

Managing solar transmittance and long-wave infrared emissivity in dual-channel smart windows

Corresponding Author: Professor Gongxun Bai

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This review addresses dual-channel smart windows for year-round thermal regulation through the coordinated control of solar transmission and long-wave infrared emissivity. The manuscript is generally well organized and covers several representative material systems. However, in its current form, the manuscript reads more like a collection of recent examples than a critical and synthetic review. Many figures are assembled directly from previously published papers and contain excessive information. In addition, the language is often verbose, with many common-sense explanations that could be shortened. Overall, the manuscript has a promising topic and a reasonable structure, but it requires substantial revision to become a high-quality review. The authors should move beyond literature compilation and provide clearer synthesis, stronger critical analysis, simplified figures, quantitative comparison, and a more forward-looking perspective. I therefore recommend major revision before the manuscript can be considered for publication.

1. The manuscript repeatedly emphasizes the importance of regulating both solar transmission and LWIR emissivity, but the discussion remains largely descriptive. The authors should provide a clearer conceptual framework that explains why dual-channel regulation is fundamentally different from conventional smart windows, what the key design parameters are, and how different material strategies address these parameters. A schematic summary or roadmap figure created by the authors would be more helpful than relying mainly on reproduced literature figures.

2. The manuscript should include more critical comparison rather than sequential description of representative works. The sections on VO₂, hydrogels, electrochromic systems, and mechanically switchable windows mainly introduce individual papers one by one. The authors should add comparative analysis across these systems. For example, they should compare transition mechanism, driving mode, visible transmittance, solar modulation efficiency, LWIR emissivity modulation, response time, durability, scalability, and practical limitations. A summary table with quantitative metrics would greatly improve the value of the review.

3. The figures should be substantially redesigned and simplified. Most figures appear to be direct compilations of many panels from published papers. Several figures contain too many subfigures, spectra, photographs, thermal images, and schematics in one panel, making them difficult to follow. The authors should reduce unnecessary panels, highlight only the most essential information, and add more author-designed summary diagrams. Each figure should communicate one clear message. For example, figures summarizing different material classes should focus on mechanism, performance comparison, and design principle rather than reproducing all details from original articles.

4. The authors should avoid excessive basic explanations and improve conciseness. The Introduction and physical-basis sections contain many general statements about windows, solar radiation, blackbody emission, and radiative cooling. While some background is necessary, many explanations are too elementary for the target readership. The authors should shorten these parts and focus more on unresolved scientific and technological challenges. The language should be tightened throughout the manuscript to make the review more concise and analytical.

5. The current classification includes VO₂-based systems, thermoresponsive hydrogels, electrochromic systems, and mechanically switchable strategies. This organization is reasonable, but the boundaries between categories are not always clear because some systems involve multiple mechanisms, such as thermochromism combined with structural reconfiguration or electrochromism combined with emissivity switching. The authors should clarify the logic behind this classification and possibly add a mechanism-based classification map, such as passive stimulus-responsive systems, electrically programmable systems, molecular-vibration engineering, and mechanically reconfigurable systems.

6. A central challenge in this field is whether solar transmission and LWIR emissivity can be independently controlled. The manuscript mentions this issue, but it is not sufficiently analyzed in the main text. The authors should explicitly identify which reported systems achieve coupled modulation and which approach independent or programmable regulation. This

distinction is crucial for evaluating the practical potential of dual-channel smart windows.

7. The current application discussion covers building energy efficiency, thermoelectric energy harvesting, and optical protection, but these sections mainly describe selected demonstrations. The authors should discuss what performance level is required for real building applications, how climate zones affect the preferred optical/emissivity state, what durability tests are needed, and what barriers remain for large-area deployment. The application section should provide design guidelines rather than only summarizing reported cases.

8. The overall number of cited references is not enough. The authors are encouraged to include more recent and representative studies from the past 3–5 years to provide a more comprehensive overview. I suggest the authors refer to the following refs. For example: 10.1016/j.cej.2025.172050; 10.1007/s40820-025-01961-4; 10.1002/adfm.202517713; 10.1021/acsnano.5c06463; 10.1016/j.jallcom.2025.185505.

9. The current Outlook identifies general challenges such as decoupled regulation, trade-offs among performance metrics, and durability. These are important but still broad. The authors should provide more concrete future directions, such as stable dynamic low-emissivity materials, scalable transparent electrodes, encapsulation strategies for hydrogels, long-term cycling under outdoor conditions, standardized testing protocols, building-level simulation under different climates, and integration with sensors or autonomous control systems.

10. For a review of this type, a quantitative comparison table is essential. The table should include material system, driving stimulus, visible transmittance, ΔT_{solar} , emissivity range or $\Delta \epsilon_{\text{LWIR}}$, response time, operating temperature or voltage, cycling stability, device size, fabrication method, and major advantages/limitations.

11. Several sentences are overly long and repetitive. Some sections contain common background descriptions that can be merged or removed. The authors should revise the manuscript for clarity, conciseness, and logical flow. In particular, each paragraph should end with a clear conclusion or insight rather than simply describing what a previous study reported.

Minor comments:

1. The authors should check all abbreviations and define them consistently at first use, especially T_{solar} , T_{lum} , ΔT_{solar} , LWIR, ϵ_{LWIR} , and atmospheric window.

2. The captions are too long in several figures. They should be shortened and focused on the key message of each panel.

3. The authors should avoid using repeated phrases such as “year-round thermal regulation”, “dual-channel modulation”, and “climate-adaptive” too frequently.

4. More attention should be paid to practical issues such as haze, color neutrality, mechanical durability, humidity stability, and cost.

Reviewer #2

(Remarks to the Author)

The authors present a review on dual-channel smart windows capable of regulating both solar transmission and LWIR emissivity for year-round thermal management. This article provides a useful overview of recently reported dual-channel strategies. The attempt to integrate solar modulation and thermal radiation management within a unified framework is valuable. However, the review remains largely descriptive and lacks sufficient critical analysis and quantitative comparison.

1. The manuscript primarily focuses on summarizing representative studies. However, a review article should provide more critical comparison among different strategies. It remains unclear which approaches are most promising for practical building applications, which performance metrics represent major bottlenecks, and under what conditions dual-channel regulation offers significant advantages over conventional solar-only smart windows. In addition, the distinction between the proposed dual-channel framework and related concepts, such as adaptive radiative cooling and dynamic emissivity regulation, should be clarified. A clearer classification framework or design guideline would strengthen the review.

2. Numerous performance metrics are presented throughout the manuscript, but they are dispersed across individual studies, making direct comparison difficult. A summary table containing key parameters such as T_{lum} , ΔT_{solar} , $\Delta \epsilon_{\text{LWIR}}$, switching speed, durability, driving mechanism, and scalability would substantially improve the readability and usefulness of the review. Comparison with conventional glazing under representative climate conditions would further help readers assess the practical significance of each strategy.

