

Article

Towards Climate-Resilient Office Façades: Integrating PCM-Enhanced Glazing with Dynamic External Louvres Under Current and Future Hot–Arid Climates

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Abstract

Phase-change material (PCM) glazing and dynamic external shading are promoted as sustainable cooling measures, yet they act on the same solar load and are rarely assessed together under a mandatory energy code. This study aims to evaluate and compare the individual and combined performance of PCM glazing and adaptive external louvres in reducing cooling demand in a code-compliant office building under present and future hot–arid climates. The reference case is an SBC 601-compliant west-facing Riyadh office under present and 2080 weather. EnergyPlus was coupled with a calibrated one-dimensional enthalpy PCM model using a one-way coupling framework. The approach was verified against a fully bidirectional co-simulation (0.5–1.8%). Adaptive louvres cut annual cooling by 10.2% (71% of the west-glazing share). A matched no-latent control attributes only 0.5 of the 9.4 points saved by PCM glazing to latent storage: the code glazing optically starves the PCM. Their combination is sub-additive by 6.6 percentage points across 21 sensitivity variants. Melt and placement sweeps favour a 35 °C melt point and the outer pane. On thermal grounds, adaptive external louvres should be prioritised for code-compliant hot–arid buildings, while PCM glazing is most beneficial where higher solar gains allow latent heat utilisation, informing sustainable façade codes.

Keywords: phase change material; PCM glazing; dynamic louvres; cooling load; thermal comfort; peak cooling load; latent heat storage; night ventilation; hot–arid climate; sustainable façade design



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1. Introduction

Buildings account for a dominant share of electricity demand in the Gulf region, and air-conditioning drives that share: Saudi offices are cooled nearly year-round, and projected warming will deepen the load [1–3]. Cooling electricity is therefore the largest single lever on the operational carbon of Gulf office buildings and on their contribution to summer peak demand, so façade measures that cut cooling energy are direct instruments of sustainable building policy rather than incremental refinements. Evidence-based assessment of such measures under future climates, with calibrated simulation and an

occupant-centred reading of the results, is now established practice in overheating-risk and retrofit research [4], and the present study adopts that framing for a new-build, code-compliant façade. In response, the national energy code (SBC 601-CR-2018 [5]) mandates low-SHGC glazing and encourages external shading in Climate Zone 1, which contains Riyadh and corresponds to ASHRAE 169 zone 1B [6]. The façade is therefore the natural battleground for cooling-demand reduction, and two façade technologies approach it from opposite directions. Dynamic external shading removes solar gain before it reaches the glazing [7–9], whereas PCM-enhanced glazing admits and buffers the gain, storing it as latent heat and releasing it later [10–12]. Both are individually well studied, but reviews note that they are rarely evaluated together [12,13], and no study known to the authors benchmarks their interaction under a mandatory hot-arid energy code using the code's own envelope, setpoints and schedules.

The code itself changes the physics of the problem. An SBC-compliant window (SHGC no greater than 0.25) transmits less than half of the solar radiation that a clear window would deliver to a PCM layer behind it. Whether a PCM glazing can still charge under such a ceiling, and whether a dynamic louvre then starves it further, is a design-critical question that generic parametric studies do not answer [14,15]. It is hypothesised here that, on a code-compliant west façade, dynamic external louvres and PCM-enhanced glazing compete for the same solar load rather than compounding.

This study therefore aims to evaluate and compare the individual and combined performance of PCM glazing and adaptive external louvres in reducing cooling demand in a code-compliant office building under present and future hot-arid climates. To this end, a factorial matrix of eight façade configurations is simulated in EnergyPlus (v25.2; U.S. Department of Energy, Washington, DC, USA) coupled with a calibrated one-dimensional enthalpy model of the PCM glazing, and the analysis is extended with a manufacturer-validated melt-temperature map, a PCM placement study and a night-ventilation assessment; the methodology is detailed in Section 3.

The study contributes, first, an SBC 601-anchored and compliance-demonstrated benchmark of PCM glazing and dynamic louvres for Riyadh Climate Zone 1 under present and 2080 weather. Second, it contributes the first annual, whole-building quantification of code-induced optical starvation of PCM glazing; the closest prior work combines PCM with solar-control glass at unit level to cure summer overheating [16], the inverse framing of the present study. Third, it quantifies the sub-additivity between shading and PCM on a single façade, whereas prior art places the PCM inside the shading device itself [17–19]. Fourth, it delivers a manufacturer-referenced melt-point map with the optimum charging and solidification settings for each melt temperature, including the boundary beyond which assisted discharge becomes necessary; earlier melt optimisation targeted opaque envelopes [20]. Finally, it resolves where the PCM belongs within the glazing unit through an outer- versus inner-pane placement analysis with an explicit inward/outward heat partition; earlier multilayer-glazing studies varied the number of layers rather than the pane that carries the PCM [21,22].

2. Literature Review

Selection of the reviewed literature: The nine categories follow the structure of the study itself—PCM fundamentals, PCM in transparent envelopes, PCM in opaque envelopes, adaptive façades and dynamic shading, slat optics and daylighting, the hot-arid and Saudi context, night ventilation and discharge, simulation methodology, and the closest prior art. Sixty core references were assembled by targeted searching within each category, retaining review articles that define the state of the art, experimental studies that provide validation anchors, and the code and standard documents on which the model depends. A further

ten were added by the systematic prior-art audit described in Section 5, which screened 345 unique journal articles. The corpus is therefore purposive rather than exhaustive, and is not presented as a systematic review.

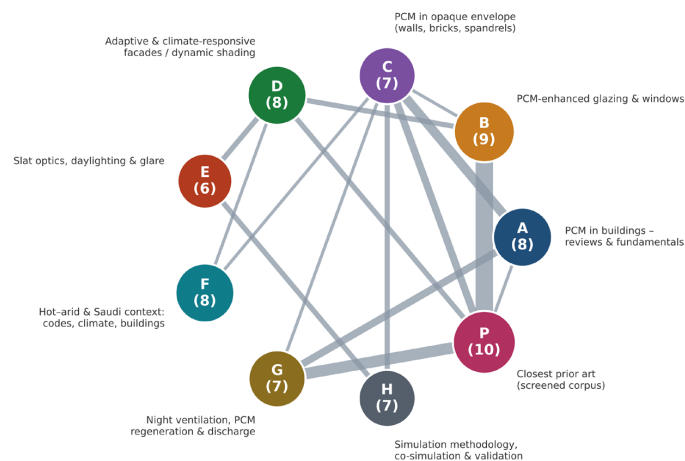
Seventy references across nine categories position the study; Figure 1a maps their co-topic network and Figure 1b maps their category structure. The following review moves from PCM fundamentals through transparent applications and dynamic shading to the hot-arid context, closing with the research gap.

PCM fundamentals and reviews: Comprehensive reviews established the material families, encapsulation routes and integration options for latent storage in buildings [23–26], and they consistently identify incomplete discharge—the failure to re-solidify overnight—as the recurring performance bottleneck [27,28]. Hot-climate reviews map where passive PCM cooling remains feasible [29,30]. On the opaque side, early experimental work demonstrated wall-integrated latent storage in test rooms [31–33], and Neeper’s analysis of wallboard dynamics showed that diurnal cycling is maximised when the melt temperature lies close to the average room temperature [34]—a principle this study extends to glazing. Evola et al. proposed utilisation metrics for PCM effectiveness in summer comfort [35], which inspired the regeneration metric used here, and simulation-based reviews addressed the modelling of such systems in whole-building tools [15,36]. Alawadhi’s brick study brought these ideas to the Gulf [37].

Literature co-topic network: 70 references, 9 categories
(Kamada-Kawai layout; node size = degree, colour = category)



Figure 1. Cont.

Category meta-graph: node = category (paper count), edge width = cross-category links

(b)

Figure 1. (a) Literature co-topic network of the 70 references [1–3,5–71] (Kamada–Kawai layout; node size = degree; colour = category; maroon = closest prior art identified by the prior-art audit). (b) Category meta-graph: node = category (paper count), edge width = number of cross-category links; this study bridges PCM glazing (B), dynamic shading (D) and hot-arid codes (F).

PCM in transparent envelopes: Ismail and Henriquez first proposed windows with a moving PCM curtain and reported strong attenuation of transmitted energy in numerical and experimental tests [10]. Weinläder et al. measured a PCM façade panel behind glazing on a test façade and found combined daylighting and heating benefits [38]. The Turin group carried the concept to full scale: Goia et al. tested a prototype PCM glazing outdoors against a conventional double-glazed unit, showing improved thermal comfort across most of the year [39] and double-digit seasonal reductions in the energy entering through the window, with the PCM cycling strongly behind a clear outer pane [11]. Gowreesunker et al. characterised the optical behaviour during phase change—transmittance rises markedly on melting [40]—which motivates the phase-dependent transmission model used here. Numerical studies then swept the design space: Li et al. examined the influence of the PCM’s optical properties in a filled double-glazed unit [41], and Zhong et al. swept its thermophysical parameters, both concluding that performance is governed by how much solar radiation actually reaches and penetrates the PCM [14]; multilayer configurations were modelled with validated transient models [21,22]. Most recently, Wang et al. combined a PCM layer with solar-control glass in a composite double-glazed unit for summer conditions in northern China, framing the solar-control layer as the cure for the overheating of pure PCM units [16]. Strategic assessments of transparent PCM envelopes flag the climate-matched melt choice as an open issue [13].

Dynamic shading and PCM-in-shading: The adaptive-façade literature supplies the control taxonomy—solar, temperature and hybrid triggers—and the performance-assessment challenges of movable systems [7,8,42,43]. Nielsen et al. quantified the energy and daylight advantage of automated dynamic shading over fixed devices in offices through integrated simulation [9], Palmero-Marrero and Oliveira mapped louvre benefits across climates [44], and Tzempelikos and Athienitis showed that shading control affects cooling and lighting in opposite directions, so over-shading carries a daylight penalty [45]. Gratia and De Herde demonstrated that the position of a shading device relative to the envelope changes its effectiveness [46]—an analogue of the PCM placement question addressed here. In hot-dry climates, Aldawoud compared fixed shading with switchable glazing [47], and morphology-driven kinetic façades target combined visual and thermal

comfort [48]. Where PCM meets shading in the literature, the PCM sits inside the shading device: Alawadhi placed PCM in window shutters in Kuwait and reduced solar heat gain by roughly a quarter in the best configuration [17], Silva et al. validated a PCM window shutter experimentally in Portugal [18], and a recent optical study examined PCM-filled blind slats in a double-skin façade [19]. The interaction between a PCM glazing and a separate dynamic louvre—the configuration studied here—has not been quantified in any of these lines.

Slat optics, codes and night ventilation: The louvre model rests on the detailed slat-optic calculations of ISO 15099 [49] and validated blind property models [50]; cut-off-angle control strategies balancing daylight and glare are established [51], with glare assessed formally through daylight glare probability [52] and validated dynamic daylight simulation [53]. The Saudi context is anchored by the code itself [5,6], national efficiency assessments [1,54] and consumption studies [2,55]; Gulf future-climate studies motivate the 2080 scenario [3]. For discharge, the night-ventilation literature shows free cooling collapsing when night air is warm [56–58]; ventilated PCM façades [59], PCM-assisted ventilation cooling [60,61], window-based PCM storage charged by night air [62], night-vented PCM surfaces in glazed high-rises [63] and recent hot-climate combinations of envelope PCM with night ventilation [64] all use outdoor air as the sink—the assumption this study relaxes. Storage-integration reviews complete the picture [65]. Methodologically, the study follows established simulation practice, with EnergyPlus as the engine [66], IEA Building Energy Simulation Test (BESTEST) diagnostics [67], published verification-and-validation templates for PCM models [68], co-simulation architecture [69], the enthalpy method [70] and performance-simulation practice [71].

Table 1 places the study against the most directly comparable published work. The columns are those a reader needs in order to judge transferability: the climate in which each study was carried out, where the PCM sits, how shading is treated, the method, whether future weather was considered, and the limitation that motivates the present work. Where a study does not address a column, it is marked as such rather than being given an inferred value.

Table 1. Comparison with the most directly comparable published studies.

Study	Climate	PCM Position	Shading Treatment	Method	Future Weather	Limitation Addressed Here
Ismail & Henriquez [10]	Tropical (Brazil)	PCM curtain inside the window cavity	None	Numerical + experimental, unit level	No	Unit level only; no whole-building or code context
Weinläder et al. [38]	Temperate (Germany)	Translucent PCM façade panel behind glazing	None	Experimental test façade	No	Heating-dominated climate; cooling not the design driver
Goia et al. [11]	Temperate continental (Turin, Italy)	PCM layer in a double-glazed unit	None	Full-scale outdoor experiment	No	Clear outer glass; no interaction with a shading device
Gowreesunker et al. [40]	Temperate (UK)	PCM-glazed unit	None	Experimental + numerical optical and thermal characterisation	No	Optical focus; no façade-level control study
Zhong et al.; Li et al. [14,41]	Temperate/mixed (China)	PCM-filled double-glazed unit	None	Numerical parametric sweep	No	Parametric; no mandatory-code envelope, no shading

Table 1. Cont.

Study	Climate	PCM Position	Shading Treatment	Method	Future Weather	Limitation Addressed Here
Wang et al. [16]	Cold/temperate (northern China)	PCM + solar-control glass in one unit	Solar-control glass as the fixed layer	Numerical, summer days	No	Solar control added to cure PCM overheating; the inverse of a code-imposed ceiling, and no annual balance
Alawadhi [17]	Hot-arid (Kuwait)	PCM inside the shading device (window shutter)	PCM-filled shutter	Numerical	No	PCM and shading fused in one element; no separate glazing store
Silva et al. [18]	Mediterranean (Portugal)	PCM inside the shading device (shutter)	PCM-filled shutter	Experimental + numerical	No	As above; interaction with a PCM glazing not examined
Wei et al.; Liu et al. [21,22]	Temperate/mixed (China)	PCM in multilayer glazing (2–4 panes)	None	Numerical, validated transient model	No	Varies the number of layers, not which pane carries the PCM; no inward/outward heat split
Saffari et al. [20]	Multiple world climates	PCM in the opaque envelope	None	Simulation-based melt-temperature optimisation	No	Opaque envelope; no glazing optics gate
Soudian & Berardi; Al-Yasiri et al. [63,64]	Cold/hot (Toronto; hot climate)	PCM on opaque interior surfaces	None	Simulation with night ventilation	No	Outdoor air assumed as the night sink; opaque PCM
This study	Hot-arid, code-compliant (Riyadh, SBC 601 Zone 1)	PCM glazing; outer/mid/inner pane compared	Separate dynamic external louvre, four control laws	EnergyPlus coupled to a 1-D enthalpy model, verified bidirectionally	Yes (2080, SSP5-8.5)	Addresses the gap: glazing-integrated PCM and a separate dynamic louvre competing for one façade under a mandatory code

Research gap: Silva et al. explicitly call for coupled assessment of PCM glazing with shading [12], and Attia et al. call for code-referenced adaptive-façade benchmarks [43]. Their intersection—a code-compliant hot-arid office in which both technologies compete for one west window, evaluated with the code’s own envelope and operation—remains unoccupied; it is the position this study takes in Figure 1b.

