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Simulation-Based Evaluation of the Impact of an Electrochromic Glazing on the Energy Use and Indoor Comfort of an Office Room

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Abstract: Electrochromic glazing alters its optical properties in the absence/presence of an electrical charge, varying from clear to dark to control daylighting and solar heat gains. This study aims to evaluate the impact of an electrochromic glazing, with indoor glare or temperature control, on the energy performance and thermal and visual comfort of an office room under three European climates, using a calibrated simulation model. The novelty of the paper lies in its combined performance assessment, using different standards and metrics. The results showed reduced climatization energy requirements with temperature control, but significantly increased artificial lighting energy use. Glare control achieved useful illuminance levels during 74–80% of working hours. Concerning temperature control, working hours within thermal comfort increased (21–43%) under a free-float regime. Moreover, the performance of this glazing was compared to that of a clear glazing with/without a reflective film and a thermochromic glazing for different solar orientations. The electrochromic glazing with glare control showed the highest energy savings (14–36%) for a western orientation, and the lowest negative impact on daylighting for a northern orientation. The best glare reduction was achieved with the reflective film. Considering the free-float regime, the electrochromic glazing, with temperature control, showed the highest increase in working hours within thermal comfort (6–9%) for a western orientation.

Keywords: electrochromic glazing; dynamic simulation; thermal performance; visual performance; energy performance; indoor comfort

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1. Introduction

Buildings account for a high energy consumption, and consequently, high CO_2 emission levels [1]. A significant amount of the consumed energy [2] is used to provide heating and cooling, along with artificial lighting, to indoor spaces. These two energy end uses are strongly influenced by the building facade [3,4], since it acts as an interface between the outdoor and indoor environments responsible for energy and mass flows.

Glazing systems allow natural light to flow towards the indoors, having a positive impact on visual comfort and artificial lighting needs [5]. However, these elements, particularly conventional clear glazing, tend to have high solar and visible transmittance values that can result in high solar heat gains and potential glare problems [6]. While the inclusion of solar control systems [7–10], such as overhangs, balconies, louvres, and shutters, into the building facade can help improve its performance by providing shade to the glazing elements and reducing excessive solar radiation levels, these solar control systems can have a negative visual impact by partial or totally blocking the outside view. It is also possible to incorporate solar control directly into the glazing systems through coatings, such as low-emissivity and reflective coatings, and/or films, such as solar control films. Coated or filmed glazing yields a better performance than conventional glazing, since it aims at decreasing climatization energy needs and potential glare [11–14]. Even though these are affordable solutions, largely available on the market, the static behavior of these coated and filmed glazing systems can limit their efficiency, particularly in hot climates with high solar radiation levels. With the ambition of achieving net-zero energy buildings [15,16] and the fact that largely glazed buildings are the tendency of modern architecture, the investment in the improvement and innovation of glazing solutions that surpass conventional glazing performance has become essential.

Smart glazing technologies [17–21], which have been increasing in recent years, can dynamically control the entrance of heat and light through the glazing by adapting to specific stimuli, aiming at improving the global performance of the building. The installation of smart glazing systems can promote the reduction of the energy needs of the building, while providing indoor comfort conditions [20]. Some smart glazing technologies present a passive reaction control, meaning that they independently react to environmental stimuli, as in the case of thermochromic (TC) glazing that autonomously and reversibly alters its optical properties due to temperature variation in the thermochromic material (with the most successfully applied being vanadium dioxide, hydrogels, ionic liquids, or perovskites [22,23]) incorporated in a thin coating in the glazing. When it reaches temperature levels higher that a specific value (transition temperature), the TC material darkens, reducing solar gains through the glazing [24,25]. If temperature levels are lower than the transition temperatures, the clear state is restored. When assessing the energy performance of TC glazing in an office environment, research studies obtained energy savings of up to 17–23% for large-area windows under temperate climates, when compared to the results for static glazing [26,27]. Under arid and continental climates, cooling energy savings were also reduced with TC glazing [28,29]. When investigating the impact of TC glazing on the visual comfort of office rooms, it was found that daylight exploitation increased by 5–20% and glare reduced by 10–50%, for higher and lower latitude locations, respectively [30,31]. Regarding thermal comfort, TC glazing can reduce the occurrence of uncomfortable conditions during summer by 36% [32]. However, the lack of control of the chromatic change by the users inherent in passive technologies acts as a disadvantage. Active smart glazing technologies [33], such as liquid crystals, suspended particles, and electrochromic (EC) glazing, can be directly controlled by users or through a computerized building management system, offering a more flexible dynamic behavior. Both liquid crystals [34,35] and suspended particle [36] glazing technologies make it possible to achieve energy savings when compared with static windows; nevertheless, their performance is usually surpassed by that of EC glazing [37], which is a more established and deeply investigated smart glazing.

EC glazing, a property-changing smart glazing technology, can reversibly alter its optical properties (transmittance and absorptance) in response to an electrical stimulus [18–20,38]. This dynamic behavior is possible due to the presence of an EC coating comprising five layers: an electron accumulation layer, an ion conductor layer, an electrode layer, and two transparent conductive oxide outer layers. When voltage is applied to the EC coating of the glazing, the transfer of ions from the electron accumulation layer to the electrode layer causes a chromatic change from a clear to a tinted state, with the possibility of achieving intermediate tinted states. The change between tinted states usually requires low energy use, with even lower energy consumption required to maintain a specific tinted state. In the absence of the electrical stimulus, the chromatic change is reversed, and the glazing returns to its clear state.

EC glazing can be manually controlled by the occupant or automatically controlled (based on control parameters, such as solar radiation, glare levels, indoor temperature, and outdoor temperature) when connecting the glazing to a terminal box, a sensor, and a control panel that can be programmed to manage tinting, based on different inputs. The type of control of an EC glazing has a strong impact on its performance [38]. Considering

EC glazing systems controlled by solar radiation and/or illuminance levels, energy saving potentials were obtained in previous studies [39–41], particularly cooling energy savings. When trying to combine indoor comfort with energy performance objectives in the EC glazing control [42–45], comfort conditions are improved, but energy requirements increase.

Existing research studies that explore the performance of smart EC glazing systems, either through a numerical simulation, experimental testing, or in combination, conclude that this innovative glazing technology contributes to the reduction of the cooling energy needs and indoor glare levels, being more suitable for hot climates. A brief description and the main findings of these studies is presented in Table 1.

Existing studies tend to focus on the energy performance of EC, evaluating energy savings and the reduction of peak energy demand. These studies concluded that EC glazing makes it possible to reduce cooling energy needs, when compared to the results for clear and low-emissivity glazing systems, particularly during summer in hot climates. However, an increase in the artificial lighting energy consumption was generally observed in those cases. Also, existing studies do not consider the energy consumption of the control of the dynamic glazing. Even though this energy end use can be low for small glazing areas, it should be considered in the energy performance analysis of this type of glazing.