3. While the strengths of each technology are discussed, the limitations and trade-offs are not sufficiently addressed. More detailed discussion on practical challenges, such as durability, manufacturability, cost, switching speed, and environmental stability, would improve the value of the review.

Reviewer #3

(Remarks to the Author)

This review summarizes recent advances in dual-channel smart windows for year-round thermal regulation by dynamically controlling both solar transmission and LWIR emissivity. It clearly discusses the net heat flow framework, the role of LWIR emissivity as a second degree of freedom, and several main strategies, including VO₂-based, hydrogel, electrochromic, and mechanically switchable systems. The topic is timely and the manuscript is generally well organized. I suggest this paper can be accepted after minor revision.

1. The authors may strengthen the review by adding a brief discussion on how humidity, water vapor, and cloud coverage affect radiative cooling through the atmospheric window, and by providing a more unified comparison of key performance metrics across different systems.

2. For the work by Zhou and co-workers (Fig. 2e(iii)), the authors provide very detailed values, such as +90.18 Wm⁻².

However, the corresponding conditions or assumptions behind these data should be stated more clearly, so that readers can better understand their practical meaning and significance.

3. The manuscript mentions that early efforts to introduce LWIR functionality into VO2 smart windows relied on optical resonance engineering by incorporating VO2 into Fabry-Pérot cavities. It would be helpful if the authors could briefly introduce the working principle of the Fabry-Pérot cavity, so that readers can better understand the role of VO2 and the underlying mechanism in this design.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors addressed all the comments. I think the revision can be published.

Reviewer #3

(Remarks to the Author)

I have no further comments. The authors have revised all my concerns. My suggestion is accepted.

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Respond to Editor and Reviewer

Manuscript ID: COMMSMAT-26-0615

Title: Dual-channel smart windows for year-round thermal regulation: Managing solar transmittance and long-wave infrared emissivity

Many thanks for the editor and reviewers who have presented valuable reports on our manuscript. We are pleased to address their comments in point-by-point form as follows. Therefore, we have revised our manuscript based on the following responses.

Editor and Reviewer comments:

Reviewer #1:

1. The manuscript repeatedly emphasizes the importance of regulating both solar transmission and LWIR emissivity, but the discussion remains largely descriptive. The authors should provide a clearer conceptual framework that explains why dual-channel regulation is fundamentally different from conventional smart windows, what the key design parameters are, and how different material strategies address these parameters. A schematic summary or roadmap figure created by the authors would be more helpful than relying mainly on reproduced literature figures.

Response: We thank the reviewer for this constructive suggestion. In the revised manuscript, we have added an author-designed **Fig. R1** to establish a clearer conceptual framework for dual-channel smart windows. The new figure contrasts conventional single-channel smart windows with the dual-channel concept, identifies the key design parameters for solar transmission and LWIR emissivity, and summarizes four representative material strategies within a unified roadmap. We have also revised the Introduction and Section 2 to compare these strategies from the perspective of channel coupling and decoupling, rather than presenting them as isolated case studies. These revisions clarify the fundamental differences between conventional and dual-channel smart windows and provide a more coherent framework for the subsequent discussion.

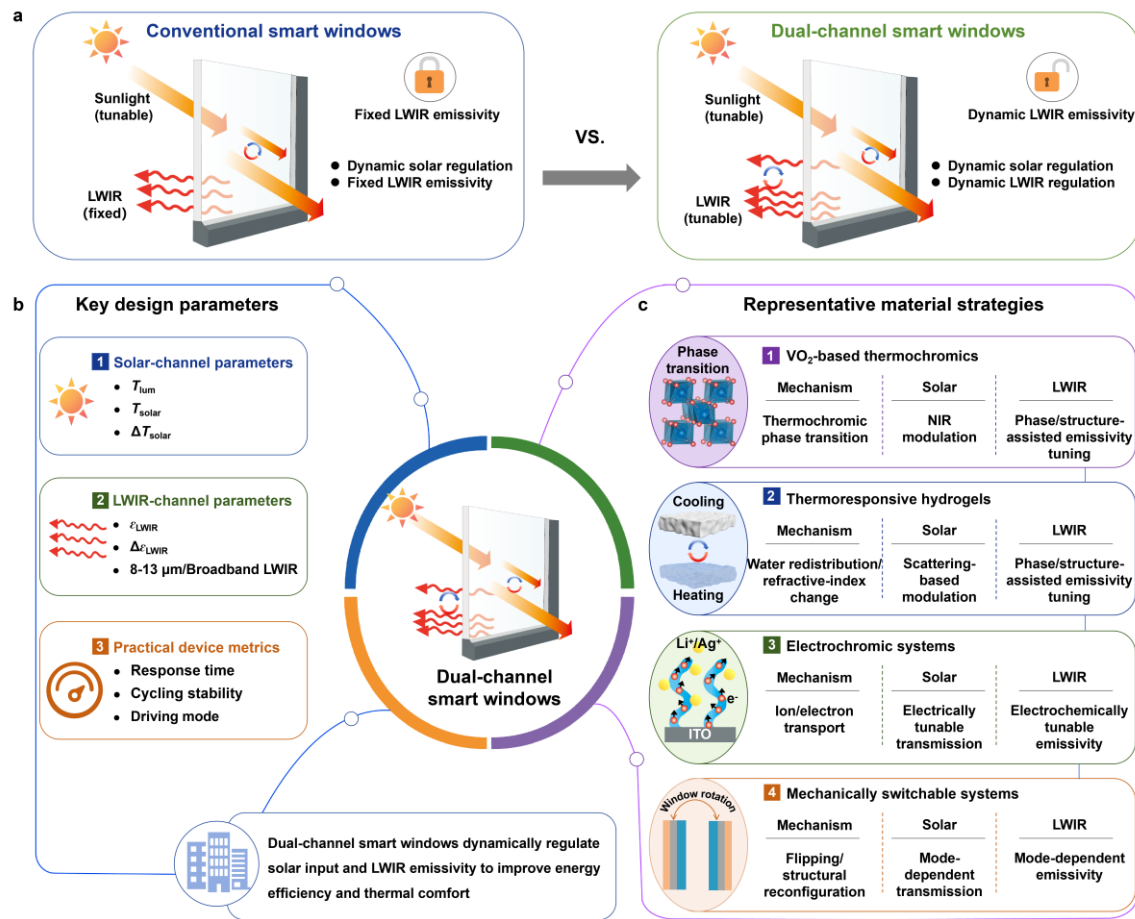


Fig. R1 | Conceptual framework and design roadmap for dual-channel smart windows. (a) Evolution from conventional single-channel smart windows to dual-channel smart windows, where conventional systems mainly regulate T_{solar} with fixed ϵ_{LWIR} , whereas dual-channel designs dynamically regulate both T_{solar} and ϵ_{LWIR} through passive stimulus-responsive or externally controlled mechanisms. (b) Key design parameters and control criteria include solar-channel metrics, LWIR-channel metrics, and practical device metrics. (c) Representative material strategies are compared in terms of regulation mechanism, solar-channel response, and LWIR-channel response.