3. Materials and Methods

The methodology adopted in this study consists of six main phases designed to evaluate the performance of PCM-integrated glazing combined with adaptive external louvres under present and future hot-arid climates. These phases comprise: (1) Base Model Development; (2) Simulation and Modelling Settings; (3) Dynamic Louvre Development; (4) PCM Glazing Co-simulation and Coupling Framework; (5) Model Validation and Verification; and (6) Performance Evaluation and Analysis. Figure 2 illustrates the overall workflow and the flow of information between the phases; the following subsections present each phase in turn.

Research methodology: six phases from code-anchored model development to performance evaluation

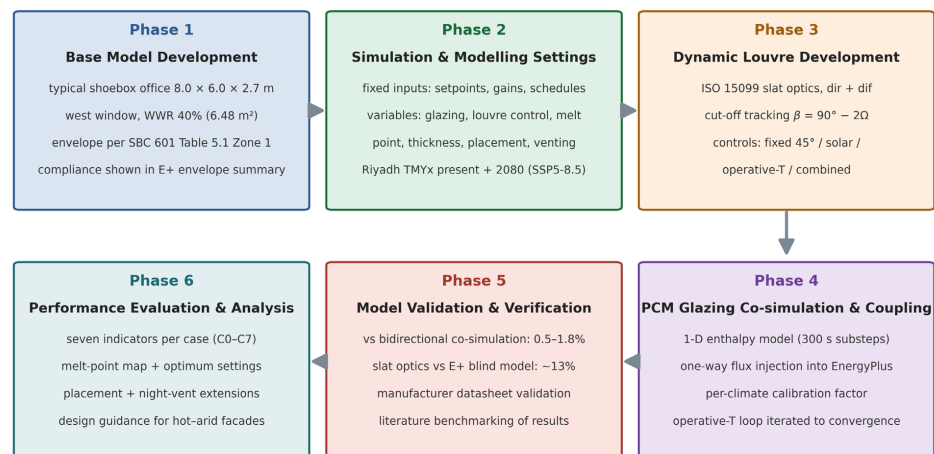


Figure 2. Research methodology: the six phases from code-anchored model development to performance evaluation and analysis.

3.1. Phase 1: Base Model Development

The base model is a typical single-zone shoebox office of $8.0 \times 6.0 \times 2.7$ m with a west-facing glazed façade (window 3.6×1.8 m, window-to-wall ratio 40%), dimensioned in Figure 3. The envelope is constructed to the Saudi Building Code: wall, roof and floor assemblies meet the Zone-1 maxima of Table 5.1 in SBC 601 [5], and compliance is demonstrated through the EnergyPlus envelope-summary audit rather than asserted (wall 1.18, roof 0.35, floor $0.40 \text{ W}/(\text{m}^2 \cdot \text{K})$ against ceilings of 1.19, 0.36 and 0.40). The conventional reference window is a double-glazed unit with $U 2.70 \text{ W}/(\text{m}^2 \cdot \text{K})$ and SHGC 0.24, below the code ceiling of 2.89 and 0.25.

Model and simulation setup - dimensioned isometric (SBC 601 Zone 1 office, west PCM glazing + external louvres)

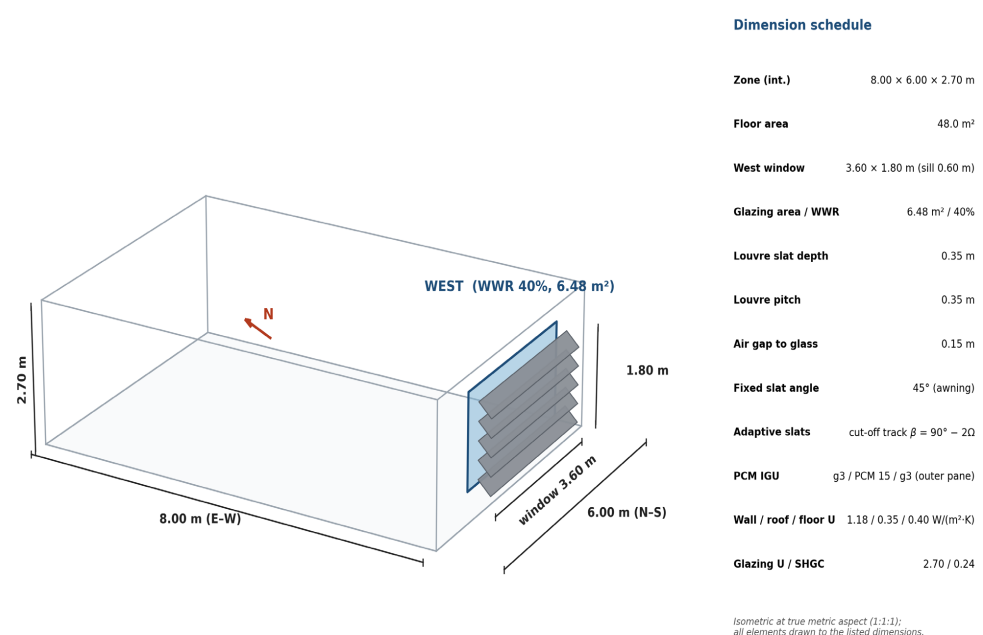


Figure 3. Base model: dimensioned isometric at true metric aspect (1:1:1) with the dimension schedule. Grey lines = zone; blue = west window; grey slats = external louvres at the fixed 45° awning position; red arrow = north; black lines = dimension lines.

3.2. Phase 2: Simulation and Modelling Settings

This phase fixes the operational boundary conditions and defines the design variables. Table 2 lists the parameters held constant across all cases, each traceable to a code table, standard or manufacturer datasheet.

Table 2. Fixed model parameters and their sources.

Parameter	Value	Source
Setpoints	cooling 24 °C/heating 21 °C; HVAC Sun–Thu 08:00–17:00	SBC 601 [5], Table 11.2
Internal gains	18.6 m ² /person; LPD 8.5 W/m ² ; EPD 8.0 W/m ²	representative Saudi office
Ventilation/infiltration	2.5 L/(s · person) + 0.3 L/(s · m ²); 0.2 ACH	ASHRAE 62.1
Louvre geometry	slat depth = pitch = 0.35 m, 1 mm slats, 0.15 m air gap, external	ISO 15099 [49] slat optics
PCM panel constants	paraffin: k 0.20 W/(m · K), ρ 850 kg/m ³ , c_p 2.0 kJ/(kg · K)	Rubitherm RT-line datasheets (Rubitherm Technologies GmbH, Berlin, Germany)
Weather	Riyadh TMYx (present); 2080 file morphed from it using NEX-GDDP-CMIP6 SSP5-8.5 monthly deltas	see Section 3.2
Engine/cycle	EnergyPlus 25.2, 3 min timestep, annual, full 24 h cycle; PCM model 300 s substeps	-

Future weather: The 2080 file is not taken directly from a climate model but morphed from the present TMYx file, so that the two climates differ only in the imposed warming signal. Monthly change factors were derived from the NASA NEX-GDDP-CMIP6 dataset [72], which is statistically downscaled and bias-corrected at source to a 0.25-degree grid, for the grid cell containing Riyadh and a three-model ensemble (ACCESS-CM2, EC-Earth3 and MPI-ESM1-2-HR, variant r1i1p1f1) under scenario SSP5-8.5: monthly climatologies of daily mean, maximum and minimum temperature, relative humidity, downwelling shortwave radiation and wind speed were formed over the historical reference window 1995–2014 and the future window 2071–2090, and their ensemble-mean differences and ratios were applied to the hourly baseline by the shift-and-stretch morphing procedure of Belcher et al. [73], which preserves the diurnal structure and the sequence of weather events while displacing the distribution. The file was cross-checked against an independent morph of the same baseline produced with the open-source Future Weather Generator [74] driven by the full CMIP6 ensemble; the two methods agree within 0.3–0.5 °C on the annual-mean and night-mean temperature, so the warming signal is not an artefact of either tool. SSP5-8.5 is used deliberately as the upper-bound scenario: it stresses the passive regeneration of the PCM most severely, so the 2080 results should be read as a bounding case rather than a central projection, and the treatment of climate uncertainty is limited to this cross-method check because the study concerns the response of one façade to a warming signal rather than the projection itself. The resulting file is a warmed version of the same typical year rather than an independent future year, which is appropriate for isolating the effect of warming on a façade but not for extreme-event analysis.

Table 3 then lists the design variables and where each is exercised. The eight cases of the factorial matrix combine them as follows: C0 is the conventional baseline; C1 and C2 add fixed 45° and solar-responsive louvres to the conventional window; C3 is the PCM glazing alone; and C4–C7 combine the PCM glazing with fixed, solar-responsive,

operative-temperature and combined louvre control, respectively. Figure 4 draws all eight cases to scale.

Table 3. Design variables and where each is exercised.

Variable	Levels	Where Used
Glazing system	conventional SBC/PCM glazing	C0–C2 vs. C3–C7
Louvre control	none/fixed 45° awning/solar (>200 W/m ²)/operative-T (>24.5 °C)/combined (>200 W/m ² and > 23.5 °C)	C0–C7
PCM melt temperature	28/31/35/47 °C (RT28HC, RT31, RT35HC, RT47)	melt map (Section 4.3)
PCM thickness	10/15/20 mm	sensitivity
Glazing transmittance to PCM, <i>sct</i>	0.45 (SBC solar-control)/1.0 (clear-daylight)	starvation variant (Section 4.2)
Night cavity venting	sealed/outdoor air/building exhaust (~24.5 °C)	regeneration (Section 4.5)
PCM placement	outer pane/mid-laminate/inner pane	placement (Section 4.4)
Climate	present/2080	all cases

Case matrix C0–C7 in dimensioned isometric (true 1:1:1 aspect). All cases share the zone of Fig. 3: 8.00 × 6.00 × 2.70 m, west window 3.60 × 1.80 m (WWR 40%); adaptive louvres are drawn mid-track – deployed they rotate outer-edge-down to the cut-off of Eq. (2).

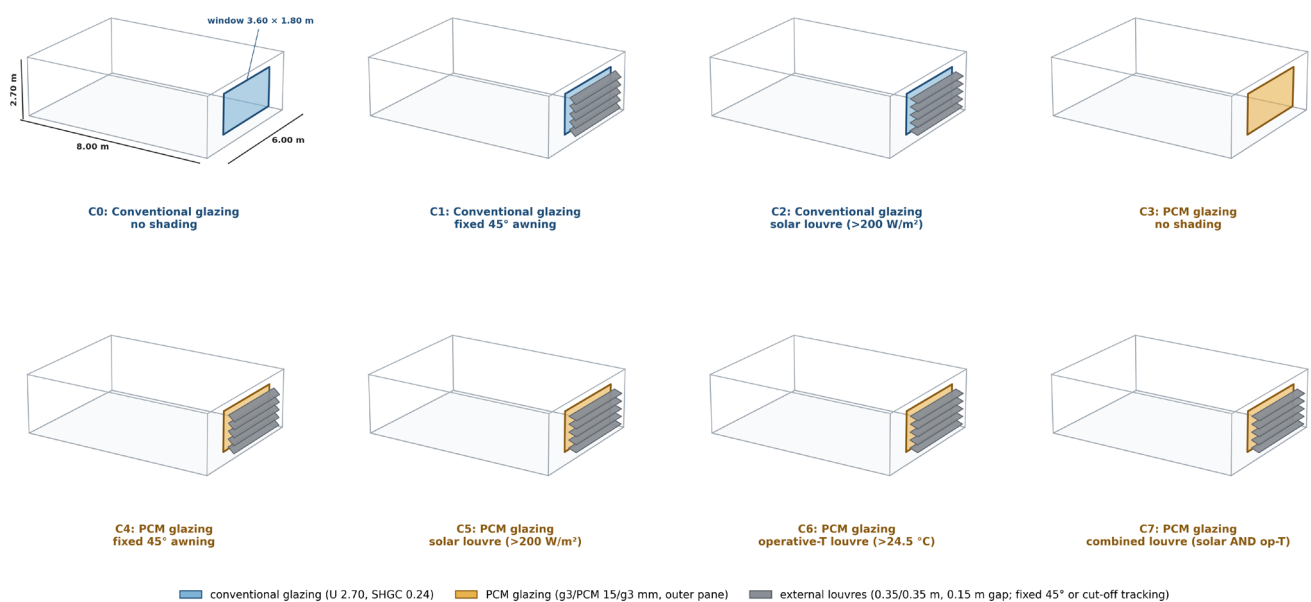


Figure 4. The case matrix C0–C7 in dimensioned isometric (true 1:1:1 aspect); blue = conventional glazing, amber = PCM glazing, grey = external louvres.

Because the PCM inputs govern the latent behaviour, they are checked against the manufacturer's datasheets before use.

Table 4 gives the complete PCM glazing assembly as modelled. The unit is a laminate of two 3 mm glass panes enclosing a 15 mm PCM layer; the assembly is matched to the conventional reference window in U-value and solar heat gain coefficient so that the cases differ only in the presence of the PCM and its optical gate.

Table 4. Complete PCM glazing assembly as modelled.