Regarding the impact on the conditions of the indoor environment, some studies assess the thermal and/or visual comfort of occupants in spaces with EC glazing installed. The thermal comfort of EC glazing is poorly explored by existing studies [44,46], which used the predicted mean vote (PMV) index and concluded that EC glazing increased thermal comfort when compared to clear glazing. The impact of EC glazing on indoor glare is investigated by some studies, mainly through the daylight glare index (DGI) [47–49] or the daylight glare probability (DGP) [49,50], which concluded that glare reduction is possible without compromising available daylight, increasing visual comfort. Since people spend a large amount of time inside buildings, the evaluation of the impact of building elements on indoor thermal and visual comfort through multiple metrics and standards is extremely important. Existing studies [44,46,47] that assess both the energy and comfort performance of EC glazing are scarce, focusing on specific standards and metrics, so the comfort performance of this smart glazing should be further investigated, along with its energy performance.

Table 1. Brief description and main findings of previous research studies on the performance of electrochromic glazing.

Ref.	Climate Group [1]	Case Study	Research Approach [2]		Performance Assessment			Main Findings
			Exp.	Sim.	Energy	Thermal Comfort	Visual Comfort	
[51]	B, C, D	Office building		✓	✓		✓	• Energy savings $\geq$ 45% compared to single glazing. • Peak load carbon emissions reduced by 35% in new construction and 50% in renovation scenario.
[52]	C	Office room		✓	✓	✓	✓	• Energy savings of 48% (no overhang) and 37% (overhang), along with a blind control algorithm. • Unobstructed view for 10 months, against a few days with venetian blinds.
[44]	A, C, D	Office building		✓	✓		✓	• Higher energy savings obtained for warmer climates with high solar radiation. • Higher positive impact on visual comfort than thermal comfort.
[47]	C, D	Office building		✓	✓			• Primary annual energy use decreased by 5–10% for large-area windows, but increased by 2–5% for moderate-area windows. • Average annual DGI levels were significantly reduced.
[53]	D	Office building		✓	✓			• Energies savings of 8%, against results for low-e glazing.
[54]	C	Office room		✓	✓			• Highest reduction of energy needs for west orientation (62%), but no advantage for south orientation, compared to conventional double glazing.
[45]	A, B, C, D	Office building/apartment		✓	✓			• Annual primary energy savings of 6–30 kWh/ft^2 of window area with a dual-band EC against static windows, and of 0–1.2 kWh/ft^2 against other EC.
[55]	A, B, D	Office building		✓	✓			• Annual reduction of cooling needs by up to 125–200 kWh/m^2 with EC coating on low-e double glazing south-oriented windows.
[56]	B, C	Office building		✓	✓		✓	• Savings of up to 39% of cooling demand and 35% of total energy demand with EC combined with integrated photovoltaic system and an energy management system.

Table 1. *Cont.*

Ref.	Climate Group [1]	Case Study	Research Approach [2]		Performance Assessment			Main Findings
			Exp.	Sim.	Energy	Thermal Comfort	Visual Comfort	
[43,57]	B, C	Office rom/building		✓	✓		✓	• Annual energy savings up to 25% against static glazing. • Nearly 83% of hours with useful illuminance levels.
[48,58–60]	C	Test-cell/family house	✓	✓	✓	✓	✓	• Cooling reduction benefits could be exceeded by the increase in lighting and heating needs for low-area windows in heating dominated climates.
[50]	C	Test-cell	✓	✓			✓	• Useful illuminance levels higher in May (40–48%) than in June (6–8%). • DGP values lower than 0.36 (comfortable) for 69% of occupancy time.
[49]	C	Test-room	✓			✓	✓	• EC glazing prevents disturbing glare for most users when the sun is close to the central field of view, but does not provide comfort.
[46,61]	A	Test-room	✓		✓	✓		• Reduction of about 80% of heat flux through the glazing and reduction of operative temperature up to 11 °C. • Total of 39% of daytime spent with visual comfort, without glare.
[62]	C	Office room	✓	✓	✓			• Annual energy consumption reduced by 39–48% and peak demand by 22–35%. • PPD reduced from 18% to 13–15%.
[63]	C	Test-room	✓		✓		✓	• Daily lighting energy savings of 8–59% against static glazing, for large-area, south-oriented windows.
[64]	C	Office room	✓		✓			• Energy efficiency and visual comfort may not be fulfilled with low solar angles. • Daily lighting energy use reduced by 3–24% against static glazing.
[65]	C	Test-room	✓		✓			• Cooling energy needs reduced by 80%, but heating increased 35%. • Payback period of 6 years, considering a residential apartment.

[1] Climate group: A—tropical, B—arid, C—temperate, D—continental; [2] research approach: Exp.—experimental, Sim.—dynamic simulation.

The studies on the performance of EC glazing existing in the literature tend to focus on energy performance analysis, usually not taking into account the energy use expended by the control of the glazing. Moreover, studies that assess the impact of this glazing on indoor comfort are in lower number, usually not considering different metrics. With the identification of these research gaps, this study aims to investigate the performance of an EC glazing (controlled by indoor glare or temperature), comprising a holistic analysis that consists of the evaluation of both the energy performance (climatization, artificial lighting, and glazing control) and the visual and thermal comfort in the presence of this smart glazing. An existing office room was used as a case study for a refurbishment scenario under the main European climates, using a calibrated dynamic simulation model. This is a follow-up study of the once conducted by Teixeira et al. [66], which evaluated the energy, thermal, and visual performance of static versus thermochromic (TC) double-glazing under the same European climate locations. While the case study and the calibration of the simulation model are retained, new features are introduced in this study, aiming at evaluating the impact of an EC glazing on building energy use and indoor comfort. In addition, a new analysis on the impact of solar orientation on the performance of the EC glazing and the other glazing solutions for solar control is introduced. The combination of an energy and comfort assessment in this study, as well as the consideration of different glazing solutions (both static and dynamic) and climates, aims at achieving more robust results that could help fill the research gaps identified in the literature.

2. Methodology

The methodology followed in the present work is shown in Figure 1.

