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Energy saving potential of advanced dual-band electrochromic smart windows for office integration

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ABSTRACT

Integrating dynamic transparent technologies into building envelopes is becoming crucial for tackling the challenges posed by climate change, improving energy efficiency, and enhancing occupant comfort. Nowadays, a range of dynamic glazing technologies exists, among which electrochromic glazing is notably effective in contributing to sustainability objectives in building design. This paper presents a comprehensive simulation analysis of the energy efficiency and interior comfort impacts of a novel class of spectrally selective dual-band electrochromic windows, also referred to as "Plasmochromic". A simplified office model, oriented both south and west, was used to compare the performance of dual-band electrochromic glazing, using experimental data collected from a window-scale prototype, with that of commercially available advanced glazing systems. The comparison was conducted under two different control strategies: a rule-based and a model-based control algorithm. Five European climate zones have been considered to cover most of the continent's climatic conditions and provide a comprehensive evaluation of the glazing performances. The simulations demonstrate the superior capability of dual-band electrochromic windows, when coupled with an intelligent control strategy, in reducing total annual energy consumption for heating, cooling, and lighting by up to 27% compared to the best-performing static solar control glazing systems. Additionally, they achieve a reduction of up to 32% in visual discomfort, measured by the cumulative value of useful daylight illuminance.

1. Introduction

The building sector accounts for over one-third of global energy consumption and approximately 26 % of global energy-related emissions, with 8 % being direct emissions from buildings and 18 % being indirect emissions from the production of electricity and heat used in buildings. These numbers pertain to the energy consumption associated with constructing, heating, cooling, and lighting homes and non-residential buildings, as well as the appliances and equipment installed in them [1].

Efficient building design and the integration of highly insulating materials and components are currently the most effective methods to reduce the thermal needs of buildings and ensure occupants' thermal comfort. In particular, the adoption of well-designed building envelopes is particularly important, given their long lifetime and the associated cost of the envelope. Windows are typically the primary source of non-controlled heat transfer as solar gains play a non-negligible role in the energy balance of the built environment: in summer they often result in overheating (and in the consequent need of larger cooling loads), while in winter they became a relevant cause of thermal losses.

The evolution of construction materials, façade systems and components over the past twenty years has led the façade sector towards the desire to convert the building envelope into an adaptative skin [2]. This is fostering the adoption of a variety of advanced smart glazing technologies [3], as viable substitutes for traditional high-performance static glazing systems [4]. Smart window technologies are generally distinguished between passive and active [5]. Passive glazing systems are those glazing types that automatically change their optical state due to a phase change in the smart material caused by variations of external boundary conditions (i.e., temperature or solar radiation). Well-known examples of passive smart glazing solutions are those based on thermochromic [6,7], thermotropic or photochromic [8].

On the other hand, active smart glazing systems can be controlled to transition to one of their tint states through an external signal, using commonly an electrical current or a voltage differential. This allows

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Nomenclature

EC	Electrochromic
DB-EC	Dual Band Electrochromic
CDD	Cooling Degree Days
COP	Coefficient of Performance
DGU	Double Glazed Unit
GA	Genetic Algorithm
GHI	Global Horizontal Irradiance
HDD	Heating Degree Days
IGU	Insulated Glazing Unit
ITO	Indium Tin Oxide
LC	Liquid Christals
LED	Light Emitting Diode
MBC	Model-Based Control
MPC	Model Predictive Control
NIR	Near-Infrared
PVB	Polyvinyl Butyral
RBC	Rule-Based Control
SCI	Solar Cover Index
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
UDI	Useful Daylight Illuminance
VIS	Visible
WWR	Window-to-Wall Ratio
AI	Artificial Intelligence
BEMS	Building Energy Management System
VCC	Visual Control Criteria

them to be programmed and adapted to various contexts and needs. Electrochromic (EC) [9] and Liquid Crystals (LC) [10] are the most commonly adopted active smart glazing technologies. They make it possible to modulate the optical properties (i.e. transmission, absorption, or reflection) of the window to assume different tint states including clear (i.e., transparent) and dark (i.e., coloured) appearance, so as to regulate the overall visible and total solar transmission reversibly [11]. Several papers reviewing the current state of advanced window technologies, including EC and other dynamic glazings, have been published recently [12–14]. The effectiveness of these systems in reducing energy consumption has been demonstrated in various types of buildings across different geographic locations [15]. However, the results have not been consistently conclusive, often depending on the type of static glazing used as a benchmark (typically not high-performance selective glazing) and the control logic employed.

The energy and occupant comfort benefits of EC glazing have been investigated extensively. They have been the objective of several simulation and experimental studies [16]. Findings suggest that when deployed with appropriate controls, they can be highly effective at reducing peak cooling loads, and in modulating daylight to capture electric lighting savings while still reducing glare. A simulation of U.S. commercial buildings indicates that deploying smart EC windows in perimeter zones can achieve primary energy savings of 10 %-20 % [17]. Simulations of EC glazings in Mediterranean climates demonstrate savings as high as 37 kWh/m^2 of glass for east and west-facing facades [18], and annual energy savings as high as 54 % [19]. Another simulation study found dynamic glazings applied to a split-pane window produced lighting savings of 37 %-48 % versus static windows with occupant-controlled blinds [20]. Dynamic glazings have been simulated or experimentally evaluated in a number of additional studies [21–28], many of which suggest variable but positive energy impacts of EC deployment.

These results highlight that the benefits of smart glazing largely depend on the control strategies adopted, whether these are focused on improving energy efficiency and/or visual comfort, in addition to the intrinsic features of the glazing system as well as optical contrast and thermal insulation. A large variety of smart window control strategies are reported in the technical literature. Most of them can be grouped into two main categories, namely:

1. Rule-Based Controls (RBC) strategies, including scheduling specific tint settings during a predefined period and/or defining a predefined set of rules mapping glazing states to the variation of internal variables (i.e. occupation, indoor temperature, work-plane illuminance, vertical eye-level illuminance etc.), and/or external variables (i.e. incident solar radiation on the façade, cloud-cover, external temperature etc.) [9].
2. Optimized control strategies, using sets of objective functions and constraints to determine tint settings through optimization techniques such as Genetic algorithms (GA) [30] and Model Predictive Controls (MPC) [31]. Usually building energy use or energy loads are considered as an objective function to minimize, constrained by comfort objectives (i.e. visual comfort ones, such as a higher probability of glare risk).

Recent studies have focused on comparing the performance of these control strategies under different climatic conditions and building configurations. Favoino et al. conducted a detailed simulation-based analysis that compared the energy and glare performance of several RBCs and optimised controls including MPCs strategies when applied to smart EC windows for an office space located in three cities with different climates, namely London, Rome, and Sydney [29]. Predictive controls are demonstrated to perform better than the reactive RBC for the three climates considered in the analysis. Nevertheless, the use of smart glazing does not always lead to higher energy efficiency than in the case of static glazing, especially with non-optimized controls [24]. This is also due to the fact that currently available EC systems present an intrinsic limitation. They employ thin films of transition metal oxides as active materials, which are typically grown through costly physical vapour processes [32]. This limitation, together with the relatively high cost, still represents the major obstacle to the widespread uptake of this technology in the windows market [33].

Ideally, a smart dynamic window, universally applicable across building types and climate zones, should be able to independently control the visible (VIS) transmittance and solar heat flow [34]. It is to say, that independent control over the VIS and near-infrared (NIR) regions of the solar spectrum is a key target for the development of advanced dynamically switchable windows and would contribute to optimum energy efficiency across a building's heating, cooling, and artificial lighting systems. In recent years new EC material and stack design allowed to achieve NIR transmission modulation only, without impacting significantly the visible transmission, exploiting plasmonic nanocrystals [34]. Unlike traditional EC materials (that primarily modulate visible light), plasmonic nanocrystals offer a unique opportunity to selectively control NIR transmission without affecting visible transparency [35]. We recently contributed to the implementation of plasmonic-based EC devices, thereafter, referred to as Dual Band EC (DB-EC) systems, as they are capable of selectively controlling the incoming solar radiation in the NIR range in response to variable operative conditions, either external or internal [34]. They can in principle allow building users to dynamically filter out the amount of thermal radiation passing through the window by means of blocking the solar heat gain during hot summer days and to allow radiation heating in winter conditions. In addition, they also permit to continuously regulate the level of visible transmittance as "traditional" EC windows. A pivotal issue in view of a viable industrialization of this technology consists in the implementation of an "easily-up-scalable" manufacturing process based on roll-to-roll printing techniques as well as on the use of free-standing ion conductive laminable electrolytes. In general, the optimization of the device architecture and the fabrication procedure of "Plasmochromic" modules in large areas are still major challenges [34].

In this work, we fabricated and tested a 45x55 cm^2 DB-EC window demonstrator, using the measured optical data to conduct an accurate simulation study aimed at evaluating its energy and visual comfort performance at the building scale. The performances of the DB-EC window have been compared with those of a set of commercially available advanced glazing systems, including a top-performing commercial EC glazing system, a low-emissivity (low-E) product, and two advanced static solar control systems used as benchmarks. Simulations have been run out in EnergyPlus® [36] to quantify the energy consumption and daylight illuminance levels in an enclosed office room with two different sun-orientated configurations (south and west) under five different climatic conditions (Sevilla, Barcelona, Turin, Berlin and Helsinki), which were selected to provide coverage of the main European climates, from south to north and west to east. In particular, the total amount of electrical heating, cooling, and lighting delivered to the office has been considered one of the most relevant key performance indicators (KPIs). In addition, indoor horizontal illuminance data have been also analysed to calculate the cumulative values of Useful Daylight Illuminance (UDI). Two different control strategies have been implemented (RBC and MBC) to optimize the performances of the smart switchable IGUs considering the influence of occupancy, internal loads and climatic boundary conditions.

2. Methodology

2.1. Manufacturing and properties of DB-EC modules

Several DB-EC device modules with an active area of 45x55 cm^2 have been fabricated as part of a collaborative project funded by the European Commission, aimed at developing industrialized, energy-efficient envelope technologies [37]. Fig. 1(c, d) provides representative pictures of a DB-EC demonstrator. The DB-EC module comprises a sandwich of two ITO-coated glass plates (each 1.1 mm thick) respectively covered by a layer of WOx and a layer of CeOx/TiO2 nanoparticles, separated by a PVB-based ion-conductive membrane [38]. The manufacturing sequence involves several crucial steps: (i) serigraphy-based ink deposition, (ii) thermal sintering, (iii) gel electrolyte deposition, and (iv) electrolyte lamination.

The optical and thermal properties of these modules have been exhaustively characterized and their key performance indicators, such as T_{VIS}, T_{SOL}, R_{VIS} and R_{SOL} calculated across various operating states. They have been used as entering data to build up realistic DB-EC Insulated Glass Unit (IGU) models. Transmittance and reflectance spectra of the DB-EC module have been measured by using a Cary 5000 spectrophotometer and used for deriving the values of T_{VIS} and T_{SOL} of the optical states adopted for the simulations. They are reported in Fig. 1 (1.