Layer/Property	Value	Source or Basis
Outer and inner panes	3 mm glass; k 1.0 W/(m · K); ρ 2500 kg/m ³ ; c_p 840 J/(kg · K)	standard soda-lime glass
PCM layer	15 mm (10 and 20 mm in the sweep); k 0.20 W/(m · K); ρ 850 kg/m ³ ; c_p 2000 J/(kg · K)	Rubitherm RT-line datasheets
Latent heat	250/165/240/160 kJ/kg for RT28HC/RT31/RT35HC/RT47	Rubitherm RT-line datasheets
Front-surface reflectance	0.10	typical uncoated glazing
Glass absorptance (per pane)	0.04	typical low-iron float glass
Long-wave emissivity	0.90 (outer surface)	uncoated glass
Solar transmittance to the PCM, sct	0.45 (SBC solar-control assembly)/1.0 (clear assembly)	matched to SHGC 0.24 and 0.70, respectively
Phase-dependent transmission	$\tau(\varphi) = 0.30 + 0.36 \varphi$, i.e., 0.30 solid to 0.66 molten	see text
Assembly U-value/SHGC	2.70 W/(m ² · K)/0.24 (matched to the conventional reference)	SBC 601 ceiling 2.89/0.25
Convective film coefficients	outer 17, inner 8 W/(m ² · K) (50 W/(m ² · K) when the cavity is vented)	standard surface films

Phase-dependent transmission requires explicit attribution because it is not taken from a published correlation. The measured optical characterisation of PCM-glazed units establishes the physical behaviour it represents: a paraffin layer scatters strongly and appears translucent while solid, and it becomes markedly more transmitting as it melts, so the short-wave transmittance of the unit rises through the phase transition [40]. The strong dependence of unit performance on those optical properties has since been confirmed parametrically [14,41]. The expression used here, $\tau(\varphi) = 0.30 + 0.36 \varphi$, linearly interpolates between a solid-state value of 0.30 and a molten value of 0.66. These end points match the reported range for a centimetre-scale paraffin layer, but the linear form itself is the authors' simplification: the measured transition is sigmoidal. It is therefore a modelling assumption, not a fitted or published curve, and it is treated as such in the limitations: because it governs only the short-wave split between the PCM and the room, and because the latent contribution behind code glazing is small in any case, the headline results are insensitive to it.

Table 5 compares the modelled melt ranges and latent heats with the manufacturer datasheets; deviations are disclosed rather than hidden.

Table 5. Manufacturer validation of the PCM inputs.

Product	Model $T_{sol}-T_{liq}$ (°C)	Model Latent (kJ/kg)	Datasheet	Note
RT28HC	27–29	250	27–29 °C, ~250 kJ/kg	matches
RT31	28–33	165	27–33 °C (broad, asymmetric), ~165 kJ/kg	range simplified; disclosed
RT35HC	34–36	240	34–36 °C, ~240 kJ/kg	matches
RT47	45–49	160	melting area 41–48 °C (broad), ~160 kJ/kg	nominal 47 ± 2 used; deviation disclosed

3.3. Phase 3: Dynamic Louvre Development

The external louvre is developed as a slat system with depth equal to pitch (0.35 m) at a 0.15 m stand-off from the glazing. For solar profile angle Ω and drawn slat angle β (positive = outer edge down), the direct-beam transmittance and the beam-excluding cut-off angle follow the ISO 15099 slat geometry:

$$\tau_{\text{dir}}(\Omega, \beta) = \max \left[0, 1 - \frac{w}{s} \frac{|\sin(\beta + \Omega)|}{\cos \Omega} \right] \quad (1)$$

$$\beta_{\text{cut}} = 90^\circ - 2\Omega \quad (2)$$

Control implementation: The four control laws are evaluated at every simulation hour from the incident solar irradiance on the west façade and, for the temperature-driven laws, the zone operative temperature of the preceding coupling pass. The slat angle is bounded to plus or minus 80 degrees and, when deployed, is held at or beyond the cut-off of Equation (2) subject to a 15-degree floor; no rate limit or actuator dead-band is imposed, so the modelled louvre responds within one hour of a threshold crossing and the reported savings are an upper bound on what a real actuator with hysteresis would deliver. Direct and diffuse radiation are treated separately: the direct beam is handled by the cut-off geometry of Equations (1) and (2), while the diffuse component uses the hemispherically integrated ISO 15099 slat transmittance and is not fully excluded even when the slats are closed.

Any slat angle at or beyond β_{cut} excludes the beam; the adaptive controller tracks Equation (2) with a 15° floor, sufficient for all profile angles at and above 45° where the cut-off becomes non-positive. Diffuse transmission uses the hemispherically integrated ISO 15099 component. In the production runs, the open, fixed-45 and deployed states are represented by their transmittance fractions of 0.85, 0.45 and 0.10, and Figure 5 shows the geometry to scale in both states. Four control laws are implemented: fixed 45°; solar-responsive (deploy above 200 W/m² incident); operative-temperature (deploy above 24.5 °C); and combined, which deploys only when both are satisfied at once (above 200 W/m² incident and operative temperature above 23.5 °C). The combined law deliberately carries a lower temperature threshold than the operative-temperature law: requiring two triggers instead of one would otherwise make it strictly more conservative than either parent law, and it would never deploy where they did not. One consequence is visible in Section 4.1—under strong afternoon sun with the zone between the two thresholds, the combined louvre is deployed while the operative-temperature louvre is still open.

External adaptive louvre + PCM glazing - to-scale section (west façade, solar profile angle $\Omega = 25^\circ$). Slat depth = pitch = 0.35 m (1:1), 0.15 m air gap; sun rays ray-traced against the ISO 15099 slat geometry.

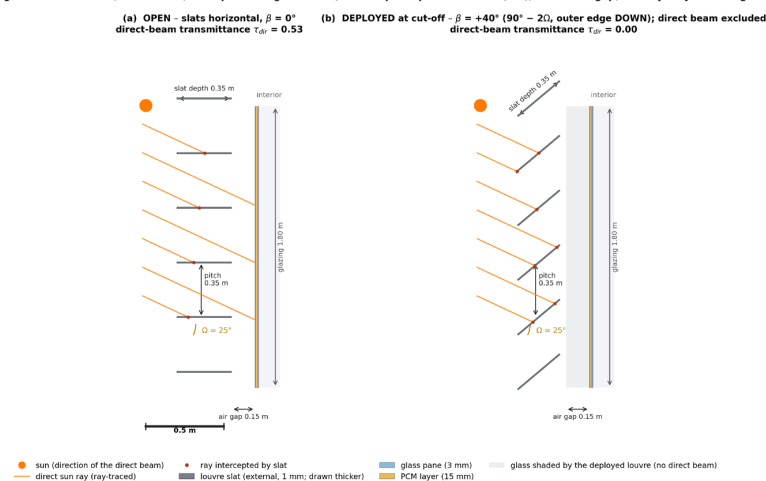


Figure 5. The louvre and PCM glazing in to-scale section (1:1): slats open (a) and deployed at the beam-excluding cut-off of Equation (2) (b), with sun rays ray-traced against the slat geometry.

3.4. Phase 4a: PCM Glazing Model Formulation

EnergyPlus resolves the zone, but its window heat balance is steady-state and cannot store latent heat in a glazing layer. The PCM glazing is therefore resolved by a one-dimensional transient conduction equation with the phase change absorbed into effective heat capacity (the effective-capacity form of the enthalpy method):

$$\rho(x)c_{\text{eff}}(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[k(x)\frac{\partial T}{\partial x}\right] + S(x,t) \quad (3)$$

$$c_{\text{eff}}(T) = \begin{cases} c_p + \frac{L}{T_{\text{liq}} - T_{\text{sol}}}, & T_{\text{sol}} \leq T \leq T_{\text{liq}} \\ c_p, & \text{otherwise} \end{cases} \quad (4)$$

$$\varphi = \left\langle \text{clip}\left(\frac{T - T_{\text{sol}}}{T_{\text{liq}} - T_{\text{sol}}}, 0, 1\right) \right\rangle_{\text{PCM nodes}} \quad (5)$$

where ρ , k and c_p are the layer density, conductivity and sensible heat capacity; L is the latent heat; $S(x,t)$ is the absorbed solar source and φ the liquid fraction. The equations are discretised by an implicit finite-volume scheme (tridiagonal solve, 300 s substeps; two nodes per glass pane, six PCM nodes). The phase-dependent optical transmission is $\tau(\varphi) = 0.30 + 0.36\varphi$, bounded between the frosted solid and the clear melt. The outer boundary combines convection with long-wave exchange through a louvre-gated sky view factor $F_{\text{sky}} \in [0.10, 0.50]$; the inner boundary is convective to the room. Night cavity venting, where active, replaces the outer film condition with $(50 \text{ W}/(\text{m}^2 \cdot \text{K}), 24.5^\circ\text{C}$ exhaust air).

The long-wave term matters because the simulation resolves the complete 24 h cycle rather than daytime hours alone: the PCM must re-freeze overnight for the store to be available the following day. Figure 6 shows the driving conditions and the resulting liquid fraction over three consecutive summer days for three boundary treatments. Omitting long-wave exchange leaves the PCM markedly more molten at dawn, while including it—with the louvre retracted so the glazing sees the cold desert sky—deepens the nightly discharge; closing the louvre at night blocks that view and suppresses part of the benefit. Night-sky radiative cooling and the louvre-gated sky view factor are therefore retained in all production runs.

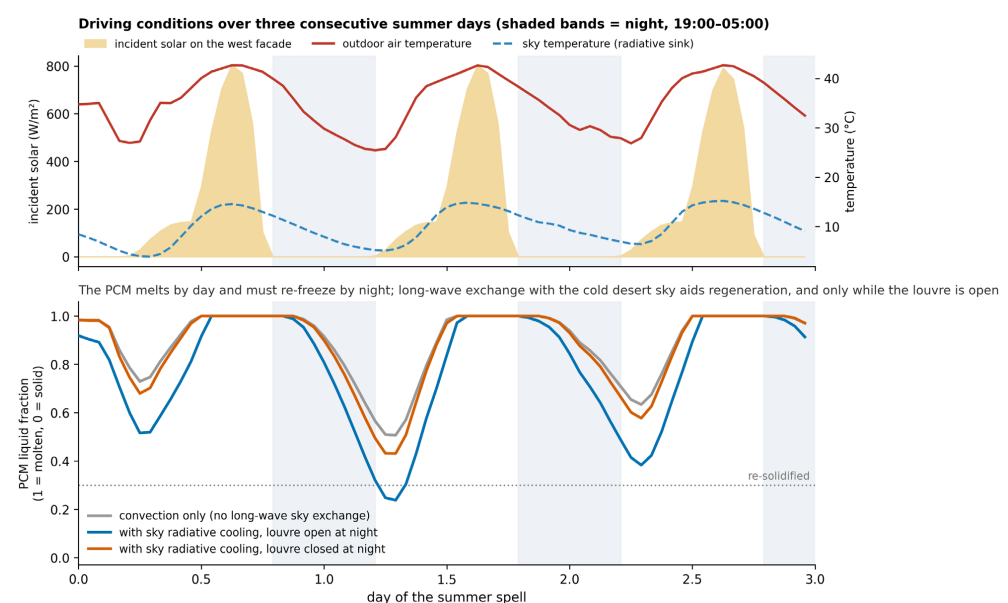


Figure 6. Full 24 h cycle over three consecutive summer days (28°C PCM, clear glazing). (Top) Driving conditions—incident solar on the west façade, outdoor air temperature and effective sky temperature;

shaded bands mark night (19:00–05:00). **(Bottom)** PCM liquid fraction for three outer-boundary treatments, showing the contribution of long-wave sky exchange and of the louvre position at night.

3.5. Phase 4b: EnergyPlus–PCM Coupling Strategy and Calibration

The enthalpy model injects its inward flux into EnergyPlus as paired OtherEquipment gains—a one-way, level-L2 coupling:

$$q_{\text{in}} = h_i(T_N - T_{\text{set}}) + \tau(\varphi)I_g \quad (6)$$

$$F = \frac{C_{C0} - C_{\text{neutral}}}{C_{\text{clear-inj}} - C_{\text{neutral}}} \quad (7)$$

The calibration factor F of Equation (7) anchors a no-PCM clear injection to the real SBC window, using the annual cooling energies of the baseline (C0), of C_{neutral} —the model with the west window replaced by a near-opaque surrogate ($U = 0.10 \text{ W}/(\text{m}^2 \cdot \text{K})$, $\text{SHGC} = 0.01$), removing the west solar path—and of $C_{\text{clear-inj}}$, the same neutral model driven by the uncalibrated one-dimensional inner-surface flux. F is therefore the fraction of that flux which must reach the zone air node for the injection to reproduce C0: it is fitted on C0 alone and verified against fully bidirectional co-simulation on the distinct cases C2, C3, C3n and C5 (Section 3.6). $F = 0.186$ for the present climate and 0.2 for 2080. The factor has a physical reading: the one-dimensional model delivers its inner-surface flux to a single node, whereas in EnergyPlus that flux is split between convection to the air node and long-wave exchange with the other surfaces, of which only part reaches the cooling coil within the hour; F is the fraction that does, and it is re-derived per climate because the same calibration triplet (C0, neutral, clear injection) is re-run under the 2080 weather. Its change from 0.186 to 0.2 reflects the larger conduction share of the window load in a warmer climate, not a re-fit to the PCM cases, which are never used in the calibration. To show that the recalibration does not bias the future-climate comparison, the 2080 cases were also driven with the present-climate factor: the C3 and C5 reductions move by +0.38 and +0.23 points and the sub-additivity gap moves by +0.42 points, without changing the ranking or the sign of any finding (Appendix A). Operative-temperature controls iterate the coupling to convergence (below 0.1°C). The PCM glazing's solar-control outer pane is represented consistently by $sct = 0.45$ across all cases. Because the headline results are ratios, a 10% change in F moves the reductions by less than one point; the factor is nonetheless carried as a limitation in the Discussion.

