

Indoor and outdoor thermal comfort impacts of dual-band electrochromic glazing: A multi-climate radiative evaluation

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ABSTRACT

Electrochromic (EC) glazing enables adaptive solar control, yet no study has jointly evaluated the indoor and outdoor thermal comfort performance of spectrally selective dual-band EC (DB-EC) devices. This work addresses that gap through coupled simulations of a perimeter office across five European climates and two façade orientations, informed by experimentally characterised, state-dependent optical properties of a DB-EC prototype. Indoor comfort is characterised at multiple distances from the window via operative temperature Discomfort Degree Hours, radiant asymmetry exceedances, and a Predicted Mean Vote-based discomfort score; outdoor pedestrian comfort is quantified through longwave mean radiant temperature and Universal Thermal Climate Index profiles along a near-façade transect. DB-EC and single-band EC, both under rule-based control, are benchmarked against three static reference glazings. Both EC technologies substantially reduce perimeter overheating and radiant asymmetry relative to high-transmittance and moderately selective static references, while avoiding the cold-discomfort penalty that strongly selective static glazing incurs in heating-dominated climates. Under the same control logic the two electrochromic options achieve very similar thermal comfort, despite the higher spectral selectivity and the demonstrated energy and daylight advantages of the dual-band device. The associated rise in external surface temperature produces only a negligible outdoor thermal penalty, confirming that absorptive spectral control markedly improves indoor comfort without compromising pedestrian conditions.

1. Introduction

The façade governs solar gains, heat losses and daylight admission, and therefore both the energy use of buildings and the thermal and visual comfort of their occupants [1]. Over the past two decades it has evolved from a static barrier into an adaptive skin [2], with smart glazing classified into passive systems, such as thermochromic and photochromic glazing, and active systems that require an external stimulus and can be operated through explicit control strategies [3–5].

Among active smart glazing options, EC technology is widely recognised as one of the most mature and façade-ready solutions due to its low-voltage operation, continuous tunability, and potential integration within building automation systems [6]. Simulation and field-oriented studies have shown that EC windows can reduce peak cooling loads

and overall delivered energy in perimeter zones while supporting daylight availability and glare mitigation when appropriate control logics are implemented [7–10]. In parallel, recent work has increasingly focused on advanced and predictive control approaches, including model predictive control (MPC), to better exploit the multi-objective potential of switchable glazing across climates and orientations [11–14].

A fundamental limitation of conventional EC devices, however, is the strong spectral coupling between the visible (VIS) and near-infrared (NIR) ranges. In many EC stacks, reducing solar heat gains through darkening also reduces daylight transmission, constraining the simultaneous optimisation of cooling demand, daylight autonomy and visual comfort [15]. DB-EC concepts address this constraint by introducing spectrally selective modulation, typically via plasmonic nanocrystals that enable quasi-independent control of NIR transmittance with limited impact on VIS transparency [15,16]. Building on recent advances in

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Nomenclature			
A_{SOL}	Solar Absorptance	MPC	Model Predictive Control
AT	Air Temperature	MRT	Mean Radiant Temperature
A_{VIS}	Visible Absorptance	NIR	Near-Infrared
CDD	Cooling Degree Days	OT	Operative Temperature
CFD	Computational Fluid Dynamics	PMV	Predicted Mean Vote
DB-EC	Dual-Band Electrochromic	PPD	Predicted Percentage of Dissatisfied
DDH	Discomfort Degree Hours	PRT	Plane Radiant Temperature
DGU	Double Glazing Unit	PVB	Polyvinyl Butyral
EC	Electrochromic	RBC	Rule-Based Control
EPW	EnergyPlus Weather file	RH	Relative Humidity
GHI	Global Horizontal Irradiance	R_{SOL}	Solar Reflectance
HDD	Heating Degree Days	R_{VIS}	Visible Reflectance
IDS	Indoor Discomfort Score	SCI	Sky Cover Index
IGDB	International Glazing Database	SHGC	Solar Heat Gain Coefficient
IGU	Insulating Glass Unit	T_{SOL}	Solar Transmittance
ITO	Indium Tin Oxide	T_{VIS}	Visible Transmittance
KPI	Key Performance Indicator	UDI	Useful Daylight Illuminance
LSPR	Localised Surface Plasmon Resonance	UTCI	Universal Thermal Climate Index
LW-MRT	Longwave-only Mean Radiant Temperature	UV	Ultraviolet
		VIS	Visible

plasmochromic module design and manufacturing [17], our previous work quantified the energy and daylight benefits of a DB-EC window in perimeter offices across representative European climates, showing that DB-EC can outperform both advanced static benchmarks and conventional EC when coupled with effective control strategies [18].

In that previous study, the DB-EC solution coupled with an intelligent control strategy achieved reductions in total annual delivered energy for heating, cooling and lighting of up to 27% compared to the best-performing static solar-control glazing per location, while also reducing visual discomfort by up to 32% (quantified through the cumulative value of useful daylight illuminance) [18].

The published work on spectrally selective electrochromics, including our own [18], has addressed energy performance, and in our case daylight, but not thermal comfort. Near-infrared switching glazing simulated in 16 US climates saved 5–11 kWh m⁻² a⁻¹ of heating and cooling energy in commercial buildings against high-performance static glazing [19], with the largest savings per unit window area in offices and mid-rise residential buildings of northern climates [20]; a dual-band device modulating the visible and near-infrared ranges independently outperformed conventional EC and static alternatives in heating- and cooling-dominated regions alike [21], and recent tri-band and dual-band devices have likewise been evaluated with energy simulations across climate zones [22,23]. None of these studies, nor our previous one, examined the thermal comfort of the occupants, and none looked at the pedestrian side of the façade.

Energy and daylight indicators are not proxies for thermal comfort, for reasons specific to electrochromic glazing. EC devices attenuate solar radiation mainly by absorption rather than reflection, so tinted states heat the glazing itself: the inner pane becomes a warm radiant surface facing the occupant and the outer pane a warm surface facing the street [24]. In clear states the transmitted shortwave radiation loads the occupants nearest to the window directly, producing the near-façade gradients and radiant asymmetries measured in glazed offices [25,26]. Switching follows a control rule and takes minutes, so the radiative load seen by an occupant is transient and control-dependent [27–30]. In heating-dominated climates, finally, the tinting that prevents overheating also removes useful solar gains and can leave the near-window zone cold. Comfort outcomes can therefore diverge from energy and daylight outcomes, especially in perimeter zones where the radiative environment is highly non-uniform in space and time.

Evidence on the thermal comfort effects of EC glazing is scarcer than

on energy and comes mostly from single spaces. In a test cell, an absorptive EC unit cut the solar heat load by up to 50–60% in its darkest state, but the absorbed energy re-emerged as secondary gains and raised the inner pane to temperatures at which local discomfort may occur [24, 31]. In climate chambers an EC window lowered the inner surface temperature by 3.0–4.4 °C and improved the peak PMV by 37–50% relative to single glazing [32], and the overheating risk of a highly glazed office with algorithm-controlled EC windows was assessed in a climatic chamber [33]. Simulations report 6–43% more working hours within comfort with temperature-based control under free-floating conditions [34], while a sensitivity analysis over 7680 scenarios found the zone-averaged PPD little affected by EC glazing [35]. Field measurements near glazed façades, however, show mean radiant temperatures of 33–51 °C at the window against 25–27 °C inside the room [25], radiant asymmetry and MRT swings of up to 7.8 °C confined to the near-window area [26,36], and a higher thermal sensitivity of the occupants seated there [37]. Two conclusions follow: the comfort effect of EC glazing depends on the control logic and on the radiative transients it produces [27–30], and it has to be assessed at the occupant position rather than at zone level.

On the outdoor side, the façade acts on pedestrians through two radiative channels. Field measurements during extreme heat show that longwave radiation from sunlit vertical surfaces dominates the pedestrian mean radiant temperature budget, so that the temperature of the walls facing the sidewalk matters as much as shade [38]; for fully glazed façades, simulations show that the emissivity of the glass changes pedestrian mean radiant temperature and physiological equivalent temperature across canyon geometries [39]. The second channel is reflected shortwave radiation: specular and near-specular reflections from glazed or solar-reflective façades raise pedestrian-level irradiance and heat-stress indices in street canyons, even when the retrofit benefits indoor cooling [40–42], and low-emissivity or heat-shading windows reflect solar radiation specularly into the street, which retro-reflective films are designed to mitigate [43,44]. Absorptive electrochromic glazing trades the second channel for the first: tinted states reduce transmission and reflection but heat the outer pane and increase longwave emission towards the street. To our knowledge, no study has quantified this trade-off for switchable glazing at pedestrian level.

This study provides a coupled indoor and outdoor thermal comfort evaluation of dual-band electrochromic smart windows. The analysis leverages experimentally characterised, state-dependent properties of a

DB-EC prototype and compares DB-EC against a conventional single-band EC glazing and advanced static solar-control benchmarks under multiple European climates and two façade orientations. Following established simulation-based evaluation approaches for innovative envelope components [45,46], the work quantifies how spectral selectivity, control strategy and climate interact to shape indoor radiative conditions and outdoor pedestrian-level thermal stress.

Indoors, a representative perimeter office is modelled in EnergyPlus [47] and comfort is assessed through near-façade surface temperatures, operative and mean radiant temperature (long and short wave), Discomfort Degree Hours, radiant asymmetry derived from plane radiant temperatures, and PMV-based indicators, building on prior evidence that EC comfort outcomes depend strongly on switching strategy and transient radiative drivers [27–30,32,34,35].

Outdoors, a geometrically consistent façade model is analysed in Rhino/Grasshopper [48,49] using Ladybug Tools [50] to compute pedestrian-level radiative exposure and UTCI along a near-façade transect, explicitly accounting for the potential influence of glazed and solar-reflective façades on shortwave and longwave exchanges in the pedestrian domain [41,42].

To the authors' knowledge, this is the first study to jointly quantify the indoor and outdoor thermal comfort implications of a dual-band electrochromic glazing.

2. Methodology

2.1. Manufacturing and optical properties of DB-EC modules

For this study, DB-EC laminates were fabricated in the framework of ongoing research on façade-integrated, spectrally selective dynamic solar control (Fig. 1). They combine conventional electrochromic absorption with plasmonic Localised Surface Plasmon Resonance (LSPR), enabling partial decoupling of VIS and NIR modulation through reversible electron-density redistribution at the nanocrystal surface [16]. This dual-band behaviour allows more independent control of daylight transmission and solar heat gains than single-band EC systems. Several batches of $60 \times 80 \text{ cm}^2$ DB-EC laminates were manufactured following the fabrication process described elsewhere [17]. Each module uses two ITO-coated glass substrates functionalised with WO_x and $\text{CeO}_x/\text{TiO}_2$ nanocrystal-based layers, separated by an ion-conductive polymer electrolyte and laminated with a PVB-based membrane providing ionic conductivity and mechanical stability. Prototypes are designed for integration into façade-grade IGUs.

Optical characterisation measured spectral transmittance and reflectance (300–2500 nm) across multiple electrochromic states using a Cary 5000 UV–VIS–NIR spectrophotometer with an integrating sphere. Eight discrete switching states were characterised (Clear, Int 1–6, Dark; see the properties in Table 1), obtained at intermediate applied voltages between the fully clear and fully dark states [17,18]; the stack is in

Table 1

Integrated solar (T_{SOL} , R_{SOL} , A_{SOL}) and visible (T_{VIS} , R_{VIS} , A_{VIS}) optical properties of the DB-EC module for the clear-to-dark switching states, derived in Optics from measured spectra [18].