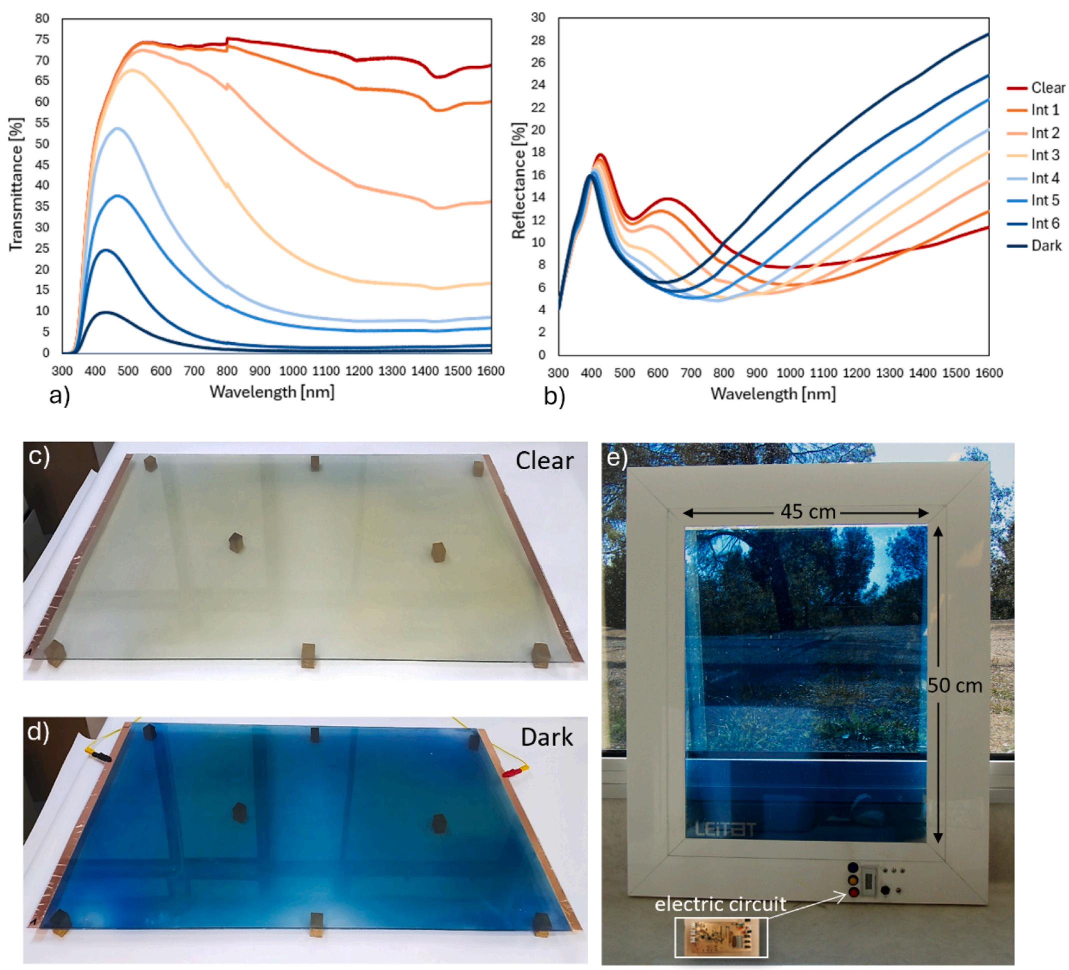

Fig. 1. A) transmittance and b) reflectance spectra (in the range from 300 nm to 1600 nm) of a DB-EC module at eight different applied potentials corresponding to the eight optical states selected for the analysis presented in this study. c), d) Pictures of a 45x50 cm^2 DB-EC prototype module, while the schematic drawing illustrates the demonstrator with an ad-hoc implemented control circuit [38].

a, 1.b).

The prototype was modelled as a single laminate whose key parameters, such as total visible transmittance (T_{VIS}), and solar transmittance (T_{SOL}), have been determined by OPTICS software [39] and are reported in Table 1.

The DB-EC device has been designed and modelled to adopt 8 different electrochromic states, each achieved by applying a different electric potential to the device (Table 1).

2.2. Simulation-based virtual experiment

This study adheres to the methodology for the comparative analysis of innovative building envelope components outlined by Loonen et al. [40] and Favoino [41], who delineated the fundamental stages for simulation-based support in the product development of dynamic building technologies. The subsequent sections detail the stages as follows: i) properties of smart glazing and benchmark technologies; ii) test case models and simulative workflow; iii) climatic conditions; iv) Key Performance Indicators (KPIs); v) control strategies.

The integration of the DB-EC laminate into a properly designed Double-Glazed Unit (DGU) includes the choice of the glass panes (we opted for a 4.8 mm low iron glass) of the PVB interlayer (we opted for extra care for a 1 mm double layer of PVB), of the low-E coatings (we assumed an emissivity on side 3 of 0.04) and the cavity gas (we assumed a cavity filled with 90 % of Argon and 10 % air). The overall thickness of the DB-EC DGU is 31 mm. The values of $T_{VIS,}$ T_{SOL}, SHGC and U-value of the DB-EC DGU for the selected 8 states are summarised in Table 2.

Energy and daylight performances of the DB-EC DGU have been simulated against four different window typologies of top-performing commercial benchmarks, all modelled by WINDOW 7.8 [42] in compliance with the specifications defined by ISO EN 410 [43] and ISO EN 673 [44].

The selected benchmarks are:

1. an EC DGU based on one of the most advanced EC technologies available on the market. It is designed to optimize indoor daylight by reducing solar heat gain and minimizing glare while maximizing the entry of natural light;
2. a spectrally selective DGU SEL 40/22, with a lower SHGC typically adopted in office buildings cooling dominated locations climates and regions with high sun exposure, as it can maintain pleasant indoor temperatures without significantly reducing natural lighting;
3. a spectrally selective DGU SEL 60/33, with higher visible transmission and SHGC typically adopted in office buildings in more temperate climates where heating and cooling loads are more balanced and where daylight is highly desirable;
4. a Low-E DGU, with a very high T_{VIS} and SHGC, which is typically adopted in more heating-dominated climates.

All the considered DGUs present the same overall thermal transmittance (1.2 W/m^2), allowing for direct comparison and evaluation of the optical impact of each IGU. Their main constructive and technical features are summarised in Table 2 and Fig. 2.

For a clearer comparative analysis of the optical capabilities of each technology mentioned, Fig. 3 displays their T_{VIS} versus SHGC. The image also includes the physical limit line, beyond which it is not physically possible for an IGU to exceed, since the maximum theoretical ratio between Tvis and SHGC, called "spectral selectivity", is 2.41. This occurs when only the visible spectrum is transmitted into the building [2].

From the plot in Fig. 3, the DB-EC technology appears to outperform the other benchmarks, as it covers a wider spectrum of SHGC and T_{VIS}. Although the EC technology is capable of achieving states with lower visible transmittance which can be very useful for reducing excessive light conditions and potentially to reduce further cooling loads.

Table 1
DB-EC Laminate layer optical properties.

State	Potential [V]	T_{SOL} [-]	T_{VIS} [-]	R_{SOL} [-]	R_{vis} [-]
Clear	+0.5	0.70	0.85	0.08	0.10
Int 1	+0.1	0.56	0.83	0.07	0.09
Int 2	−0.2	0.44	0.80	0.06	0.08
Int 3	−0.5	0.31	0.73	0.05	0.06
Int 4	−2.0	0.16	0.47	0.04	0.05
Int 5	−2.4	0.10	0.30	0.04	0.05
Int 6	−2.6	0.06	0.18	0.04	0.05
Dark	−2.9	0.03	0.06	0.04	0.04

2.3. Office model and simulative workflow

The virtual test case building adopted in this work is an office room 3 m wide x 5 m deep x 3 m high, with a window-to-wall ratio (WWR) of approximately 50 % on the sun-oriented façade, which is shown in Fig. 4. The benchmark case test room adopts a building envelope with thermo-optical properties complying with the minimum requirements of national regulations.

For this study, two different simulation models are built to evaluate the performance of the different smart and static glazing: a thermal model, and a daylight one, with identical characteristics, to integrate workplane illuminance results for different EC states within the thermal model, considering complex control strategies. EnergyPlus version 22.2 was used for the thermal model and to perform the energy simulations [36]. Since the purpose of this paper is to evaluate the energy performance of the newly developed DB-EC, prior to the integration of occupant comfort evaluation (visual and thermal comfort), no co-simulation strategy with raytracing software is considered at this stage to account for illuminance and luminance values within the indoor space. Nevertheless, to consider appropriately the impact of control strategies considering also daylight on building energy use, a specific daylight data integration strategy was adopted considering pre-simulated horizontal illuminance values at desk levels in two selected reference points (at desk level, 0.8 m high, at 1.67 m, for RP1, and at 3.33 m, for RP2, far from the sun-exposed façade). The indoor horizontal illuminance data corresponding to the different states of the EC glazing (both DB-EC and EC) and of the static glazing, evaluated using the Daylight module of EnergyPlus, are then integrated by means of the PythonPlugin of EnergyPlus within the control strategies described in Section 2.5, to dim the lighting power density and to calculate electrical energy use due to artificial lighting primarily, but also to preliminarily evaluate potential visual comfort differences between the different glazing. The DB-EC glazing controls, described in the next sections, as well as the data integration of the pre-simulated illuminance results with the artificial light dimming and with the control of the EC glazings, are carried out by means of the EnergyPlus PythonPlugin. The simulation algorithms in EnergyPlus have been chosen to achieve a balance between accuracy and a reasonable computational time of a single simulation run (solar calculations 15 days, conduction transfer function method with a 15-minute time step, adaptive convection algorithm, initialization period 25 days).

The opaque walls of the office model comprise four main layers: an exterior and interior plaster layer each 0.15 cm thick, a 12 cm thick insulation layer with low thermal conductivity, and a 20 cm thick concrete layer for structural strength and thermal mass. The U-value of the entire wall is approximately 0.264 W/m^{2}K. All walls of the test office room, except for the one with the window facing the sun, have been set as adiabatic. This setup isolates the room thermally from adjacent spaces, ensuring that only heat transfer occurs through the sun-exposed window.

Indoor comfort is considered a requirement of the indoor space which is always met by the building services: indoor temperature has fixed set-points for heating and cooling (20 °C and 26 °C respectively); primary air ventilation rate is set to 1.4 l/sm^2; threshold of 300 lx is considered for the minimum illumination level, as suggested by

Table 2
Main Optical and thermal properties of the modelled DGUs considered for this study.