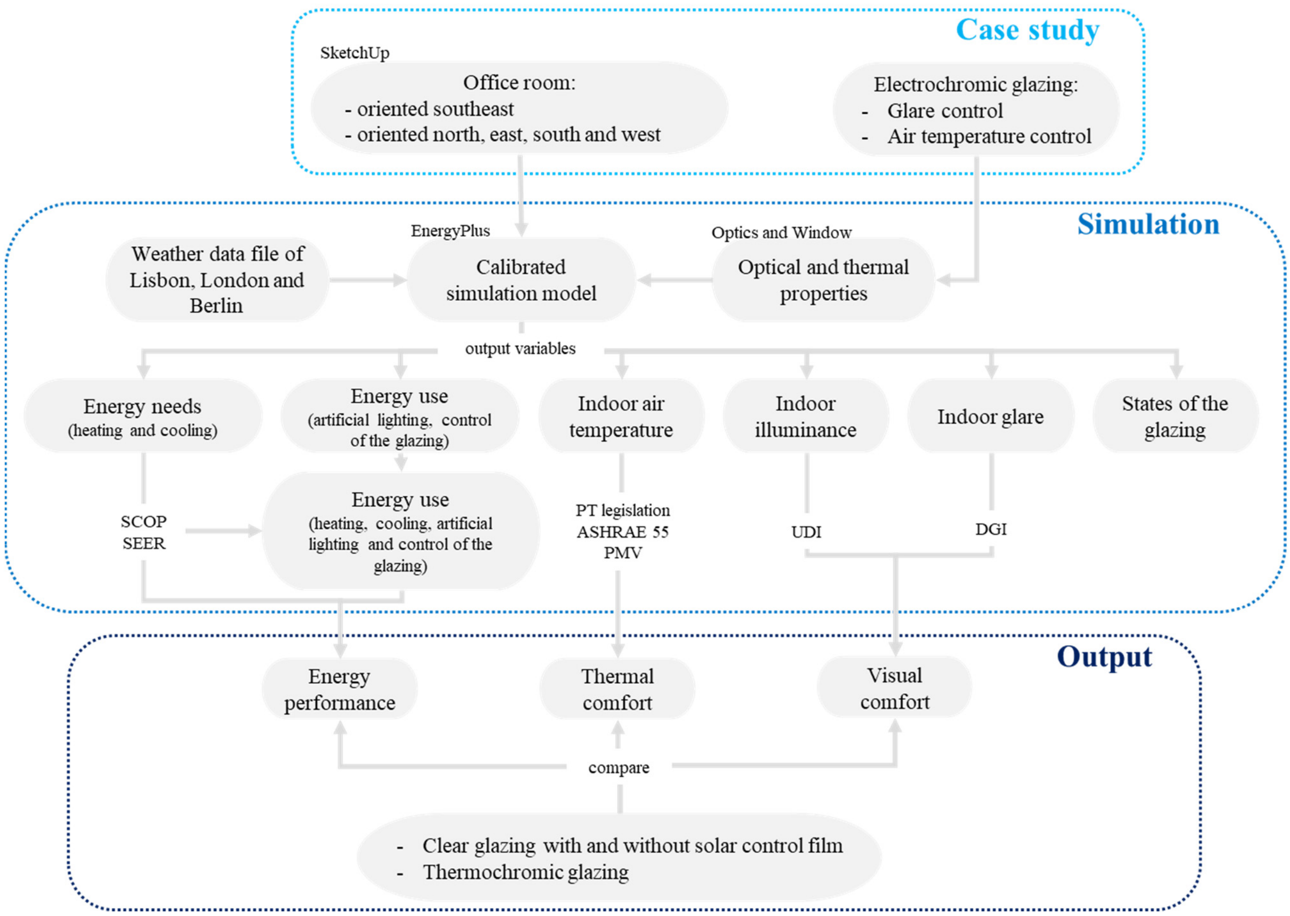


Figure 1. Methodology adopted.

An office room with an EC double-glazing, located in Lisbon, was used as a case study. The analyzed EC glazing was controlled by indoor air temperature or glare levels, with the aim of promoting indoor quality thermal and luminous conditions, while trying to achieve energy savings, similar to the methods of previous studies [27,39,43,45]. The thermal and optical properties of the EC glazing system were computed by Optics (version 6; Optics, Berkeley, CA, USA) [67] and Window (version 7.6; Berkeley Lab WINDOW, Berkeley, CA, USA) [68] software. A 3D model of the office room was constructed using SketchUp [69]. The energy performance and indoor comfort results were obtained through a dynamic simulation model in EnergyPlus [70], previously calibrated [66] with experimental data measured during an in situ experimental campaign under real occupancy conditions [66,71]. The synthetic weather data files [72] of the cities of Lisbon, London, and Berlin were associated to the dynamic simulation model to evaluate and compare the performance under the three European climates (hot-summer Mediterranean climate, temperate oceanic climate, and warm-summer humid continental climate, in accordance with the Köppen–Geiger climate classification [73]).

The annual energy needs (heating and cooling) and energy use (climatization, artificial lighting, and control of the dynamic glazing) were computed and analyzed to evaluate the energy performance of the glazing system. The indoor thermal comfort was evaluated through the percentage of annual working hours within the comfort ranges of the following standards: Portuguese legislation [74], ASHRAE 55 adaptive model [75], and PMV [76]. The indoor visual comfort was evaluated through the percentage of annual working hours within the comfort ranges of the following indexes: useful daylight index (UDI) [77,78] and DGI [79].

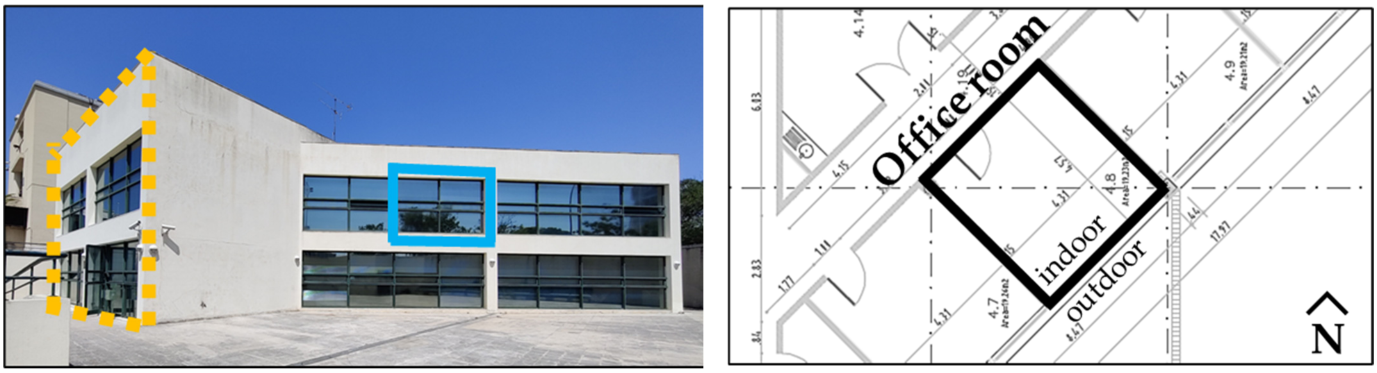
A comparative assessment on the performance of the EC glazing compared to other glazing solutions with different types and levels of solar control (clear glazing with a solar control film and a TC glazing) was also conducted, using a clear glazing as reference. These comparative glazing solutions, whose properties are shown in Table 6 of Section 4, correspond to the ones considered in the previous study conducted by Teixeira et al. [66], adopting the same case study and climate locations. The comparative analysis was carried out for the climates of the same European cities (Lisbon, London, and Berlin), and the impact of the solar orientation (north, east, south, and west) on the performance of different glazing systems was also addressed. It is expected that this comparison will yield additional insights regarding the potential of installing dynamic glazing solutions under these European climates.

2.1. Case Study

An individual office room (Figure 2a), located on the top floor of a university building of Instituto Superior Técnico, Lisbon, was used as a case study. A shading effect on the facade of the building, caused by a protruding wall (south facade), is usually noticed around 12 a.m. (summer) or 2 p.m. (winter).

The glazed facade is southeast oriented (Figure 2b). The original glazing system consisted of a conventional double-glazing unit of clear float glass, with an air gap, and a green aluminum frame (without a thermal break). Due to high solar heat gains through the glazing, a reflective solar control film was later installed on the interior surface of the glazing.