State	T_{SOL} [-]	T_{VIS} [-]	R_{SOL} [-]	R_{VIS} [-]	A_{SOL} [-]	A_{VIS} [-]
Clear	0.70	0.85	0.08	0.10	0.22	0.05
Int 1	0.56	0.83	0.07	0.09	0.37	0.08
Int 2	0.44	0.80	0.06	0.08	0.50	0.12
Int 3	0.31	0.73	0.05	0.06	0.64	0.21
Int 4	0.16	0.47	0.04	0.05	0.80	0.48
Int 5	0.10	0.30	0.04	0.05	0.86	0.65
Int 6	0.06	0.18	0.04	0.05	0.90	0.77
Dark	0.03	0.06	0.04	0.04	0.93	0.90

principle continuously tunable, but characterisation and control use these eight states. The measured range covers the full solar spectrum of ISO 9050 and EN 410, so the integrated solar properties are obtained without spectral extrapolation. The state-resolved spectra were imported into Optics [51] to derive integrated solar and visible properties for simulation and comparison; Table 1 reports T_{SOL} , R_{SOL} , T_{VIS} , R_{VIS} and the corresponding absorptances (A_{SOL} , A_{VIS}) from energy conservation. Progressive tinting reduces solar and daylight transmission while keeping reflectance comparatively low and increasing absorptance, which is critical for thermal interpretation because it governs the fraction of incident shortwave converted into heat within the active stack.

2.2. Thermal characterisation experiments

To experimentally support the coupled comfort assessment of this study with physically grounded radiative boundary conditions, the DB-EC glazing was thermally characterised in a climatic chamber under controlled convective and radiative forcing. A BF SUN 4000 W metal halide solar simulator (BF Engineering; OSRAM HMI 4000 W lamp, correlated colour temperature 6000 K), one of the two source types that dominate solar simulators for thermal applications [52], was operated without additional spectral filtering, and incident irradiance was measured with a Kipp & Zonen CMP11 pyranometer, so that the irradiance levels reported below are broadband values that do not depend on the lamp spectrum. The chamber tests are used for the two properties that do not depend on the spectral match of the source: the ordering of the switching states, which is the same for the visible and for the total solar absorptance of every state (Table 1), and the near-linear dependence of surface temperature on irradiance. The spectral properties entering the simulations come from the spectrophotometric measurements of Section 2.1 (300–2500 nm), not from these tests.

Tests were performed at 25°C and 40% RH on a $60 \times 80 \text{ cm}^2$ prototype mounted horizontally and exposed to incident irradiance levels from 450 to 850 Wm^{-2} selected to represent high clear-sky loads achievable on vertical façades. Four electrochromic states were

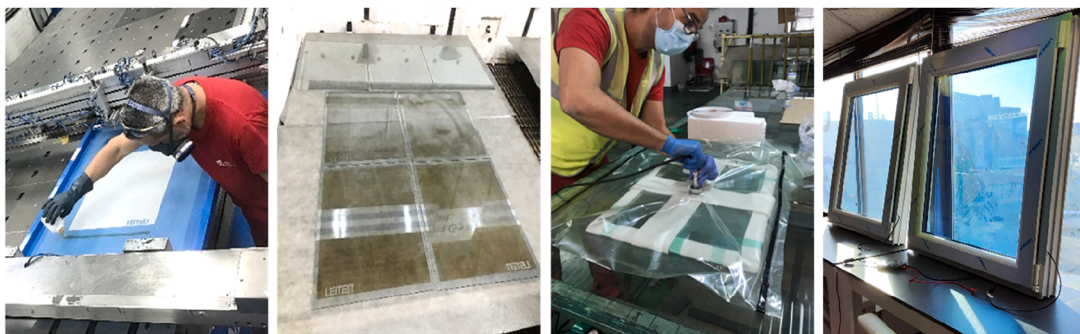


Fig. 1. Manufacturing process and window-scale demonstrators of the DB-EC glazing prototypes. From left to right: screen printing of electrochromic layers, thermal treatment of the coated substrate, lamination of the multilayer assembly, and the fully assembled $60 \times 80 \text{ cm}^2$ DB-EC module integrated in a test frame, shown in two representative switching states (clear and partially tinted).

investigated (Clear, Int 2, Int 4, Dark). Surface temperature was measured at the centre of the active area using a PT1000 contact sensor, while infrared thermography provided spatial maps to verify temperature uniformity and confirm that the central measurement was representative of the irradiated region (Fig. 2).

2.3. Simulation-based virtual experiment

2.3.1. Window models

All glazing systems were modelled through a single workflow that starts from experimentally grounded optical data and produces window constructions used unchanged in both EnergyPlus [47] (indoor) and Ladybug Tools [50] (outdoor). In Optics [51], DB-EC was modelled as a single equivalent laminate and state-wise T_{VIS} and T_{SOL} were derived from measured spectra for eight tint levels (Table 1). In WINDOW 7.8 [53], all options were assembled as DGUs to derive the thermal and solar inputs for simulation (Table 2); the DB-EC unit comprises a 9.8 mm laminate, a 16 mm 90% Ar/10% air cavity, and a 4.8 mm inner low-e pane ($\epsilon = 0.04$), for 31 mm total thickness. The EC reference used a representative IGDB laminate (IDs 61166–61173) in a DB-EC-like DGU to isolate spectral-control effects, while static benchmarks (SEL40–22, SEL60–33, Low-E) were chosen to span high-selectivity solar-control to high-transmittance low-e solutions. All DGUs were matched to $U = 1.2 \text{ W m}^{-2} \text{ K}^{-1}$ with similar cavity gas to emphasise optical/radiative and control-driven differences over conductive effects. The WINDOW (Table 2) datasets were used to define EnergyPlus window constructions and, in parallel, consistent Honeybee glazing properties. Spectral measurements refer to normal incidence; the angular dependence of transmittance and absorptance is computed by WINDOW and EnergyPlus from the normal-incidence data with their standard angular models for coated and laminated glazing [53].

2.3.2. Indoor simulation framework

The indoor virtual experiment quantifies the impact of glazing technologies and control on indoor thermal comfort. WINDOW-derived [53], state-resolved properties (SHGC, U-value, and solar and visible transmittance for each tint state) were implemented in EnergyPlus [47] to couple measured optics with transient whole-zone heat balance calculations and derive comfort-relevant boundary conditions (surface temperatures and radiative exchange) under realistic weather and operation.

The reference space is a single perimeter office zone (3 m × 5 m × 3 m, width × depth × height) with approximately 50% window-to-wall ratio (2.2 m × 2.2 m window) on the exterior façade (Fig. 3); all other envelope surfaces are adiabatic, representing an

intermediate office surrounded by identical conditioned spaces, an assumption also adopted in comparative studies of solar control in perimeter offices [54]; the influence of this assumption is tested below and discussed in Section 4. Opaque components use a high-insulation construction (U-value $0.26 \text{ W m}^{-2} \text{ K}^{-1}$) to minimise conductive losses and keep differences primarily driven by window radiative behaviour and control. South and West orientations are simulated to capture distinct solar-exposure patterns. Dynamic simulations were performed in EnergyPlus v22.2 [47] with a 15-minute timestep, using the conduction transfer function method and the TARP convection algorithms, across five European climates (Sevilla, Barcelona, Turin, Berlin, Helsinki), each with both orientations.

The zone is conditioned by an ideal air system that holds the air temperature between 20 and 26 °C at all hours; no mechanical ventilation is modelled, and outdoor air enters at a constant rate of about 19 L s^{-1} (about 6.5 L s^{-1} per occupant), which affects the loads but not the comfort indicators because the air temperature is held within the set-point band. Internal gains follow office schedules ($0.2 \text{ occupants m}^{-2}$ at 125 W each, lighting 12 W m^{-2} with daylight dimming, equipment 13.5 W m^{-2}). Entering solar radiation is distributed with the Full-InteriorAndExterior option of EnergyPlus [47], an engine tested against the IEA BESTEST suites of ASHRAE Standard 140 [55].

The adiabatic internal surfaces were tested by re-simulating the extreme cases (Sevilla and Helsinki, South; DB-EC and Low-E) with the internal surfaces coupled to conditioned neighbouring spaces, either at the zone air temperature or at 23 °C (film coefficient $7.7 \text{ W m}^{-2} \text{ K}^{-1}$); the effect on the indicators is discussed in Section 4 and reported in Supplementary Table S2.

Further details of the model, including the ventilation implementation, are given in Supplementary Table S1 and in our previous study [18].

To capture spatial gradients not available from zone-level reporting, which misrepresents the temperature at a specific point near the window [56], EnergyPlus outputs were post-processed in Python to reconstruct point-based metrics at multiple indoor reference points located at 1.10 m height along a line normal to the façade, spaced every 0.5 m from the window into the room. For each point and timestep, a custom Python shortwave ray-tracing routine implementing a first-order (one-bounce) model was used to resolve the shortwave contribution to MRT as the sum of: (i) directly transmitted solar radiation reaching the point (window crossing, occlusion and point visibility tests), (ii) diffuse radiation transmitted by the window, modelled as a Lambertian emitter, and (iii) diffuse radiation re-emitted by interior surfaces discretised into 0.5 m^2 patches, where sunlit patches at each timestep behave as Lambertian emitters converting incident direct radiation into diffuse according to

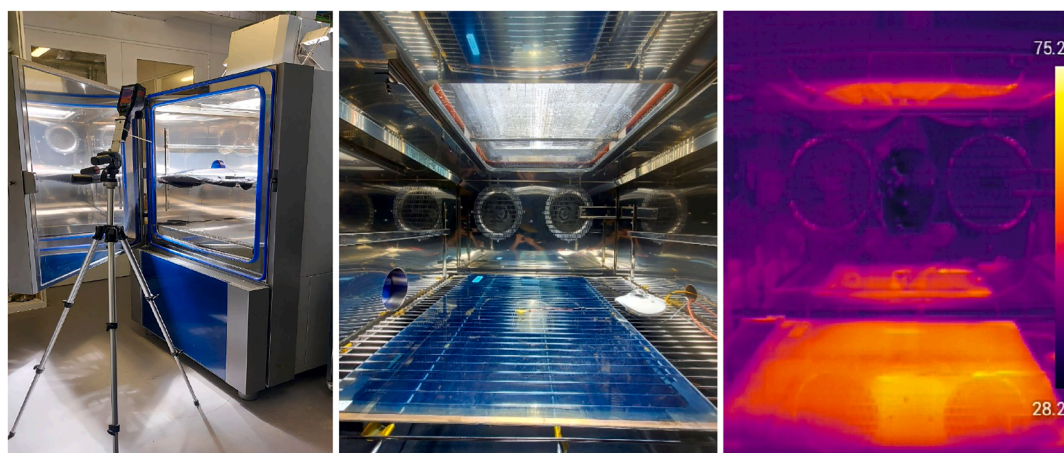


Fig. 2. Thermal characterisation of the DB-EC prototype in a climatic chamber (25 °C, 40% RH) under a metal halide solar simulator. Test setup, sample placement, and representative infrared thermography.

Table 2

Main optical and thermal properties of the modelled DGUs considered for this study [18].