2. The manuscript should include more critical comparison rather than sequential description of representative works. The sections on VO₂, hydrogels, electrochromic systems, and mechanically switchable windows mainly introduce individual papers one by one. The authors should add comparative analysis across these systems. For example, they should compare transition mechanism, driving mode, visible transmittance, solar modulation efficiency, LWIR emissivity modulation,

response time, durability, scalability, and practical limitations. A summary table with quantitative metrics would greatly improve the value of the review.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have substantially strengthened the comparative analysis throughout the review. Rather than presenting representative studies sequentially, each strategy section (VO₂-based thermochromic systems, thermoresponsive hydrogels, electrochromic systems, and mechanically switchable architectures) now includes a summary table (**Tables R1-4**) that compares representative materials in terms of their control mechanism, solar modulation, LWIR modulation, and practical limitations. In addition, we have expanded the concluding discussion of each section to highlight the common advantages, limitations, and design trade-offs within each strategy. To further address the reviewer's suggestion, we have added **Table R5**, which provides a unified cross-strategy comparison of the four representative approaches in terms of driving/control mode, channel coupling, main strengths, and key bottlenecks. Together with the conceptual framework introduced in **Fig. R1**, these revisions provide a more systematic comparison of different material strategies and clarify their respective design principles, practical limitations, and application potential.

Table R1 | Comparison of VO₂-based strategies for solar-LWIR dual-channel regulation.

Material system	Control mechanism	Solar modulation	LWIR modulation	Key limitation
VO ₂ /PMMA/ITO multilayer ¹	VO ₂ phase transition combined with F-P resonance	$\Delta T_{\text{lum}} = 0.02$; $\Delta T_{\text{solar}} = 0.09$	$\epsilon_{\text{LWIR}}: 0.21 \rightarrow 0.61$; $\Delta \epsilon_{\text{LWIR}} = 0.40$	Thermally coupled; limited T_{lum}
VO ₂ (M)/TiO ₂ (A)/ITO multilayer ⁵²	VO ₂ phase transition switches IIM/MIM F-P cavity	$\Delta T_{\text{solar}} = 0.09$	$\Delta \epsilon_{\text{LWIR}}$ up to 0.43	Multilayer complexity
PNIPAm/W-VO ₂ -PMMA/low-E ⁶³	PNIPAm controls solar opacity; W-VO ₂ /PMMA/low-E stack regulates ϵ_{LWIR}	$\Delta T_{\text{lum}} = 0.21$; $\Delta T_{\text{solar}} = 0.20$	$\epsilon_{\text{LWIR}}: 0.35 \rightarrow 0.69$; $\Delta \epsilon_{\text{LWIR}} \approx 0.34$	Complex stack
VO ₂ array-based F-P resonator ⁶⁵	VO ₂ phase transition with angle-dependent metasurface/F-P resonance	$\Delta T_{\text{solar}} = 0.31$	$\Delta \epsilon_{\text{LWIR}} \approx 0.40$	Angle-sensitive response
W _x V _{1-x} O ₂ /porous SiO ₂ /FTO F-P cavity ⁶⁶	W-VO ₂ phase transition activates F-P resonance; roughness/ZnSe layer improves ΔT_{solar}	$\Delta T_{\text{solar}} = 0.06$	$\Delta \epsilon_{\text{LWIR}} = 0.48$	Weak ΔT_{solar}
VO ₂ /core@VO ₂	VO ₂ particles regulate solar band;	$\Delta T_{\text{solar}} = 0.15$	$\Delta \epsilon_{\text{LWIR}} = 0.32$	Thickness-depende

Material system	Control mechanism	Solar modulation	LWIR modulation	Key limitation
hybrid particle film ⁶⁷	core@VO ₂ particles enhance $\Delta\epsilon_{\text{LWIR}}$			nt trade-off
W-doped	W-VO ₂ phase transition with core-shell	$\Delta T_{\text{lum}} = 0.03$;	$\epsilon_{8-13\text{ }\mu\text{m}}: 0.71 \rightarrow 0.94$;	Shell/dispersion
VO ₂ @SiO ₂ /PVP ⁶⁸	scattering/absorption-enhanced $\Delta\epsilon_{\text{LWIR}}$	$\Delta T_{\text{solar}} = 0.11$	$\Delta\epsilon_{8-13\text{ }\mu\text{m}} = 0.23$	dependence

Table R2 | Comparison of hydrogel-based strategies for solar-LWIR dual-channel regulation.

Materials system	Control mechanism	Solar modulation	LWIR modulation	Response/durability	Key limitation
pNIPAm hydrogel/AgNW ⁷⁶	Water redistribution at an infrared-reflective AgNW interface	$\Delta T_{\text{solar}} = 0.58$	$\epsilon_{\text{LWIR}}: 0.35 \rightarrow 0.92$; $\Delta\epsilon_{\text{LWIR}} = 0.57$	LCST $\approx 31\text{ }^{\circ}\text{C}$; >500 cycles; optical loss <5%	Solar and LWIR channels coupled by the same LCST transition; water retention; AgNW durability
PAM/PAA/PVA/HPC/PDMS-OH/SiO ₂ hydrogel ⁷⁷	Water-content-driven surface reconstruction	$\Delta T_{\text{solar}} = 0.79$	$\epsilon_{\text{LWIR}}: 0.40 \rightarrow 0.90$; $\Delta\epsilon_{\text{LWIR}} \approx 0.50$	Thermal response $\approx 74\text{ s}$; humidity response $\approx 832\text{ s}$; 100 cycles	Water-content cycling; rehydration control; long-term surface-reconstruction reversibility
D ₂ O-pNIPAm/PVA hydrogel/AgNW ³⁹	Solvent vibrational engineering with AgNW-enabled LWIR control	$\Delta T_{\text{solar}} = 0.66$	$\Delta\epsilon_{\text{LWIR}} = 0.32$	LCST $\approx 32\text{ }^{\circ}\text{C}$; 90-day stability; >200 cycles; 256 h aging test	D ₂ O cost and scalability; solvent retention; AgNW oxidation/encapsulation

Table R3 | Comparison of electrochromic strategies for solar-LWIR dual-channel regulation.