The indoor air temperature of the office can be controlled during working hours through an HVAC system, with an established setpoint of 22 ± 2 °C, which is within the thermal comfort temperature range for commercial buildings (20–25 °C), according to Portuguese legislation [74]. Table 2 shows a brief description of the case study. More information regarding the office room can be found in the study by Teixeira et al. [66].



(**a**) (**b**)

Figure 2. Case study: (**a**) location of the individual office room (contour in full blue) and the protruding south wall (contour in dotted orange) in the university building; (**b**) office room outline (contour in full black) and solar orientation of the glazed facade.

Table 2. Characterization of the office room.

Location	38°44′14.1″ N 9°08′12.7″ W
Solar orientation	Southeast
Geometry	4.31 m (width) × 4.57 m (depth) × 2.97 m (height)
Floor area	19 m^2
Glazing area	10.4 m^2
Window to wall ratio	81%
Shading system	Manual interior venetian blinds with metallic horizontal slats
Occupation	one person during working hours
Artificial lighting	LED lights
Electric equipment	Laptop and desktop computer
HVAC system	SCOP—4.43; SEER—7.98

Since the process behind electrochromism lies on the dual adjustment of electrons and ions, the transmission kinetics of the chosen electrolyte plays a key role in an EC device. There is a vast variety of EC materials that can be incorporated into EC devices, as reviewed by Ding et al. [80], with lithium-ion-based EC devices being the most common. EC thin films with vanadium pentoxide grown by spray pyrolysis [81,82] have proved to be a simple and cost-effective deposition method suitable for large areas, like building glazing. Figure 3 shows the different layers of the EC glazing system (7 + 12 + 4 mm) evaluated in this study that comprises an EC coating with tungsten oxide. This glazing can reversibly change its optical properties, shifting between clear and tinted states in response to applying a small electrical charge that transfers lithium ions between five layers of ceramic material coated onto a thin annealed glass pane, darkening the glass. By reversing the polarity, the glass returns to its clear state. The chromatic change can be manual or automatically controlled and aims at increasing energy efficiency and indoor comfort by modeling sunlight passing through the glazing and offering solar protection. The EC glazing can shift between five tinted states: a fully clear state, three intermediate states, and a fully tinted state.

As part of a previous research study that focused on the assessment of the thermal and luminous performance of solar control films [71], an extended field experimental campaign was conducted under real occupancy conditions in the office room. During a heating (11 March to 16 April) and a cooling (28 May to 28 June) period, the following data were simultaneously and continuously collected: indoor and outdoor solar radiation; indoor and outdoor illuminance; indoor and outdoor air temperature; surface temperature of the glazing system and shading system; indoor relative humidity; heat flux through the glazing. For more information regarding the methodology, equipment, and results of this experimental campaign, please refer to Teixeira et al. [71]. Some of the data collected during this experimental campaign were used to calibrate the dynamic simulation model of the office room used in this work and described in the next subsection.

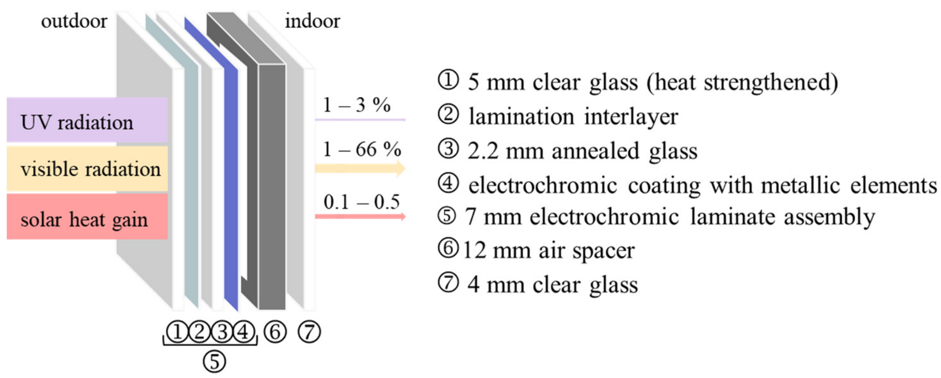


Figure 3. Layers of the electrochromic glazing system analyzed in this study, and respective UV transmittance (clear—3%, dark—1%), visible transmittance (clear—66%, dark—1%), and solar heat gain (clear—0.5, dark—0.1).

2.2. Dynamic Simulation

A 3D geometric model of the office room was created using SketchUp [69]. Apart from the exterior wall (U-value = 2.63 W/m·K) and the flat roof (U-value = 0.77 W/m^2·K), all other opaque elements of the facade were considered adiabatic in the simulation model. The thermal and optical properties of the existing static glazing with the solar control film were computed using Optics [67] and Window [68] software and were used to calibrate the dynamic simulation model.

The properties of the existing glazing system and the 3D model of the office room, together with the meteorological data gathered during the experimental campaign [71], were used as inputs in the EnergyPlus (version 9.5) [70] dynamic simulation model for the calibration procedure. The simulation model was calibrated by computing the NMBE and Cv (RMSE) statistical parameters to compare the simulated data with the experimental data previously collected [71]. After editing the input schedules and the airflow of the simulation model, the NMBE and Cv (RMSE) values of the selected calibration variables were within the limits for manually hourly calibration ($|NMBE| \leq 10\%$; Cv (RMSE) $\leq 30\%$ [83]); therefore, the simulation model was found suitable to accurately reproduce the office room. The calibration variables and respective NMBE and Cv (RMSE) for the heating (1 to 7 April) and cooling (6 to 12 July) periods are shown in Table 4. The calibration procedure is more deeply explained in the previously published study by Teixeira et al. [66].

The simulation model was used, after calibration, to evaluate the energy performance and the indoor comfort in the presence of the EC glazing. Two different controls were given to the EC glazing using the energy management system group in the EnergyPlus [70] software (Figure 4): the indoor glare levels and the indoor air temperature levels. These controls were selected with the aim of achieving energy efficiency, while providing good indoor thermal and visual conditions, similar to the methods used in previous studies [27,39,43,45]. The thermal and optical properties of the glazing system, computed with Optics [67] and Window [68] software, are shown in Table 3. Due to the low thermal transmittance and solar factor values of the EC glazing, a good thermal performance is expected. The EC glazing presents a large modulation range, with visible and solar transmittance values significantly lower than those of the clear glazing, even in the clear state. The EC glazing shows a higher solar absorption of the external pane, particularly for darker states that block excessive solar radiation gains through absorption. The EC glazing blocks 99% of the UV radiation incident on the glazing, having a positive impact on the duration and maintenance of furniture and on the occupant's health.