DGU	Layout	T_{VIS} [-]	T_{SOL} [-]	SHGC [-]	U-value [W/ m ² K]
DB-EC	Clear	0.78	0.45	0.53	1.2
	Int 1	0.76	0.36	0.46	
	Int 2	0.73	0.28	0.40	
	Int 3	0.67	0.20	0.32	
	Int 4	0.43	0.11	0.25	
	Int 5	0.27	0.06	0.21	
	Int 6	0.16	0.04	0.19	
EC	Dark	0.06	0.02	0.17	1.2
	Clear	0.61	0.29	0.39	
	Int 1	0.57	0.26	0.37	
	Int 2	0.51	0.22	0.33	
	Int 3	0.41	0.16	0.29	
	Int 4	0.31	0.11	0.24	
	Int 5	0.20	0.07	0.21	
SEL40–22	Int 6	0.09	0.03	0.17	1.2
	Dark	0.02	0.01	0.15	
SEL60–33	Clear glass with Double silver selective coating 40/22, 5.8 mm/ Argon 90% Air 10%, 16 mm/ Planibel clear, 5.8 mm.	0.4	0.16	0.22	1.2
SEL60–33	Clear glass with Double silver selective coating 60/33, 5.8 mm/ Argon 90%, Air 10%, 16 mm/ Planibel clear, 5.8 mm.	0.6	0.27	0.33	1.2
Low-E	Laminated Low-Iron 33.1, 6.1 mm/ Argon 90%, Air 10%, 16 mm/ Low E 0.04 clear glass, 4.8 mm.	0.81	0.52	0.6	1.2



Fig. 3. 3D rendering of the indoor office environment showing the reference points and a hypothetical occupant. The dots mark the reference points at 1.10 m height along the façade-normal line (0.5 m spacing) at which the point-based radiative post-processing of Section 2.3.2 is evaluated.

their radiative properties. The first-order truncation omits second- and higher-bounce inter-reflections. For typical office surface reflectances (0.3–0.5), the second-bounce contribution at the most exposed position (0.5 m from the façade) does not exceed 4–8% of the total shortwave irradiance, and diminishes rapidly with distance. More fundamentally, the ray-tracing routine is used exclusively to compute inter-technology differences in shortwave MRT: all scenarios share identical room geometry, surface properties and occupant position, so any systematic error in the absolute shortwave field (including the truncation bias) cancels in the relative comparison between glazing options.

Longwave MRT and PRT were computed with a separate script using the EnergyPlus [47] surface temperatures and point-to-surface view factors. MRT and operative temperature were then computed in accordance with the adopted assumptions, and PMV was evaluated to obtain time-series and aggregated discomfort indicators.

2.3.3. Outdoor simulation framework

Outdoor thermal comfort was evaluated with a Rhino 3D model and a fully automated Grasshopper workflow using Ladybug Tools 1.9 [50] in Rhino 8 [48], where geometry generation, boundary-condition assignment, electrochromic state switching, MRT and UTCI calculations, and export were executed reproducibly across all scenarios. Parts of these workflows have been experimentally validated in previous studies: Ladybug/Honeybee daylighting simulations against field illuminance measurements [57], and Ladybug Tools' mean radiant temperature calculations against in-situ measurements in real urban spaces [58].

The outdoor model represents a mid-rise office building with three storeys and nine perimeter zones (3 × 3 shoebox modules) on an open ground plane representing road and sidewalk. Façade variants are shown side by side for illustration (Fig. 4), but each case was simulated

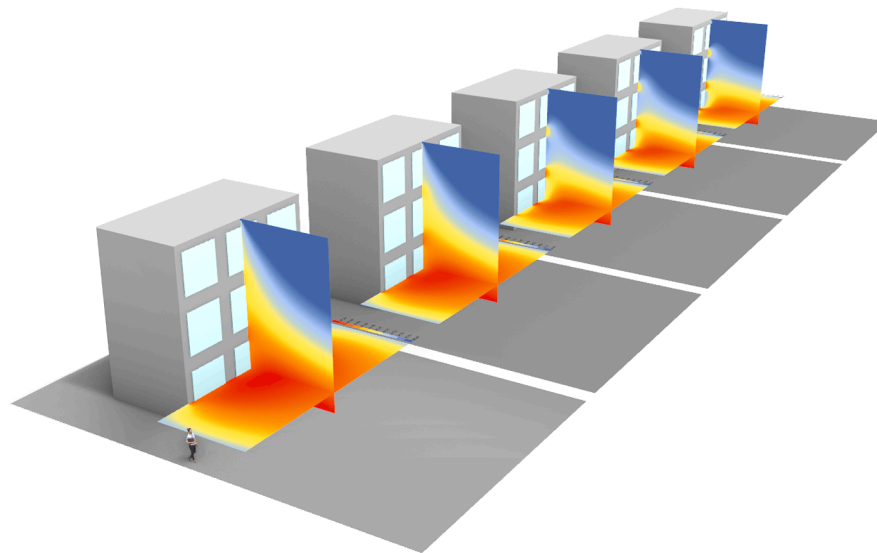


Fig. 4. Rhino-Grasshopper outdoor model at a representative simulative timestep (13:00 on 21 June in Sevilla), showing the different façade glazing cases side by side, each representing a different window technology, and the two analysis planes used to compute MRT fields.

independently on its own ground patch, with no mutual shading/radiative exchange and no opposite building; roof and opaque elements used properties consistent with the indoor assumptions. Window definitions were imported from the WINDOW models [53]: for each location and orientation (South, West), Honeybee used the same U-value, SHGC, and state-dependent VIS and NIR transmittance and reflectance as in EnergyPlus [57].

At solver level, the Ladybug Tools components coupled Radiance-based ray tracing and EnergyPlus-based thermal modelling. Radiance [59] resolved the shortwave radiative environment, while EnergyPlus [47] represented the thermal response of envelope and ground surfaces and provided surface-temperature and longwave-exchange boundary conditions. Weather forcing used the same EPW files as indoors; to limit runtime, each city was simulated on three typical days per season (winter, mid-season, summer) selected near the seasonal median of dry-bulb temperature and global horizontal irradiance (nine days total), over 09:00–18:00 at an hourly timestep. Indoor to outdoor coupling was enforced by exporting indoor-derived tint-state schedules as CSV and importing them into Grasshopper [49]. Outdoor comfort was evaluated along a pedestrian transect at 1.10 m above ground, with points every 0.5 m from 0.5 m to 5.0 m from the façade. MRT fields were also evaluated on two analysis planes (a vertical section in front of the façade and a horizontal plane at 1.10 m, Fig. 4) to visualise near-façade radiative gradients (Section 3.4.1). For each timestep and point, the Honeybee UTCI workflow output UTCI and the associated radiative variables, including MRT. Two MRT definitions were used: full MRT (shortwave plus longwave) for standard UTCI [60], and longwave-only MRT (LW-MRT) to isolate façade and ground longwave effects. Air temperature, relative humidity, and wind speed were drawn from the EPW file and held constant across scenarios; inter-state UTCI differences are therefore driven entirely by the radiative term.

2.4. Climate zones

To test the robustness of the indoor and outdoor thermal comfort outcomes across substantially different boundary conditions, five European locations were selected to span a wide range of latitude, solar availability, and heating and cooling dominance (Table 3): Sevilla, Barcelona, Turin, Berlin, and Helsinki. They belong to the Köppen-Geiger classes Csa, Csa, Cfa, Cfb and Dfb [61], derived from the same weather files used in the simulations, and are the same set used in the energy study of the same device [18], so that the comfort and energy results can be read together. The same EPW weather files are used consistently for both the indoor EnergyPlus [47] simulations and the outdoor simulations, ensuring that indoor and pedestrian-level comfort indicators are driven by identical climatic forcing (air temperature, humidity, wind, and solar radiation) for each location.

The five climates span cooling-dominated, high-irradiance conditions (Sevilla), Mediterranean intermediate conditions (Barcelona), a mixed continental regime (Turin), and heating-dominated high-latitude scenarios with lower solar resource and longer cold seasons (Berlin, Helsinki).

2.5. Smart windows control algorithm

The electrochromic technologies investigated in this work were operated through discrete tint states controlled by a supervisory rule-based control (RBC), whose logic is illustrated in Fig. 5. During occupied hours, the controller mapped two readily available variables, indoor air temperature (T) and total incident solar irradiance on the façade (G), to the eight available electrochromic states: darker states were selected under warm indoor conditions and high solar loading, to suppress shortwave gains and near-window radiative peaks, while clearer

Table 3

Climatic data overview for the selected European cities. SCI denotes the Sky Cover Index, i.e. the annual mean total sky cover expressed in tenths of the sky dome, derived from the same TMY weather files used in the simulations.

CITY	Latitude [°N]	HDD-10 [K-days]	CDD-18 [K-days]	GHI [kWh/m ²]	T Max [°C]	T Min [°C]	T Mean [°C]	SCI [tenths]
Sevilla	37.42	59	1024	1842	43	−2	18.4	3.1
Barcelona	41.28	146	557	1619	30.6	−1	15.7	4.3
Turin	45.22	835	360	1476	31	−6	12.2	4.6
Berlin	52.47	1126	160	1068	32.8	−9.1	9.8	6.1
Helsinki	60.32	1821	30	987	28.7	−21.7	5.2	6.8

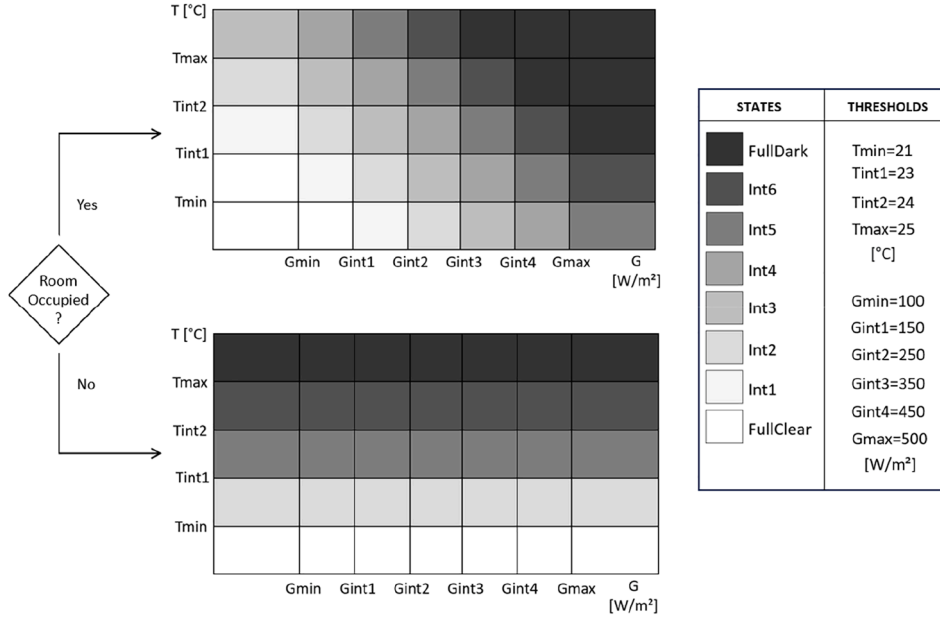


Fig. 5. Rule-based control (RBC) algorithm adopted for the electrochromic smart glazing [18].

states were favoured when temperatures were below the comfort target or solar loading was limited, to preserve daylight and allow beneficial free gains. During unoccupied hours, the selection was simplified to indoor air temperature alone, prioritising thermal management without explicit daylight constraints.

This control logic was developed in [18]. During occupied hours, indoor air temperature is split into five bands by the thresholds 21, 23, 24 and 25 °C and incident irradiance into seven bands by 100, 150, 250, 350, 450 and 500 W/m²; each (T, G) pair maps to one of the eight states, darkening progressively as both bands increase. During unoccupied hours only temperature applies: FullClear below 21 °C, Int 2 up to 23 °C, Int 5 up to 24 °C, FullDark above. If no condition is met, the previous state is retained. The same thresholds and mapping drive both glazings, ensuring a control-neutral comparison (verified in Section 3.5).

2.6. KPIs for thermal comfort assessment

2.6.1. Indoor thermal comfort KPIs

Indoor KPIs are evaluated during occupied hours at point level to resolve near-façade gradients. Reference points are located at 1.10 m height along a line normal to the façade, spaced every 0.5 m from the window plane toward the room depth. The height corresponds to the head of a seated person in ISO 7726 [62] and coincides with the pedestrian height used outdoors; the spacing resolves the near-façade gradient at the scale of a workstation, the first point representing the nearest realistic seat and the room centre the reference for zone-level assessments.