DGU		Layout	T_{VIS} [-]	T_{SOL} [-]	SHGC [-]	U-value [W/m^{2}K]
DB-EC	Clear	DB-EC laminate, 9.8 mm/ Argon 90 %, Air 10 %, 16 mm/ Clear Glass + Low-E 0.04, 4.8 mm.	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	
	Dark		0.06	0.02	0.17	
EC	Clear	EC laminate [IGDB: 61166–61173], 14 mm/ Argon 90 % Air 10 % 16 mm/ Clear Glass + Low-E 0.04, 4.8 mm.	0.61	0.29	0.39	1.2
	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	
	Int 6		0.09	0.03	0.17	
	Dark		0.02	0.01	0.15	
SEL 40/22		Clear glass with Double silver selective coating 40/22, 5.8 mm/ Argon 90 % Air 10 %, 16 mm/ Planibel clear, 5.8 mm.	0.40	0.16	0.22	1.2
SEL 60/33		Clear glass with Double silver selective coating 60/33, 5.8 mm/ Argon 90 %, Air 10 %, 16 mm/ Planibel clear, 5.8 mm.	0.60	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	0.60	1.2

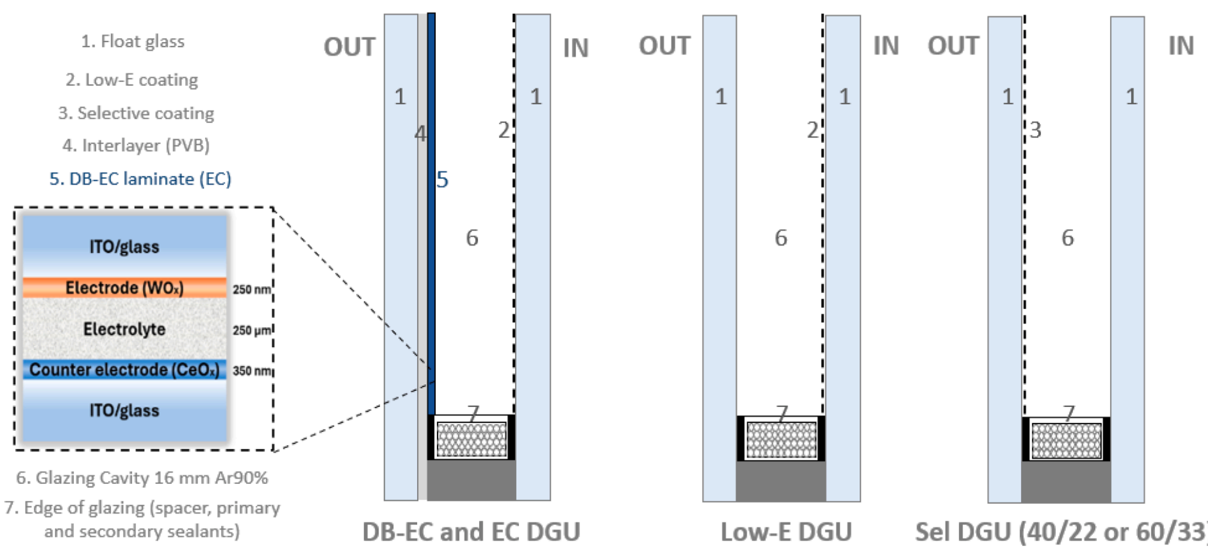

Fig. 2. Build-up of the different DGU compared (from left to right): the Dual Band Electrochromic (DB-EC) and the Electrochromic (EC) Double Glaizng Unit (DGU), with the build-up of the DB-EC laminate: the DGU with the low emissivity coating (Low-E DGU): the DGU with the selective coatings (SEL DGU), either 40/22 or 60/33.

Mardaljevic et al. [45], to be maintained by a combination of daylight and adaptive dimmable artificial lighting system [46]. Schedules and peak loads for the building services, lighting, equipment and occupation are defined according to the ASHRAE standard 90.1 [47]. The lighting power density is set to 12 W/m^2, the equipment power density is 13.5 W/m^2, and the room is occupied by 2 people, all following pre-established schedules [47]. The office room model is configured to accommodate a maximum of 3 persons from 7 AM to 6 PM, reflecting a typical office occupancy profile. A reversible heat pump is considered to provide heating and cooling to the office building, with an average seasonal COP of 2.5 for the winter and a Seasonal Energy Efficiency Ratio of 3.5 for the summer, as for similar studies [29,48,49]. Given that all energy uses (heating, cooling and lighting), no conversion to primary energy is done, and the site building energy is considered as a performance indicator, as described in Section 2.5, so not to introduce local national consideration as far as the primary energy factors are concerned.

2.4. Climate zones

Various European climates are analysed to provide a comprehensive evaluation of the performance of Dual-Band EC technology in common temperate climate scenarios and to compare it with the best-performing benchmarks. The Heating Degree and Cooling Degree days are shown for the five European locations in Table 3 and Fig. 5, according to the baseline of 10°C and 18°C respectively [50]. Table 3 enumerates the latitudes, the Heating Degree Days (HDD-10), Cooling Degree Days (CDD-18), Global Horizontal Irradiance (GHI), maximum (T Max), minimum (T Min), average temperatures (T Avr), and Average Solar Cover Index (SCI Avr) for each city considered in the study.

The selected locations represent diverse climatic conditions across Europe, forming the basis for comprehensive energy simulations and providing a broad spectrum of environmental scenarios. Annual simulations were conducted for each of these five locations, with the model oriented towards both the South and the West, allowing for an assessment of the impact of orientation on the control capabilities of smart

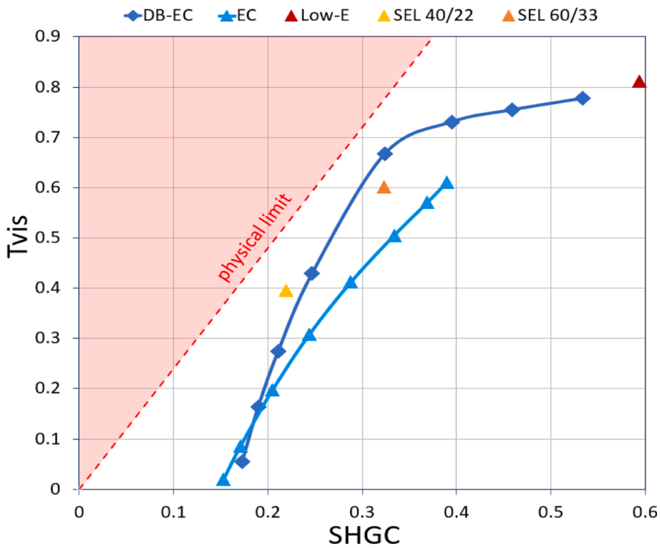

Fig. 3. Relationship between the Visible Transmittance (T_{VIS}) and the Solar Heat Gain Coefficient (SHGC) of the electrochromic technologies and the Static Benchmarks.

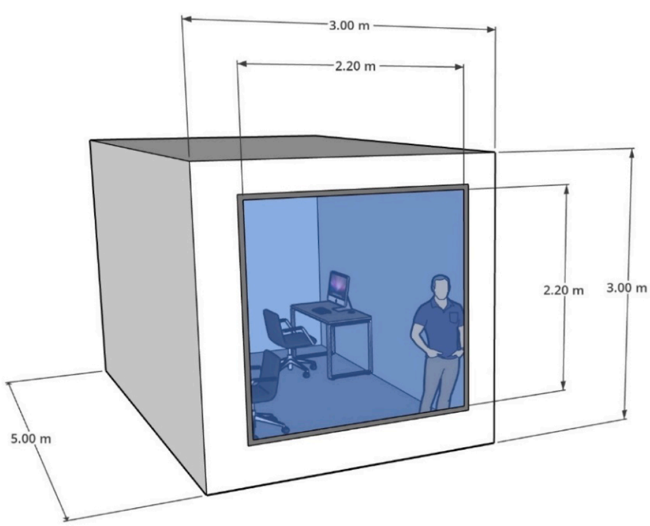

Fig. 4. 3D view of the office model.

windows compared to static technologies. This selection of different location aimed to capture a wide range of climatic conditions across Europe from predominantly cooling requirements and lower latitudes to more balanced heating and cooling requirements, to predominantly heating requirements and higher latitudes. In fact, Berlin and Helsinki represent colder regions with shorter daylight hours during winter; Seville represents a hotter climate with abundant sunlight; while Barcelona and Turin offer more moderate climates, providing a balanced reference point. This approach ensures a comprehensive evaluation of the adaptability and effectiveness DB-EC windows across a spectrum of challenging and typical environmental conditions, from extreme cold or hot to more temperate settings. Moreover, it is expected that the DB-EC could offer also energy-saving advantages in colder climates (i.e. Berlin and Helsinki), differently from a traditional EC, provided its capability to modulate g-value at higher T_{vis} (cf. Fig. 3).

2.5. Smart windows control strategies

The total amount of electrical heating, cooling, and lighting delivered to the office environment throughout the simulated year has been considered as one of the most relevant key performance indicators (KPIs). The formula used to calculate the building-delivered energy (DE) (electrical lighting, heating, and cooling) is:

$$DE = Lighting\,Consumption + \frac{Heating\,Energy\,Need}{\eta_{h,sub} \bullet COP} + \frac{Cooling\,Energy\,Need}{\eta_{c,sub} \bullet SEER}$$

In this formula, COP = 2.5 and SEER = 3.5 represent typical performance coefficients for modern heat pumps and air conditioning systems, respectively. The values $\eta_{h,sub} = \eta_{c,sub} = 0.9$ reflects the global efficiency of the technical sub-system for heating and cooling, excluding the generation. In addition, indoor horizontal illuminance data have been also analysed to calculate the cumulative values of UDI_fs (Useful Daylight Illuminance falling short) and UDI_ex (Useful Daylight Illuminance for excessive light) during all occupied hours over a simulated year in the considered two reference points (RP1 and RP2) inside of the office [45].

Regarding the artificial lighting system, LED dimmable lighting is considered, with continuous dimming between 100 and 300 lx.

The DB-EC glazing controls, described in the next sections, as well as the data integration of the pre-simulated illuminance results with the artificial light dimming and with the control of the EC glazings, are carried out by means of the EnergyPlus PythonPlugin [51].

The key prescriptions to include in the control algorithms are described as follows in order of priority:

1. in the presence of the occupants and with non-overcast sky conditions, to guarantee satisfactory visual comfort in the office by keeping the indoor work plane horizontal Illuminance between 300 lx and 3000 lx, to minimise energy use for lighting while reducing glare risk [45];
2. maximise solar gains in heating conditions (i.e. indoor air temperature equal to the heating set-point temperature) by maintaining the highest possible glazing SHGC, without hindering visual comfort objectives in the presence of the occupants;
3. minimise solar gains in cooling conditions (i.e. indoor air temperature equal to the cooling set-point temperature) by maintaining the lowest possible SHGC which could achieve visual comfort objectives in the presence of the occupants;
4. control solar gains in free-floating conditions (i.e. indoor air temperature between heating and cooling set-points) in the presence of the occupants.

Based on these descriptions two different control strategies have been implemented and evaluated in this work, respectively a rule-based control (RBC) algorithm and a model-based control (MBC) algorithm, detailed in the following sections.

Table 3
Climatic data overview for the selected European cities.

CITY	Latitude [°N]	HDD-10 [K-days]	CDD-18 [K-days]	GHI [kWh/m^2]	T Max [°C]	T Min [°C]	T Avr [°C]	SCI Avr [-]
Sevilla	37.42	59	1024	1842	43	−2	18.4	1.9
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

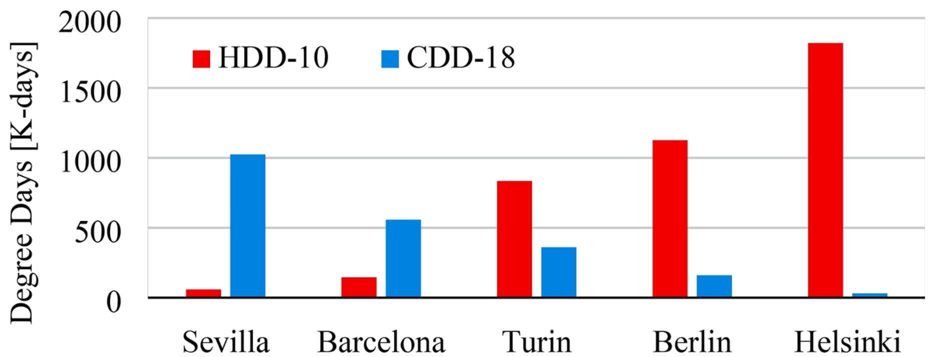

Fig. 5. Heating Degree Days histogram respectively referred to the 10 °C and 18 °C reference temperatures of each location considered in the study.