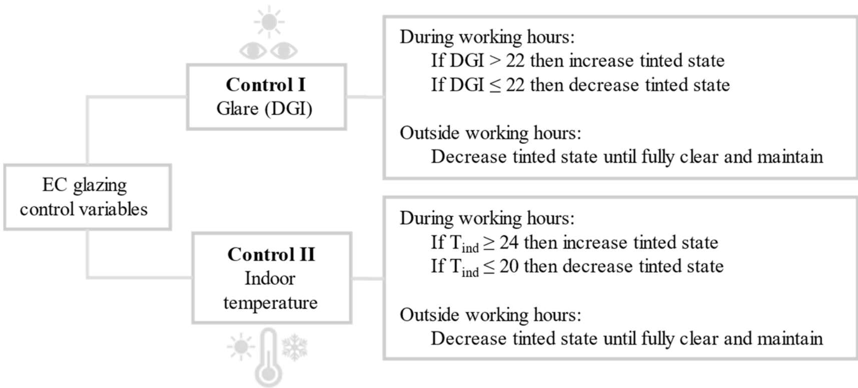


Figure 4. Controls of the electrochromic glazing considered in the simulation model.

Table 3. Thermal and optical properties of the electrochromic glazing system computed with Optics [67] and Window [68] software: thermal transmittance, *U*-value; solar factor, *g*; visible transmittance, τ_{vis}; visible front, ρ_{visF}, and back, ρ_{visB}, reflectance; solar transmittance, τ_{sol}; solar front, ρ_{solF}, and back, ρ_{solB}, reflectance; ultraviolet transmittance, τ_{UV}; absorptance of the external, α_1, and internal, α_2, glass panes.

Electrochromic Glazing States	*U*-Value [W/m^2·K]	g [-]	τ_{vis} [%]	ρ_{visF} [%]	ρ_{visB} [%]	τ_{sol} [%]	ρ_{solF} [%]	ρ_{solB} [%]	τ_{UV} [%]	α_1 [%]	α_2 [%]
Fully clear state	1.9	0.5	66	10	11	38	12	17	3	48	2
Intermediate state 1	1.9	0.2	18	6	9	7	7	16	1	85	0
Intermediate state 2	1.9	0.1	11	5	9	4	7	16	1	88	0
Intermediate state 3	1.9	0.1	6	5	9	2	7	15	1	91	0
Fully tinted state	1.9	0.1	1	5	9	0	8	16	0	92	0

Some of the parameters considered in the simulations of the energy performance and the indoor visual and thermal comfort are shown in Table 4. For a better understanding of the impact of the EC glazing on the performance of the office room, the existing venetian blinds were not considered in the simulation, making it possible to obtain results focused on the potential benefits of EC glazing installation in the considered case study, without the interference of a shading system. A "continuous off" type of control was assigned to the artificial lights in the simulation model, with a setpoint of 500 lx. The HVAC system was not considered in the simulations of the indoor thermal comfort under free-float conditions, except when computing the PMV [76] values (which require the operation of the HVAC system).

Table 4. Calibration variables, with respective NMBE and Cv (RMSE) for the heating and cooling period, and main parameters considered in the annual simulations of the energy performance and indoor comfort.

Calibration Variables	Indoor Temperature (T_{ind}) Interior (T_{si}) and Exterior (T_{se}) Surface Temperature of the Glazing
NMBE/Cv(RMSE)	Heating period: T_{ind}—0.49/4.60; T_{si}—−4.46/20.04; T_{se}—−11.15/22.60 Cooling period: T_{ind}—−1.84/4.41; T_{si}—−3.94/13.94; T_{se}—−8.23/13.89
Shading system	Not considered
Occupation	one person sitting at the desk during working hours (from 9 a.m. to 6 p.m. on weekdays)
Air changes per hour	1.0 h^{-1}
Artificial lighting	LED lights (110 W) on during working hours, if needed ("continuous off" control)
Electric equipment	Laptop computer (30 W) on during working hours, off otherwise Desktop computer (155 W) on during working hours, suspended otherwise
HVAC system	Available during working hours with deadband (20–24 °C)

To evaluate the energy performance in the presence of the EC glazing with the two implemented controls, both the energy needs and energy use of the office room were computed. Energy needs only include climatization needs, meaning heating and cooling. Energy use includes climatization (heating and cooling), artificial lighting, and control of the glazing. The energy use of the electric equipment (desktop and laptop computers) was not considered, since it is not affected by the type of glazing system. The energy needs were estimated using the simulation model, considering an ideal HVAC system. Knowing the seasonal energy efficiency values (SEER—7.98; SCOP—4.43) of the HVAC installed in the office room, the heating energy use was computed through the ratio between the heating energy needs and the SCOP value, and similarly, the cooling energy use was computed through the ratio between the cooling energy needs and the SEER value. The artificial lighting energy use was directly obtained from the simulation model. The energy consumed to control the EC glazing tinted states was calculated through the evolution of tinted states given by the simulation and the following energy consumption values of the control: clear state—0 W/m^2; change state—5 W/m^2; maintain state—1.4 W/m^2.

The visual comfort was evaluated based on the percentage of monthly and annual working hours with specific simulated illuminance levels at the center of the desk (Figure 5) and glare levels at eye level, with the occupant sitting at the desk facing the southwest wall (Figure 5). The UDI and the DGI were used to analyze the illuminance and glare values, respectively. The UDI metric [77,78] expresses the percentage of working hours with horizontal illuminance values at work plane that are within a specific range considered useful for occupants: from 0.1 klx to 3.0 klx. Illuminance values lower than 0.1 klx are considered insufficient to provide visual comfort, while illuminance values higher than 3.0 klx are associated with visual discomfort (high glare probability) [77,78]. The DGI metric [79] expresses glare values caused by daylight based on the following comfort ranges: DGI $\leq$ 16—imperceptible glare; 16 < DGI < 20—perceptible glare; 20 $\leq$ DGI < 24—uncomfortable glare; DGI $\geq$ 28—intolerable glare.

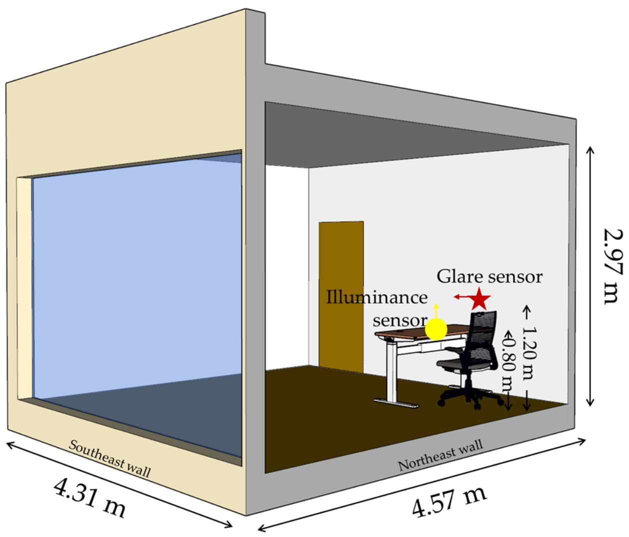


Figure 5. Location of the glare and illuminance sensors in the dynamic simulation.