Materials system	Control mechanism	Solar modulation	LWIR modulation	Response/stability	Key limitation
ITO/SiO ₂ /ITO VED + WO ₃ /NiO ECD ⁸⁰	Module-level decoupling: ECD controls solar; VED controls IR emissivity	$\Delta T_{\text{solar}} = 0.31$	$\epsilon_{2.5-25\text{ }\mu\text{m}}: 0.80 \rightarrow 0.38$; $\Delta\epsilon_{2.5-25\text{ }\mu\text{m}} = 0.42$; $\Delta\epsilon_{8-14\text{ }\mu\text{m}} = 0.53$	VED switching: 33.7 s/44.6 s; memory >3600 s	Multilayer stacking; separate functional modules
LHE-ED three-electrode window ⁴⁰	Electrode-level decoupling: inner electrode controls VIS/NIR; outer electrode controls LWIR	$\Delta T_{\text{VIS}} = 0.41$; $\Delta T_{\text{NIR}} = 0.54$	$\epsilon_{8-13\text{ }\mu\text{m}}: 0.73 \rightarrow 0.38$; $\Delta\epsilon_{8-13\text{ }\mu\text{m}} = 0.35$	Six electro-driven states	Ag deposition uniformity; electrolyte sealing
NH-WO ₃ nano-helix ⁸¹	Intrinsic multiband coupling: ion/electron insertion regulates VIS/NIR and MIR/LWIR	$\Delta T_{\text{VIS-NIR}} = 0.79$	$\epsilon_{4-25\text{ }\mu\text{m}}: 0.72 \rightarrow 0.48$; $\Delta\epsilon_{4-25\text{ }\mu\text{m}} = 0.24$	Coloration/bleaching: 3.9 s/1.8 s; 10000 cycles	Limited independent solar-LWIR control
GP-ITO/a,c-WO ₃ ⁸²	Partially coupled intrinsic regulation: heterojunction and porous electrode co-design	Dark state blocks 0.87 solar radiation	Film-level $\Delta\epsilon_{4-8/8-25\text{ }\mu\text{m}} = 0.61/0.59$; device-level = 0.11/0.21	Coloration/bleaching: 12.4 s/15.4 s; >8000 cycles	Device-level emissivity contrast decreases
PANI liquid-flow electrochromic window ⁸³	Flow-state-assisted decoupling: PANI controls VIS/NIR; electrolyte state controls LWIR	$\Delta T_{\text{VIS+NIR}} = 43.53\%$	$\epsilon_{8-13\text{ }\mu\text{m}}: 0.19 \rightarrow 0.93$; $\Delta\epsilon_{8-13\text{ }\mu\text{m}} = 0.74$	Flow-assisted seasonal switching	Liquid management; sealing and leakage risk

Table R4 | Comparison of mechanically switchable strategies for solar-LWIR dual-channel regulation.

Materials system	Control mechanism	Solar modulation	LWIR modulation	Response/durability	Key limitation
HVTW based on 2W-SMP ⁸⁷	Thermal coiling/flattening	$\Delta T_{\text{NIR}} = 0.44$; $T_{\text{VIS}} > 0.5$	$\Delta \epsilon_{2.5-20 \mu\text{m}} = 0.77$	100 cycles; 3-month stability	Coupled solar-LWIR response
Ag electrodeposition electrochromic glass ⁸⁸	Ag deposition/dissolution + flipping	$R_{\text{solar}} = 0.88 \rightarrow 0.20$ $\Delta R_{\text{solar}} = 0.68$	$\epsilon_{2.5-20 \mu\text{m}}: 0.91 \rightarrow 0.11$; $\Delta \epsilon_{2.5-20 \mu\text{m}} = 0.80$	~1000 EC cycles	Ag cycling and electrolyte sealing
MPDLC Janus window ⁵	LC scattering + emissivity-side switching	$\Delta T_{\text{solar}} \approx 0.42$; $\Delta T_{\text{lum}} \approx 0.36$	$\Delta \epsilon_{2.5-14 \mu\text{m}} = 0.65$	35 ms LC switching	Complex rotary LC architecture
DDP photochromic window ⁸⁹	Photochromism + seasonal rotation	$\Delta T_{\text{lum}} = 0.39$; $\Delta \text{SHGC} = 0.36$	$\Delta \epsilon_{5-25 \mu\text{m}} \approx 0.67$	50 cycles	Rotation/glazing design sensitive

Table R5 | Cross-strategy evaluation of dual-channel smart-window systems.

Strategy	Driving mode	Channel coupling	Main strength	Key bottleneck
VO ₂ -based thermochromics	Passive thermochromic phase transition	Mostly coupled	Power-free response; mature optical design platform	Transition-temperature tuning; limited T_{lum} ; coupling constraint
Thermoresponsive hydrogels	Passive thermal or hydration transition	Mostly coupled or partially decoupled	Large ΔT_{solar} ; low-cost water-mediated LWIR control	Water retention; freezing; humidity sensitivity; encapsulation stability
Electrochromic systems	Voltage-driven redox, ion insertion, or electrodeposition	Partially decoupled to independently programmable	Active multistate control; building-control compatibility	Electrode/electrolyte stability; sealing; device complexity
Mechanically switchable systems	Bending, flipping, rotation, or structural reconfiguration	Partially or spatially decoupled	Clear separation of solar and LWIR functions	Moving parts; fatigue; sealing; large-area actuation

3. The figures should be substantially redesigned and simplified. Most figures appear to be direct compilations of many panels from published papers. Several figures contain too many subfigures, spectra, photographs, thermal images, and schematics in one panel, making them difficult to follow. The authors should reduce unnecessary panels, highlight only the most essential information, and

add more author-designed summary diagrams. Each figure should communicate one clear message. For example, figures summarizing different material classes should focus on mechanism, performance comparison, and design principle rather than reproducing all details from original articles.

Response: We thank the reviewer for this constructive suggestion. Following the reviewer's advice, we have substantially redesigned and simplified the figures throughout the manuscript to improve clarity and readability. Redundant subpanels and secondary characterization results have been removed where appropriate, and the remaining panels have been reorganized to emphasize the working mechanism, representative performance, and design principle of each material strategy, rather than reproducing extensive details from the original publications. To further improve the presentation, quantitative performance comparisons have been consolidated into summary tables (Tables R1-5), allowing the figures to focus on conveying one clear message instead of combining multiple types of information within a single panel. As a result, the revised figures are more concise, logically organized, and better aligned with the comparative and critical discussion developed throughout the review.

4. The authors should avoid excessive basic explanations and improve conciseness. The Introduction and physical-basis sections contain many general statements about windows, solar radiation, blackbody emission, and radiative cooling. While some background is necessary, many explanations are too elementary for the target readership. The authors should shorten these parts and focus more on unresolved scientific and technological challenges. The language should be tightened throughout the manuscript to make the review more concise and analytical.

Response: We thank the reviewer for this valuable suggestion. Following the reviewer's advice, we have substantially revised the Introduction and the Physical Basis and Design Principles section to improve conciseness and better match the target readership. General background on windows, solar radiation, blackbody emission, and radiative cooling has been significantly reduced, while greater emphasis has been placed on the scientific motivation for dual-channel smart windows, key design

parameters, and channel coupling/decoupling. Specifically, the Introduction has been reorganized to focus on the fundamental distinction between conventional and dual-channel smart windows, rather than providing extensive background on window heat transfer. In addition, the original descriptive discussion of radiative heat transfer has been condensed into Fig. R2, where four representative panels summarize the heat-flow framework, blackbody emission, radiative power, and the influence of atmospheric emissivity on radiative cooling. Throughout the manuscript, repetitive explanations have been removed and the language has been tightened to strengthen the analytical nature of the review.