3.6. Phase 5: Model Verification and Evaluation

The model is evaluated at four levels, which are kept distinct because only the first three were possible without an experiment, following the practice of published simulation-based studies of PCM envelopes [67,68]. First, at input level, the PCM properties are validated against the manufacturer's datasheets (Table 5) and the envelope is validated against the code tables through the EnergyPlus envelope-summary audit. Second, at solver level, the production one-way coupling is verified against a fully bidirectional co-simulation in which the same PCM model runs inside the EnergyPlus timestep loop: annual cooling agrees within 0.5–1.8% across the principal cases (C2, C3, C3n and C5, both climates; Table A1), the largest difference belonging to the clear-glazed louvre case C2, whose injected flux is the largest and switches most sharply with the louvre, while all PCM cases lie within 0.8%. The agreement holds hour by hour: the hourly cooling rate has a coefficient of variation of the root-mean-square error of 1.7–4.1% and a normalised mean bias within 1.8%, well inside the ASHRAE Guideline 14 hourly criteria of 30% and 10%, and the peak-hour load agrees within 2.5% (Figure A1), so the faster one-way scheme

is used for production. The ray-traced slat-optic model is verified against EnergyPlus's native blind model at the integrated level: the annual effective blind transmittance under the beam-blocking control of EnergyPlus differs by approximately 13% between the two implementations. This is a comparison of two independent optic models, not a coupling error; the same slat model is used in every louvre case, so an optical bias of that size would scale the louvre-attributable saving in all of C1, C2 and C4–C7 together, and the case ranking is therefore expected to be insensitive to it. The direct sensitivity of Table A2 supports this: shifting the louvre transmittance fractions by ± 0.05 moves the C5 reduction by 0.14 points at most and the sub-additivity gap by 0.34 points at most, without changing the ordering of the re-run cases. The base model belongs to a BESTEST-heritage shoebox lineage [67]. Third, at the result level, each headline finding is compared with published ranges in the Discussion—dynamic-shading savings, PCM-glazing behaviour behind clear glass, the melt-point principle and warm-night ventilation limits—and found to be consistent. Fourth, reproducibility is enforced mechanically: the reproducibility package (File S1) re-checks forty pinned result values from checksummed outputs, and the derived arithmetic of the paper is machine-verified. It is acknowledged that no experimental work was performed in this study: validation is numerical (inter-model) and literature-based, and an experimental cell test of the outer-pane PCM glazing unit is identified as the priority for future work. Table 6 summarises the checks.

Table 6. Verification and validation summary.

Check	Method	Result	Status
Input validation	PCM properties vs. Rubitherm datasheets; envelope vs. SBC 601 [5], Table 5.1 (E+ envelope summary)	matches; deviations disclosed	pass
Coupling verification	one-way (L2) vs. bidirectional (L1) co-simulation per case (C2, C3, C3n, C5; both climates), 178,080 callbacks/yr	annual cooling within 0.5–1.8%; hourly CV(RMSE) 1.7–4.1%, NMBE within 1.8%; peak within 2.5% (Table A1)	pass
Louvre optics	ray-traced ISO 15099 model vs. EnergyPlus WindowMaterial:Blind (integrated annual effective transmittance)	within ~13% between the two optics models; louvre transmittance sensitivity in Table A2	pass (disclosed)
Results vs. literature	headline findings vs. published ranges (Discussion)	consistent	pass
Reproducibility	packaged verification harness on checksummed outputs; checklist in Appendix A	40/40 values match	pass

3.7. Phase 6: Performance Evaluation and Analysis

Comfort assumptions: Fanger PMV and PPD are computed by EnergyPlus with a metabolic rate of 120 W per person (about 1.2 met), work efficiency zero, clothing insulation 0.5 clo, air speed 0.10 m/s, and humidity from the zone moisture balance; the mean radiant temperature is taken from the zone surface temperatures. Because the west-glazing heat is delivered as an injected radiant and convective gain rather than through a resolved glazing surface, the mean radiant temperature—and hence PMV—carries a modelling uncertainty that is revisited in the limitations.

Two derived quantities used throughout require definition. A charging day is a day on which the PCM actually undergoes a meaningful melt–freeze excursion, defined here as

a daily liquid-fraction swing greater than 0.10; the regeneration efficiency of Equation (8) is averaged over charging days only, so that a PCM which barely cycles is not credited with perfect regeneration. The west-glazing share of the cooling load is the portion of annual cooling attributable to the west window, obtained by differencing the baseline against a neutral model in which the west glazing is replaced by an opaque, near-adiabatic surface ($U\ 0.10\ \text{W}/(\text{m}^2 \cdot \text{K})$, $\text{SHGC}\ 0.01$): the difference, 0.76 MWh of the 5.36 MWh baseline, is the load the façade measures can act upon. Façade-relative reductions are expressed against this 0.76 MWh rather than against the whole-office total.

Seven performance indicators are evaluated per case: (i) annual cooling energy; (ii) peak cooling load; (iii) indoor operative temperature; (iv) thermal comfort as the share of occupied hours with Fanger $|\text{PMV}| \leq 0.5$; (v) PCM liquid fraction, Equation (5); (vi) overnight regeneration efficiency, Equation (8); and (vii) annual heating energy, with the solar balance of the glazing reported separately (Section 4.2). The regeneration efficiency over charging days (daily melt swing above 0.10), the annual latent throughput with PCM mass $m = 82.62\ \text{kg}$, and the sub-additivity index over the whole-office cooling reductions r are defined as follows:

$$\eta_{\text{regen}} = \left\langle \frac{\varphi_{\text{max}} - \varphi_{\text{min,night}}}{\varphi_{\text{max}} - \varphi_{\text{morning}}} \right\rangle_{\text{charging days}} \quad (8)$$

$$E_{\text{lat}} = \sum_d (\varphi_{\text{max}} - \varphi_{\text{min,night}}) \frac{Lm}{3.6 \times 10^6} [\text{kWh/yr}] \quad (9)$$

$$\Delta = [1 - (1 - r_{C3})(1 - r_{C2})] - r_{C5} \quad (10)$$

The bracketed term of Equation (10) is the multiplicative null: combined reduction is expected if the two measures act independently, with the second acting only on the load the first leaves. A positive Δ therefore demonstrates overlap of the two measures on the same solar load; a simple additive null $r_{C3} + r_{C2}$ would overstate the expected combination, because the second measure cannot remove energy the first has already removed. Because C0, C2, C3 and C5 form a complete 2×2 factorial in the two factors louvre and PCM, the overlap can also be stated without a null model, as the two-factor interaction $I = (C_{C5} - C_{C3}) - (C_{C2} - C_{C0})$ in MWh/yr: the louvre's saving when the PCM is present minus its saving when it is absent. $I = 0$ means the two measures act on separable loads; $I > 0$ means each saves less once the other is present, that is, antagonism. Δ and I carry the same information (Δ equals I expressed as a share of C0 minus the second-order product $r_{C3} r_{C2}$), and both are reported so that the finding does not rest on the choice of null. Figure A2 illustrates the two constructions with the study's own numbers. The placement study additionally reports the inward and outward shares of the PCM panel's heat exchange, defined as the time-integrals of the positive inner- and outer-boundary fluxes normalised by their sum.

4. Results

The simulation outcomes are reported below with brief interpretation of the observed trends; the mechanisms behind the trends, their comparison with previous studies and their implications are examined in the Discussion (Section 5).

4.1. Case Matrix: Energy, Peak Load and Comfort

The eight façade configurations are first evaluated against the seven performance indicators under present weather; Table 7 presents the results.

Table 7. Annual performance of the eight cases under present Riyadh weather: cooling energy, reduction relative to C0, peak cooling load, thermal comfort as the share of occupied hours with $|PMV| \leq 0.5$, and annual heating energy. The matched no-latent control C3n (Section 4.2) is reported for cooling only.

Case	Description	Cooling (MWh/yr)	vs C0	Peak (kW)	Comfort $ PMV \leq 0.5$	Heating (kWh/yr)
C0	Conventional, no shading (baseline)	5.355	0.0%	5.68	47.0%	12
C1	Conventional + fixed 45°	4.967	7.2%	5.57	51.0%	12
C2	Conventional + solar louvre	4.810	10.2%	5.53	51.4%	13
C3	PCM, no shading	4.851	9.4%	5.53	51.0%	13
C4	PCM + fixed 45°	4.752	11.3%	5.49	51.5%	14
C5	PCM + solar louvre	4.711	12.0%	5.47	51.8%	15
C6	PCM + operative-T louvre	4.715	12.0%	5.47	52.1%	14
C7	PCM + combined louvre	4.716	11.9%	5.47	51.9%	14
C3n	PCM assembly, latent heat disabled (matched control)	4.877	8.9%	-	-	-

The comfort figures deserve comment, since they remain between 47 and 52 percent of occupied hours even though the zone is mechanically cooled. The cooling setpoint of 24 °C is an upper bound on the air temperature, not a target: the zone is allowed to drift up to it, and the occupied-hour mean operative temperature is 25.6 °C at the baseline because the west glazing adds a radiant component above the air temperature. At 0.5 clo and 0.10 m/s this places the predicted mean vote above +0.5 for roughly half the occupied hours, so the comfort metric is measuring the strictness of the $|PMV| \leq 0.5$ band under a warm-side setpoint rather than a failure of the cooling system. The façade measures improve it by removing part of that radiant asymmetry.

Annual heating is 12–15 kWh across all cases—0.2–0.3% of the cooling energy—so cooling dominates the HVAC balance and the reductions below are materially unchanged when expressed against total HVAC energy.

The adaptive-louvre PCM cases C5–C7 lead the matrix and are mutually equivalent, within 1% of each other. Control sophistication beyond the simple solar-responsive law buys comfort (52.1% for C6, the best) but no additional energy saving. Expressed against the west-glazing share of the cooling load (0.76 MWh), the louvre alone removes 71% and the best combined case removes 84%. Under 2080 weather, the baseline grows to 7.15 MWh and the reductions persist (C5 9.8%, C6 9.7%, C7 9.8%); consequently, the ranking is climate-robust.

Numerical robustness of the case ranking: Because several cases differ by less than a tenth of a percentage point, the ranking is only meaningful if the model uncertainty is smaller still. Perturbing the calibration factor by plus and minus ten percent, refining the PCM grid from six to twelve nodes and coarsening it to three, and running the zone model at one-minute and six-minute timesteps shifts the C5 reduction by at most 0.22 percentage points, the calibration factor being the only influential term. Cases C5, C6 and C7 span 0.1 percentage points, which is below that figure; they are therefore equivalent within the numerical uncertainty of the model and are not ranked against one another in what follows.

The hypothesis of Section 1 is resolved by Equation (10). PCM alone saves 9.4% and the louvre alone saves 10.2%, which would give 18.6% if the measures acted independently, each on the load the other leaves, yet the combination delivers 12.0%. The overlap $\Delta = 6.6$ percentage points therefore confirms that both measures act on the same west solar load.

The factorial interaction confirms the overlap without reference to a null model: $I = +0.405$ MWh/yr, or 7.6% of the baseline cooling, in the present climate and $+0.426$ MWh/yr (6.0%) in 2080; the louvre saves 0.545 MWh/yr on the conventional window but only 0.140 MWh/yr once the PCM glazing is present (Figure A2). The finding is also robust to the modelling assumptions: across the 19 present-climate one-at-a-time perturbations of Table A2, which move the optical transmission end points and shape, the latent heat, the melt-range width, the film coefficients, the louvre transmittance fractions and the calibration factor, the C3 reduction stays within 8.9–9.9%, the C5 reduction within 11.8–12.3%, the latent share within 0.36–0.63 points and the sub-additivity gap within 6.3–6.9 points; in the two 2080 rows, the gap is 5.3 and 5.8 points, so it is positive in all 21 variants.

Figure 7 illustrates the moment at which the four control laws diverge most. At 13:12 on the March shoulder day, the solar-responsive and combined louvres are deployed at the cut-off while the operative-temperature louvre is still open—the zone has not yet crossed 24.5°C —so it admits the midday beam and its PCM is the only adaptive case charging. Within the following hour, the zone crosses the threshold and all three adaptive controls converge to the deployed state; on the May peak-summer day, they are deployed from late morning onward. This behaviour underlies both the near-identity of C5 and C7 and the comfort advantage of C6.

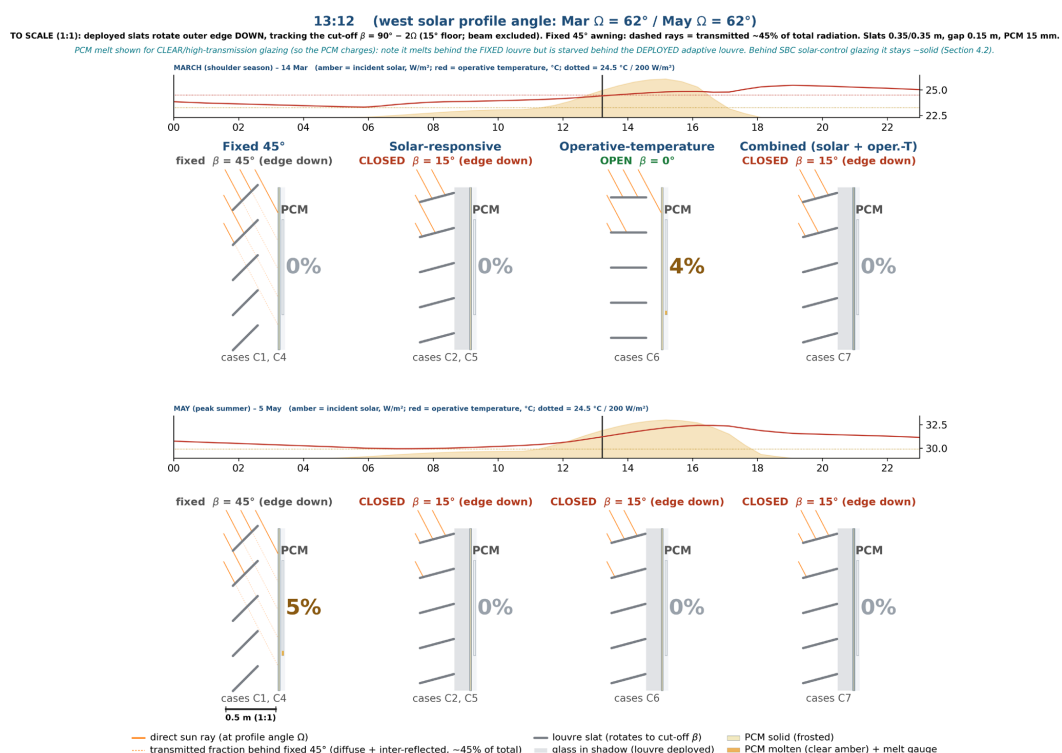


Figure 7. Snapshot of the 24 h animation at 13:12 (to scale, ray-traced): March shoulder day (**top**) versus May peak-summer day (**bottom**). Dashed rays are the fixed awning's transmitted fraction; the animated version is provided in File S1.