Mean Radiant Temperature: The longwave component is computed from analytical point-to-surface view factors and EnergyPlus inside surface temperatures [62]:

$$T_{r,LW}(p) = \left(\sum_{i=1}^{N_i} F_{p \rightarrow i} T_{s,i}^4 \right)^{1/4}, \sum_i F_{p \rightarrow i} = 1. \quad (1)$$

where $F_{p \rightarrow i}$ is the view factor between point p and surface i , and $T_{s,i}$ is the surface temperature (K) from EnergyPlus.

To include shortwave solar gains, a solar-adjusted MRT is defined as [28,63]:

$$T_r^s(p) = \left(T_{r,LW}(p)^4 + \frac{\alpha_p (f_{sv} I_{dir}(p) + f_{eff} [I_{diff}(p) + I_{ref}(p)])}{\epsilon_p \sigma} \right)^{1/4} \quad (2)$$

where $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, $\epsilon_p = 0.95$ is the longwave emissivity of the human body, $\alpha_p = 0.7$ is the average solar absorptivity of typical clothing, $f_{sv} = 0.35$ represents the fraction of body surface exposed to direct solar radiation (sunlit fraction), and $f_{eff} = 0.70$ is the effective radiative area factor of the human body. These values follow the indoor solar-adjusted MRT formulation of Arens et al. [28], in which $f_{sv} = 0.35$ and $f_{eff} = 0.70$ are derived from the projected area geometry of the human body as standardised in ISO 7726 [62] and Fanger [64]. $I_{dir}(p)$, $I_{diff}(p)$, and $I_{ref}(p)$ are the transmitted direct, transmitted diffuse (sky plus ground), and internally reflected shortwave irradiances at point p , obtained from the point-based ray-tracing described in Section 2.3.2.

Operative Temperature: Operative temperature combines convective and radiative exchange [64–66]:

$$T_{op} = \frac{h_c T_a + h_r T_r}{h_c + h_r} \quad (3)$$

where T_a is the air temperature, T_r is the mean radiant temperature, and h_c and h_r are the convective and radiative heat transfer coefficients, respectively. For low air speed ($v_a < 0.2 \text{ m/s}$), $T_{op} \approx (T_a + T_r)/2$, which is adopted here.

Operative Temperature Discomfort Degree Hours: Thermal discomfort is quantified relative to a comfort band of 20–26 °C, bounded by the heating-season lower limit (20 °C, 1.0 clo) and the cooling-season upper limit (26 °C, 0.5 clo) prescribed for offices in category II of EN 16798–1, a category defined by $|PMV| \leq 0.5$ [67]. Since the HVAC system controls the air temperature within the same 20–26 °C band (Section 2.3.2), applying the band to the operative temperature isolates the radiant component of discomfort, which an air-temperature controller does not register. DDH is expressed as the time-integral of the deviation of operative temperature from the nearest band limit:

$$DDH = \begin{cases} T_{op}(t) - 26 & \text{if } T_{op}(t) > 26 \\ T_{op}(t) - 20 & \text{if } T_{op}(t) < 20 \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

Radiant Asymmetry: Plane radiant temperature (PRT) is computed hemispherically for a given direction d [64–66]:

$$T_{pr,d} = \left(\sum_{i \in d} F_{p \rightarrow i}^{(d)} T_{s,i}^4 \right)^{1/4} \quad (5)$$

Radiant asymmetry is the PRT difference between opposite directions (for example window vs opposite wall along the front–back axis). Each occupied timestep is classified against ASHRAE 55 radiant temperature asymmetry limits [64–66], selecting the warm or cool criterion based on the sign of ΔT_{PRT} : walls 23 °C (warm) and 10 °C (cool), ceiling–floor 5 °C (warm ceiling) and 14 °C (cool ceiling). Results are reported as the percentage of occupied hours exceeding the applicable threshold for each direction and point.

Predicted Mean Vote: PMV is computed following Fanger (ISO 7730) [64–66]:

$$PMV = (0.303 e^{-0.036M} + 0.028) L \quad (6)$$

Point-wise PMV is evaluated at each reference point using fixed office inputs: air speed $v_a = 0.05$ m/s, external work $W = 0$, metabolic rate derived from 125 W/person (assuming 1.8 m² body surface area), and a seasonal clothing schedule (0.85 clo Jan 1 to Apr 30, 0.70 clo May 1 to Sep 30, 0.85 clo Oct 1 to Dec 31). Relative humidity is taken from the simulation and the metabolic rate corresponds to 1.2 met. The air speed of 0.05 m s^{−1} represents still air at the occupant position, since the ideal loads system meets the sensible load without a modelled supply air jet; in the Fanger model the convective coefficient is the larger of the natural and forced terms, so PMV is insensitive to air speed below about 0.1 m s^{−1}. Recomputing PMV with 0.10 m s^{−1} changes it by 0.03 on average (0.06 at most), moves 1.8% of the occupied time steps to an adjacent class and does not alter the ordering of the glazings in any city or orientation. For post-processing and discomfort aggregation, PMV is discretised into seven bins centred on integer intensities $k \in \{-3, -2, -1, 0, +1, +2, +3\}$, using 1.0-PMV-wide intervals with thresholds at $\pm 0.5, \pm 1.5, \pm 2.5$ (neutral for $-0.5 \leq PMV < 0.5$; extreme bins for $PMV < -2.5$ and $PMV \geq 2.5$).

Indoor Discomfort Score (IDS): To synthesise the full PMV distribution while preserving information on discomfort intensity, the Indoor Discomfort Score (IDS) is defined and split into two independent components:

$$IDS_{warm} = \sum_p \sum_{k \in H} k f_k \quad IDS_{cold} = \sum_p \sum_{k \in C} k f_k \quad (7)$$

where f_k is the fraction of occupied hours in PMV class k , and $H = \{+1, +2, +3\}$ and $C = \{-3, -2, -1\}$ are the warm and cold classes.

2.6.2. Outdoor thermal comfort KPIs

Outdoor comfort is evaluated at pedestrian level in front of the façade by quantifying how façade technologies modify the local radiative environment and the resulting thermal stress. As indoors, results are sampled on a façade-normal transect at 1.10 m height, with points every 0.5 m from 0.5 m to 5.0 m from the façade. The analysis includes the external window surface temperature as a proxy for façade longwave emission, and radiative indicators separating shortwave solar (about 0.3–2.5 µm) from longwave thermal infrared exchange (about 4–100 µm), to distinguish glazing-driven absorption and surface heating from direct and reflected solar exposure.

Universal Thermal Climate Index (UTCI): Outdoor thermal stress is quantified using UTCI [60]:

$$UTCI = f(T_a, T_{mrt}, v, RH) \quad (8)$$

evaluated at pedestrian points along the façade transect (0.5–5.0 m from the façade, at 1.10 m height), for each timestep (see Section 2.3.3). T_a , RH , and v are taken from the EPW boundary conditions, while T_{mrt} is computed by the Honeybee UTCI workflow by coupling Radiance ray

tracing for the shortwave field (direct plus diffuse) with surface thermal modelling for longwave exchange based on surface properties and temperatures.

3. Results

3.1. DB-EC device thermal characterisation under controlled climatic conditions

The thermal characterisation experiments showed a repeatable dynamic response: a rapid temperature rise after irradiation onset followed by an asymptotic approach to quasi-steady state within about 20–30 min. Fig. 6-left illustrates this for the Dark state at five irradiance levels, where saturation occurs within approximately 20 min and the steady-state temperature ranges from about 56 °C at 450 Wm^{−2} to 75 °C at 850 Wm^{−2}. Across all states, steady-state surface temperature increases monotonically with irradiance, producing a consistent ordering from Clear (lowest) to Dark (highest).

Within each state the temperature-irradiance trend is close to linear, with fitted slopes ranging from approximately 0.023 °C/(Wm^{−2}) for Clear to 0.053 °C/(Wm^{−2}) for Dark, and intermediate states Int 2 and Int 4 at approximately 0.035 and 0.045 °C/(Wm^{−2}), respectively. The Dark-to-Clear slope ratio of roughly 2.3 reflects the corresponding absorptance ratio between the two extreme tint states, confirming that the additional absorption from electrochromic darkening translates directly into a steeper thermal response.

A consistency check against EnergyPlus-predicted outer-laminate temperatures of the DB-EC DGU under comparable outdoor air conditions (24–26 °C) confirms the same monotonic ordering and near-linear irradiance dependence, now resolved across all eight tint levels (Fig. 7). Simulated slopes span a wider range, from approximately 0.040–0.045 °C/(Wm^{−2}) (Clear) to 0.075–0.080 °C/(Wm^{−2}) (Dark), with a Dark-to-Clear ratio of approximately 1.8.

Simulated medians range from approximately 35–36 °C (Clear, 450 Wm^{−2}) to approximately 72 °C (Dark, 750 Wm^{−2}), consistent with the chamber data once differences in heat-transfer configuration are considered (horizontal prototype under chamber convection versus an external DGU pane with wind-dependent convection and sky longwave exchange).

This consistency check, comparing chamber measurements and EnergyPlus predictions under necessarily different heat-transfer configurations, cannot constitute a formal validation of the simulation tool. It confirms, however, that the model reproduces the correct physical ordering (Clear < Int 2 < Int 4 < Dark) and the near-linear irradiance dependence, which are the properties relevant to deriving relative inter-state and inter-technology surface temperature differences used as radiative boundary conditions in the subsequent comfort analyses.

3.2. Façade surface temperatures

The chamber tests in Section 3.1 showed that DB-EC self-heating is primarily absorptance-driven and strongly state dependent. Here, we translate that material-level behaviour into building-scale thermal boundary conditions by reporting annual-average surface temperatures from the simulations (Table 4), which are directly relevant for longwave exchange indoors and façade longwave emission outdoors.

The table shows two robust drivers that apply across all technologies: a clear climatic gradient (all temperatures decrease from Sevilla to Helsinki) and a consistent orientation effect (South-facing cases are warmer than West-facing ones due to higher cumulative solar exposure). Superimposed on these drivers, technology modifies indoor- and outdoor-facing surfaces differently. For the indoor-facing metrics (IN and SUR), the ranking reflects how each glazing option shapes time-averaged indoor radiative conditions: the high-transmittance Low-E case yields the warmest inner glazing and wall surfaces, selective static references reduce both, and the electrochromic solutions yield the

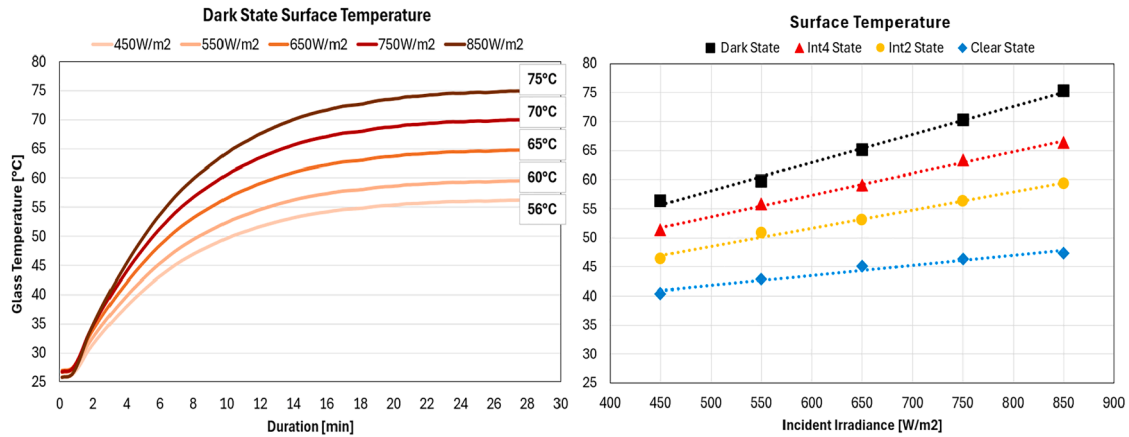


Fig. 6. Thermal characterisation of the DB-EC device. Left: transient surface temperature of the Dark state at five irradiance levels (450–850 Wm⁻²), showing quasi-steady-state attainment within approximately 20 min. Right: steady-state surface temperature versus incident irradiance for four tint states (Clear, Int 2, Int 4, Dark); dashed lines are linear fits with slopes increasing from 0.023 °C/(Wm⁻²) (Clear) to 0.053 °C/(Wm⁻²) (Dark).