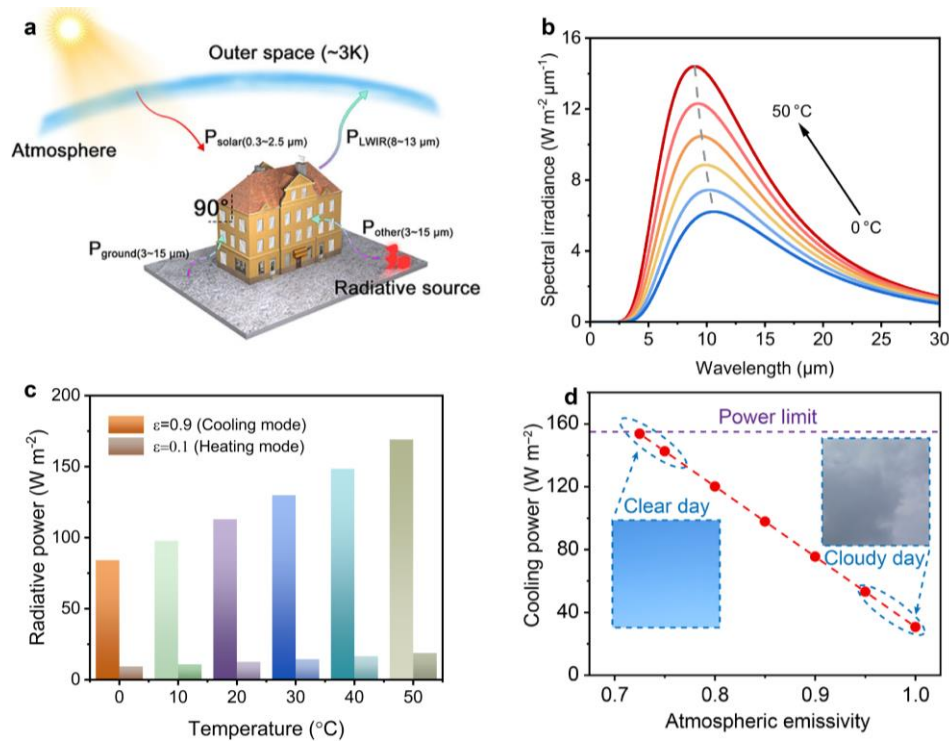


Fig. R2 | Physical basis of LWIR emissivity regulation in dual-channel smart windows. (a) Radiative heat-flow environment of a window, including solar irradiation, atmospheric LWIR radiation, ground and surrounding thermal radiation, and outward thermal emission through the 8-13 μm atmospheric window. Reproduced with permission from ref. 39. Copyright 2025 Springer Nature. (b) Blackbody spectral irradiance at different temperatures, showing that near-ambient surfaces emit predominantly in the LWIR region. Reproduced with permission from ref. 45. Copyright 2023 Springer Nature. (c) Radiative power comparison between high-emissivity and low-emissivity surfaces, highlighting $\varepsilon_{\text{LWIR}}$ as a key thermal-control variable for window heat

exchange. (d) Radiative cooling power as a function of atmospheric emissivity, showing that increased atmospheric emissivity under humid or cloudy conditions reduces the net cooling benefit of atmospheric-window radiation. Reproduced with permission from ref. 56. Copyright 2022 American Association for the Advancement of Science.

5. The current classification includes VO₂-based systems, thermoresponsive hydrogels, electrochromic systems, and mechanically switchable strategies. This organization is reasonable, but the boundaries between categories are not always clear because some systems involve multiple mechanisms, such as thermochromism combined with structural reconfiguration or electrochromism combined with emissivity switching. The authors should clarify the logic behind this classification and possibly add a mechanism-based classification map, such as passive stimulus-responsive systems, electrically programmable systems, molecular-vibration engineering, and mechanically reconfigurable systems.

Response: We thank the reviewer for this insightful comment. We agree that some dual-channel smart-window systems involve multiple regulation mechanisms, and that a classification based solely on individual material types may lead to overlap between categories. In the revised manuscript, we have clarified that the four strategy categories are organized according to their dominant driving mechanism and primary regulation pathway, rather than as mutually exclusive material classes. We have also strengthened the conceptual framework in Fig. R1 and the discussion in Section 2.2 to emphasize channel coupling, partial decoupling, and independent programmability as a unified basis for comparing different strategies. **The relevant text has been revised as follows:** “Rather than treating these strategies as isolated case studies, we compare how each one controls T_{solar} and $\varepsilon_{\text{LWIR}}$, what degree of channel decoupling it can achieve, and which practical bottlenecks remain for real deployment.” This revised framework clarifies the rationale behind our classification while providing a consistent perspective for discussing hybrid systems that combine multiple regulation mechanisms.

6. A central challenge in this field is whether solar transmission and LWIR emissivity can be independently controlled. The manuscript mentions this issue, but it is not sufficiently analyzed in the main text. The authors should explicitly identify which reported systems achieve coupled modulation and which approach independent or programmable regulation. This distinction is crucial for evaluating the practical potential of dual-channel smart windows.

Response: We thank the reviewer for highlighting this central issue. In the revised manuscript, we have strengthened the analysis of solar–LWIR channel interaction and explicitly distinguish three levels of regulation: coupled modulation, partial decoupling, and independently programmable control. Coupled systems use the same stimulus or structural transition to regulate both channels, as commonly observed in VO₂ thermochromic devices and most thermoresponsive hydrogel windows. These systems are simple and often passive, but solar transmission and LWIR emissivity cannot be optimized independently. Partially decoupled systems assign the two functions to different layers, interfaces, electrodes, or exposed surfaces, as demonstrated in several electrochromic and mechanically switchable architectures. Independently programmable systems use separate control inputs or functionally separated modules to regulate solar transmission and LWIR emissivity with greater flexibility, although this usually increases device complexity. This distinction has now been incorporated into Section 2.2, the strategy-specific discussions in Sections 3.1-3.4, and the cross-strategy comparison in Table R5. These revisions make it possible to evaluate reported systems not only by modulation amplitude, but also by the degree of channel independence and the corresponding trade-off between control flexibility and practical complexity. The relevant text has been revised as follows: “To synthesize the strategies discussed in Sections 3.1-3.4, Table 5 compares the four representative strategies in terms of driving mode, channel coupling, main strengths, and key bottlenecks. Rather than repeating the mechanism-solar-LWIR roadmap in Fig. 1, this table emphasizes design trade-offs and deployment considerations.”