2.5.1. *Rule-Based control algorithm*

In this case, the principles of energy conservation and occupant comfort are translated into simple if-then rules based on environmental measurements, making them easy to implement in practice. This involves mapping the eight possible tinting states of the EC smart glazing to total incident solar radiation (G) and indoor air temperature (T) when occupants are present, and to indoor air temperature only during non-occupancy hours (see Fig. 6).

2.5.2. *Model-Based control algorithm*

In this case, a two-step approach has been defined to (i) first identify for each time-step of the simulation the glazing tinting states that would pass the Visual Comfort Criteria (VCC) based on simulated work-plane illuminance values in the two reference points (RP1, RP2), when the office is occupied; (ii) then, by mapping the remaining glazing tinting states that meet the VCC when the office is occupied, to the neutral zone between the heating and cooling set-points (20 ÷ 26 °C), and choosing the final state based on the internal temperature at each timestep. For the VCC the work plane illuminance at the reference point closest to the window (RP1) must be maintained below 3000 lx to reduce glare risk in all points of the room, while the one at the reference point farther from the window (RP2) must remain above 300 lx, to ensure minimum artificial light energy use for the whole room [45]. This Model-Based control algorithm (Fig. 7) is based on the perfect knowledge of work-plane illuminances in the two reference points for each time step of the simulation, for all the possible glazing tinting states, which assumes the presence of a model enabling forecasting this for the current control time step. This is representative of an idealistic condition, which is hardly implementable in practice on a real building, representing a performance bound of visual performance for an optimally controlled smart glazing. No prediction over the influence of climatic conditions and entering solar gains on the room energy balance for time steps after the current control time step (Receding Horizon Control, [29]).

3. Results

The results are herewith presented by (i) first discussing the impact on the energy use of the DB-EC technology, compared to the benchmark products, on typical days in winter, summer and shoulder season; (ii) secondly by presenting year-long energy use performance of the

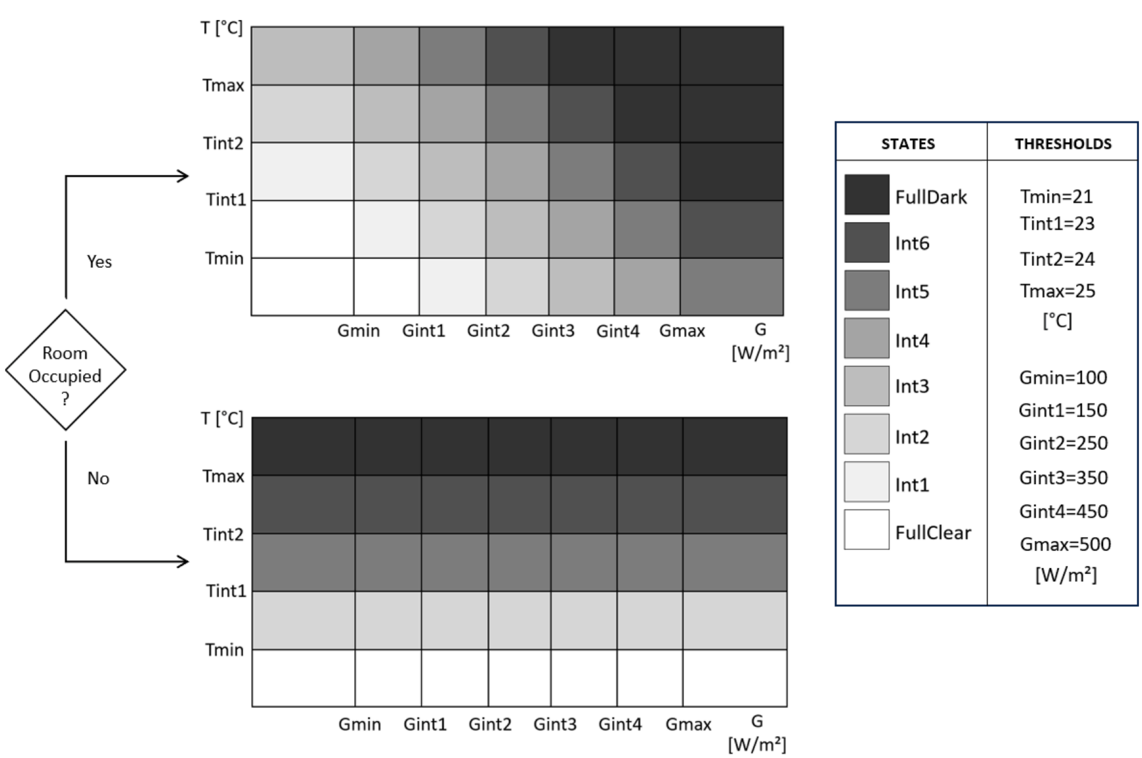

Fig. 6. Diagram refpresenting the logic of the RBC algorithm controlling the electrochromic windows in the study. To the right, the legend includes the names corresponding to the eight tinting states, as well as the internal temperature (T) and incident irradiance on the window (G) thresholds.

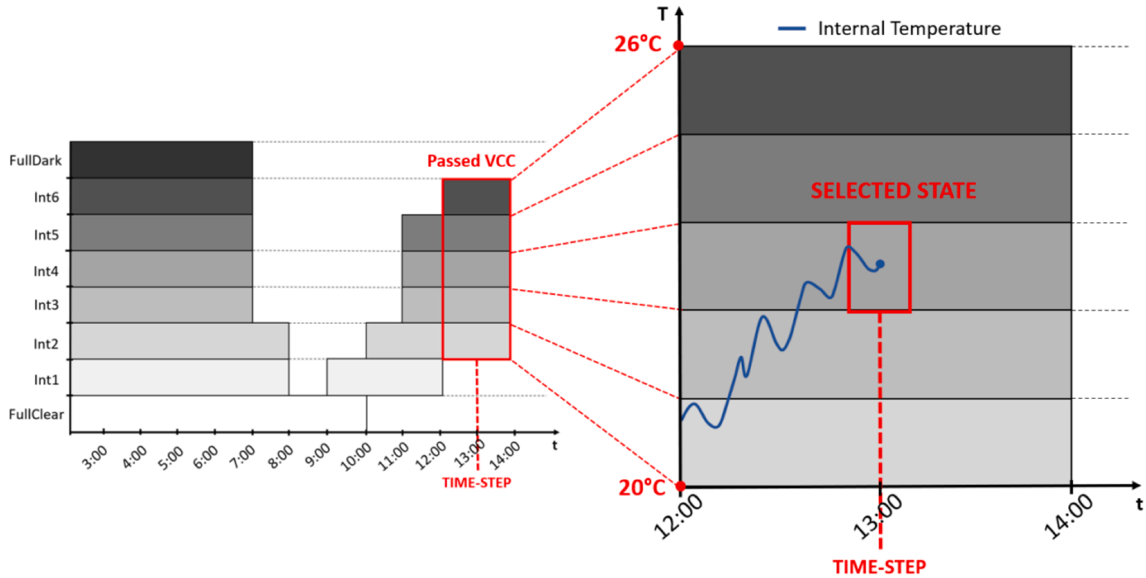

Fig. 7. Diagram depicting the workflow logic of the MBC Algorithm used to control the electrochromic windows in the study. It operates in two steps: (i) it selects glazing tints that meet Visual Comfort Criteria (VCC) by ensuring work-plane illuminance stays below 3000 lx near windows (RP1) and above 300 lx further away (RP2) to minimize glare and artificial lighting use; (ii) it maps these tints to the thermal set-points dead-band (20–26 °C) and then selects the final state according to the internal temperature at each timestep.

different glazing performances; (iii) finally by calculating the energy saving ratio of the DB-EC and EC IGU compared to the best static IGU alternative for each climate condition. All the results are available in graphical and tabular form within the paper and for some of them as additional material.

3.1. Representative days and smart glazing control

Prior to discussing the annual results Fig. 8 shows two representative days with clear sky (winter, left part of Fig. 8, and summer, right part) the boundary conditions (Fig. 8a), the states assumed by the rule-based and model-based control (Fig. 8b and c respectively) and the differences in energy uses (Fig. 8d) between the DB-EC and EC glazing (continuous line), and between the DB-EC and the best static glazing solution (dotted line), for different control strategies, in a representative case. The south-oriented office in Barcelona was selected as the case model for the typical days analysis because this climate and orientation offer a balanced scenario between heating and cooling energy uses compared to other configurations. This setup highlights the differences between the DB-EC, the EC, and the best static glazing options. In this climate, the best static glazing configuration that can be adopted as a benchmark is the SEL 40/22 (DGU with selective coating with $T_{VIS} = 0.40$ and SHGC $= 0.22$).

From Fig. 8b and c it is possible to appreciate the effect of different control strategies on the states that the DB-EC and the EC are assuming for winter and summer typical days. In grey, it is highlighted the area of the graphs in which the DB-EC has a higher selectivity compared to the EC, while in yellow is the area in which the DB-EC is able to achieve higher T_{VIS} and SHGCs compared to the EC. On a typical winter day, the RBC strategy is selecting smart glazing states that have a lower visible transmission (hence SHGC) than the MBC one when higher solar radiation is present, thus implying a higher energy use for lighting during the day, as shown for the DB-EC in Fig. 8d.left (positive values indicate a higher energy use of the DB-EC compared to the SEL 40/22). Nevertheless, on the other side, the higher maximum SHGC and T_{VIS}, as well as the better selectivity, achievable by the DB-EC, show that the lighting energy uses for DB-EC is always lower than traditional EC in all the different parts of the day, especially when lower solar irradiance is present (first and last part of the day) in which the DB-EC can achieve a higher T_{VIS} than EC which is corresponding to when indoor illuminances could be lower in a day with clear sky. On the other hand, the possibility to change dynamically the SHGC compared to the static glazing (SHGC constant at 0.22), thus admitting higher solar-free gains in winter, results in lower energy use for heating in the case of the two smart glazing solutions, with very minor differences between RBC and MBC, but with a significant improvement of the DB-EC compared to the EC (red lines in Fig. 8d), provided to the consistent higher SHGC achievable during day time.

Regarding lighting energy use in the typical summer scenario (Fig. 8d.right), the results confirm the considerations from typical winter days, further emphasizing the selectivity differences of DB-EC and its impact on lighting energy use compared to SEL 40/22 glazing (orange lines) and EC glazing (light yellow lines). Given that in summer much lower SHGCs are chosen by the RBC strategies, due to the high solar irradiances and indoor temperatures, the static glazing has a lower energy use than the DB-EC (positive orange curve in Fig. 8d.right). Nevertheless, DB-EC would increase lighting energy less than traditional EC do, due to their higher selectivity (higher T_{VIS} with similar SHGC). On the other hand, MBC tends to null these differences, prioritising the achievement of minimum workplane illuminance level. As far as cooling energy use is concerned, as expected, there is a significant improvement in the ability to modulate the SHGC well below the 0.22 of the static glazing (dark blue lines in Fig. 8d.right), with notable differences between RBC and MBC. There is also a significant difference in performance between the DB-EC and EC, especially in the second part of the day, when better selectivity (lower SHGCs with similar visible transmission) could play an important role.