The thermal comfort was evaluated at the sitting position at the desk (Figure 5), based on the monthly and annual percentage of working hours within the ranges of the following standards: Portuguese legislation [74]; ASHRAE 55 adaptive model (80% acceptability limit) [75]; PMV [76]. Following the Portuguese legislation [74], indoor air temperature values between 20 °C and 25 °C are considered comfortable for occupants of commercial buildings. No other parameters, like metabolic rate, clothing insulation, air speed, and relative humidity, are considered by this standard. The ASHRAE 55 adaptive model [75] defines the acceptable thermal conditions in spaces with natural ventilation controlled by occupants, relating acceptable temperature ranges to climatological parameters. This standard is only applicable when spaces are occupied, and the average outdoor air dry-bulb temperature is between 10 °C and 33.5 °C over the last 7 days. The 80% acceptability limit [75] was considered in this study. The PMV index [76] predicts the mean value of votes of a group of occupants, through a thermal sensation scale, in an air-conditioned space. This index considers that when the internal heat production of the occupant equals its heat loss, the thermal equilibrium is achieved. The range ($-0.7 \leq$ PMV ≤ 0.7) for category III, in accordance with EN 16798 [84], was adopted in the present study. All of the energy produced by the occupant was assumed to being converted to heat. The dynamic predictive clothing insulation model, developed by Schiavon and Lee [85], was adopted, as well as an indoor air velocity of 0.2 m/s.

The typical meteorological year weather data of the three European cities of Lisbon, London, and Berlin were associated with the simulation model to evaluate the impact of the type of climate on the performance of the glazing systems. These three cities were selected to be representative of the main European climates: Lisbon—hot-summer Mediterranean climate; London—temperate oceanic climate; Berlin—warm-summer humid continental climate. Some geographic and climatic characteristics of the three cities are shown in Table 5. The assessment under different climates aims to enable the identify the impact of climatic conditions on the performance of the EC glazing. The results of the dynamic simulation of the energy performance and the thermal and visual comfort of the EC glazing, under the different climates, are shown and analyzed in the next section.

Table 5. Geographical and climatic characteristics of the cities of Lisbon, London, and Berlin.

		Lisbon (PT)	London (UK)	Berlin (DE)
Elevation [m]		71	44	147
Latitude [°]		38.73 N	51.15 N	52.47 N
Longitude [°]		9.15 W	0.18 W	13.4 E
Köppen–Geiger climate classification [73]		Csa	Cfb	Dfb
Monthly average outdoor air dry-bulb temperature [°C]	Minimum	10.6	3.9	0.3
	Average	16.3	10.2	9.8
	Maximum	22.6	17.3	19.1
Monthly average accumulated solar radiation incident on a south-facing vertical surface [kWh/m^2]	Minimum	76.1	28.6	17.4
	Average	102.0	68.0	64.9
	Maximum	120.8	93.4	96.3

3. Results

As previously mentioned, the tinted state of the EC glazing is controlled in the present study by the indoor glare (control I) or air temperature (control II) levels. Figure 6a shows the evolution of the solar factor and the transmittance of the EC glazing between tinted states. A significant decrease in the values of these properties can be noticed when the glazing alters from the fully tinted to the first intermediate state.

Figure 6b shows the percentage of working hours with specific tinted states of the EC glazing simulated throughout the year under the different climates. Since the operation of the HVAC system is expected to have an impact on the tinted states of the EC glazing with control II, and its operation is not considered in the computation of the thermal comfort in accordance with the Portuguese legislation [74] and the ASHRAE 55 adaptive model [75], both scenarios (with the HVAC system on and off) are shown. When considering control I (glare), for nearly the totality of working hours, the EC glazing is in the fully clear state for the three climates. This might be explained by the fact that the desk is located far away from the glazing, so there is limited need to tint the glazing when the control is indoor glare. Even though the accumulated vertical solar radiation levels are lower for the climates of London and Berlin (Table 5), the activation of the fully tinted state in these climates can be explained by the higher latitudes, when compared to the city of Lisbon, which result in lower solar angles and consequently, higher maximum values of indoor illuminance/glare. The EC glazing with control II (temperature) presents a similar dynamic behavior in both

HVAC on and off scenarios, under the climate of the city of Lisbon, with a higher percentage of working hours in the fully tinted state (HVAC on—83%; HVAC off—90%), followed by the climates of Berlin (HVAC on—29%; HVAC off—43%) and London (HVAC on—28%; HVAC off—41%). These results are in agreement with the temperature and solar radiation levels, previously shown in Table 5, which are higher for the city of Lisbon.

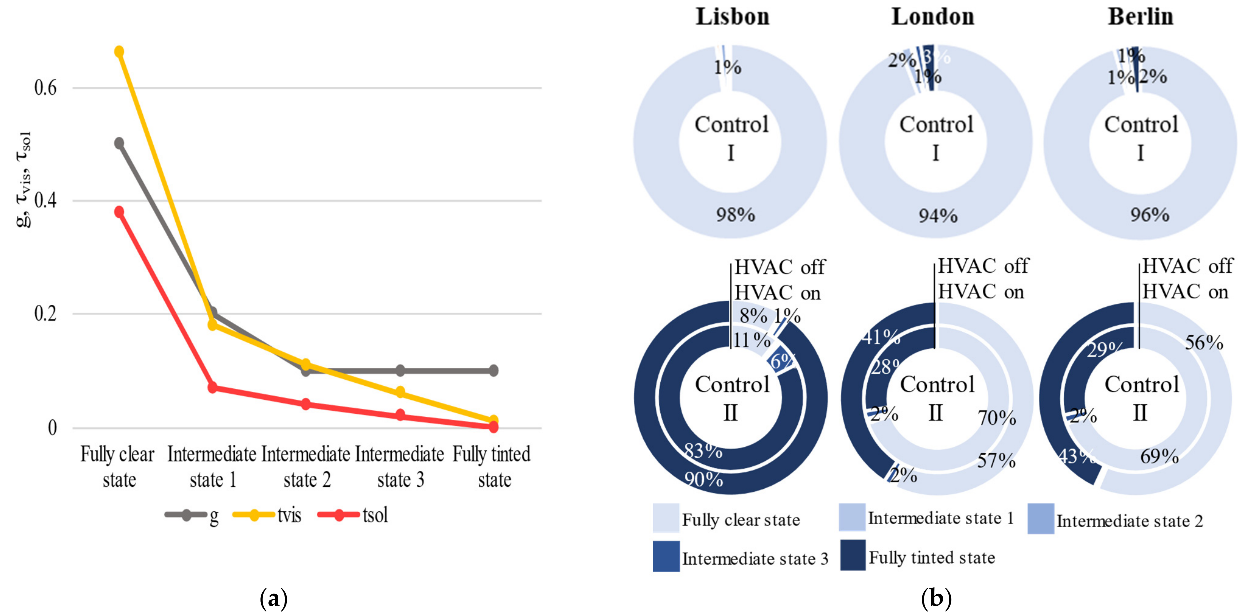


Figure 6. Dynamic behavior of the electrochromic glazing during the simulations: (**a**) evolution of the solar factor (g), the visible transmittance (τ_{vis}) and the solar transmittance (τ_{sol}) of the EC glazing depending on its tinted state; (**b**) percentage of working hours with specific tinted states of the glazing.

The following subsections present the results of the dynamic simulation for the energy performance and visual and thermal comfort of the office room in the presence of the EC glazing, under the different climates. The real solar orientation of the office room (southeast) was considered in this assessment.