7. The current application discussion covers building energy efficiency, thermoelectric energy harvesting, and optical protection, but these sections mainly describe selected demonstrations. The

authors should discuss what performance level is required for real building applications, how climate zones affect the preferred optical/emissivity state, what durability tests are needed, and what barriers remain for large-area deployment. The application section should provide design guidelines rather than only summarizing reported cases.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have substantially **strengthened the application discussion by moving beyond representative demonstrations toward a more design-oriented perspective.** In addition to summarizing reported applications, we now discuss the key requirements for practical deployment, including the need to balance solar transmission, LWIR emissivity, durability, switching reliability, and large-area manufacturability. We have also expanded the discussion to emphasize that the preferred optical state depends on climatic conditions, weather environments, and operating scenarios. **As illustrated in the revised Fig. 2d, the dominant thermal exchange pathways vary under different environmental conditions,** such as sunny daytime, cloudy weather, and nighttime operation, leading to different requirements for solar and LWIR regulation. Rather than assuming a universal optimum, the revised manuscript highlights that cooling-dominated climates generally favor low solar transmission and high LWIR emissivity, whereas heating-dominated climates benefit from the opposite combination. Furthermore, we discuss the importance of long-term environmental stability, including resistance to UV exposure, humidity, thermal cycling, and mechanical fatigue, as well as the remaining challenges associated with scalable fabrication, device integration, and autonomous control.

8. The overall number of cited references is not enough. The authors are encouraged to include more recent and representative studies from the past 3–5 years to provide a more comprehensive overview. I suggest the authors refer to the following refs. For example: 10.1016/j.cej.2025.172050; 10.1007/s40820-025-01961-4; 10.1002/adfm.202517713; 10.1021/acsnano.5c06463; 10.1016/j.jallcom.2025.185505.

Response: We thank the reviewer for this valuable recommendation. All of the suggested recent

studies have been carefully reviewed and incorporated into the revised manuscript where most relevant. Rather than simply increasing the number of citations, these references have been integrated into the corresponding discussions to support the relevant topics and broaden the coverage of recent advances. In the revised manuscript, these papers correspond to Refs. 37, 57, 69, 99, and 103, respectively.

9. The current Outlook identifies general challenges such as decoupled regulation, trade-offs among performance metrics, and durability. These are important but still broad. The authors should provide more concrete future directions, such as stable dynamic low-emissivity materials, scalable transparent electrodes, encapsulation strategies for hydrogels, long-term cycling under outdoor conditions, standardized testing protocols, building-level simulation under different climates, and integration with sensors or autonomous control systems.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have substantially expanded the Outlook section to provide more concrete and application-oriented future perspectives. Beyond the general discussion of decoupled solar–LWIR regulation and performance trade-offs, we now explicitly discuss several key research directions, including the development of stable dynamic low-emissivity materials, scalable transparent electrodes, encapsulation strategies for hydrogel-based systems, long-term environmental stability under UV exposure, humidity, thermal cycling, and mechanical fatigue, as well as standardized testing protocols and building-level evaluation under different climate conditions. We also highlight the integration of dual-channel smart windows with sensors, intelligent control systems, and autonomous operation as important directions for future development. These revisions provide more specific design guidelines and practical perspectives for translating laboratory demonstrations into real-world applications. The relevant text has been revised as follows: “Finally, dual-channel smart windows should be integrated into controlled building and device systems rather than treated as isolated optical materials. Combining smart windows with temperature, light, humidity...may further support self-regulated operation.”

10. For a review of this type, a quantitative comparison table is essential. The table should include material system, driving stimulus, visible transmittance, ΔT_{solar} , emissivity range or $\Delta \epsilon_{\text{LWIR}}$, response time, operating temperature or voltage, cycling stability, device size, fabrication method, and major advantages/limitations.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have substantially strengthened the quantitative comparison throughout the review by introducing a comprehensive set of summary tables. Rather than providing a single comparison table, we have organized the quantitative information at two complementary levels. Specifically, **Tables R1-4** summarize representative studies within each material strategy, including the material system, driving stimulus, solar modulation (ΔT_{solar}) performance, LWIR emissivity modulation ($\Delta \epsilon_{\text{LWIR}}$), response conditions, cycling stability, fabrication characteristics, and main advantages and limitations where available. To further facilitate cross-strategy comparison, we have added **Table R5**, which compares the four representative dual-channel smart-window strategies in terms of driving/control mode, channel coupling, main strengths, and key bottlenecks. Together, these tables provide both detailed quantitative comparisons within each strategy and an overall comparison across different material systems, enabling readers to evaluate their respective characteristics and practical potential more efficiently.

11. Several sentences are overly long and repetitive. Some sections contain common background descriptions that can be merged or removed. The authors should revise the manuscript for clarity, conciseness, and logical flow. In particular, each paragraph should end with a clear conclusion or insight rather than simply describing what a previous study reported.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have carefully edited the entire text to improve clarity, conciseness, and logical flow. Long and repetitive sentences have been shortened, redundant background descriptions have been removed or consolidated, and terminology has been made more consistent throughout the manuscript. In addition, we have strengthened the analytical nature of the review by revising the organization of

individual sections. Rather than ending paragraphs with descriptions of representative studies, each subsection now concludes with a concise summary that highlights the common design principles, major advantages, practical limitations, and future challenges of the corresponding strategy. The application and outlook sections have also been revised to emphasize broader design insights rather than simply summarizing reported demonstrations.

Minor comments:

1. The authors should check all abbreviations and define them consistently at first use, especially T_{solar} , T_{lum} , ΔT_{solar} , LWIR, $\varepsilon_{\text{LWIR}}$, and atmospheric window.

Response: We thank the reviewer for this careful suggestion. In the revised manuscript, we have thoroughly checked all abbreviations and ensured that they are defined consistently at their first appearance and used uniformly thereafter. In particular, solar transmittance (T_{solar}), luminous transmittance (T_{lum}), solar modulation ability (ΔT_{solar}), long-wave infrared (LWIR), LWIR emissivity ($\varepsilon_{\text{LWIR}}$), LWIR emissivity modulation ($\Delta \varepsilon_{\text{LWIR}}$), and the 8–13 μm atmospheric window have been standardized throughout the text, figures, tables, and captions. The relevant text has been revised as follows: “Smart windows address part of this challenge by dynamically regulating solar transmittance (T_{solar}), especially in the visible (VIS) and near-infrared (NIR) regions^{6–10}.” “This contrast indicates that the optimal emissivity state is not universal: high LWIR emissivity ($\varepsilon_{\text{LWIR}}$) benefits cooling, whereas low $\varepsilon_{\text{LWIR}}$ is preferred for heating.” “The solar channel is commonly evaluated using luminous transmittance (T_{lum}), T_{solar} , and solar modulation ability (ΔT_{solar}).” “The LWIR channel is characterized by $\varepsilon_{\text{LWIR}}$ and its modulation amplitude ($\Delta \varepsilon_{\text{LWIR}}$), which are typically evaluated within the 8–13 μm atmospheric window or across a broader thermal-infrared wavelength range, depending on the intended thermal-management objective.”