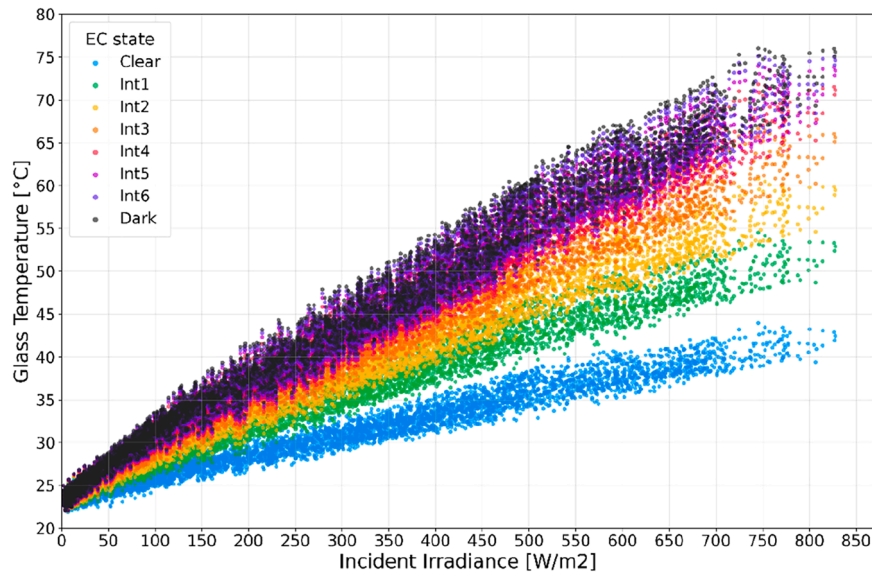


Fig. 7. EnergyPlus-predicted outer-laminate temperature of the DB-EC DGU versus incident irradiance for all eight tint states (Clear, Int 1–Int 6, Dark) at 24–26 °C outdoor air. The monotonic ordering and near-linear trends are consistent with the right panel of Fig. 6, with steeper slopes due to the inclusion of the low-irradiance regime.

Table 4

Annual-average surface temperatures (°C): OUT outer glazing (daytime), IN inner glazing (occupied), SUR indoor walls (occupied).

	DB-EC			EC			SEL40–22			SEL60–33			Low-E		
	OUT	IN	SUR	OUT	IN	SUR	OUT	IN	SUR	OUT	IN	SUR	OUT	IN	SUR
Sevilla - S	37.6	29.2	25.6	36.6	29.2	25.6	27.9	27.7	26	27.5	28.8	27.1	25.1	31	28.5
Barcelona - S	31.7	27.3	24.6	31.1	27.2	24.6	24	25.9	24.8	23.7	27	25.8	21.6	29.4	27.7
Turin - S	28.2	26	23.9	27.9	25.9	23.8	21.2	24.5	23.9	20.8	25.5	24.6	18.7	27.4	26.2
Berlin - S	20.7	23.6	22.9	20.7	23.6	22.7	16.2	22.6	22.8	15.9	23.4	23.5	14.5	24.9	24.7
Helsinki - S	17.2	22.4	21.9	17.3	22.2	21.7	12.7	21.1	21.6	12.4	22.1	22.5	10.9	23.8	24
Sevilla - W	30.9	27.4	25	30.4	27.4	25	24.7	26.2	25.3	24.4	26.9	25.8	22.7	28.6	27
Barcelona - W	26.6	25.9	24.2	26.3	25.8	24.2	21.5	24.8	24.3	21.2	25.5	24.8	19.8	26.9	25.9
Turin - W	23.2	24.6	23.4	23.2	24.5	23.4	18.6	23.5	23.4	18.3	24.1	23.9	16.8	25.3	24.9
Berlin - W	17.6	22.6	22.5	17.8	22.6	22.4	14.6	21.9	22.5	14.4	22.4	22.9	13.4	23.4	23.8
Helsinki - W	13.3	21	21.4	13.5	20.9	21.2	10.6	20.1	21.1	10.4	20.8	21.7	9.5	21.9	22.8

lowest annual means, with DB-EC and EC remaining very close under the adopted control. For the exterior surface (OUT), the ranking reverses: DB-EC and EC show the highest outer-glazing temperatures, consistent with absorption-dominated solar-control and the self-heating

mechanism observed in Section 3.1, while the static references remain cooler. Short-term extremes depart substantially from these means: the outer glazing of the electrochromic options reaches annual daytime peaks of 75–83 °C in the sunniest cases, against roughly 40–60 °C for the

static references, with the near-façade implications discussed in Section 4.

3.3. Indoor thermal comfort results

3.3.1. Indoor near-façade radiative environment

Fig. 8 illustrates the case of Barcelona on 04 January under clear sun exposure, comparing a high-transmittance reference (Low-E) against DB-EC, and analysing two occupant positions along the façade-normal line, at 0.5 m (perimeter) and 2.5 m (room centre).

At 0.5 m, the point has a large solid angle toward the glazing, so the radiative environment is strongly sensitive to what the window transmits. For Low-E, the dominant contribution during direct exposure is typically the transmitted direct beam, which can reach the point directly and also creates high-irradiance footprints on the floor and nearby surfaces. The combined effect is a sharp shortwave-driven increase in radiative load near the façade, often reinforced by secondary re-diffusion whenever strong sun patches form. For DB-EC, the reduction of near-façade radiative load acts on multiple terms of this balance. Switching reduces the transmitted beam power, directly weakening the most intense contribution and limiting the formation and intensity of sunlit interior patches. As a result, the near-façade radiative environment shifts from a beam-dominated regime, amplified by secondary re-diffusion, to a more moderated and temporally stable shortwave field. At 2.5 m, geometric coupling to the window is weaker and beam penetration is less effective, so the direct transmitted beam reaching the point is reduced or absent for much of the exposure period. Since the direct term is already less influential at 2.5 m, the contrast between technologies narrows relative to the perimeter point, and longwave exchange and air temperature contribute more strongly to the local comfort

conditions.

3.3.2. Operative temperature discomfort degree hours (DDH)

Here, the same mechanism is quantified on an annual basis using DDH, computed during occupied hours relative to the 20–26 °C band and shown in Fig. 9 at 1.10 m height for two distances from the façade (0.5 m and 2.5 m).

The technologies are most differentiated at 0.5 m. Low-E dominates overheating in every location, with the most extreme case reaching nearly 10,000 °C·h in Sevilla South; even at 2.5 m the same case remains on the order of 4000 °C·h. The static solar-control references reduce overheating, but their effectiveness depends on selectivity: SEL60–33 still exhibits substantial overheating in warm and intermediate climates (notably at 0.5 m), whereas SEL40–22 is consistently lower. DB-EC and EC form the lowest-DDH group across climates and orientations, typically remaining in the low-thousands or below at 0.5 m and dropping further at 2.5 m.

The underheating side of Fig. 9 becomes relevant mainly in the northern climates (Berlin and Helsinki) and is again more pronounced at 0.5 m, highlighting that cold discomfort also has a façade-driven radiative component (lower near-window MRT). Here the ranking tends to invert: technologies that most strongly suppress solar admission show larger underheating DDH because they reduce beneficial shortwave gains during occupied hours. DB-EC and EC sit between these extremes, avoiding the overheating penalty of Low-E while not exhibiting the systematic cold penalty of the most selective static options.

3.3.3. Radiant asymmetry

Complementing the DDH results, Fig. 10 quantifies the frequency of warm-wall radiant-asymmetry exceedances (ASHRAE 55, 23 °C) during

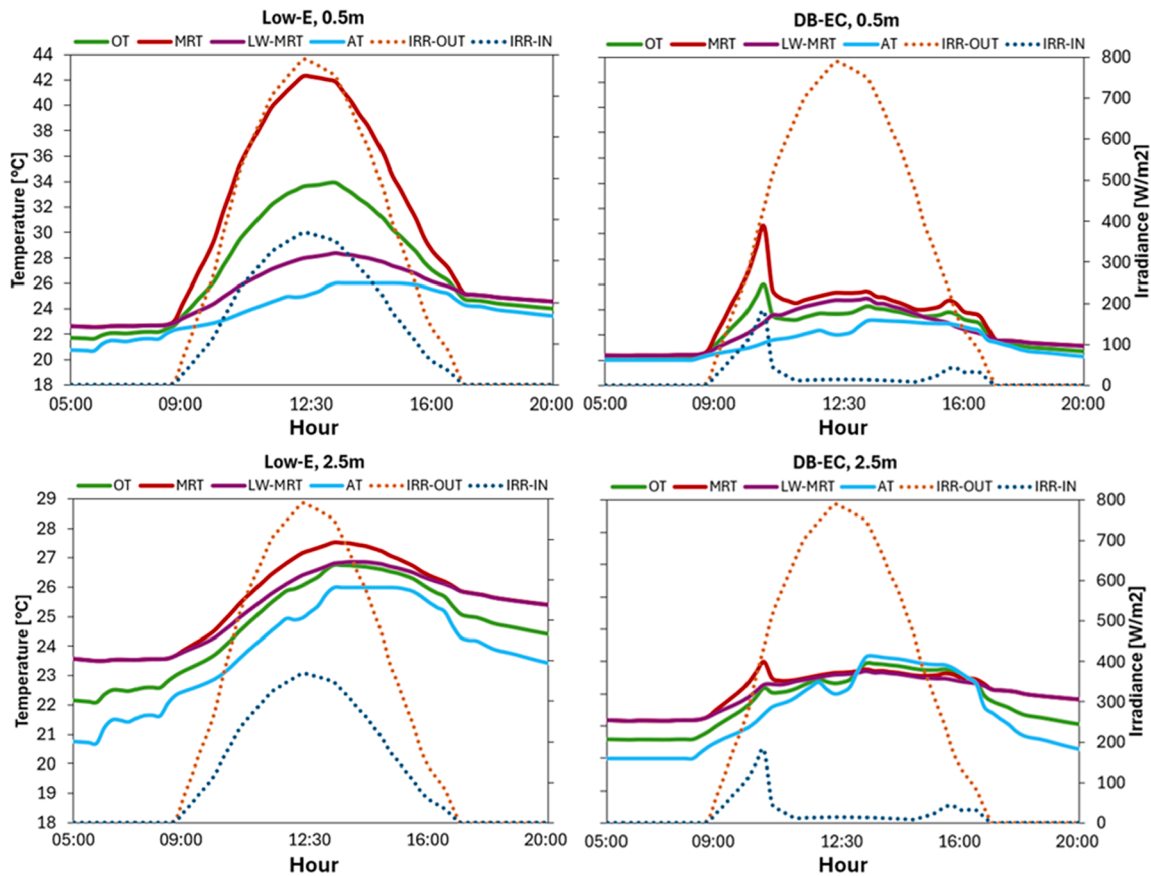


Fig. 8. Barcelona, 04 January. Time-series comparison of air temperature (AT), operative temperature (OT), mean radiant temperature (MRT), longwave-only MRT (LW-MRT), outdoor incident irradiance on the façade (IRR-OUT) and transmitted indoor irradiance (IRR-IN) for Low-E and DB-EC, evaluated at 0.5 m and 2.5 m from the façade.