3.1. Energy Performance

Both the energy needs and energy use are assessed in this subsection. As previously stated, energy needs only include climatization, and in addition, energy use includes artificial lighting and control of the glazing.

Figure 7a shows the (monthly and annual) energy needs, in kWh/m^2 of floor area, of the office room with the EC glazing (control I and II) under the three climates, as computed from the simulation. Due to the warmer climate and the higher solar radiation levels, the EC glazing showed higher cooling energy needs in Lisbon than in London and Berlin throughout the year. The dynamic behavior of the EC glazing made it possible to obtain practically null energy needs in some months, for all climates. The cooling energy needs were lower with control II, with reductions of approximately 30% when compared to control I for all climates. A small decrease in the heating energy needs (4–6%) was obtained, meaning the EC glazing also helped to increase solar heat when needed during cold months.

Figure 7b shows the (monthly and annual) energy use, in kWh/m^2 of floor area, of the office room with the EC glazing (control I and II) under the different climates, as obtained from the simulation. The significant difference between climatization energy needs and energy use is explained by the high efficiency of the HVAC system considered in the case study. Since the EC glazing spends more time in the fully tinted state with control II, the artificial lighting energy use suffered a significant increase throughout the year, for all climates, but more strongly for the climate of Lisbon. The activation of the tinted states with control II led to an increase in the energy use to control the glazing. The type of control had a stronger impact on the energy use under the climate of Lisbon, with a difference of approximately 7 kWh/m^2 between the total energy use values of both control types. The highest total energy use was obtained with control II under the climate of Lisbon (27 kWh/m^2), closely followed by the same control type in Berlin (26 kWh/m^2). The lowest total energy use was achieved with control I in London (17 kWh/m^2).

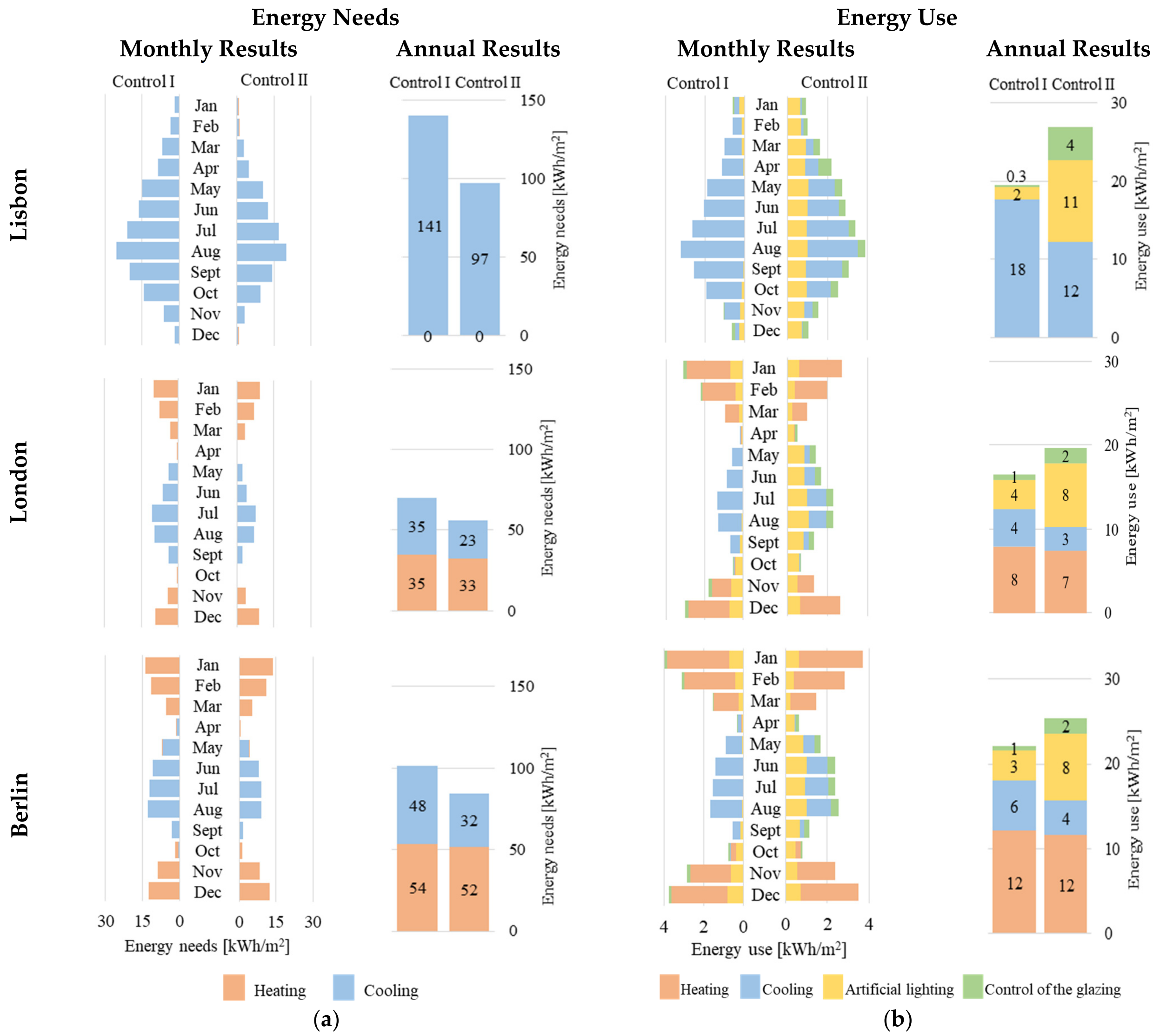


Figure 7. Energy performance of the electrochromic glazing, considering the two different controls (control I and II), under the climates of the cities of Lisbon, London, and Berlin: (**a**) simulated monthly and annual energy needs, in kWh/m^2, and (**b**) simulated monthly and annual energy use, in kWh/m^2.

3.2. Visual Comfort

Figure 8a shows the percentage of monthly and annual working hours with specific simulated indoor horizontal illuminance levels at the desk, in accordance with the UDI ranges [77,78], in the presence of the EC glazing (control I and II) under the different climates. When considering control I, higher percentages of working hours with exceeded illuminance levels were achieved throughout the year, particularly for the climate of Lisbon (20%). Control II shows a similar visual performance regarding illuminance levels under the climates of the cities of London and Berlin. The highest percentages of annual working hours with useful illuminance levels were obtained with control I (Lisbon—75%; London—80%; Berlin—77%). The lowest percentage of annual working hours with useful illuminance levels was obtained with control II in Lisbon (16%), with the large majority of working hours (79%) showing insufficient illuminance levels.

Figure 8. Visual comfort in the presence of the electrochromic glazing, considering the two different controls (control I and II), under the climates of the cities of Lisbon, London, and Berlin: (**a**) percentage of monthly and annual working hours within specific UDI ranges at the desk center throughout the year, and (**b**) percentage of monthly and annual working hours within specific DGI ranges at eye level.

