge separation, cracking, or VO₂-film delamination (Supplementary Video S1). VO₂ regulates nearly infrared spectra with minimal visible transmittance variation, rendering its phase transition invisible to human eyes; the video thus captures only hydrogel behavior. This confirms the two functional layers achieve compatible short-term operation in a single sealed laminated device.

To examine longer-term stability, a prototype fabricated in April 2025 was inspected after more than one year of storage under ambient laboratory conditions (Figure S12). The glass assembly, VO₂ coating, and peripheral seal remained macroscopically intact; however, the hydrogel exhibited partial contraction and did not completely recover its initial uniform transparent appearance. This observation indicates gradual water redistribution or loss through the laboratory-scale edge seal. The long-term observation and thermal-cycle documentation are presented in Supplementary Note 7.

DISCUSSION AND CONCLUSION

Reverse design analysis: climate-driven material optimization

The simulation results across Chinese municipalities and representative international climates reveal that the hierarchical composite window delivers the strongest overall energy performance (national mean TESR of 12%), with cooling savings maximized in solar-driven regions and net annual benefits concentrated in cooling-dominated climates.

This climate-dependent performance gradient provides concrete guidance for reverse material design. In hot climates where the VO₂ layer activates frequently, future efforts should focus on broadening its spectral control through co-doping strategies or dielectric layer integration to further enhance ΔT_{sol} while maintaining high T_{lum} . For the hydrogel component, optimizing the sequential modulation window width can be achieved by engineering LCST values that are specifically tailored to different climate zones, exemplified by lowering the LCST to approximately 35 °C for hot-arid regions and raising it to approximately 45 °C for mixed climates. Building orientation and window-to-wall ratio must also guide material selection. South-facing facades in cold climates benefit from hydrogel's high pre-transition transmittance for passive solar heating, while east-west exposures in hot climates prioritize the NIR modulation of low-threshold materials.

Limitations and future perspectives

Several limitations warrant acknowledgment. First, the simulation model employs literature-benchmark optical spectra representing state-of-the-art performance rather than the current laboratory prototype. The assembled-

device spectra confirm the expected sequence of a VO₂-dominated near-infrared response followed by hydrogel-dominated broadband attenuation, but they also quantify the remaining performance gap. The optical performance of this lab-scale prototype cannot yet reach the benchmark spectral parameters adopted in simulation literature. Nevertheless, the prototype validates its physical feasibility and stable short-term cyclic switching, while identifying moisture retention and edge sealing longevity as key bottlenecks for subsequent optimization. The modulation limitation is discussed in Supplementary Note 7. Future optimization should combine more controllable VO₂ deposition or multilayer antireflection designs with improved hydrogel formulation, thickness, and optical-path control.

Second, the present durability evidence remains preliminary. For façade-scale application, the functional layers must therefore be developed as an integrated glazing component rather than as isolated functional films. Future designs should integrate the functional laminate as one lite within a sealed insulating-glass unit, with the spacer, desiccant, and gas cavity isolated from the hydrogel chamber. UV protection may be provided by UV-absorbing outer glass, interlayers or coatings, together with compatible UV stabilizers or protective overcoats. ASTM E3119 [44] and ASTM E3120 [45] provide the directly relevant accelerated-ageing framework for thermochromic dynamic glazing. These limitations reflect the necessary transition from a proof-of-concept laminate to a durable building-window component. Accordingly, the present prototype validates the physical compatibility, assembly feasibility, and sequential response mechanism, but its measured spectra are not used as substitutes for the literature-benchmark simulation inputs.

CONCLUSION

This study established a cross-scale, simulation-first and prototype-verified reverse-design framework for evaluating a hierarchical thermochromic smart window in which near-infrared (NIR) and visible-light regulation are separated in temperature and activated sequentially. The framework distinguishes literature-benchmark technology comparison from matched-parameter controls and links material spectra and transition thresholds to climate-dependent building operation. The main conclusions are as follows:

(1) The validated simulation framework provides a reliable basis for climate-scale assessment. Full-scale field measurements yielded an indoor-temperature RMSE of 0.45 °C. Across more than 3600 global administrative units, 96% and 79% of valid units achieved cooling and total energy saving rates above 30%, respectively, with the hierarchical composite window. Across 370 Chinese municipal-level units, it delivered a mean cooling energy saving rate of 32.18% and a mean total energy saving rate of 11.45%; 84.1% of the units exceeded 20% cooling savings.

(2) Across five window configurations evaluated through two complementary simulation sets, including the literature-benchmark comparison and the matched-parameter comparison, the composite window showed its strongest overall performance in cooling-dominated and high-solar-radiation regions. In the matched-parameter assessment, it delivered positive total energy savings in 93% of Chinese units. Its advantage therefore arises from coordinating the duration and spectral depth of shading to improve the annual balance among cooling, heating, and electric lighting. In addition, the hierarchical response effectively resolves the “under-shading” limitation of VO₂ and the “over-shading” problem of hydrogels, suppressing over-illumination to <10% while maintaining high useful daylight illuminance across diverse climates.

(3) The assembled VO₂-hydrogel prototype verifies the intended response sequence and physical compatibility. From 20 to 35 °C, visible transmittance decreased by only 0.31%, whereas transmittance over 1000–1300 nm decreased by 5.44%, confirming a VO₂-dominated NIR-first state. At 50 °C, T_{lum} , T_{sol} , and T_{NIR} decreased to 0.02%, 2.33%, and 6.81%, respectively, indicating hydrogel-dominated broadband attenuation. The prototype therefore demonstrates feasibility and mechanism rather than reproducing the optimized literature spectra used in the simulations.

Overall, this work demonstrates that sequential, multi-band thermochromic regulation provides a practical pathway to reconcile the long-standing energy-daylighting contradiction of single-component thermochromic smart windows. The simulation-first, reverse-design framework offers quantitative, climate-aware guidance for future material tuning and

façade-scale deployment of adaptive building envelopes.

Nomenclature

T_c	Phase transition temperature
T_{lum}	Visible light transmittance
T_s	Window outdoor surface temperature
T_{sol}	Solar radiation transmittance
ΔT_{sol}	Solar modulation ability
$\varphi_{lum}(\lambda)$	Standard luminous efficiency function
$\varphi_{sol}(\lambda)$	Solar irradiance spectrum of air mass 1.5
$T(\lambda)$	Spectral transmittance
$T_{sol,b}$	Solar transmittance at low temperatures (transmittance state)
$T_{sol,c}$	Solar transmittance at high temperatures (tinted state)

Abbreviation

APS	Ammonium persulfate
AM	Acrylamide
CDD	Cooling degree days
CESR	Cooling Energy Saving Rate
COP	Coefficient of performance
DSC	Differential scanning calorimetry
HDD	Heating degree days
HPC	Hydroxypropyl cellulose
HVAC	Heating, ventilating and air-conditioning
LCST	Lower critical solution temperature
NIR	Near-infrared light
PNIPAM	Poly(N-isopropylacrylamide)
TESR	Total Energy Saving Rate
UDI	Useful daylight illuminance
VIS	Visible light
WWR	Window-to-wall ratio

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AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Shuangdui Wu conceived the content and wrote the original manuscript. Bingqian Ren assisted in conducting the literature research and data analysis. Borong Lin and Yucan Peng guided the framework and writing method of the essay, and provided ideas for the paper, guided the framework and provided financial support. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

Borong Lin is an Editorial Board member of The Innovation Energy and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.

DATA AND CODE AVAILABILITY

The data that support the findings of this work are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at: <https://doi.org/10.59717/j.xinn-energy.2026.100189>