4.2. Code-Induced Starvation of the PCM

Separating the mechanisms: Case C3n repeats case C3 with an identical assembly—the same layer thicknesses, conductivities, densities, optical properties and solar gate—but with the latent term removed from the effective heat capacity, so that the only difference between the two simulations is the phase change itself. The comparison decomposes the reduction of C3 directly: of the 9.44% total, 8.94 percentage points come from the optical

and sensible behaviour of the assembly and only 0.50 points, or 27 kWh/yr, from latent storage. The same decomposition holds under 2080 weather (7.54% total, 7.04 optical and sensible, 0.50 latent). The headline reduction of this case is therefore predominantly an optical and thermal-mass effect, and only about one twentieth of it is attributable to the phase-change material acting as a latent store.

Removing the latent term also lets the layer run hotter, which shifts its liquid fraction and hence $\tau(\varphi)$, so the C3n difference contains small optical feedback as well as the storage term. A second control isolates the storage term alone: the latent heat is disabled but $\tau(\varphi)$ is driven by the hourly liquid-fraction trajectory of the latent run, so the optical state of the two runs is identical and only the heat capacity differs. This optics-matched control attributes 0.15 points to storage, against 0.49 points for the plain C3n control; the latent contribution behind code glazing is therefore bounded between 0.15 and 0.49 points, and the 0.5-point figure used in the text is its upper bound.

The effect of the glazing's solar transmittance on the PCM is isolated by holding the PCM identical and varying only sct (Table 3). Behind the code window, the PCM's peak daily liquid fraction is 0.28 and its isolated latent savings amount to 27 kWh/yr, whereas behind clear glazing it reaches 0.59 and 216 kWh/yr—more than six times greater. The attribution of the 9.4% savings of case C3 therefore requires care. That figure is the whole effect of replacing the conventional window with the PCM assembly, and it combines three mechanisms: the optical gate of the assembly, the added sensible mass and absorption of the PCM layer, and the latent storage itself. The decomposition of case C3n above assigns almost all of it to the first two: the reduction is predominantly optical and sensible, and it should not be reported as latent heat saving. The binding constraint is therefore the code's SHGC ceiling, not the PCM itself.

Table 8 reports the full annual solar balance of the PCM assembly at the glazing plane, before the coupling calibration, and resolves the apparent contradiction between the solar-gain magnitudes of the conventional and PCM cases. Of the 8726 kWh incident on the window, the solar-control outer treatment rejects 4799 kWh; front reflection and glass absorption remove a further 593 kWh; 1906 kWh is absorbed in the PCM layer; and 1427 kWh is transmitted as short-wave—the same order as the conventional window's 1111 kWh. The effective assembly solar heat gain coefficient, computed as the coupled inward flux with minus without sun over the incident total, is 0.233, demonstrating the match to the conventional reference (0.24). Zone-side injected quantities carry the calibration factor and are not comparable to glazing-plane quantities, which is why Table 7 reports heating rather than a mixed solar column.

Table 8. Annual solar balance of the PCM glazing assembly at the glazing plane (case C3 optics, pre-calibration).

Solar Balance Term (Annual, Whole Window)	kWh/yr
Incident on the west window	8726
Rejected by the solar-control outer treatment	4799
Front-surface reflection	393
Absorbed in outer/inner glass	141/59
Absorbed in the PCM layer	1906
Transmitted short-wave	1427
Balance residual	0.0
Effective assembly SHGC (with-sun minus dark inward flux/incident)	0.233
Conventional window transmitted solar (EnergyPlus, C0)	1111

4.3. Melt-Temperature Map and Optimum Settings

For each of the four melt temperatures taken from manufacturer datasheets, the combination of louvre state, glazing transmittance and night venting that maximises healthy latent cycling is identified; Figure 8 maps the annual latent throughput of Equation (9) across all settings. The sealed and exhaust-vented columns are identical for the 35 and 47 °C paraffins because both already return completely to solid overnight in a sealed cavity (mean nightly minimum liquid fraction 0.00 and 0.00, respectively), so no additional night sink can increase their throughput; only the 28 °C product, which still retains a liquid fraction of 0.26 at dawn when sealed, has anything left for venting to recover. The optima are additionally robust to the definition of the regeneration gate: selecting the mean nightly minimum liquid fraction instead (at or below 0.10, i.e., the store demonstrably returns to solid) leaves all four selections unchanged, since every selected setting reaches a nightly minimum of 0.00. RT28HC charges most overall (1749 kWh/yr) but only with clear glazing, no shading and exhaust-air night venting; without that assisted discharge, its throughput falls by a third. RT31 behaves similarly (1111 kWh/yr, assisted). In contrast, RT35HC reaches 1167 kWh/yr in a sealed unit: it is the highest melt point that regenerates passively in Riyadh nights, which makes it the robust self-sufficient choice. RT47 never exceeds a liquid fraction of 0.51 and is consequently unsuitable in glazing. The pattern indicates a general rule: below about 32 °C the Riyadh night constrains the cycle and discharge must be engineered; above about 40 °C the day constrains it and the PCM never charges; 35 °C threads the diurnal band.

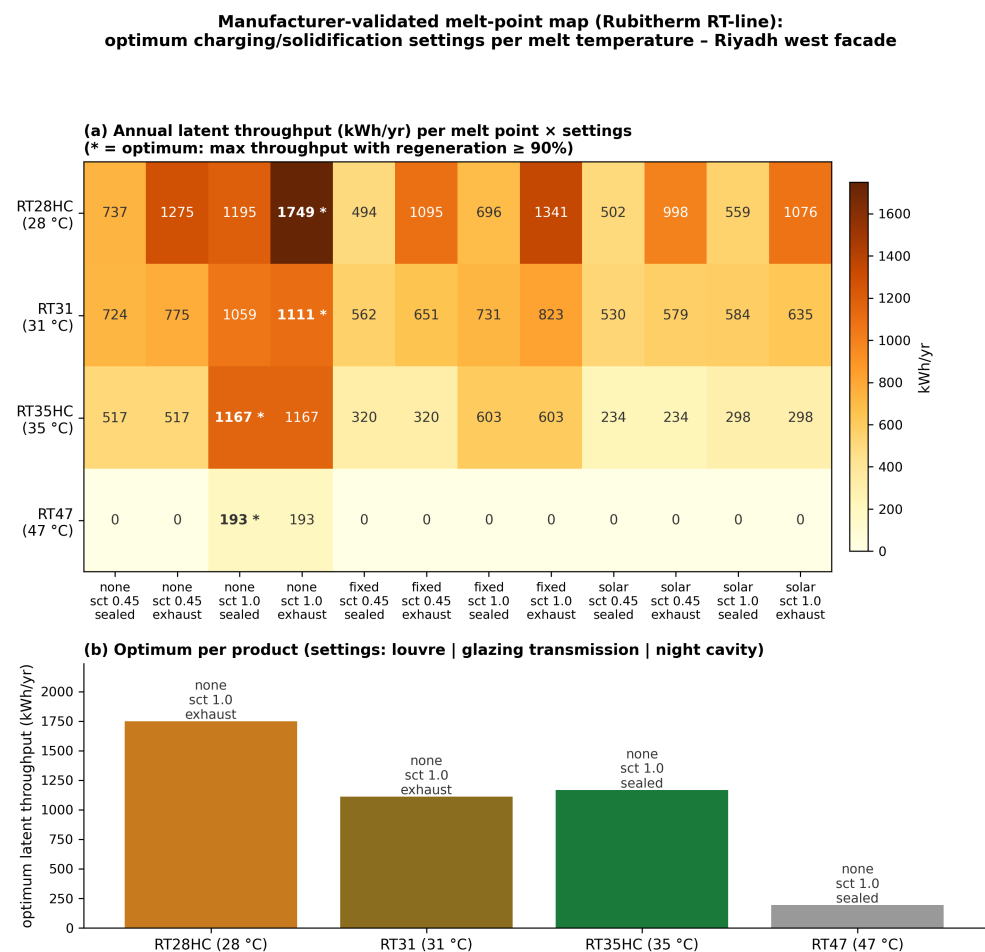


Figure 8. Manufacturer-validated melt-point map: annual latent throughput per melt point and setting combination; the star marks each product's optimum (maximum throughput with regeneration efficiency of at least 90%).

The ranking does not depend on the phase-change range assumed. Re-running the melt map with the melt range halved and widened by half, with the full datasheet melting areas of RT31 (27–33 °C) and RT47 (41–48 °C) in place of the narrowed ranges used above, and with the latent heat varied by $\pm 20\%$, leaves the same product in each role (Table A3): RT35HC returns fully to solid every night in every variant, RT28HC never does so passively (its summer nightly minimum liquid fraction stays at 0.23–0.29), and RT47 never melts beyond a daily liquid fraction of 0.63 behind clear glazing, so 35 °C remains the highest melt point that regenerates passively under every perturbation.

4.4. PCM Placement in the Glazing System

The objective here is to determine how the location of the PCM layer within the glazing unit influences thermal performance and latent heat utilisation; placement is compared at RT35HC in the charging regime. With the PCM laminated to the outer pane of a double-glazed unit, annual latent cycling reaches 771 kWh/yr sealed and 796 with exhaust venting, against 603 for the baseline laminate and 506 for the inner-pane position (Figure 9). The heat partition explains the ordering: in the outer position, 66% of the panel's heat exchange is rejected outward, whereas the inner position delivers 63% of it inward as cooling load. In a cooling-dominated climate, the outer pane is therefore the preferred position; inner placement would suit heating climates instead.

PCM placement in the glazing system: OUTER-pane placement charges most and rejects heat outward - the cooling-climate choice

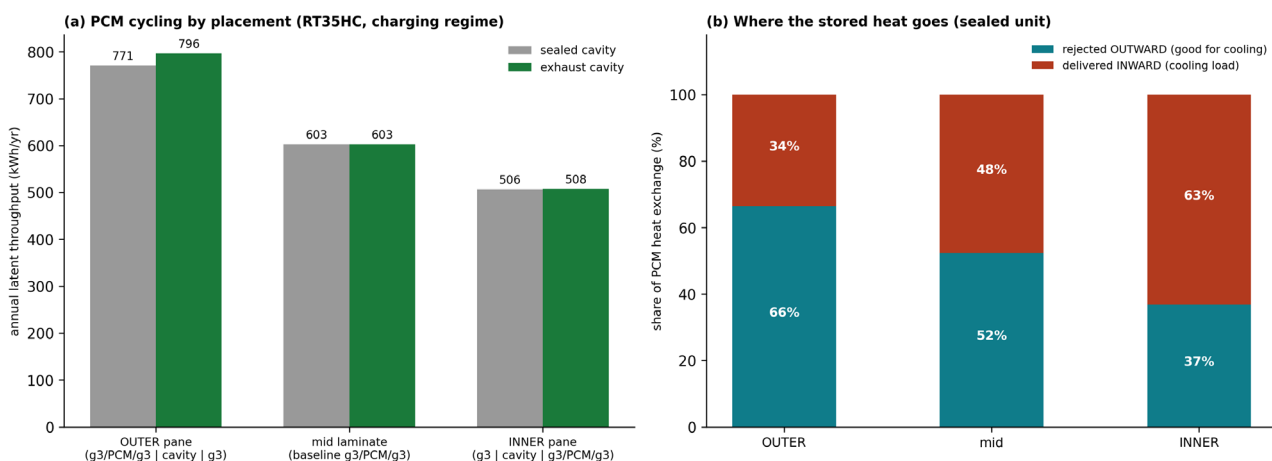


Figure 9. PCM placement: the outer-pane position maximises cycling and outward heat rejection (RT35HC, charging regime; cavity conductance $6 \text{ W}/(\text{m}^2 \cdot \text{K})$).

The annual shares are the integral of a daily mechanism that Figure A3 makes visible over three consecutive July days. In the charging regime, all three placements return to solid each night, but they charge and discharge through different faces: the outer-pane PCM reaches a daily liquid fraction of 0.89 against 0.72 for the mid-laminate and 0.46 for the inner pane, because it receives the beam before the inner glass absorbs it, and it rejects that heat outward in the evening at a peak of $79 \text{ W}/\text{m}^2$ through the outer film and sky exchange, against $65 \text{ W}/\text{m}^2$ for the mid-laminate and only $18 \text{ W}/\text{m}^2$ for the inner pane, whose store is insulated from the outdoor sink by the cavity and therefore discharges into the room (peak inward exchange $68 \text{ W}/\text{m}^2$ against $39 \text{ W}/\text{m}^2$ for the outer pane). The outer position is preferable in a cooling-dominated climate precisely because its discharge path faces the night sky rather than the occupied space.

4.5. Night Ventilation for Solidification

The effectiveness of night ventilation in regenerating the PCM is evaluated for summer conditions, when passive re-solidification is most at risk. For a charging low-melt PCM (28 °C), the sealed unit fails to re-solidify: the June–August nightly minimum liquid fraction is 0.62 (Figure 10a). Venting the cavity with outdoor air worsens the outcome (0.72), because Riyadh summer nights remain far above the solidus—outdoor air averages 32.1 °C over these hours. Supplying the cavity with air at 24.5 °C instead restores complete regeneration (0.00) and raises the annual latent throughput from 1255 to 1743 kWh/yr.