2. The captions are too long in several figures. They should be shortened and focused on the key message of each panel.

Response: We thank the reviewer for this helpful suggestion. In the revised manuscript, we have

carefully shortened and revised the captions throughout the manuscript to improve readability and better emphasize the key message of each figure. Detailed descriptions of individual experimental results and secondary information have been removed or condensed where appropriate. Instead, the captions now focus on the underlying working mechanism, representative performance, and the primary conclusion illustrated by each panel. For example, the caption of Fig. 3 has been reduced from approximately 210 words to 140 words while retaining the essential information on the working mechanism and representative performance. Similar revisions have been made to the other figure captions.

3. The authors should avoid using repeated phrases such as “year-round thermal regulation”, “dual-channel modulation”, and “climate-adaptive” too frequently.

Response: We thank the reviewer for this helpful suggestion. In the revised manuscript, we have carefully revised the language to reduce repetitive use of phrases such as “year-round thermal regulation”, “dual-channel modulation”, and “climate-adaptive”. Redundant repetitions have been removed or replaced with more appropriate alternative expressions to improve readability while maintaining conceptual consistency. For example, the occurrences of “year-round thermal regulation” and “climate-adaptive” have been substantially reduced, while the previously repeated expression “dual-channel modulation” has been replaced by the more consistent terminology “dual-channel regulation” throughout the manuscript where appropriate.

4. More attention should be paid to practical issues such as haze, color neutrality, mechanical durability, humidity stability, and cost.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have strengthened the discussion of practical limitations across the different material strategies. In particular, the revised comparison tables now summarize the **key limitations** of representative systems, while the main text and **Outlook** further discuss issues including **cycling and mechanical durability, humidity and water-management stability in hydrogel-based devices,**

encapsulation reliability, large-area fabrication, and device integration. These revisions provide a more practical assessment of the deployment potential of dual-channel smart windows, rather than evaluating the reported systems solely on the basis of their optical modulation performance.

Reviewer #2

1. The manuscript primarily focuses on summarizing representative studies. However, a review article should provide more critical comparison among different strategies. It remains unclear which approaches are most promising for practical building applications, which performance metrics represent major bottlenecks, and under what conditions dual-channel regulation offers significant advantages over conventional solar-only smart windows. In addition, the distinction between the proposed dual-channel framework and related concepts, such as adaptive radiative cooling and dynamic emissivity regulation, should be clarified. A clearer classification framework or design guideline would strengthen the review.

Response: We thank the reviewer for this insightful comment. In the revised manuscript, we have strengthened the review from a study-by-study summary to a **framework-based comparative analysis**. The four representative strategies are now evaluated in terms of driving mode, solar–LWIR channel coupling, modulation performance, practical limitations, and deployment potential. **Tables 1–4 (shown as Tables R1–4 in this response document)** provide quantitative comparisons within each strategy, while **Table 5 (shown as Table R5 in this response document)** summarizes the main strengths and key bottlenecks across the four approaches.

We have also clarified that the practical promise of each strategy depends on the application context rather than on a single performance metric. Passive thermochromic and hydrogel systems offer simple, low-power operation but generally retain coupled solar–LWIR responses and face limitations in transparency, environmental stability, or encapsulation. Electrochromic systems provide greater programmability and are more compatible with building control, but require improvements in electrode stability, sealing, and device complexity. Mechanically switchable systems can spatially separate solar and LWIR functions, although moving

components, fatigue, and large-area actuation remain major barriers. **In addition, the revised manuscript now specifies the conditions under which dual-channel regulation offers clear advantages over conventional solar-only smart windows.** Its benefit is most pronounced when the preferred LWIR state changes with climate, season, sky condition, or thermal demand, such as switching between high outward emissivity for cooling and low emissivity for heat retention. Under humid or cloudy conditions, where atmospheric-window cooling is weakened, the benefit depends more strongly on solar blocking, indoor heat-load reduction, and building operation. **Finally, we have clarified the distinction between the proposed framework and related concepts.** Adaptive radiative cooling mainly concerns the dynamic regulation of thermal emission for heat dissipation, while dynamic emissivity regulation focuses on the LWIR channel alone. By contrast, dual-channel smart windows coordinate solar transmittance and LWIR emissivity within one window platform and explicitly consider whether the two channels are coupled, partially decoupled, or independently programmable. These revisions establish a clearer classification framework and provide more practical design guidance for evaluating different strategies.

2. Numerous performance metrics are presented throughout the manuscript, but they are dispersed across individual studies, making direct comparison difficult. A summary table containing key parameters such as T_{lum} , ΔT_{solar} , $\Delta \epsilon_{LWIR}$, switching speed, durability, driving mechanism, and scalability would substantially improve the readability and usefulness of the review. Comparison with conventional glazing under representative climate conditions would further help readers assess the practical significance of each strategy.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have reorganized the dispersed performance data into a series of structured comparison tables. **Tables 1–4** summarize representative systems within each strategy, including the material system, driving mechanism, solar modulation, LWIR emissivity modulation, available response or stability information, and key limitations. **Table 5** further provides a cross-strategy comparison of driving/control mode, channel coupling, main strengths, and key bottlenecks. These tables enable

more direct comparison among different systems and improve the readability and usefulness of the review. We have also strengthened the discussion of climate-dependent performance and the practical distinction between dual-channel regulation and conventional fixed-property or solar-only windows. The revised manuscript now clarifies that the preferred combination of T_{solar} and ϵ_{LWIR} depends on thermal demand and sky conditions. **The relevant text has been revised as follows:** “The preferred combination of T_{solar} and ϵ_{LWIR} depends on the thermal demand. Under cooling-dominated conditions, low T_{solar} limits solar heat gain, while high outward ϵ_{LWIR} promotes radiative heat dissipation, particularly through the atmospheric window. Under heating-dominated conditions, high T_{solar} enables passive solar gain, whereas low outward ϵ_{LWIR} suppresses radiative heat loss to the colder outdoor environment⁵⁰⁻⁵².” “Increasing humidity, atmospheric water vapor, and cloud coverage raises the effective sky emissivity, reduces atmospheric-window transmittance, and increases downward LWIR irradiation. Consequently, the available radiative cooling power decreases as atmospheric emissivity increases, and the atmospheric window may be substantially weakened or nearly closed under humid or cloudy conditions (Fig. 2d)⁵⁶. High outward ϵ_{LWIR} is therefore most beneficial under clear and dry skies. Under humid or cloudy conditions, the overall thermal benefit depends more strongly on solar blocking, indoor heat-load reduction, window orientation, and building operating conditions.”