These results are useful to better understand and interpret the differences in energy uses (total, but also broken down between heating, cooling and lighting) by comparing the different technologies and control strategies, for the different climatic conditions, analysed in the next section.

3.2. Annual results

Fig. 9 (left side) shows a breakdown of the specific delivered building energy use for heating, cooling and lighting energy of the typical enclosed office room, comparing the different glazing systems (from

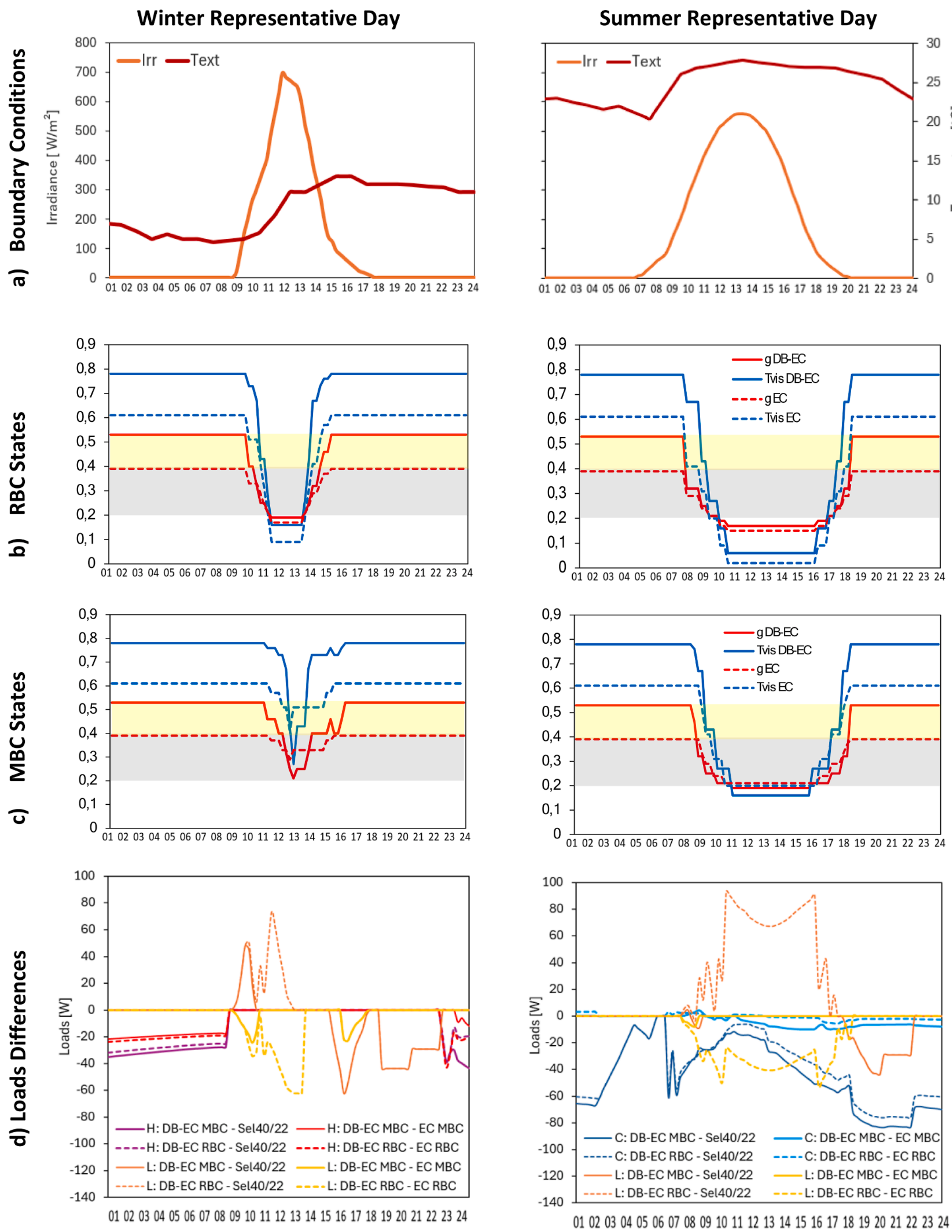

Fig. 8. Example graphs for South office room in Barcelona, for winter (left) and summer (right) representative days, illustrating trends of boundary conditions((a) – External temperature and Vertical Irradiance on the South facade), and the states selected by the RBC (b) and MBC (c) algorithms during these days for comparison, and related differences between DB-EC and EC energy uses (for heating, cooling and lighting) for RBC and MBC (d).

static benchmarks to the DB-EC and EC IGUs), for the different climates under consideration (from lower to higher HDD) in South and West orientation. While on the right side of Fig. 9, the sum of UDI-fs (workplane illuminances lower than 100 lx for RP2, point further from the facade) and UDI-ex (workplane illuminances higher than 3000 lx for RP1, point closer to the facade) is shown, as a proxy for visual discomfort. Moreover, the dashed horizontal lines represent the performance of the static IGU with the lowest energy use, which is also adopted to evaluate energy-saving rates (cf. Table 4). For the sake of comparison, it is fundamental to choose the correct benchmark for considering the energy-saving potential of the DB-EC and EC smart glazing technologies investigated, which is climate-specific. It is evident that by increasing the HDD (climate locations from Seville to Helsinki), and therefore the balance between heating and cooling energy needs, the best static IGU benchmark varies from selective glazing with nearly 40 % T_{VIS} and 20 % SHGC for cooling-dominated climates (Barcelona and Seville), to a selective IGU with 60 % T_{VIS} and 33 % SHGC for more temperate (Turin) and heating dominated climates (Berlin and Helsinki). These are indicated with a grey background in Fig. 9, and their performance is shown by dashed dark horizontal lines. On the other hand, the clearer low-E IGU is never the best performing from an energy-saving point of view, among the static IGU solutions, therefore it would not be a correct benchmark from an energy-saving perspective for solar control smart glazing technologies in office buildings for the climate

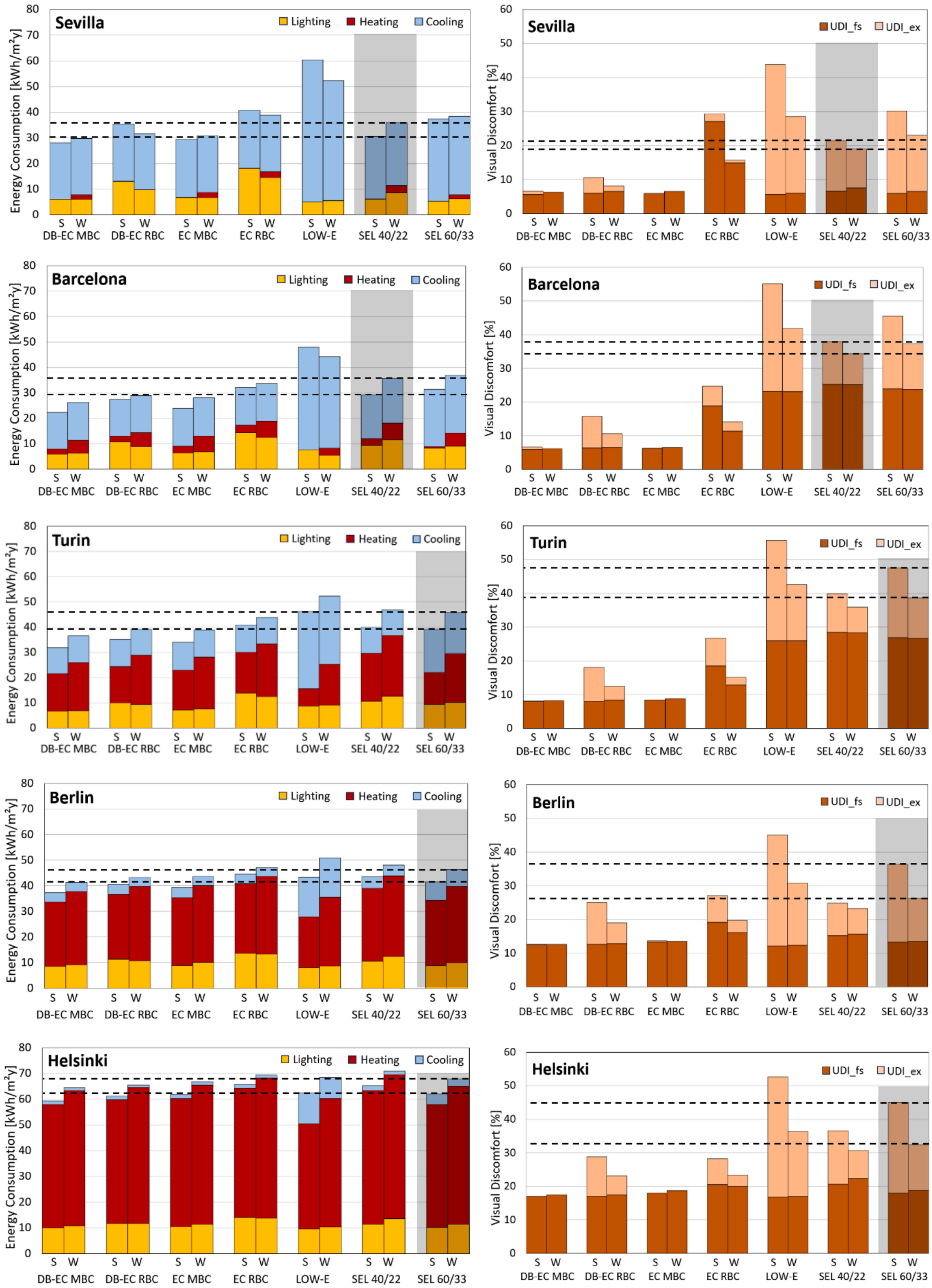

Fig. 9. Left: Yearly delivered specific energy uses for artificial lighting, heating, and cooling for South (S) and West (W) orientations, for MBC and RBC controls, for the five climates considered (Seville, top, to Helsinki, bottom). Right: Visual Discomfort levels are shown, calculated by summing UDI-fs and UDI-ex for the reference point closer to the window (RP1).

under analysis. Moreover, in order to understand better the differences in improvements of DB-EC and EC technologies between them and compared to the best climate-specific static benchmark, Table 3 shows the energy saving percentages (broken up between heating, cooling or lighting, and total), where negative percentages indicate energy use increase, while positive percentages indicate energy savings.

In particular, in Seville, a city characterized by a high amount of CDD and extreme summer temperatures, the total delivered energy use of the

Table 4
Energy Saving. This table compares the performance of active technologies with MBC and RBC algorithms, showing reductions in energy use against top benchmarks for each location and orientation over one year.