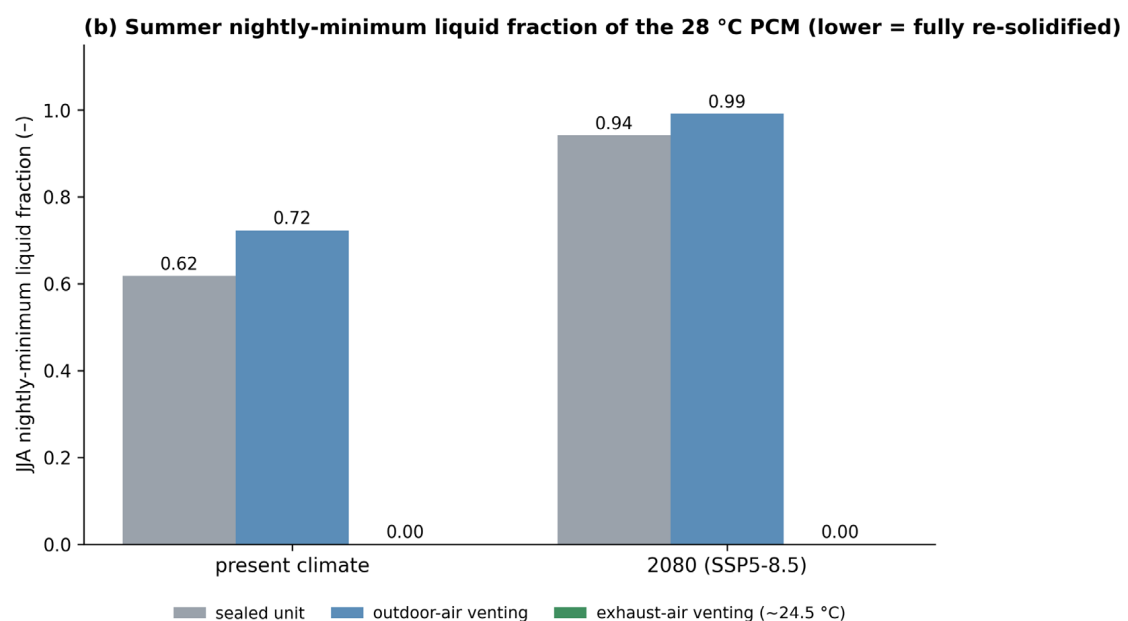
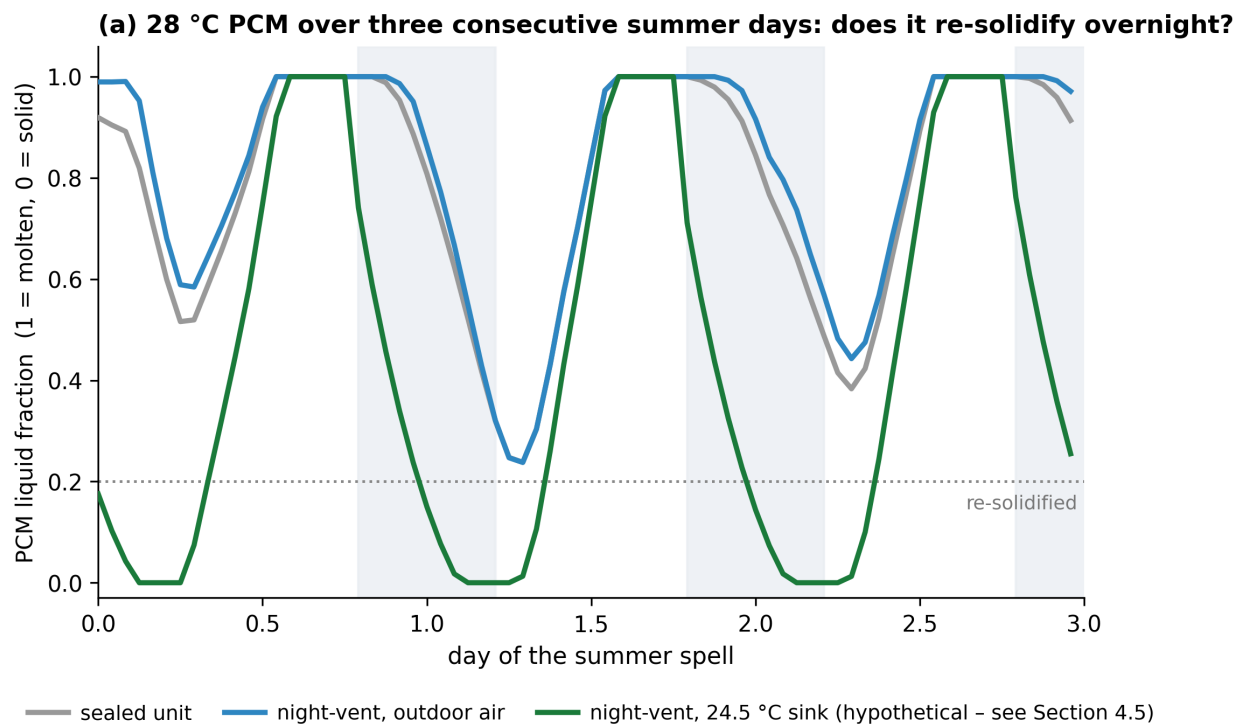


Figure 10. Cont.

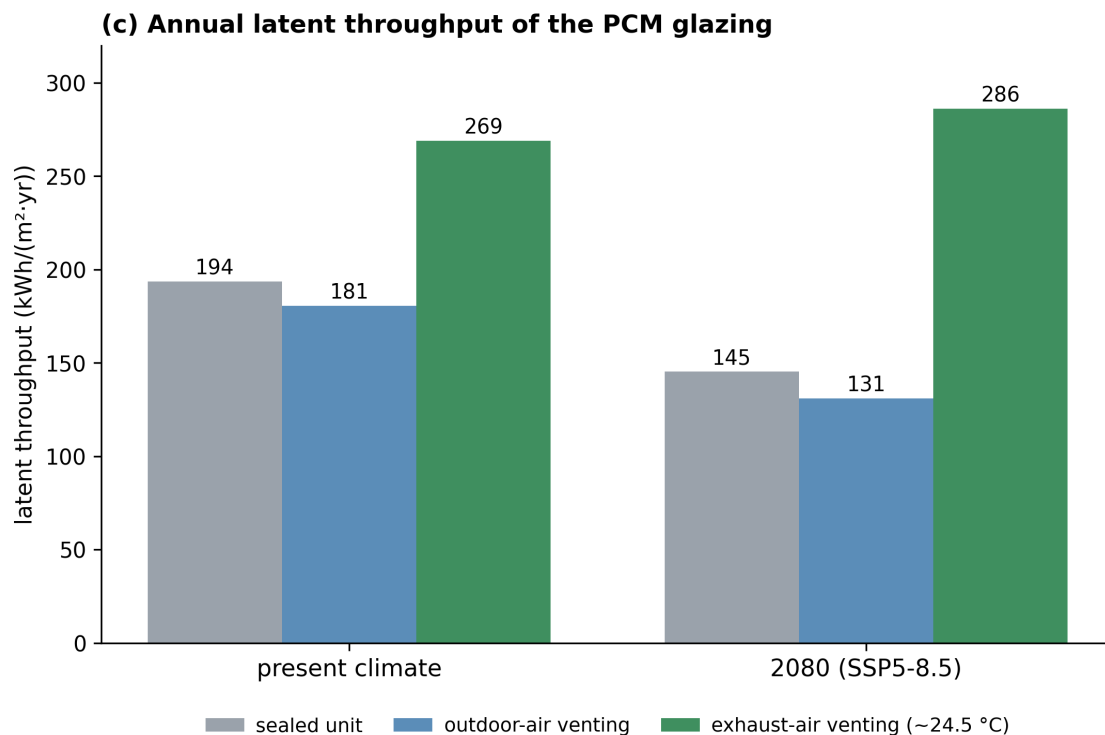


Figure 10. (a) PCM liquid fraction over three consecutive summer days for the three venting regimes (28 °C PCM, present climate; shaded bands = night). The sealed and outdoor-air cases never reach the re-solidified state, whereas exhaust-air venting drives the PCM fully solid each night. (b) Summer (JJA) nightly minimum liquid fraction by venting strategy, present and 2080 climates (lower = better regeneration). (c) Annual latent throughput of the PCM glazing by venting strategy.

The availability of that cool air must, however, be examined rather than assumed. The office is conditioned only during occupied hours (Sun–Thu 08:00–17:00) and free-floats overnight, so its own extract air is not a 24.5 °C stream: the simulated night-time zone temperature averages 34.0 °C in June–August and does not fall to 24.5 °C in any of the 736 night hours. Re-running the model with the actual free-floating zone air as the cavity sink confirms the consequence—the nightly minimum rises to 0.96 and the latent throughput collapses to 146 kWh/yr, close to the sealed case. A sink at 26 °C still regenerates the store almost completely (0.05), which places the practical requirement at roughly 26 °C or below.

The strategy therefore depends on a dedicated cool sink—for example, extract air from a space that remains conditioned overnight, a small dedicated night-cooling coil, or a ground-coupled or evaporative pre-cooler—and not on the building’s own night-time exhaust. Its parasitic energy is modest: removing one full melt–freeze cycle of the panel (5.74 kWh) over an eight-hour night requires about 119 L/s of cavity air at a 5 K rise, giving 70–158 kWh/yr of fan electricity across a specific fan power of 0.8–1.8 W/(L/s). Against a latent thermal gain of 488 kWh/yr (about 163 kWh/yr electrical at a coefficient of performance of 3), the strategy remains net-positive, but by a margin that narrows to near zero at the least efficient fan specification. Night ventilation is thus a genuine remedy for low-melt PCM, conditional on engineering a cool sink and an efficient fan rather than on free cooling.

Practicability of the cavity loop: Four further conditions bound the recommendation. **Airflow:** the 119 L/s required to remove one melt–freeze cycle overnight is about 6 times the zone’s own design ventilation rate of 21 L/s, so the loop cannot be fed from the office extract even during occupied hours; it needs a dedicated fan and a dedicated cool source, and the 488 kWh/yr of latent heat it removes must be rejected by that source, which at

the coefficient of performance of 3 assumed in this section costs roughly one third of that thermal value in electricity. Condensation: extract air from a space at 24 °C and 50% relative humidity has a dew point near 13 °C, whereas the coldest cavity surface is the PCM face at or above its solidus (27 °C for RT28HC, 34 °C for RT35HC), so no surface in the cavity approaches the dew point and condensation is excluded by the temperatures themselves; outdoor-air venting, already rejected on thermal grounds, would be the only configuration that admits humid air. Control: the loop should open only when the sink is at least 2 K below the PCM temperature and the incident radiation is below 50 W/m², and it should close at sunrise, so that it never cools a store that the next day is meant to charge; the sink-temperature sensitivity above (regeneration complete at 24.5 °C, nearly complete at 26 °C, negligible at 34 °C) sets its set point. Constructability and maintenance: the arrangement is a ventilated double-skin cavity of the kind used in closed-cavity façades, with a filtered dry-air supply, top and bottom dampers and an annual inspection of filter and seals; the edge seals of the PCM unit itself, discussed under durability below, are the more demanding item. The cavity loop is therefore feasible but is an engineered subsystem with its own fan, source and maintenance, which is why the passive 35 °C option is preferred wherever it suffices.

5. Discussion

The results are robust because every headline number traces to a physical mechanism rather than a modelling coincidence, and each mechanism is corroborated by independent literature. The first mechanism is optical starvation: the code's SHGC ceiling gates the flux the PCM needs. This is consistent with the numerical finding that PCM-window performance is governed by the radiation actually reaching the PCM [14,41], and it inverts the framing of Wang et al., who added solar-control glass to a PCM unit to cure summer overheating [16]: under a mandatory code, the solar-control layer is already present, and it is the PCM's latent function that is sacrificed. The practical consequence is that PCM glazing is not an upgrade to a code-compliant solar-control window but a daylight-preserving alternative to one, buffering the gain that clear glass admits—the regime in which the full-scale experiments of Goia et al. observed strong cycling [11,39].

The second mechanism is sub-additive competition: the louvre and the PCM address the identical west beam, so their combination saves less than independent action would predict (6.6 points below the multiplicative null). The adaptive louvre's own saving (10.2% whole-office, 71% of the west-glazing load) falls within the 10–30% range reported for dynamic shading of single-façade offices in hot climates [9,44,45,47]. The competition finding complements the PCM-in-shading line of Alawadhi and Silva et al. [17–19]: where those studies fuse storage and shading into one element, the present results quantify what happens when the two remain separate elements on one façade—they overlap, and one primary solar strategy per façade should be specified, or the two must be controlled cooperatively. The over-shading penalty of the comfort-first control (C6) parallels the shading-control trade-offs documented by Tzempelikos and Athienitis [45].

The third mechanism is melt-band matching. The melt map generalises Neeper's wallboard principle—cycling is maximised near the average driving temperature [34]—to glazing, and it extends the climate-matched optimisation of Saffari et al. [20] with a product-anchored boundary: below roughly 32 °C, the constraint is the warm Riyadh night; above roughly 40 °C, it is the shaded day; and 35 °C threads the band. The fourth mechanism is sink-limited discharge. The failure of outdoor-air venting on warm nights is exactly the collapse documented in the night-ventilation literature [56–58], and the exhaust-air remedy parallels mechanically assisted PCM discharge [60,62–64] while relocating the sink from outdoor air to the building's own exhaust stream. The placement result, finally,

transfers Gratia and De Herde's lesson that position governs shading effectiveness [46] to storage: the outer pane charges from direct sun and rejects two-thirds of its heat outward, whereas multilayer studies that vary only the number of PCM layers [21,22] leave this partition unexamined.

For design, the implications order themselves by robustness. On a code-compliant west façade, the first investment is dynamic shading—a saving the code itself encourages (SBC 601 clause 5.5.4.2.1) that holds into the 2080 climate. PCM glazing earns its place where a higher-transmittance glazing is wanted for architectural reasons, acting as the solar-control layer itself, with the melt point chosen at 35 °C for passive self-sufficiency (or 28–31 °C where an exhaust-air cavity can be engineered) and the PCM placed in the outer pane. The novelty of these claims was checked against a systematic prior-art search (345 journal articles screened across nineteen queries; the corpus and the audit records are provided in File S1), which located the closest prior work cited above and confirmed that the code-anchored interaction quantified here had not been reported.

Scope of the placement recommendation: The outer-pane result is established for a west-facing façade in a cooling-dominated hot-arid climate, where rejecting stored heat outward is unambiguously beneficial and no heating season competes for it. It should not be generalised to other orientations, to mixed or heating-dominated climates, or to façades where the store is intended to supply heat to the room; in those settings, the inner-pane position, which delivers the majority of the stored heat inward, may be preferable.

Scope of the conclusions: All results are established for one façade: west-facing, 40% window-to-wall ratio, 6 m deep, in Riyadh, under one code. They are not directly transferable to other orientations, where the profile angles, the cut-off geometry of Equation (2) and the timing of the beam relative to the occupied hours all differ; a south façade in Riyadh receives a high-angle beam that a horizontal louvre excludes at a much smaller slat angle, and an east façade loads the PCM in the morning when the store is coldest. The four mechanisms are physical and are expected to survive qualitatively wherever a beam-dominated load meets a prescriptive solar-gain ceiling, but their magnitudes, the melt-point optimum and the placement preference are façade-specific and should be re-derived for other orientations, window-to-wall ratios, room depths, cities and façade systems before the guidance is applied; that generalisation is identified as future work rather than claimed here.