3. While the strengths of each technology are discussed, the limitations and trade-offs are not sufficiently addressed. More detailed discussion on practical challenges, such as durability, manufacturability, cost, switching speed, and environmental stability, would improve the value of the review.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have substantially strengthened the discussion of limitations and trade-offs across all four strategy sections. Specifically, **Tables 1–4 now summarize the response or durability information and key limitations of representative systems within each strategy, while Table 5 provides a cross-strategy comparison of driving mode, channel coupling, main strengths, and key**

bottlenecks. In addition, the concluding paragraph of each strategy section has been revised to provide a critical assessment rather than only summarizing representative studies. For example, the revised discussion highlights the trade-off between LWIR modulation and optical loss in VO₂ Fabry–Pérot systems, the challenges of water retention, freeze resistance, and encapsulation in hydrogel-based devices, the balance between programmability and electrode/electrolyte complexity in electrochromic systems, and the mechanical fatigue, sealing, and large-area actuation issues of reconfigurable architectures. These revisions provide a more practical evaluation of durability, switching performance, manufacturability, environmental stability, and deployment barriers. **The cross-strategy comparison is introduced as follows:** “To synthesize the strategies discussed in Sections 3.1-3.4, Table 5 compares the four representative strategies in terms of driving mode, channel coupling, main strengths, and key bottlenecks. Rather than repeating the mechanism-solar-LWIR roadmap in Fig. 1, this table emphasizes design trade-offs and deployment considerations.”

Reviewer #3

1. The authors may strengthen the review by adding a brief discussion on how humidity, water vapor, and cloud coverage affect radiative cooling through the atmospheric window, and by providing a more unified comparison of key performance metrics across different systems.

Response: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have added a dedicated discussion of the influence of sky conditions on atmospheric-window radiative cooling and incorporated this effect into **Fig. 2d (shown as Fig. R2d in this response document)**. The revised text clarifies that increasing humidity, atmospheric water vapor, and cloud coverage raises the effective sky emissivity, reduces atmospheric-window transmittance, increases downward LWIR irradiation, and thereby decreases the available radiative cooling power. It also emphasizes that high outward ϵ_{LWIR} is most beneficial under clear and dry skies, whereas under humid or cloudy conditions the overall thermal benefit depends more strongly on solar blocking, indoor heat-load reduction, window orientation, and building operating conditions. The relevant text has

been revised as follows: “Moreover, the effectiveness of atmospheric window heat dissipation is strongly affected by sky conditions. Under clear and dry skies, the atmosphere exhibits relatively low emissivity within the 8–13 μm range and can function as an effective radiative heat sink⁵³⁻⁵⁵. Increasing humidity, atmospheric water vapor, and cloud coverage raises the effective sky emissivity, reduces atmospheric-window transmittance, and increases downward LWIR irradiation. Consequently, the available radiative cooling power decreases as atmospheric emissivity increases, and the atmospheric window may be substantially weakened or nearly closed under humid or cloudy conditions (Fig. 2d)⁵⁶. High outward ϵ_{LWIR} is therefore most beneficial under clear and dry skies. Under humid or cloudy conditions, the overall thermal benefit depends more strongly on solar blocking, indoor heat-load reduction, window orientation, and building operating conditions.”

We have also provided a more unified comparison of key performance metrics. **Tables 1–4** (shown as **Tables R1–4** in this response document) summarize representative systems within each material strategy, including solar modulation, LWIR emissivity modulation, response or durability information, and key limitations, while **Table 5** (shown as **Table R5** in this response document) provides a cross-strategy comparison of driving mode, channel coupling, main strengths, and key bottlenecks. Together, these revisions strengthen both the physical discussion of atmospheric-window cooling and the systematic comparison across different dual-channel smart-window systems.

2. For the work by Zhou and co-workers (Fig. 2e(iii)), the authors provide very detailed values, such as $+90.18 \text{ Wm}^{-2}$. However, the corresponding conditions or assumptions behind these data should be stated more clearly, so that readers can better understand their practical meaning and significance.

Response: We thank the reviewer for this important comment. In the revised manuscript, we have removed the original Fig. 2e, including panel (iii) and the specific value of $+90.18 \text{ Wm}^{-2}$, together with the corresponding discussion. Rather than retaining a literature-specific performance value whose practical meaning depends strongly on particular assumptions and boundary conditions, we

have redesigned the Physical Basis and Design Principles section to focus on the general physical framework of dual-channel regulation.

The revised **Fig. 2** (shown as **Fig. R2** in this response document) now contains four representative panels. Fig. 2a summarizes the relevant solar, LWIR radiative, and non-radiative heat flows; Fig. R2b shows the spectral characteristics of near-ambient blackbody emission; Fig. 2c illustrates how LWIR emissivity affects radiative power; and Fig. 2d highlights the influence of atmospheric emissivity and sky conditions on atmospheric-window radiative cooling. In particular, the revised discussion explains that increasing humidity, atmospheric water vapor, and cloud coverage raises the effective sky emissivity, reduces atmospheric-window transmittance, and increases downward LWIR irradiation, thereby weakening the radiative-cooling benefit of high outward $\varepsilon_{\text{LWIR}}$. This redesign avoids relying on a highly specific value from an individual study and instead provides readers with a clearer and more generally applicable understanding of the physical conditions that govern the practical significance of LWIR regulation in dual-channel smart windows.

3. The manuscript mentions that early efforts to introduce LWIR functionality into VO₂ smart windows relied on optical resonance engineering by incorporating VO₂ into Fabry-Pérot cavities. It would be helpful if the authors could briefly introduce the working principle of the Fabry-Pérot cavity, so that readers can better understand the role of VO₂ and the underlying mechanism in this design.

Response: We thank the reviewer for this helpful suggestion. In the revised manuscript, we have added a brief explanation of the Fabry-Pérot (F-P) cavity principle and clarified the specific role of VO₂ in enabling LWIR emissivity modulation. The revised text explains that an F-P cavity consists of two reflective interfaces separated by a dielectric spacer. When the optical phase accumulated within the spacer satisfies the resonance condition, the electromagnetic field is enhanced inside the cavity, producing strong absorption at selected wavelengths. In VO₂-based F-P structures, VO₂ acts as a temperature-dependent optical boundary: insulating VO₂ couples only weakly to the cavity at

low temperature, whereas metallic VO₂ behaves as a lossy reflective layer at high temperature and strengthens resonant absorption near the atmospheric window. According to Kirchhoff's law, this enhanced absorption corresponds to increased LWIR emissivity. The relevant text has been revised as follows: "Fabry-Pérot (F-P) resonance engineering offers the most direct route to LWIR regulation in VO₂ smart windows⁶³. A F-P cavity consists of two reflective interfaces separated by a dielectric spacer. When the accumulated phase in the spacer satisfies the resonance condition, the optical field is enhanced inside the cavity, producing strong absorption at selected wavelengths. In VO₂-based F-P emitters, VO₂ acts as a temperature-dependent optical boundary: insulating VO₂ weakly couples to the cavity at low temperature, whereas metallic VO₂ behaves as a lossy reflective layer at high temperature and strengthens resonant absorption near the atmospheric window, especially around 10 μm (Fig. 3a)⁶⁴. According to Kirchhoff's law, this enhanced absorption corresponds to increased ϵ_{LWIR} ."