Energy Saving Results			**SEVILLA** (SEL 40/22)		**BARCELONA** (SEL 40/22)		**TURIN** (SEL 60/33)		**BERLIN** (SEL 60/33)		**HELSINKI** (SEL 60/33)	
Comparison	**Control**	**Energy need**	**S**	**W**	**S**	**W**	**S**	**W**	**S**	**W**	**S**	**W**
EC – Best Static	**MBC**	LIGHTING	−10 %	22 %	32 %	40 %	23 %	25 %	0 %	−2%	−4%	−1%
		HEATING	−36 %	25 %	−2%	8 %	−25 %	−5%	−4%	−1%	−4%	−1%
		COOLING	7 %	10 %	14 %	14 %	36 %	34 %	46 %	44 %	63 %	60 %
		TOTAL	**4 %**	**14 %**	**18 %**	**22 %**	**13 %**	**15 %**	**5 %**	**5 %**	**0 %**	**2 %**
	RBC	LIGHTING	−195 %	−67 %	−53 %	−8%	−49 %	−24 %	−55 %	−35 %	−37 %	−21 %
		HEATING	−118 %	11 %	−16 %	1 %	−27 %	−8%	−7%	−1%	−5%	−2%
		COOLING	8 %	11 %	15 %	17 %	37 %	36 %	48 %	47 %	66 %	61 %
		TOTAL	**–33 %**	**−8%**	**−10 %**	**6 %**	**−4%**	**4 %**	**−8%**	**−2%**	**−6%**	**−2%**
DB-EC – Best static	**MBC**	LIGHTING	1 %	29 %	37 %	46 %	29 %	32 %	4 %	8 %	1 %	6 %
		HEATING	−18 %	35 %	19 %	21 %	−17 %	2 %	1 %	4 %	0 %	2 %
		COOLING	10 %	11 %	17 %	16 %	39 %	36 %	49 %	46 %	67 %	61 %
		TOTAL	**8 %**	**17 %**	**24 %**	**27 %**	**18 %**	**20 %**	**10 %**	**11 %**	**4 %**	**5 %**
	RBC	LIGHTING	−113 %	−14 %	−14 %	23 %	−6%	7 %	−27 %	−9%	−15 %	−2%
		HEATING	−36 %	26 %	14 %	15 %	−14 %	−1%	0 %	3 %	−1%	1 %
		COOLING	9 %	12 %	16 %	18 %	37 %	37 %	48 %	47 %	66 %	63 %
		TOTAL	**−16 %**	**7 %**	**6 %**	**19 %**	**10 %**	**14 %**	**2 %**	**7 %**	**1 %**	**3 %**
DB-EC – EC	**MBC**	LIGHTING	12 %	7 %	5 %	6 %	5 %	7 %	5 %	9 %	5 %	7 %
		HEATING	18 %	10 %	20 %	13 %	8 %	7 %	5 %	5 %	4 %	3 %
		COOLING	3 %	1 %	3 %	2 %	3 %	1 %	3 %	2 %	4 %	1 %
		TOTAL	**4 %**	**3 %**	**5 %**	**5 %**	**5 %**	**5 %**	**5 %**	**5 %**	**4 %**	**3 %**
	RBC	LIGHTING	82 %	54 %	39 %	31 %	42 %	31 %	28 %	26 %	22 %	19 %
		HEATING	82 %	15 %	30 %	14 %	13 %	7 %	7 %	4 %	5 %	3 %
		COOLING	1 %	1 %	1 %	1 %	1 %	1 %	0 %	0 %	0 %	1 %
		TOTAL	**17 %**	**15 %**	**16 %**	**13 %**	**15 %**	**10 %**	**10 %**	**8 %**	**7 %**	**6 %**

best static glazing solution among the ones considered (i.e. IGU with Selective coating 40/22) is between 30 and 36 kWh/m^2y (respectively for South and West orientation), of which 20–25 % is represented by the lighting energy use, and 80-70′% by cooling energy use, while a very minor contribution is provided by heating (0–7 %). The use of a traditional EC, in this climate, does not directly imply a lower total energy use, as this is strongly affected by the control strategy. For the South orientation, the rule-based control is increasing total energy use by nearly 10 kWh/m^2y, reducing cooling due to the lower SHGCs achieved by the EC, but at the same time increasing significantly lighting energy use (nearly tripling it), provided that glazing states with much lower visible transmission are chosen by this control strategy. The latter is visible from Fig. 9 (Seville, right), as for EC RBC results with higher percentages of time with work desk illuminance lower than 100 lx (UDI-fs), despite the higher visible transmission of the clearest states of the EC glazing compared to the DGU with SEL 40/22 coating. On the other side MBC, which prioritises first the achievement of sufficient indoor workplane daylight levels (without hindering visual discomfort due to too high ones), ensures a minor reduction of total energy use for the South (4 % better, increasing lighting only by 10 % in South orientation), while for West orientation all energy uses are reduced, achieving nearly 5 kWh/m^2y less total energy use (14 % energy saving compared to the best static solution). EC MBC not only does not increase the percentage of time of UDI-fs compared to the best static solution for RP2, but also reduces the UDI-ex for RP1 (percentage of time with workplane illuminances higher than 3000 lx). When Dual-Band EC are integrated, if RBC results are adopted, slightly higher energy uses compared to the best static glazing are achieved, even though this is only 16 % higher, which is due to a lower increase of lighting energy uses (50 % less increase than traditional EC) and 1 % higher energy saving for cooling. On the other hand, UDI-fs are achieved for a much lower percentage of time. These effects are due to the inherently higher visible transmissions and selectivity (T_{VIS} / SHGC) of the DB-EC for higher SHGCs, as visible in Fig. 3. The combination of DB-EC and MBC, results in the lowest delivered energy use for this climate, 28–30 kWh/m^2y for South and West respectively, being respectively 8 and 17 % lower than the best static IGU. This is achieved by the ability of the DB-EC to maintain higher visible transmissions and lower SHGCs at the same time, then the EC and the static glazing, resulting in a reduction of energy for lighting (1–30 % lower for South and West) and for cooling (about 10 % lower for both orientation) at the same time. This is reflected also in an improvement of visual comfort compared to all other competing technologies and control strategies, with less than 6 % of the time with workplane illuminances lower than 100 lx, and only a few instances higher than 3000 lx (only 1 % of the time in South).

The office reference room, either South and West oriented, in the climate of Barcelona, holds the same static benchmark technology of Seville (DGU with SEL 40/22 coating), resulting in similar total delivered energy use (from 29 to 36 kWh/m^2y for South and West), which is divided between nearly 32 % for lighting, 50–60 % cooling and the remainder 8–18 % heating. The higher energy use for lighting is confirmed by a higher percentage of UDI-fs (from 7 % in Seville to 25 % in Barcelona). As for Seville, in Barcelona adopting a traditional EC with rule-based control allows to reduce cooling energy use significantly (15–17 %), inversely affecting heating (16 % more, only for South) and lighting energy use (53–8 % more, for South and West). This is not reflected by a higher amount of time of UDI-fs (Fig. 9, Barcelona, right) but rather with an increase of UDI-s (workplane illuminances between 100 and 300 lx, which requires integration with artificial lighting). Overall these variations could increase the amount of delivered energy use for the EC, if not properly controlled, compared to a dark selective IGU (SEL 40/22 static benchmark). When MBC is adopted for EC technology, a significant reduction in lighting energy use can be achieved (30–40 % lower) without compromising cooling energy saving (in the order to 14 %, slightly lower than RBC), thus resulting in a strong improvement in total energy saving (18 % for South and 22 % for West) and a reduction of visual discomfort (sum of UDI-fs and UDI-ex) below 7 %. When adopting a Dual-Band EC the reduction in total energy use is even higher compared to EC, resulting in 28–29 kWh/m^2y for RBC (for South and West, respectively 6 and 19 % improvement compared to the static solution, and 16–13 % better than EC), and 22–26 kWh/m^2y for MBC (24 and 27 % better than SEL 40/22 and 5 % better than EC). This difference between MBC and RBC is mainly due to a more important reduction of lighting energy uses for DB-EC in MBC, maintaining higher energy saving than EC for cooling energy use (1–3 % higher than EC) and for heating as well (13–30 % heating energy saving compared to EC), which was not visible in the hotter climate of Seville. In the climate of Barcelona, which has outdoor temperature conditions closer to the human thermal comfort range for a higher amount of time, the highest energy savings are achievable with smart glazings, both in terms of EC and DB-EC. The latter though is able to maximise such energy saving, even more in this climate, due to the higher visible transmission achievable both in clear and intermediate states, together with the more selective behaviour (higher ratio between visible transmission and total solar heat gains). Such features of the DB-EC allow to achieve on average higher levels of indoor workplane illuminances throughout the year compared to the EC, with in comparison higher SHGC during the heating and mid-season, and similar SHGC during the cooling one.

In a more continental climate like Turin, a static benchmark with higher SHGC and selective behaviour is the best solution from an energy point of view (SEL 60/33), resulting in an energy use of 40 to 47 kWh/m^2y from South to West, which consists of approximately 26 % energy use for lighting, 25–21 % cooling and the remainder 47–51 % heating (South − West, respectively). From a visual comfort perspective, in this location, there is the highest percentage of time with lower illuminances (UDI-fs) and with too high ones (UDI-ex). As for Barcelona and Seville, when RBC is adopted, smart glazing integration does not automatically imply a lower energy use, as for orientations where lighting energy use and heating energy uses are significant (i.e. South in this case), this control strategy applied to a traditional EC results in a decrease of cooling energy use (36–37 %), which is counterbalanced by an increase in lighting (49–24 % increase) and heating energy uses (27–8 % increase, respectively South − West). As for Barcelona, the lighting energy use increase is due to a higher percentage of time with workplane illuminances between 100 and 300 lx. On the other side, MBC for EC glazing is able to maintain the reduction in cooling energy uses, but with a 24 % average lower lighting energy use as well (visible from Fig. 9, Turin, right, with minimization of UDI-fs). As far as the heating is concerned, even with an MBC, an EC glazing is increasing the amount of energy need for heating (25–5 % increase for South – West orientations, compared to the best static solution). In this climate, the main advantages of adopting a DB-EC (with either RBC and MBC) become more and more visible. The higher level of visible transmission allows to reduce the increase in lighting energy when a smart glazing is adopted with RBC. The higher selectivity and SHGC for the DB-EC, more transparent states compared to the EC glazing (for T_{VIS} of DB-EC higher than 0.20), allows to increase further the energy saving for cooling (from 34-36 % to 37–39 %) and to either (i) reduce the heating energy increase compared to the static solution with higher SHGC in South (14–17 % more heating energy, instead of 25–27 % for EC), or (ii) start realizing heating energy saving where such energy uses are more significant (i.e. West orientation, 2 % energy saving in DB-EC with MBC compared to the best static glazing, differently from EC increase heating energy use by 5–8 %).

For Berlin, and even more for Helsinki (Fig. 9), where heating constitutes more than 60 % of total delivered energy use (and still lighting is within 20–25 %), while cooling is minimized (2–10 %), the results visible for Turin climate (which holds the same static DGU benchmark, SEL 60/33) are confirmed. For EC glazing, provided the milder summer temperatures, cooling energy savings are even higher than the previous climates in relative terms compared to the static benchmark (45–67 % cooling energy saving). On the other side lighting energy is strongly increased for RBCs and almost constant for model-based controls, while heating energy use is slightly increased for RBC and even more slightly for MBC in relative terms. Nevertheless, these increases in absolute terms are counterbalancing cooling energy saving, so that EC with rule-based controls results in higher energy uses for these climates (heating dominated in higher latitudes), while only model-based controls are able to produce energy-saving if standard electrochromic glazings are adopted. In contrast, DB-EC is able to maintain the same energy saving for cooling, but achieve at the same time energy saving for heating and for lighting (the latter only if MBC is adopted), provided their higher level of visible transmission and selectivity for T_{VIS} between 0.20 and 0.73, and the higher SHGCs reachable for T_{VIS} higher than 0.73 (further interval of SHGC of 0.13 is achievable due to the high contrast of the DB-EC in transmission in the IR range). Overall, in absolute terms, this results always in an energy saving compared to the best static solution, when a DB-EC is adopted, regardless of the control strategy (i.e. 2–7 % and 10–11 % energy saving for Berlin, and 1–3 % and 4–5 % energy saving for Helsinki, respectively for RBC and MBC for South-West).