Cost and operation: The guidance can be placed on a first-order economic footing from the study's own numbers without asserting product prices, which vary by market. The cooling figures of this study are thermal energy transfer at the cooling coil, so they are converted to electricity before pricing at an assumed seasonal coefficient of performance of 3, the value used for the fan comparison of Section 4.5. The adaptive louvre removes 545 kWh/yr of cooling energy transfer from a 6.48 m² window, or about 182 kWh/yr of electricity, which is 28 kWh of electricity per square metre of glazing per year. At the prevailing Saudi commercial tariff of 0.20–0.30 SAR/kWh, which is below the cost of generation [1], this is worth 1.5–2.2 USD per square metre of glazing per year, so a simple payback of ten years is reached only if the installed louvre system costs no more than about 15–22 USD/m² of glazing, and twenty years at 30–45 USD/m²; motorised external louvres normally cost more than this, and PCM glazing, whose saving is 504 kWh/yr thermal (168 kWh/yr of electricity), is in the same position. At subsidised tariffs, therefore, neither measure is repaid by energy alone, and the case for either rests on the peak-load reduction (2.6% for the louvre, 3.7% for the combination), on comfort, on code compliance and on the unsubsidised value of avoided generation, which practitioners should evaluate with local quotations and the tariff that applies to their client. Operationally, the louvre requires actuator maintenance and cleaning in a dust-laden climate, the PCM unit requires the seal

and optical-stability verification discussed under durability, and the cavity loop requires the fan, source and inspections set out in Section 4.5; these recurring items belong in the same comparison.

Durability of an outer-pane PCM: Placing the PCM in the outermost pane exposes it to the most severe conditions in the assembly, and the practical consequences bound the recommendation. The layer receives the full ultraviolet flux, and paraffins are known to discolour and to degrade optically under prolonged ultraviolet exposure unless stabilised or protected by a filtering outer pane. Edge seals experience the highest temperatures and the largest thermal cycling, which raises the risk of seal fatigue and of leakage of the liquid phase, and the volume change on melting must be accommodated. The optical stability of the layer over thousands of melt-freeze cycles determines whether the transmission model used here remains representative over the service life. These are material and detailing questions that the present thermal model cannot answer, and they should be resolved experimentally before the configuration is specified in practice.

The limitations delimit the claims: The model is a single-zone shoebox with a one-way coupling verified per case against a bidirectional co-simulation within 0.5–1.8% and a disclosed scalar calibration; the mean radiant temperature, and hence the comfort figures, carry uncertainty because the injected-flux representation does not resolve the glazing inner-surface temperature; no daylight or glare metric was computed: the louvre cut-off of Equation (2) is a beam-exclusion screening proxy only, not a daylight-glare-probability evaluation, and no useful daylight illuminance or lighting energy result is reported, so statements about admitting radiation are thermal statements and carry no daylight or visual comfort claim, and the louvre priority stated in the conclusions is a thermal ranking; the placement study uses first-order cavity optics; manufacturer data are cited from vendor datasheets; and the C3n decomposition shows that 94.7% of the C3 saving flows through the assumed optical transmission $\tau(\varphi)$, so the magnitude, though not the sign, of the optical mechanism is bounded by that assumption pending experimental characterisation. The uncertainty introduced by the linear form of $\tau(\varphi)$ is bounded directly in Table A2: moving its solid-state end point between 0.20 and 0.40, its molten end point between 0.55 and 0.75, or replacing the line by a sigmoid changes the C3 reduction by at most 0.44 points and the latent share by at most 0.14 points, so the assumption affects the second decimal of the headline figures and none of the conclusions. Two further modelling conventions are noted: the regeneration efficiency of Equation (8) measures amplitude recovery rather than absolute return to solid, and the inner-surface boundary condition uses the conditioned setpoint rather than the free-floating night zone temperature, so night-time discharge is an upper bound; the daytime mechanisms that drive the case ranking are unaffected. Above all, no experimental work was performed: validation is numerical and literature-based, and an experimental cell test of the outer-pane PCM glazing unit is the natural next step. None of these limitations plausibly reverses the sign of the four mechanisms.

6. Conclusions

This study set out to evaluate and compare the individual and combined performance of PCM-enhanced glazing and adaptive external louvres in a code-compliant west-facing office under present and future hot-arid climates. Its central conclusion is that the two technologies, though often proposed together, compete for the same solar resource: on a façade already governed by a mandatory low-SHGC code, dynamic shading is the robust and code-aligned intervention, while the PCM's latent function is largely pre-empted by the very glazing the code requires. The combination is accordingly sub-additive, and a single primary solar strategy should be specified per façade unless the two are controlled cooperatively. This ranking is a thermal one, resting on annual cooling energy, peak

load and PMV; lighting energy, daylight availability and glare were not evaluated, so the louvre priority is not a whole-building or visual comfort verdict. Joint specification of the two measures remains justified under three boundary conditions: where clear or high-transmittance glazing is retained for daylight, so that the PCM actually cycles and the louvre can be operated as a PCM-aware controller that admits the beam while latent capacity remains and shades once it saturates; where peak load or comfort governs, since the combination C5 gives the lowest peak (5.47 kW against 5.53 kW for the louvre alone) and the highest comfort share; and where a low-melt product is paired with an engineered cool-sink discharge that decouples the store from the shaded day. Outside these conditions, the second measure adds cost without proportionate benefit.

An implication requires explicit statement: the regime in which the PCM functions as a latent store—clear glazing with SHGC 0.70—does not comply with the SBC 601 solar-gain ceiling (SHGC 0.25) that defines the reference case of this study. Within the code envelope, the PCM's contribution is optical and sensible rather than latent; the latent benefit becomes accessible only where the ceiling does not bind, through performance-based compliance paths that trade envelope measures, or by relocating the storage to opaque assemblies such as spandrels. The finding is therefore also a policy observation: a prescriptive solar-gain ceiling forecloses glazing-integrated latent storage even in the climate where its diurnal cycling is most reliable. Concretely, PCM glazing is proposed here as a daylight-first alternative under the code's whole-building performance route, not as an addition to the prescriptive SHGC table: compliance would be demonstrated by annual simulation of the actual assembly, as done here. Three implementation ideas follow from mechanisms present in current code practice; they are offered as proposals for code development, not as provisions SBC 601 currently grants. The assembly could be credited at its effective SHGC (Table 8) rather than at a nominal centre-of-glass value; storage-integrated glazing could be treated analogously to the dynamic-glazing provision of the International Energy Conservation Code, on which SBC 601 is modelled, which lets automatically controlled glazing comply at its lower labelled SHGC; and the projection-factor credit that the code applies to fixed external shading could be extended to controllable louvres, which the present results show to be the larger and more robust of the two measures.

The corollary is that PCM glazing should be repositioned rather than dismissed. Where architecture calls for higher-transmittance glazing, the PCM layer itself can take the role of the solar-control element, buffering the admitted gain as latent heat; in that regime, its contribution is eightfold larger than behind code glass. Its engineering then reduces to three choices that this study resolves: a melt temperature matched to the diurnal band (35 °C for passive self-sufficiency in Riyadh, lower melt points only with an engineered cool-sink discharge such as an exhaust-air cavity), placement in the outer pane so that stored heat is predominantly rejected outward, and a control philosophy that recognises that comfort-first shading suppresses both transmitted radiation and storage.

Beyond the specific façade, the findings carry two broader implications. For façade design in hot-arid regions, they provide a decision order—shade first, store only where high solar transmittance is retained, engineer the discharge—that remains valid under the 2080 climate scenario. For building energy codes, they reveal an unintended interaction: prescriptive SHGC ceilings, while effective against solar gain, foreclose latent-storage strategies in transparent envelopes; future code revisions could recognise dynamic shading and storage-integrated glazing as alternative compliance paths. In sustainability terms, the ranking is a carbon and resilience ranking: every percentage point of cooling removed at the code baseline is avoided electricity and avoided peak capacity in a grid whose summer load is dominated by cooling, and a measure that keeps its savings under the 2080 scenario, as the louvre does, is a resilience measure rather than a present-day optimisation. The

code implication points the same way: a solar-gain ceiling written for static glass should not, by accident, exclude the storage-integrated and dynamic façades that the transition to low-carbon buildings in hot-arid regions will need. Future work should prioritise experimental validation of the outer-pane PCM unit, PCM-aware shading control that turns the demonstrated competition into cooperation, and extension to multiple orientations and cities.

7. Recommendations and Future Work

Six directions follow from the findings. The first regards HVAC coupling: integrating the PCM state into the cooling plant—pre-cooling with off-peak capacity and supervisory control of louvre, PCM and setpoints together—would convert the passive buffer into a schedulable resource. The second involves night ventilation for solidification: exhaust-air cavity venting should be adopted as the default discharge path for melt points at or below 31 °C, with fan energy weighed against the latent benefit and stack-driven alternatives explored. The third is deliberate recharge by heat release: scheduling an evening release window (louvre open, cavity vented, night-sky exposure) so the PCM enters each day fully solid, which the 2080 results indicate will become mandatory for low-melt products. The fourth concerns PCM on spandrels and walls: relocating the PCM to the opaque west envelope, where no code glazing gates the flux, and re-evaluating higher-melt products there. The fifth consists in balancing heat admission to the PCM: PCM-aware shading control that admits the beam while latent capacity remains and shades once saturated; its daylight co-optimisation belongs to the planned companion daylighting study. The sixth direction regards methodological consolidation: per-case bidirectional runs, Radiance-based glare evaluation, multi-orientation and multi-city generalisation, and the experimental cell test identified in the Discussion. Finally, beyond the configurations examined here, other innovative envelope approaches merit exploration—among them, the combination of PCM with photovoltaics and the integration of latent storage into spandrel and opaque façade systems—which lie outside the scope of the present study but represent promising directions for climate-resilient façade design.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su181910168/s1>, File S1: Supplementary Reproducibility Package (ZIP) containing the simulation code, result data, figures and a verification harness.

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Nomenclature

The symbols and abbreviations used throughout the paper are listed below.

Symbol/Abbrev.	Meaning	Units
SHGC/VLT	solar heat gain coefficient/visible light transmittance	-
WWR	window-to-wall ratio	-
LPD/EPD	lighting/equipment power density	W/m ²
PMV/PPD	predicted mean vote/percentage dissatisfied (Fanger)	-/%
MRT/DGP	mean radiant temperature/daylight glare probability	°C/-
TMY _x	typical meteorological year (extended set)	-
JJA	June–July–August (summer)	-
DGU/IGU	double-glazed/insulated glazing unit	-
L1/L2	coupling fidelity: bidirectional co-simulation/calibrated one-way injection	-
<i>sct</i>	solar transmittance of the glazing outer treatment to the PCM layer	-
$\varphi/\tau(\varphi)$	PCM liquid fraction/phase-dependent optical transmission	-
Ω/β	solar profile angle/slat angle (positive = outer edge down)	°
F_{sky}	louvre-gated sky view factor	-
L	latent heat of fusion	J/kg
$\eta_{\text{regen}}/E_{\text{lat}}$	regeneration efficiency/annual latent throughput	%/kWh/yr
Δ	sub-additivity index	% points

Appendix A Sensitivity and Verification Detail

This appendix collects the verification detail and the additive sensitivity analyses added at review. All of them re-execute the frozen production model; none alters a result reported in the main text, and the reproduction rows of each table are asserted against the frozen result set by the scripts in the reproducibility package.

Table A1 gives, per case and climate, the annual cooling of the bidirectional co-simulation (L1) and of the production one-way coupling (L2) together with the hourly agreement metrics; Figure A1 shows the hourly cooling rate of case C5 over one summer week and the annual scatter.

Table A1. Bidirectional (L1) versus one-way (L2) coupling per case: annual cooling, hourly CV(RMSE) and NMBE of the sensible cooling rate, daily-total CV(RMSE) and peak-hour difference (ASHRAE Guideline 14 hourly criteria: 30% and 10%).

Case	Climate	L1 (MWh/yr)	L2 (MWh/yr)	Annual Diff.	Hourly CV(RMSE)	Hourly NMBE	Daily CV(RMSE)	Peak Diff.
C2	present	4.724	4.810	−1.78%	4.1%	−1.79%	2.7%	−2.49%
C3	present	4.824	4.850	−0.55%	2.1%	−0.56%	1.3%	−1.16%
C3n	present	4.850	4.877	−0.55%	2.3%	−0.57%	1.4%	−1.97%
C5	present	4.682	4.711	−0.61%	2.2%	−0.62%	1.4%	−1.24%
C2	2080	6.449	6.554	−1.60%	3.5%	−1.62%	2.3%	−2.34%
C3	2080	6.574	6.607	−0.50%	1.7%	−0.52%	1.1%	−2.23%
C3n	2080	6.593	6.643	−0.75%	2.4%	−0.76%	1.5%	−2.07%
C5	2080	6.403	6.443	−0.62%	1.9%	−0.63%	1.2%	−2.26%

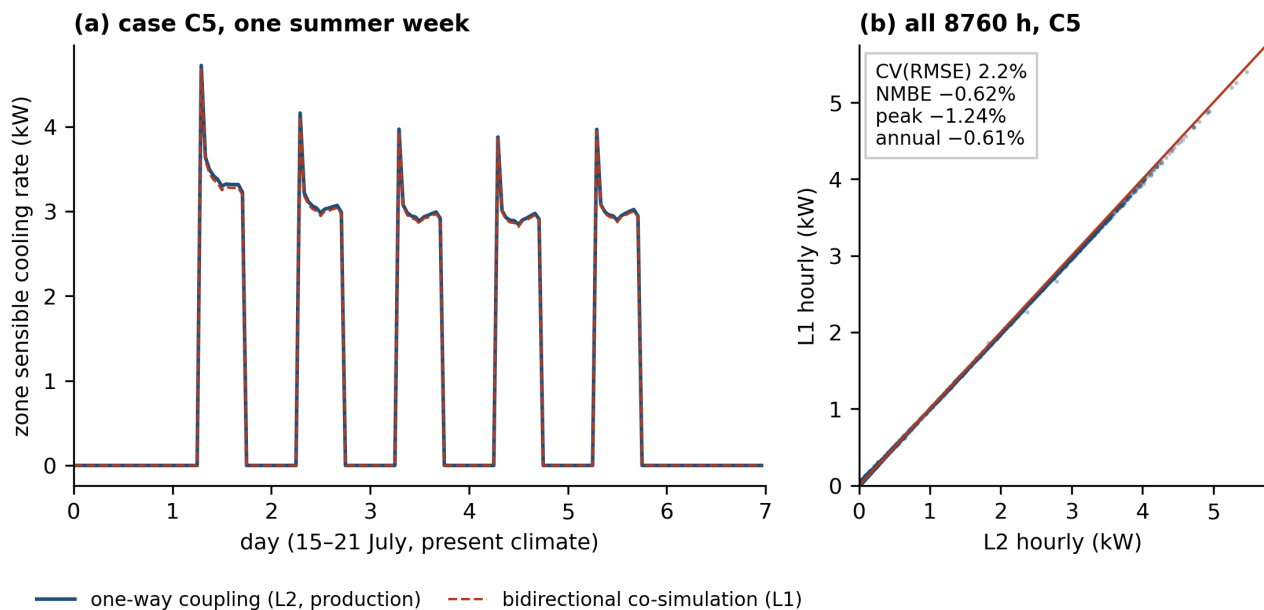


Figure A1. Hourly zone sensible cooling rate, one-way coupling (L2) against bidirectional co-simulation (L1), case C5, present climate: (a) one summer week; (b) all 8760 h with the Guideline 14 metrics.