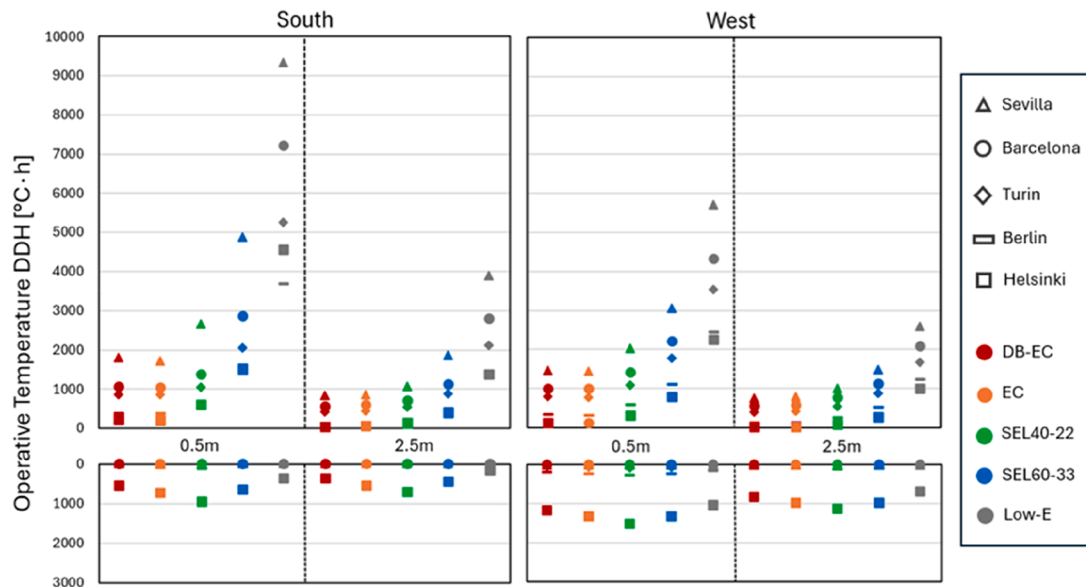


Fig. 9. Operative Temperature DDH for South and West orientations, split into overheating (top) and overcooling (bottom), at 0.5 m and 2.5 m from the window. Marker shape indicates location; colour indicates window technology.

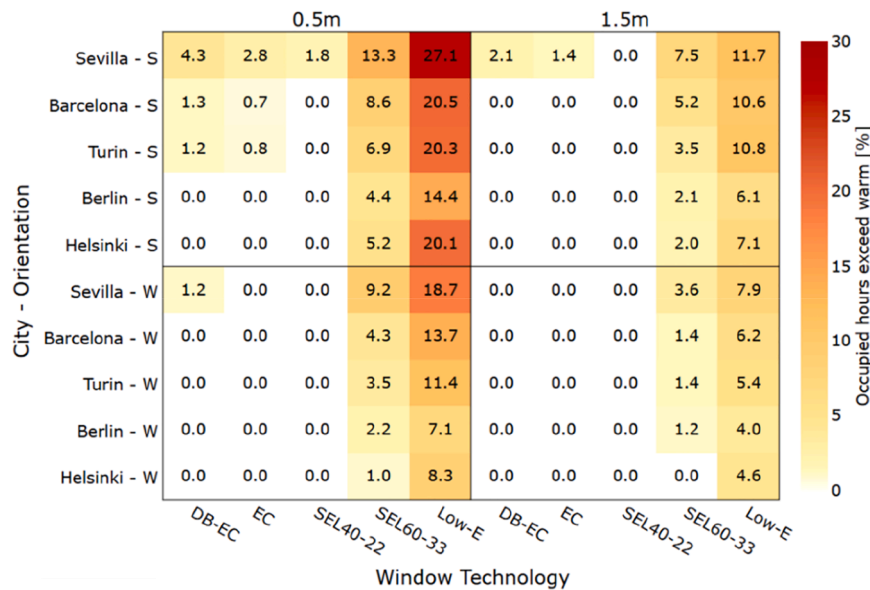


Fig. 10. Occupied-hour exceedance (%) of the ASHRAE 55 warm-wall radiant asymmetry limit (23 °C) in the front-back direction (PRT-based), across five cities and South/West orientations at 0.5 m and 1.5 m from the window, for all glazing technologies.

occupied hours at 1.10 m height, evaluated at 0.5 m and 1.5 m from the façade. All other asymmetry types and directions (including cool-wall and ceiling–floor criteria, and the remaining directional components) are not reported because exceedances were zero across the analysed scenarios. Points farther from the façade are also omitted because exceedances were mostly zero or negligible, providing limited technology differentiation.

A clear technology ranking emerges in the perimeter. Low-E shows the highest exceedance rates across all climates and both orientations, peaking at 27.1% in Sevilla South at 0.5 m, and remaining substantial even in heating-dominated climates under winter sun. SEL60–33 reduces these exceedances but still exhibits non-negligible warm-wall events at 0.5 m, indicating that partial solar control does not fully suppress near-window directional loading under strong exposure. In contrast, DB-EC and EC markedly mitigate warm-wall exceedances:

values are generally low and often near zero outside the most exposed cases; for example, in Sevilla South at 0.5 m, exceedances drop from 27.1% (Low-E) to 4.3% (DB-EC) and 2.8% (EC). SEL40–22 is essentially zero throughout the dataset, with only a small residual in the most demanding case (Sevilla South at 0.5 m), consistent with its stronger shortwave suppression. At 1.5 m the ranking persists but compressed, with residual exceedances only for Low-E and, to a lesser extent, SEL60–33.

3.3.4. PMV and indoor discomfort score

Thermal sensation is synthesised through the PMV-based Indoor Discomfort Score (IDS) defined in Section 2.6. In Fig. 11, positive bars represent cumulative warm discomfort and negative bars cumulative cold discomfort.

Fig. 11 confirms a strong climatic shift in the IDS balance. In Sevilla

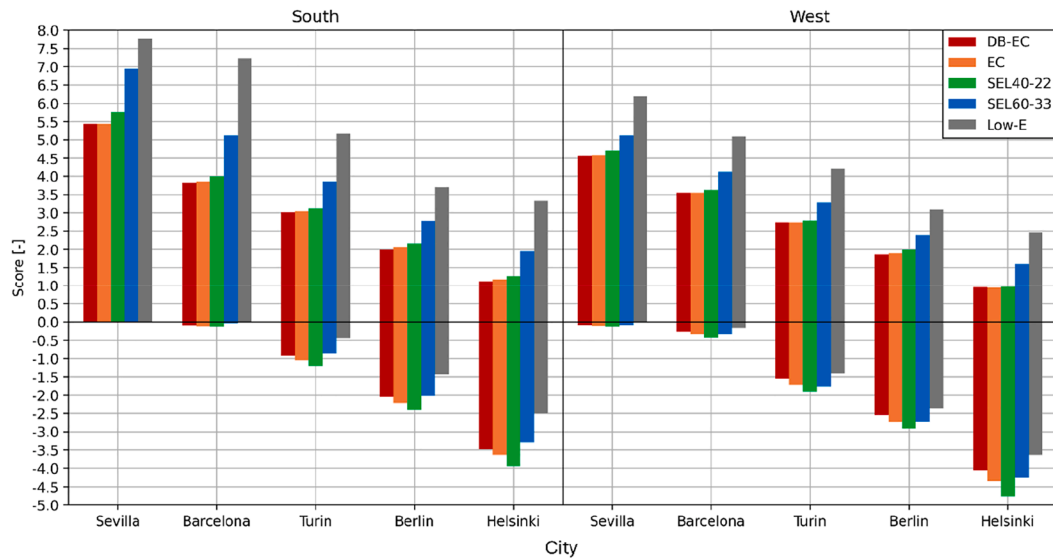


Fig. 11. PMV-based IDS for South (left) and West (right) orientations across the five climates, computed during occupied hours and aggregated across all analysed indoor points. Positive bars indicate IDS_{warm} and negative bars indicate IDS_{cold} .

and Barcelona, IDS is dominated by the warm component and the ranking is driven by solar admission. Under South, Low-E yields the highest warm scores (about 7.8 in Sevilla and about 7.2 in Barcelona), followed by SEL60-33 (about 6.9 and 5.1), while DB-EC and EC form the lowest group (about 5.4 in Sevilla and 3.8 in Barcelona), close to SEL40-22 (about 5.8 and 4.0). Turin behaves as a transition regime where both components matter: under South the warm score falls from about 5.2 (Low-E) to about 3.0 for the two electrochromics, at the price of a cold component of about -1.0 . In Berlin and Helsinki the trade-off reverses and cold discomfort dominates: under South the electrochromics cut the warm score to about 2.0 and 1.1 respectively, against 3.7 and 3.3 for Low-E, but their cold component deepens to about $-1.9/-2.2$ and $-3.3/-3.6$ (DB-EC/EC), against -1.4 and -2.5 for Low-E, with SEL40-22 the most penalised (about -2.5 and -4.0). The West orientation shifts every case towards the cold side by roughly 0.5 to 1 point without altering the ranking.

Table 5 summarises how the indoor indicators at 0.5 m depend on climate. Overheating scales with the cooling resource. Across the ten city-orientation cases the overheating DDH of DB-EC correlates with cooling degree days (Pearson $r = 0.98$) and with global horizontal irradiance ($r = 0.97$), and so does its warm IDS. The relative benefit of dynamic control grows in the opposite direction. The overheating DDH reduction of DB-EC against Low-E rises from 74 to 81% in Sevilla to 94–95% in Helsinki ($r = 0.85$ with heating degree days), because Low-E keeps overheating under low winter sun while the controller admits

little radiation. Helsinki South departs from this gradient, with Low-E overheating exceeding Berlin South, because a south-facing vertical surface at 60°N receives more beam radiation than at 52°N (1580 against 1285 h with beam irradiance above 50 W m^{-2} in the weather files used); this is also where dynamic control delivers its largest benefit. The cold side follows heating degree days. The cold DDH of DB-EC is negligible in Sevilla and Barcelona (0.6°C h at most), $9\text{--}44^\circ\text{C h}$ in Turin, $68\text{--}193^\circ\text{C h}$ in Berlin and $548\text{--}1172^\circ\text{C h}$ in Helsinki, and its cold IDS deepens from 0 to -4.0 along the same gradient ($r = -0.97$), exceeding that of Low-E in every heating-dominated case.

3.4. Outdoor thermal comfort results

3.4.1. Outdoor mean radiant temperature analysis

In this subsection, the focus is on longwave-only MRT, obtained by filtering out the shortwave contribution in the Honeybee UTCI workflow. The shortwave component was verified not to differentiate the compared technologies: across all simulated hours, the mean shortwave contribution to pedestrian-level MRT (SW-MRT, as resolved by the Honeybee workflow) in the $0.5\text{--}2.5 \text{ m}$ band differs by less than 0.15°C between glazing options, with hourly inter-technology spreads of $1.5\text{--}3.7^\circ\text{C}$ on average against absolute levels of up to 58°C . This follows from the exposure geometry, where the pedestrian shortwave load is dominated by direct, diffuse and ground-reflected irradiance identical across scenarios. Specular façade reflections add little: the

Table 5

Climate dependence of the indoor indicators at 0.5 m from the façade during occupied hours: overheating and overcooling Discomfort Degree Hours (DDH, $^\circ\text{C h}$) of Low-E and DB-EC, and Indoor Discomfort Score (IDS) of Low-E and DB-EC, against the heating and cooling degree days (HDD-10 and CDD-18, K-days) and global horizontal irradiance (kWh/m^2) of Table 3.