In both relative and absolute terms, in more extreme climates, like heating-dominated ones such as Berlin and Helsinki, and cooling-dominated ones like Seville, the advantages of adopting an EC glazing are reduced from an energy saving perspective (0–5 % for Helsinki and Berlin, and 4–14 % for Seville South-West, if MBC is adopted). On the other side in more temperate climates (in mid-latitudes) EC glazing, if properly operated, can achieve up to 13–22 % energy savings, confirming results from previous studies [49,52,53]. Nevertheless, if simplistic rule-based controls are adopted, EC glazing may result in increased energy uses, compared to an optimized static transparent façade, especially for climates with higher energy use for lighting and heating. Overall, West orientations, although having a higher energy use compared to South, are always holding higher energy savings (2–9 % difference for MBC for both DB-EC and EC and even more pronounced for RBC). This is because the most significant savings are for lighting energy use, and West has a higher amount of energy for lighting (and therefore higher total energy use as well) in the first place. Moreover the higher the energy use for cooling (i.e. Seville) and the higher the difference in energy saving between South and West, which is due to the fact that in West orientations, in hotter conditions, EC glazing tends to assume states with lower SHGC and T_{VIS}, thus affecting even more significantly energy use for lighting as well. When DB-EC is adopted these differences are maintained, even though, regardless of the control strategy, higher energy savings are in general achievable, also reducing the probability of an increase in energy use. However, for locations with extreme climates, either very hot and sunny like Sevilla or very cold and cloudy like Helsinki, the advantage of active technology over the best static benchmarks is significantly reduced. This trend is attributed to the fact that in these more extreme climates, very efficient static benchmarks, such as the SEL 40/22 for Sevilla or the SEL 60/33 for Helsinki, can effectively mitigate the impact of these extreme conditions. In contrast, in more variable and moderate climates like Barcelona and Turin, the flexibility of active electrochromic technologies proves to be ideal.

As far as visual comfort is concerned (Fig. 9 right), when RBC is adopted, DB-EC is able to reduce significantly the amount of time with lower illuminances (UDI-fs) compared to EC, provided the higher T_{VIS} for SHGCs higher than 0.20 and hence better selectivity (cf. Fig. 3). Nevertheless this is counterbalanced by the amount of probable glare linked to workplace illuminance levels higher than 3000 lx (UDI-ex). These differences are less and less evident by increasing the latitude under analysis. On the other side with MBC controls, lower and lower differences between DB-EC and conventional EC are measured by increasing the latitude, but it is noteworthy the fact that with model-based control is possible to maximise access to daylight and at the same time minimise visual discomfort anyway by means of DB-EC, as compared to EC technologies.

By looking at the same time at the potential reduction of total delivered energy use and reduction of visual discomfort, as a cumulative percentage of time for UDI-fs and UDI-ex, in Fig. 10 (energy use on the Y-Axis and Visual Discomfort on the X-axis, for South and West orientation), it is possible to note that for each climate, the static glazing solutions considered are either reducing energy use or improving visual comfort. For South orientations, EC adopting RBC is generally able to improve visual comfort, to the expenses of energy use though. While DB-EC adopting RBC is improving both objectives at the same time. If more complex model-based controls are adopted in operation, both energy saving and visual comfort objectives are ensured for both technologies, and the differences between DB-EC, considering the current properties

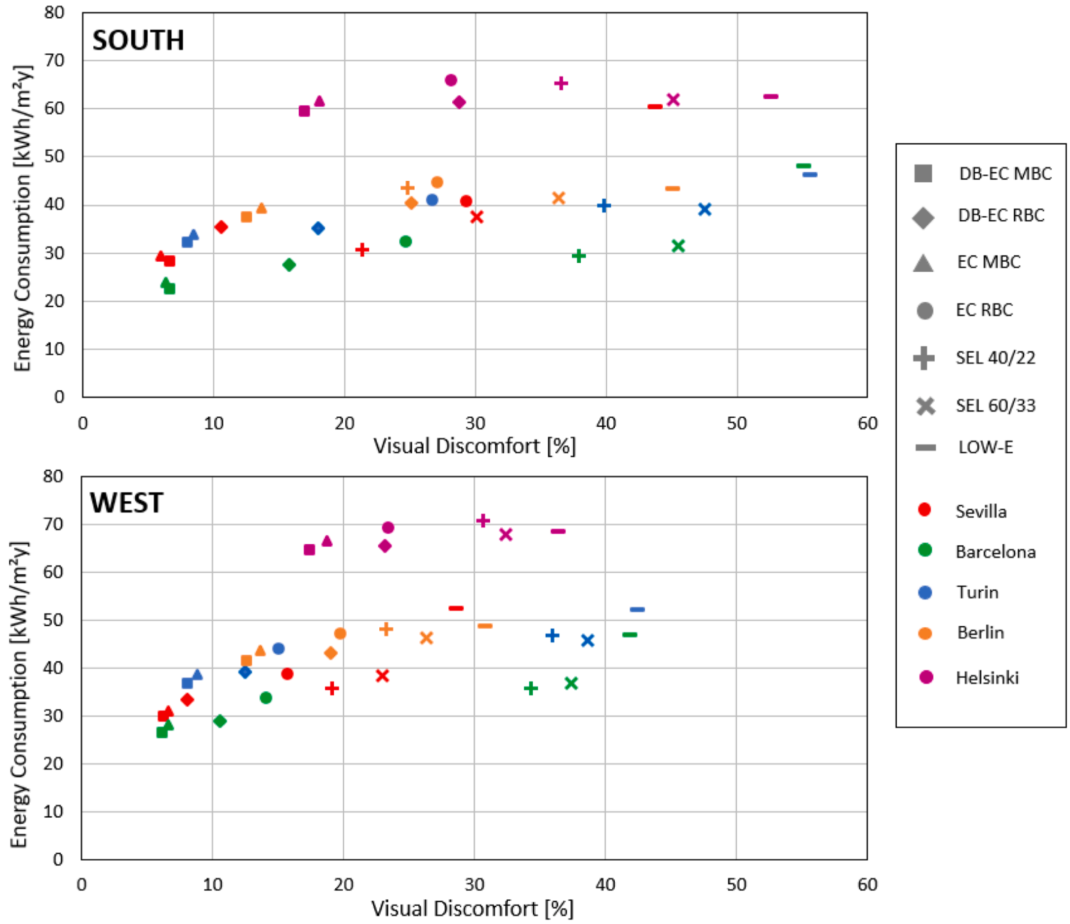

Fig. 10. Scatterplots depicting the relationship between energy consumption and Visual Discomfort Level (UDI_fs + UDI_ex) for each model orientation across all technologies and control strategies. Closer to the origin indicates a more favourable case.

of the developed technology, and traditional EC are minimised. Nevertheless, by looking at a single climate at once, both in South and West orientation, the variability of energy use and visual comfort performance of DB-EC across different control strategies is much lower than such variation for EC technologies controlled in different ways, and for static technologies. This ensures a more consistent building performance by varying use, operations and climate variability if a DB-EC technology is adopted.

4. Discussion

The performance of smart glazing (EC and DB-EC) relies in the ability to reduce significantly the energy need for cooling, compared to static glazing technologies, by modulating the unwanted amount of entering solar radiation during summer and shoulder seasons, which is particularly evident in cooling dominated climates (i.e. Seville and Barcelona), and even more so for West orientations. Nevertheless, this capacity alone does not imply a better performance compared to static solutions in terms of total energy use, as on one side this might be hindered by an increased energy need for artificial lighting (due to decreased level of indoor illuminance), and on the other by an increased energy for heating (due to reduction of free solar gains in winter). The decrease in overall energy use by means of a traditional EC glazing technology is guaranteed, in all the climatic conditions considered, in a range of up to 22 % by the implementation of a correct control during building operations (cf. Table 4), such as model-based controls not decreasing cooling energy to the expense of lighting and heating energy. Otherwise simple rule-based controls, provided they could be focused only on one specific priority at the time (i.e. reduction of energy use for cooling, or daylight comfort, or others), might result in marginal energy improvements (below 10 %) in the best case represented by temperate climates and mid-latitudes, while in the worst one in energy use increase (even up to 30 % for cooling dominated climates, mainly due to an increase in lighting energy demand, and below 10 % increase for heating-dominated ones). Differently, a smart glazing technology such as the DB-EC glazing presented in this paper, relying mainly on the inherently high contrast in solar transmission in the IR region, is able to: (i) modulate between higher SHGCs compared to traditional EC for high T_{VIS} (for approx. $T_{VIS} > 0.70$, the modulation capability of SHGC is between 0.44 and 0.53); (ii) in the region of T_{VIS} between 0.70 and 0.20 have a better selectivity (lower SHGCs compared to EC counterpart, with higher T_{VIS}); iii) achieve a minimum SHGC and T_{VIS} comparable with traditional EC. These features provide (i) slightly higher energy saving for cooling (due to the higher selectivity) compared to traditional EC; (ii) a lower increase in energy use for lighting if rule-based controls are adopted; (iii) when more daylight-based advanced control strategies are used, reductions in energy use for lighting are achievable; (iv) energy saving as far as heating energy uses are concerned.