Table A2 lists the one-at-a-time sensitivity sweep. Each row perturbs one assumption from the reproduced base and re-runs the cases C3, C3n and C5 (and C2 where the louvre optics change); the multiplicative null and the gap are recomputed with the louvre-alone reduction of the same climate. The two 2080 rows compare the published 2080 factor with the present-climate factor applied to the 2080 fluxes.

Table A2. One-at-a-time sensitivity of the headline reductions (whole-office annual cooling, % of C0) to the modelling assumptions, on the frozen model. Latent = C3 minus C3n; null = multiplicative null of Equation (10) with the louvre-alone reduction of the same climate; gap = null minus C5.

Variant	C3 (%)	C3n (%)	Latent (pts)	C5 (%)	Null (%)	Gap (pts)
published model (reproduction)	9.42	8.93	0.49	12.03	18.64	6.61
$\tau(\varphi)$ solid end 0.20 (pub. 0.30)	9.83	9.20	0.63	12.20	19.03	6.83
$\tau(\varphi)$ solid end 0.40 (pub. 0.30)	8.98	8.62	0.36	11.87	18.26	6.39
$\tau(\varphi)$ liquid end 0.55 (pub. 0.66)	9.53	9.10	0.43	12.04	18.76	6.72
$\tau(\varphi)$ liquid end 0.75 (pub. 0.66)	9.34	8.82	0.52	12.02	18.59	6.57
sigmoidal $\tau(\varphi)$, same end points	9.47	8.89	0.58	12.04	18.70	6.66
latent heat -20% (192 kJ/kg)	9.37	8.93	0.44	12.03	18.61	6.58
latent heat +20% (288 kJ/kg)	9.47	8.93	0.54	12.04	18.70	6.66
melt range ± 1 K (pub. ± 2 K)	9.43	8.92	0.51	12.03	18.67	6.64
melt range ± 3 K (pub. ± 2 K)	9.40	8.93	0.47	12.04	18.64	6.60
outer film 13 W/(m ² · K) (-25%)	9.57	9.09	0.48	12.19	18.79	6.60
outer film 21 W/(m ² · K) (+25%)	9.30	8.80	0.50	11.91	18.55	6.64
inner film 6 W/(m ² · K) (-25%)	9.69	9.10	0.59	12.25	18.90	6.65
inner film 10 W/(m ² · K) (+25%)	9.21	8.79	0.42	11.86	18.47	6.61
louvre closed fraction 0.05 (pub. 0.10)	9.42	8.93	0.49	12.17	19.10	6.93
louvre closed fraction 0.15 (pub. 0.10)	9.42	8.93	0.49	11.91	18.18	6.27

Table A2. Cont.

Variant	C3 (%)	C3n (%)	Latent (pts)	C5 (%)	Null (%)	Gap (pts)
louvre open fraction 0.80 (pub. 0.85)	9.42	8.93	0.49	12.05	18.70	6.65
louvre open fraction 0.90 (pub. 0.85)	9.42	8.93	0.49	11.98	18.53	6.55
calibration factor −10%	9.91	9.46	0.45	12.26	19.10	6.84
calibration factor +10%	8.94	8.39	0.55	11.81	18.23	6.42
2080 climate, its own factor (reproduction)	7.53	7.03	0.50	9.83	15.18	5.35
2080 climate with the present factor	7.91	7.45	0.46	10.06	15.83	5.77

Table A3 shows the melt-point ranking under perturbations of the phase-change range and latent heat, evaluated on the passive setting (no louvre, clear glazing, sealed cavity): the highest melt point that charges, melts fully on some days and regenerates passively is 35 °C in every variant.

Table A3. Melt-point ranking under perturbations of the phase-change range and latent heat (passive setting: no louvre, clear glazing, sealed cavity; summer nightly minimum liquid fraction and regeneration efficiency over charging days).

Variant	RT28HC Regen. (%)	RT28HC Night Min.	RT35HC Regen. (%)	RT35HC Night Min.	RT47 Max. Daily Liquid Fraction	Highest Passively Regenerating Melt (°C)
published	89.3	0.26	100.0	0.00	0.51	35
range × 0.5	88.2	0.28	100.0	0.00	0.52	35
range × 1.5	90.4	0.25	100.0	0.00	0.50	35
latent −20%	90.2	0.23	100.0	0.00	0.53	35
latent +20%	88.3	0.29	100.0	0.00	0.48	35
datasheet full range	89.3	0.26	100.0	0.00	0.63	35

Figure A2 illustrates the sub-additivity construction and Figure A3 the placement dynamics referred to in Sections 4.1 and 4.4. Table A4 is the reproducibility checklist requested at review; every item is contained in File S1.

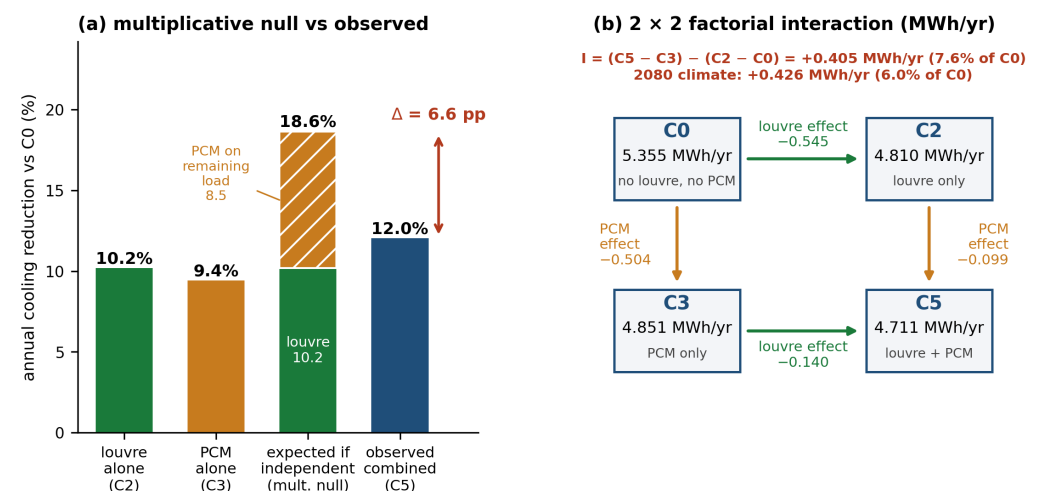


Figure A2. Sub-additivity made explicit: (a) the multiplicative null of Equation (10)—the louvre saving plus the PCM saving applied only to the load the louvre leaves—against the observed combination; (b) the 2 × 2 factorial C0, C2, C3, C5 in MWh/yr and its interaction term I .

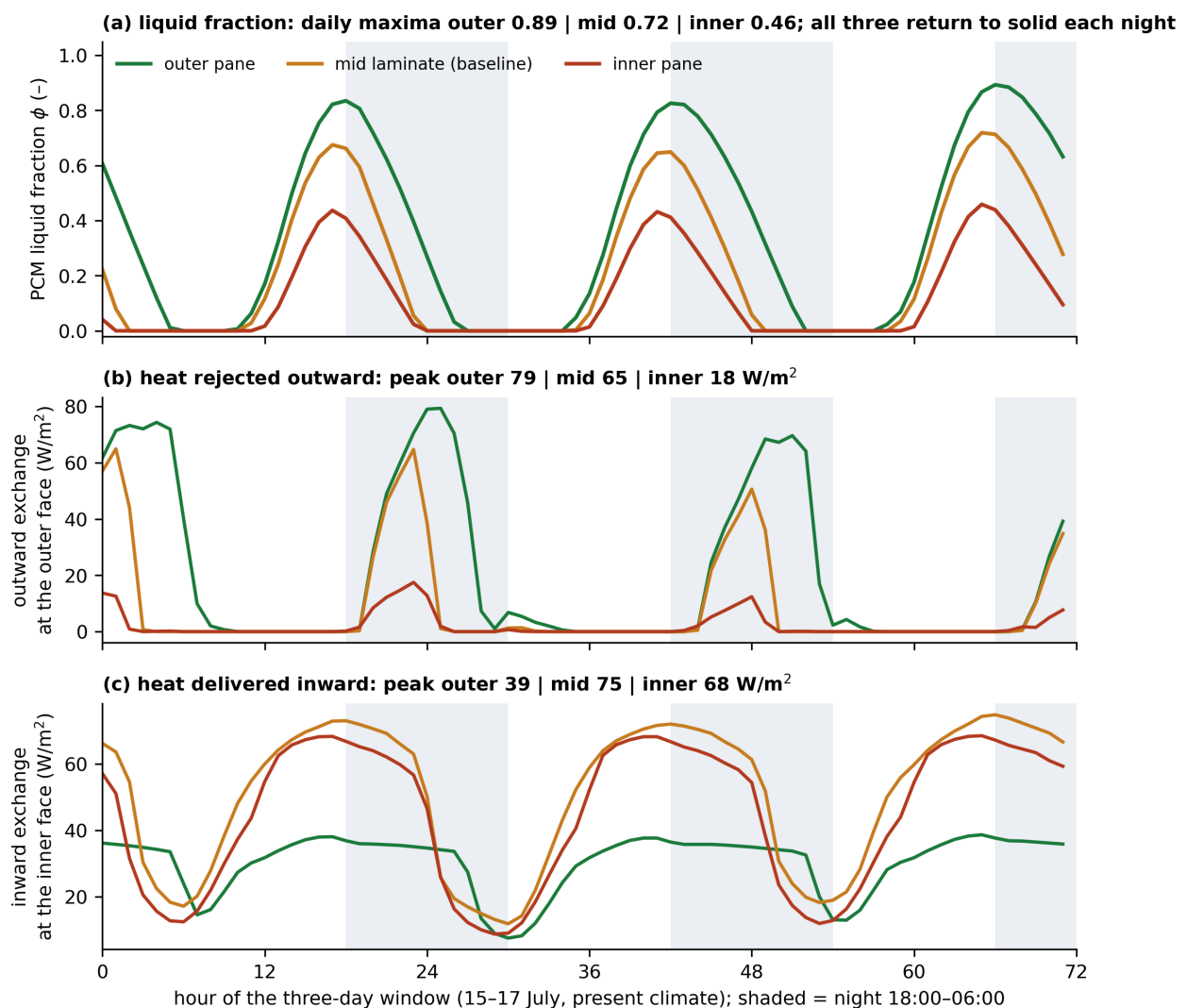
PCM placement dynamics, RT35HC, charging regime (fixed louvre, clear glazing, sealed cavity)

Figure A3. PCM placement dynamics over three consecutive July days (RT35HC, charging regime: fixed louvre, clear glazing, sealed cavity): (a) liquid fraction; (b) heat rejected outward at the outer face; (c) heat delivered inward at the inner face. Shaded bands are night hours.

Table A4. Reproducibility checklist: what each element of the model is, where it is set, and where it is found in File S1.

Element	Setting	Location in File S1
Simulation engine	EnergyPlus 25.2 (Version object in every IDF); Ideal Loads air system; 20 timesteps per hour (3 min); annual run period	03_simulation_code/run_sbc_study.py
Base model and envelope	single-zone shoebox $8.0 \times 6.0 \times 2.7$ m, west window 6.48 m^2 (WWR 40%); SBC 601-CR-2018 Zone 1 envelope; setpoints, gains and schedules of Table 2	Case_SBC_Riyadh_WEST.idf (packaged)
Weather files	Riyadh TMYx baseline (climate.onebuilding.org); 2080 file morphed from it with NEX-GDDP-CMIP6 3-GCM ensemble change factors, SSP5-8.5, 2071–2090 vs. 1995–2014, shift-and-stretch (Section 3.2)	02_weather (EPW files)

Table A4. Cont.

Element	Setting	Location in File S1
PCM glazing model	1-D enthalpy model, 2 glass + 6 PCM nodes, 300 s sub-steps, outer/inner films 17/8 W/(m ² · K), linear $\tau(\varphi)$ from 0.30 (solid) to 0.66 (molten), melt range ± 2 K, RT-line latent heats	glazing_1d() in run_sbc_study.py; Tables 2 and 5
Louvre model and controls	ISO 15099 slat optics (slat_optics.py); transmittance fractions 0.85/0.45/0.10; controls fixed 45°, solar above 200 W/m ² , operative T above 24.5 °C, combined (both, above 23.5 °C)	slat_optics.py; validate_blind.py (13% check)
Coupling and calibration	inward flux injected as OtherEquipment schedules; per-climate calibration factor F of Equation (7); operative-T controls iterated to 0.1 °C	run_sbc_study.py; sbc_results.json (_meta)
Bidirectional verification	EnergyPlus Python API callback each zone timestep (178,080 per year); annual, hourly, daily and peak metrics	run_reviewer_studies.py; run_l1_timeseries.py; l1_timeseries.json
Sensitivity and extensions	one-at-a-time sweep (21 variants); optics-matched control; melt-range ranking; placement time series; night-vent realism and fan energy	run_sensitivity_sweep.py; run_placement_series_meltrange.py; run_nightvent_realism.py
Verification harness	verify_results.py re-checks 40 pinned values against checksummed result files in seconds, without EnergyPlus	05_results_data + verify_results.py

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