City, orient.	HDD	CDD	GHI	DDH warm		DDH cold		IDS warm		IDS cold	
				Low-E	DB-EC	Low-E	DB-EC	Low-E	DB-EC	Low-E	DB-EC
Sevilla S	59	1024	1842	9316	1791	0.0	0.0	7.77	5.38	0.00	-0.01
Sevilla W				5691	1463	0.0	0.0	6.19	4.54	-0.02	-0.11
Barcelona S	146	557	1619	7214	1048	0.0	0.0	7.23	3.81	0.00	-0.09
Barcelona W				4323	997	0.1	0.6	5.09	3.51	-0.17	-0.29
Turin S	835	360	1476	5250	858	3.9	9.0	5.17	3.03	-0.44	-0.87
Turin W				3534	782	35.7	44.1	4.21	2.72	-1.41	-1.59
Berlin S	1126	160	1068	3678	377	38.9	68.3	3.69	2.00	-1.44	-1.93
Berlin W				2439	319	160.7	193.2	3.08	1.85	-2.36	-2.57
Helsinki S	1821	30	987	4560	229	355.1	548.3	3.33	1.15	-2.50	-3.28
Helsinki W				2256	124	1047.9	1171.9	2.47	0.94	-3.63	-4.03

electrochromic options attenuate mainly by absorption (measured DB-EC solar reflectance 0.04–0.08 across states, Table 1), and the sub-0.15 °C spread reported above includes the static references.

Fig. 12 provides a spatial illustration of the LW-MRT field for a high-load summer condition (Sevilla, South, 15 July at 13:00), comparing first the Low-E façade and then the DB-EC façade. The panels show a vertical section in front of the façade, a horizontal plane at pedestrian level (1.10 m high) and the full 3D setup. The sensor line used for quantitative post-processing is visible on the pedestrian plane, enabling the extraction of LW-MRT profiles as a function of distance from the façade. The comparison highlights a systematic increase of LW-MRT in

the near-façade region for DB-EC relative to Low-E, with the strongest differences concentrated close to the building and progressively fading with distance. Fig. 13 condenses these fields into LW-MRT distance profiles for Barcelona, South orientation, extracted on the days of the selected seasons (winter, spring and summer) at three representative hours (10:00, 13:00, 16:00), comparing all façade technologies. Two distinct profile shapes emerge depending on solar altitude. Under low solar angles (winter, and morning/afternoon in spring), the vertical façade receives significant direct irradiance and constitutes the hottest surface in the radiant field; LW-MRT therefore decays with distance as the view factor to the façade diminishes. Under high solar altitude

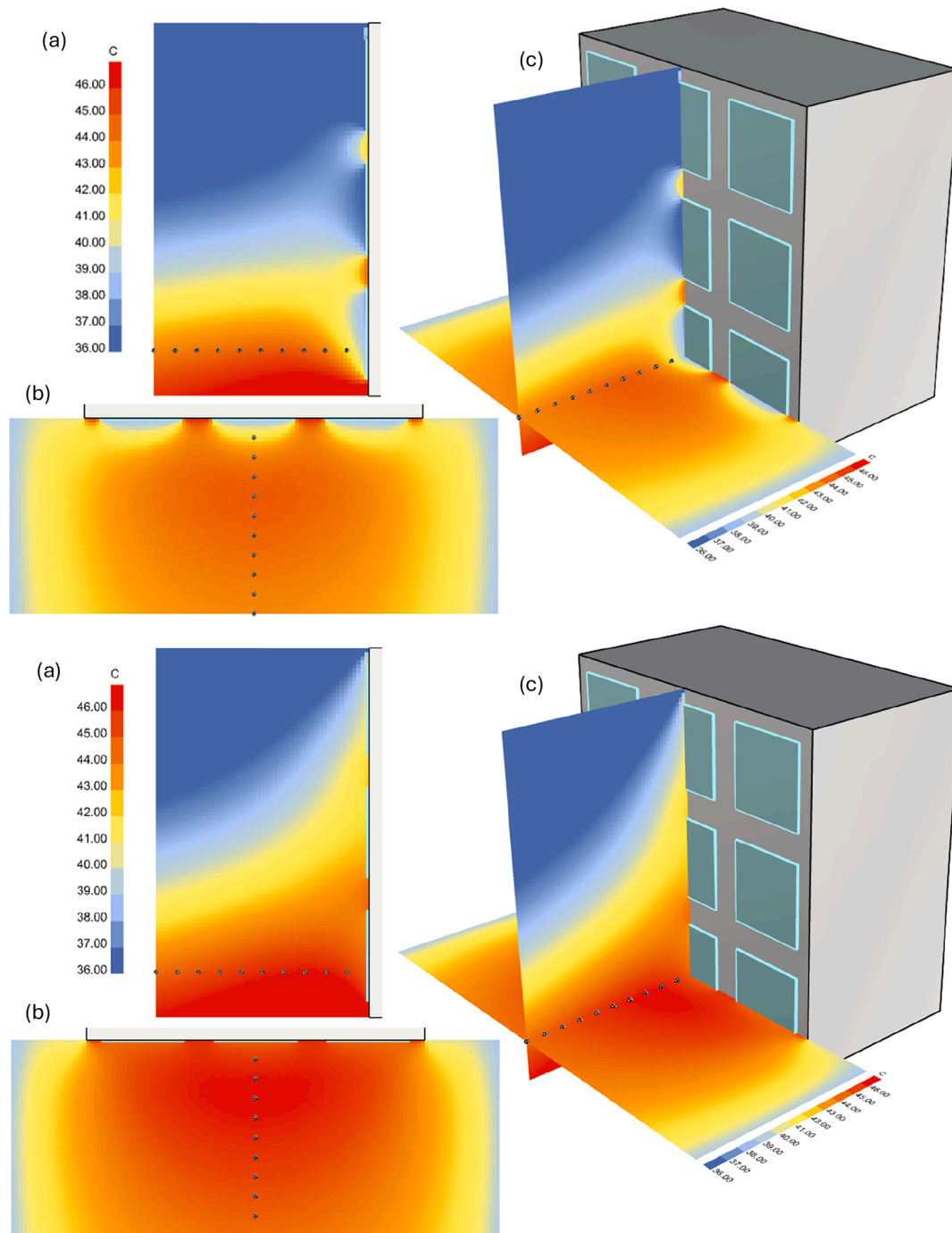


Fig. 12. Longwave mean radiant temperature (LW-MRT) fields examples around the façade for Sevilla (South orientation) on 15 July at 13:00, comparing Low-E (top) and DB-EC (bottom). Panels show (a) horizontal LW-MRT map at pedestrian level, (b) vertical section LW-MRT map in front of the façade, and (c) 3D view of the model and analysis domains. Dots indicate the pedestrian sensor points used to extract distance-based LW-MRT profiles.

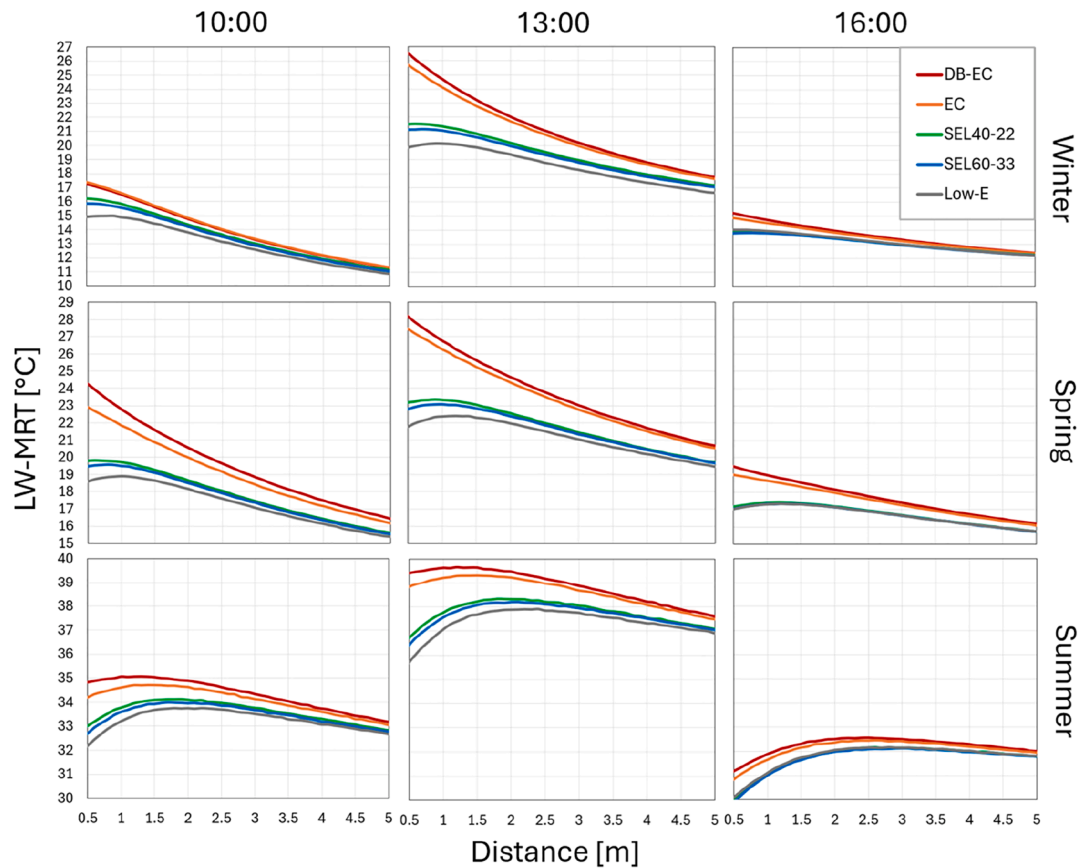


Fig. 13. Longwave mean radiant temperature (LW-MRT) profiles as a function of distance from the façade for Barcelona (South orientation), extracted on winter, spring and summer example days at 10:00, 13:00 and 16:00, comparing DB-EC, EC and the static benchmarks. Curves are extracted along the pedestrian sensor line shown in Fig. 12.

(midday in spring and summer), the horizontal ground absorbs substantially more direct radiation than the vertical façade, which consequently acts as a relatively cooler surface in the longwave field. Profiles accordingly exhibit a local maximum at approximately 1–1.5 m from the façade: at very close range the large view factor to the cooler glazed surface suppresses LW-MRT, while at 1–1.5 m this cooling influence diminishes and the hot ground dominates, producing a peak that then attenuates at greater distances.

The technology ranking is stable across all conditions: DB-EC and EC consistently produce the highest near-façade LW-MRT, followed by SEL40–22 and SEL60–33, while Low-E yields the lowest values, directly reflecting the outer surface temperatures driven by solar absorptance. The separation is most pronounced within 0.5–1.5 m at midday, where differences in glazing temperature amplify longwave emission contrasts, and all curves converge beyond approximately 3–5 m, confirming that façade-driven longwave forcing is a predominantly near-field effect. This finding is the longwave counterpart of the indoor results: DB-EC reduces transmitted shortwave loads indoors, but shifts part of the solar energy balance into absorption and surface heating, which manifests outdoors as higher LW-MRT very close to the façade.

3.4.2. The universal thermal climate index

Fig. 14 reports some example days of the mean UTCI response in the near-façade region by averaging UTCI across the sensor points located within the first 2.5 m from the façade. Despite the differences in outer surface temperature and LW-MRT, the UTCI pattern is consistent across locations and orientations: DB-EC and conventional EC systematically yield slightly higher UTCI than the static references, but the increase is small and practically negligible across all climates and both orientations. Quantitatively, averaged over the sensor points within 2.5 m of the

façade and over all simulated hours, DB-EC raises UTCI by 0.5 °C with respect to the coolest static reference at each hour, with a maximum of 2.5 °C in a single hour (Helsinki, South, spring midday) and values above 1 °C in 18% of the simulated hours; the single-band EC behaves almost identically (0.5 °C on average, 2.2 °C maximum). For reference, the narrowest UTCI stress category spans 6 °C, so the façade-induced shift corresponds on average to less than one tenth of a category. A category boundary is crossed in about 6% of the simulated hours, and only where the static reference already lies within roughly 1 °C of a threshold.

When UTCI is computed using total MRT, the longwave increase is diluted by the dominant shortwave and ambient contributions, and the overall index remains primarily governed by the background meteorological forcing (air temperature, wind and humidity) rather than by the modest façade-induced radiative shift. It should be noted, however, that outdoor air temperature is taken directly from the EPW file and is not modified by convective heat transfer from the heated façade. A hotter glazing would locally warm the adjacent air, potentially increasing UTCI beyond what is captured here. Quantifying this effect would require coupling with a microclimate or CFD model (e.g. ENVI-met) and is left as future work.