This is supported by a comparison of the solar properties (in terms of T_{VIS} and SHGC) assumed by the EC and DB-EC for the ideal case of the model-based control. Fig. 11 analyses the cumulated frequency of smart glazing properties (EC with dotted line and DB-EC with continuous line) for two representative intermediate climates between the 5 analysed, either cooling (Barcelona, Fig. 11a and.b) or heating dominated (Berlin, Fig. 11c and.d), respectively for the winter season (blue lines) or for the summer and mid-season together (red lines). The yellow area in the graph represents the additional capacity to modulate between 0.40 and 0.53 of the DB-EC compared to the EC, while the grey area between T_{VIS}

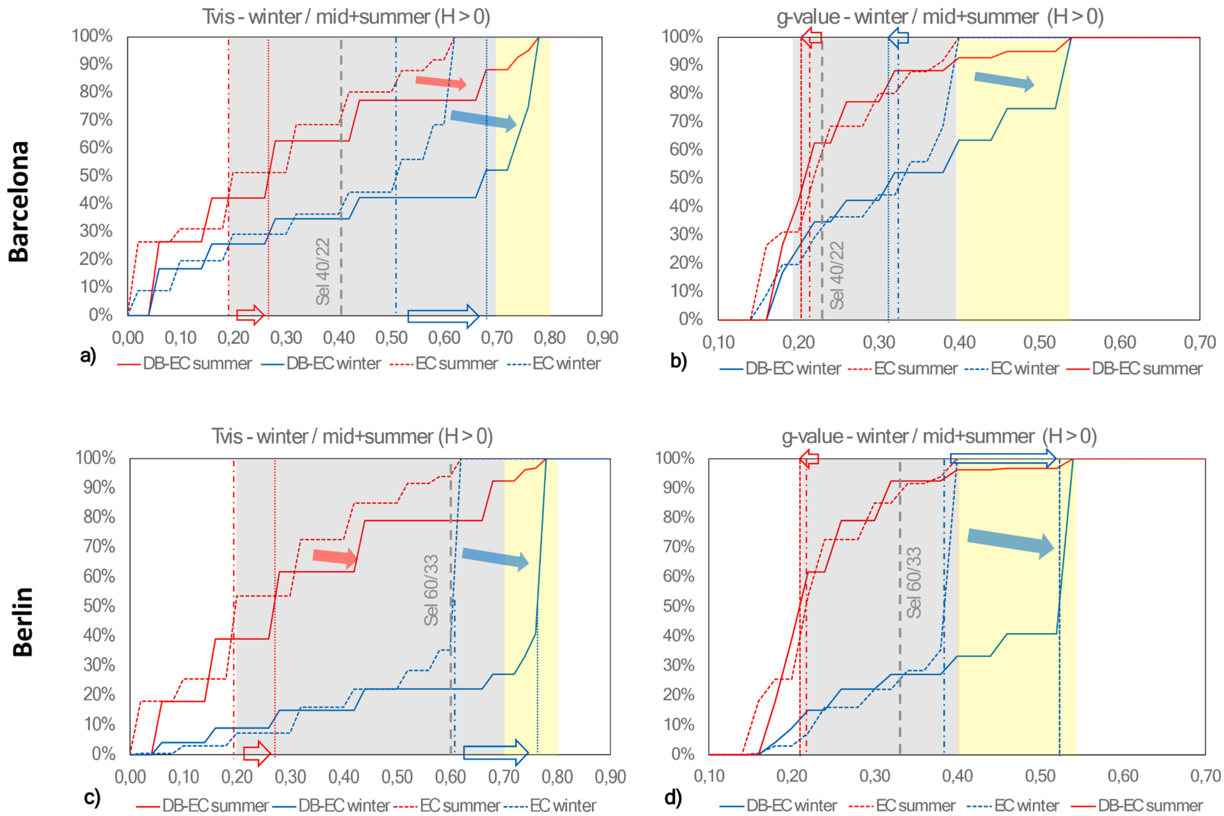

Fig. 11. Cumulative frequency analysis for T_{VIS} (left graphs, a. and b.) and SHGC (right graphs, b. and d.) distribution over the year for DB-EC (continuous line) and EC technologies (dotted line), considering only results when irradiances are positive and differentiated between winter season (blue lines) and summer and mid season (red lines), for the climate of Barcelona (top graphs, a. and b.) and Berlin (bottom graphs, c. and d.). The vertical lines are representing: (i) the properties of the best static glazing solution from an energy point of view in the specific climate (grey); the average property (corresponding to a cumulated frequency of 50%) for the winter season (blue lines) and summer and mid season (red lines) for the DB-EC (dotted line) and EC (dashed and dotted line) technologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.20 and 0.70, is where DB-EC has a higher selectivity than EC (higher T_{VIS} with similar SHGCs) due to its capability of modulating the NIR solar spectrum. From this analysis it is possible to appreciate that:

For both climates in the heating-dominated season (blue lines) a DB-EC tends to have higher SHGCs than a conventional EC for almost 70 % of the time for Berlin (Fig. 11d) and nearly 40 % of the time in Barcelona (Fig. 11b). The former brings the average SHGC for the winter season from 0.38 to 0.51 (vertical blue lines), while in Barcelona, provided the higher frequency in which the T_{VIS} is between 0.20 and 0.70 where DB-EC have higher selectivity, it results in slightly lower average SHGCs. This is reflected by a significantly higher average T_{VIS} in winter achieved by the DB-EC compared to conventional EC for both climates (vertical blue lines), from 0.50 to 0.69 for Barcelona (Fig. 11a) and from 0.60 to 0.75 for Berlin (Fig. 11c). These results in higher lighting and heating energy saving at the same time, due to higher illuminances and free solar gains reached in the indoor environment;

Similarly in the mid and cooling season (red lines) for both climates and due as well to its higher selectivity, a DB-EC is able to reach on average a slightly lower SHGC (Fig. 11b and d), with a higher visible transmission (similarly passing from 0.20 to 0.27 in Barcelona and Berlin, Fig. 11a and c respectively). This allows for a significant increase in indoor illuminances in summer and mid-season, while not admitting unwanted solar radiation in summer causing higher cooling needs or potential overheating risk.

In the cooling seasons (or in cooling-dominated climates) the higher SHGC (and T_{VIS}) modulation capability is only activated for a marginal time frame (no more than 10 % of the time when solar irradiation is present), while what matters is the capability of the DB-EC of having a higher selectivity, as it assumes solar properties in the grey region of Fig. 11 for about 60 % of the time. On the other hand in the heating season (or heating-dominated climates), both the higher selectivity and the higher modulation capabilities are important, as DB-EC assume such properties for a variable time between 20 % and 40 % (depending on the amount of heating time in such climate), and in the remainder 70 % to 40 % time, SHGCs higher than what possibly achievable by their EC counterpart is reached. These findings can provide future direction for further product improvements for both EC and DB-EC, which is climate-specific.

All these considered, DB-EC results always in energy saving compared to their climate-specific static best benchmarks, regardless of the complexity of the control strategy considered, in the order of 5 % to 27 % for MBC (for heating-dominated and temperate climates, respectively) and of 1 % to 19 % for RBC (cf. Table 4), to the exception of DB-EC with RBC for South orientation in cooling dominated climates with lower latitudes, such as Seville. In fact, where very high cooling loads are present, simple rule-based controls may strive to tune the necessity for low SHGCs with sufficient daylight. In light of the above, it appears that the impact on building performance of DB-EC smart glazing is less sensitive to the variability and uncertainty of the control strategy implemented in operations, compared to the conventional EC counterpart. DB-EC with RBC results in an additional 6–17 % energy saving compared to EC glazing, while for MBC control, DB-EC technologies achieve an additional average of 5 % energy saving. This translates to a 25 % to 100 % increased performance compared to traditional EC, depending on whether the climate is cooling or heating-dominated, when MBC strategies are considered (which represents the best implementation scenario for EC).

Finally, provided its versatile features in terms of independent modulation of transmitted solar radiation between VIS and IR spectrum, improved selectivity, and larger modulation range of T_{VIS} and SHGC, the building performance impact of Dual Band Electrochromic glazing technology is less sensitive to the climate locations, resulting in improved energy uses in a wider range of climates, such as: (i) climatic locations that are more heating dominated and/or at higher latitudes, in which conventional EC technologies strive to counterbalance visual comfort requirements (i.e. low illuminance level or possible glare risk) with heating energy needs; (ii) climatic locations that are prevalently cooling dominated (like Seville) and/or lower latitudes, in which conventional EC technologies tend to increase lighting energy use to a higher degree compared to how much they are able to reduce cooling (due to a lower selectivity of their solar properties modulation). This is particularly important when it is considered that the balance between cooling and heating energy needs can vary significantly in the future due to increasing minimum levels of insulation and air-tightness, on one side, and human-driven urban heat island effect and increase average temperature and heat waves on the other.

The present study highlights the potential of DB-EC glazing in different climates and orientations, nevertheless, it presents different limitations related to the breadth of the analysis, which concerns commercial application (by adopting a small office reference room) with South and West orientation, and current climate scenario (TMY 3). Nevertheless, the specific features of DB-EC could make it a promising technology also for residential scenarios, and it could be particularly versatile considering the fact that the balance between heating, cooling and lighting energy needs could change in the feature due to changing climate scenarios. As mentioned before, the current analysis cannot be considered as an accurate representation of daylight comfort performance as well, as no co-simulation strategy with raytracing software was considered to evaluate workplane illuminances, while daylight data integration strategy was adopted considering pre-simulated horizontal illuminance by means of EnergyPlus Delight module, for the purpose of simulating the effect of glazing control on energy considerations. Finally, this analysis should be completed by comparing the DB-EC glazing to the other technologies also in terms of return on investment and in terms of whole-life carbon. These considerations will be taken into consideration for future work.

5. Conclusions

This study quantifies the potential of DB-EC SWs to enhance building performance both in terms of energy use and visual comfort across various climatic conditions. To this aim the data delivered from thermo-optical characterisation of a DB-EC laminate have been used to evaluate thermal and solar properties of a DB-EC IGU. Then an extensive virtual performance analysis was carried out for different climatic locations (from cooling, to temperate, to heating dominated) adopting two different control strategies, rule- and model-based controls. The performance of the DB-EC and EC glazing are compared with those of effective climatic-specific static glazing as benchmarks. The identification of this correct benchmark is fundamental to truly describe the energy-saving potential of smart glazing technologies and is seldom retrieved in the literature, where most of the time standard low-E DGU is adopted to maximise the performance difference compared to more advanced glazing solutions.

The most relevant findings of this research can be summarized as follows:

1. DB-EC technology outperforms EC technology in both energy savings and visual comfort, regardless of the control strategy adopted;
2. Energy savings are more pronounced in West-oriented office rooms, due to the bigger impact on lighting energy consumption of smart glazing technologies in office buildings, while South-oriented ones see greater improvements in visual comfort;
3. The control algorithms strongly affect the performance of the smart glazing, and conventional EC when operated with RBC could also have energy use increase and lower visual comfort, especially for more extreme climates;
4. The MBC algorithm consistently surpasses the simpler RBC in effectiveness across all tested climates, orientations, and active technologies;
5. Due to their larger variation of solar and visible properties and independent tuning between VIS and IR spectrum, DB-EC integration results in:
   - 5-a. positive energy saving, ranging from 1 to 19 % for RBC and 4 to 27 % for MPC compared to the climate-specific best static solution;
   - 5-b. positive energy savings achieved in extreme climates, especially in heating-dominated and higher latitude regions (up to 11 %), while conventional EC technologies save energy mainly in temperate climates.
   - 5-c. significant reductions in visual discomfort levels during occupied hours, up to 32 % both in MBC and RBC mode.

Based on the here presented results, DB-EC glazing is prospected as a potentially disruptive SW technology if combined with an appropriate intelligent control strategy. Future advancements in DB-EC technology could focus on maximizing the blue shift of plasmonic resonance to reduce the minimum achievable T_{VIS} and SHGC, as well as tuning the redshift to expand the modulation range in the IR spectrum. These advancements may have climate-specific implications, allowing the technology to be tailored to different needs unique to specific climate conditions and/or building uses. It is expected that over the next 10 years, the adoption of smart EC glazing could be triggered on one side from the lower production costs of the smart layers, while on the other by the vast diffusion of AI-driven predictive control systems that will be capable of maximizing thermal and visual comfort in real-time, by exchanging data and signals with the building's utility platform (BEMS) and the building occupants, directly controlling the smart windows.

CRediT authorship contribution statement

Mirco Riganti: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ginevra Li Castri:** Software, Investigation, Data curation. **Valentina Serra:** Supervision, Data curation. **Michele Manca:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Fabio Favoino:** Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, 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 Leitat Technological Center, Energy & Engineering Division, Energy Conversion & Photonics Unit. Michele Manca has patent #EP4038451C0 licensed to Leitat Technological Centre. 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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Data availability

Data will be made available on request.

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