3.5. Dual-band versus single-band electrochromic operation

Across every indoor and outdoor metric considered here, the dual-band and the single-band electrochromic glazing perform almost identically, and this equivalence is not an artefact of the control layer. Driven by the same supervisory logic with identical thresholds (Section 2.5), the two devices follow essentially the same tint-state sequences: their annual state-occupancy distributions differ by about one percentage point at most in every state, climate and orientation, while the

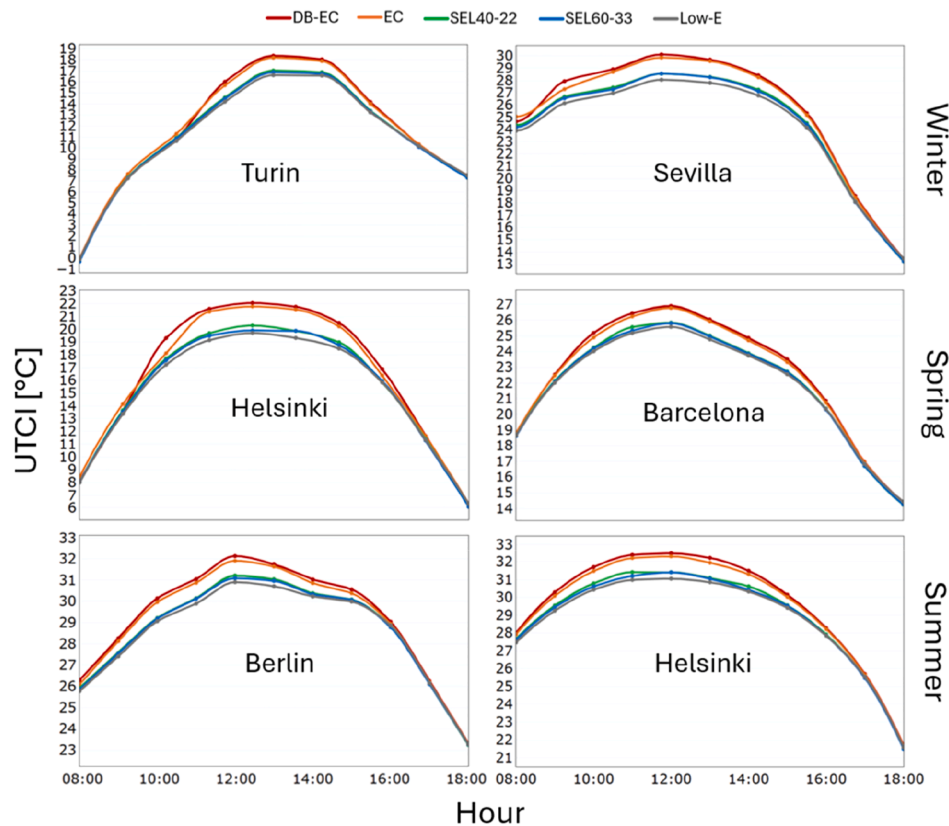


Fig. 14. Mean UTCI computed using total MRT (shortwave plus longwave) at pedestrian height for four representative days across four different simulated climates. Curves represent UTCI averaged across the sensor points located within the first 2.5 m from the façade, at 1.10 m from the ground, highlighting the near-façade pedestrian microclimate response.

intermediate states account for roughly 35–65% of the occupied hours, confirming that the controller exploits the full set of available states. The two glazings therefore differ only in their state-resolved optical properties (Table 2), and the thermal outcome is governed by how much solar radiation is admitted rather than by its spectral distribution. The two devices differ, however, on the daylight channel: under the shared control the dual-band glazing reduces UDI-fs (workplane daylight below 100 lx) by 4–14 percentage points, against a 2–6 point rise in UDI-ex (above 3000 lx), improving the combined visual-discomfort proxy in nine of the ten cases, consistent with the energy and daylight advantages of the dual-band device reported in [18].

4. Discussion

Indoors, both DB-EC and conventional EC substantially outperform high-transmittance glazing (Low-E) in mitigating near-façade overheating across all climates and orientations. The two electrochromic technologies remain closely aligned across all indoor metrics: DDH, radiant-asymmetry exceedances, and IDS show only marginal differences between DB-EC and EC under the adopted rule-based control. This indicates that, for thermal comfort purposes, the primary driver is the dynamic modulation of transmitted solar gains, not the spectral selectivity that distinguishes DB-EC from a standard single-band EC.

These indoor conclusions are robust to the main modelling assumption. Coupling the internal surfaces to conditioned neighbouring spaces (Section 2.3.2) changes the interior surface temperatures by -3.3 to $+0.8$ °C; overheating DDH and warm IDS are highest with the adiabatic model in every case, so the values of Section 3.3 are upper bounds. The DB-EC reduction of overheating DDH relative to Low-E at 0.5 m moves from 81% to 85–92% in Sevilla and from 95% to 97–98% in Helsinki, the ordering of the technologies is unchanged in every

indicator, and the cold-side penalty in Helsinki keeps its sign with a magnitude that follows the temperature of the neighbouring spaces (Supplementary Table S2).

Outdoors, the picture inverts relative to the static benchmarks. The absorption-driven solar control of both DB-EC and EC raises outer glazing temperatures and increases longwave radiative forcing in the first 0.5–1.5 m from the façade. However, this effect is of limited practical consequence at pedestrian-relevant distances: when integrated into UTCI through total MRT, the pedestrian thermal stress increase is consistently small and negligible across all simulated conditions. These conclusions are robust to the representative-day sampling adopted for the outdoor simulation: even under the median seasonal conditions simulated, EC-induced outer surface temperatures already substantially exceed those of static references (Table 4), yet the resulting UTCI increment remains a small fraction of a stress-category width, confirming that the negligible outdoor penalty is not an artefact of conservative sampling. Taken together, the indoor and outdoor findings define a clear trade-off: absorptive electrochromic control strongly improves perimeter-zone indoor thermal comfort at the cost of a minor increase in near-façade outdoor longwave loading, which remains thermally negligible at the UTCI level.

These results agree with the measurements available for glazed offices. The near-façade gradient computed here, with operative-temperature discomfort concentrated at 0.5 m and largely dissipated at 2.5 m, matches field observations of mean radiant temperatures of 33–51 °C at the window against 25–27 °C inside the room [25] and of radiant asymmetry and MRT swings confined to the near-window area [26,36]; the ranking of the static references by SHGC also follows [25]. The 1–2 °C lower annual mean inner-glass temperature of the electrochromic options relative to Low-E in the Mediterranean cases (Table 4) is the annual counterpart of the 3.0–4.4 °C instantaneous reductions

measured under sunny conditions in [32], and the warm outer pane of tinted absorptive states noted in test-cell experiments [24] is the mechanism behind the higher OUT temperatures of DB-EC and EC in Table 4. The small effect of EC glazing on zone-averaged PPD found in a large sensitivity analysis [35] does not contradict these results, because the benefit quantified here is spatial and vanishes when comfort is averaged over the zone. Outdoors, the 0.5 °C mean UTCI increase of an absorptive façade complements the evidence on reflective glazed façades, whose specular reflections can double the irradiance at pedestrian level [41] and raise UTCI in urban canyons [42]. Read against the assessment criteria proposed for reflected sunlight [68], absorption and reflection shift the pedestrian penalty between the longwave and the shortwave channel. In the present case the longwave penalty stays below one tenth of a UTCI stress category.

This UTCI-level neutrality refers, however, to the transect average. Within 0.5 m of the façade, where the view factor of a pedestrian toward the glazing approaches 0.4–0.5, the peak outer-glazing temperatures of the electrochromic options (annual daytime peaks of 75–83 °C in the sunniest conditions, against roughly 40–60 °C for the static references) can raise the local mean radiant temperature by roughly 10–15 °C relative to a static façade during peak hours. This implies a transient local discomfort, and a surface-contact consideration under EN ISO 13732-1, that the transect-averaged UTCI does not capture.

Thermal parity between the two electrochromic technologies should not be read as an absence of benefit from spectral selectivity, because the advantage of the dual-band device lies on channels that the comfort metrics adopted here do not resolve. For the same two technologies operated with the same rule-based control, [18] reported an additional 6–17% saving in total delivered energy for heating, cooling and lighting relative to the single-band EC, with lighting-energy savings of 19–82% depending on climate and orientation. Selecting a dual-band over a single-band device is consequently a decision driven by energy use and daylight provision, not by thermal comfort, for which the two are interchangeable under the control logic considered.

5. Conclusions

This study delivered a coupled assessment of indoor and outdoor thermal comfort impacts of a spectrally selective DB-EC glazing, benchmarked against a commercial single-band EC and three advanced static references (Low-E, SEL40–22, SEL60–33) across five European climates and two orientations.

The main findings are the following.

- Self-heating of the device is absorptance-driven and state-dependent: in the climatic chamber (60 × 80 cm² prototype, horizontal, 25 °C and 40% RH, metal halide solar simulator, 450–850 W m⁻²) the Dark state stabilised between about 56 °C at 450 W m⁻² and 75 °C at 850 W m⁻², with a Dark-to-Clear slope ratio of about 2.3, and EnergyPlus reproduced the same ordering and near-linear irradiance dependence.
- Near-façade overheating is strongly reduced by dynamic operation: at 0.5 m in Sevilla South, overheating Discomfort Degree Hours fell from nearly 10,000 °C·h with Low-E to the low thousands with either electrochromic option, and warm-wall radiant-asymmetry exceedances from 27.1% to 4.3% (DB-EC) and 2.8% (EC) of occupied hours.
- The balance reverses on the cold side in heating-dominated climates: in Helsinki South the electrochromics reduce the warm IDS component to about 1.1, against 3.3 for Low-E, but deepen the cold one to about -3.3 (DB-EC) and -3.6 (EC), against -2.5 in the adiabatic configuration; the penalty keeps its sign when the internal surfaces are coupled to conditioned neighbours, with a magnitude that follows their temperature (Supplementary Table S2).
- DB-EC and the single-band EC are almost indistinguishable on every indoor metric and in every climate, confirming that active solar modulation, not spectral selectivity, drives the near-façade comfort

benefit; the distinctive value of selectivity lies on the energy and daylight channel: a 4–14 percentage-point reduction in UDI-fs, consistent with the energy advantage reported under the same control in [18].

- The outdoor penalty is real but inconsequential: outer-surface peaks of 75–83 °C, against roughly 40–60 °C for the static references, raise LW-MRT within 0.5–1.5 m of the façade, yet pedestrian UTCI within 2.5 m rises by only 0.5 °C on average and 2.5 °C at most, less than one tenth of the narrowest stress category.

Future work should extend the framework to full-year outdoor simulations with microclimate or CFD coupling (e.g. ENVI-met) to capture convective feedback from heated façades and should explore advanced control strategies such as model predictive control to assess whether DB-EC spectral selectivity yields larger differentiation from standard EC under comfort- and energy-oriented multi-objective optimisation, should explicitly address glare through ray-traced luminance simulations, and should validate the indoor workflow against measurements in a full-scale test room.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Claude (Anthropic) to support the re-analysis of the simulation outputs and the drafting and editing of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Mirco Riganti: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Fabio Favoino:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation. **Francesco Isaia:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Michele Manca:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Aleix Alva:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mirco Riganti reports financial support was provided by European Commission. Michele Manca has patent #Thermo-Responsive Dual Band Electrochromic Device, US 12,117,708 B2 issued to Acondicionamiento Tarrasense (Leitat Technological Center). Fabio Favoino serves as a Young Editorial Board member of Building and Environment. Given his role as Young Editorial Board member, he had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. - F.F. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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