Figure 8b shows the percentage of monthly and annual working hours with specific simulated indoor glare levels at eye level, in accordance with the DGI metric ranges [79], with the EC glazing (control I and II) under the different climates. The highest percentages of working hours with imperceptible glare levels were obtained with control II during summer months because the high temperature values triggered the fully tinted state of the glazing. Uncomfortable and intolerable glare levels were obtained during winter months in the presence of the EC glazing with control II, for the climates of London and Berlin. The highest percentages of annual working hours with imperceptible glare (83–93%) were achieved with control II for all climates.

3.3. Thermal Comfort

The percentages of working hours within thermal comfort with each glazing control (control I and II), considering the comfort ranges defined by the Portuguese legislation, the adaptive model of ASHRAE 55, and PMV, are shown in Figure 9. The investigation of thermal comfort, taking into account these different approaches, makes it possible to assess the impact of the type of glazing control under a free-float regime (Portuguese legislation comfort range and ASHRAE 55 adaptive model comfort range) and with the operation of the HVAC system (PMV comfort range).

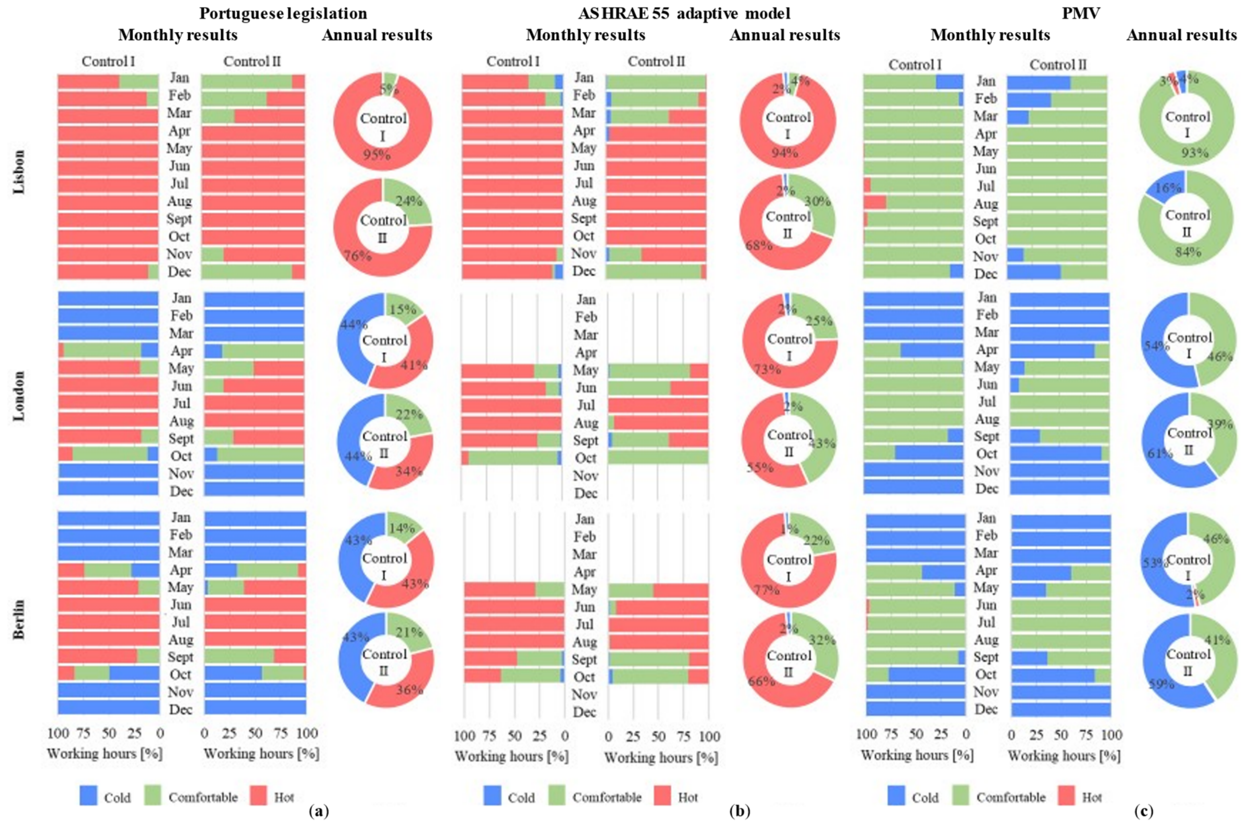


Figure 9. Thermal comfort in the presence of the electrochromic glazing (control I and II) under the climates of the cities of Lisbon, London, and Berlin: (**a**) percentage of monthly and annual working hours within the Portuguese legislation [43] thermal comfort ranges; (**b**) percentage of monthly and annual working hours within the ASHRAE 55 adaptive model [44] thermal comfort ranges (80% acceptability limit); (**c**). percentage of monthly and annual working hours within the predicted mean vote [45] thermal comfort ranges.

Figure 9a shows the percentage of monthly and annual working hours with specific indoor air temperature levels, in accordance with the Portuguese legislation [74], in the presence of the EC glazing (control I and II) under the different climates. Indoor air temperature levels higher than the comfort range were obtained during the large majority of working hours in the hot climate of Lisbon throughout the year. The results are similar for the cities of London and Berlin, with 100% of working hours with cold temperature levels during winter months. The highest percentages of annual working hours with too hot temperature levels were obtained for the city of Lisbon (control I—95%; control II—76%). Nevertheless, the highest percentage of annual working hours within thermal comfort (24%) was achieved with control II under the climate of the city of Lisbon. Control II made it possible to reduce too hot temperature levels and, in this way, increase the percentage of annual working hours within thermal comfort (London—22%; Berlin—21%), while maintaining the percentage of working hours with too cold indoor temperature levels in the climates of London and Berlin.

Figure 9b shows the percentage of monthly and annual working hours within the thermal comfort ranges of ASHRAE 55 adaptive model (80% acceptability limit) [75], in the presence of the EC glazing (control I and II) under the three climates. For the climate of Lisbon, too hot temperature levels were obtained for practically 100% of monthly working hours between April and October, considering both control types. The highest percentages of annual working hours within thermal comfort were again obtained with control II (Lisbon—30%; London—43%; Berlin—32%). Control II made it possible to achieve reductions of the percentage of working hours with too hot temperature levels of up to 26%.

Figure 9c shows the percentage of monthly and annual working hours within the comfort ranges of the PMV index [45], in the presence of the EC glazing with both controls (control I and II), under the different climates. High percentages of working hours within thermal comfort were obtained throughout the year under the climate of Lisbon. Considering both control types, 100% of working hours showed too cold temperature levels during winter months under the climates of London and Berlin. The highest percentages of annual working hours within thermal comfort were obtained under the climate of Lisbon (control I—93%; control II—84%). The percentages of annual working hours within thermal comfort are very similar for the climates of London and Berlin. In contrast to what was observed in the previous results of the other two thermal comfort standards, control II did not increase the percentage of annual working hours within thermal comfort, compared to the results for control I, when computing thermal comfort with the PMV index.

As expected, thermal comfort results are improved with the operation of the HVAC system, making it possible to achieve high percentages of working hours within thermal comfort with both glazing controls. The reduction of the transmittance of solar gains with temperature control was beneficial under a free-float regime but had a negative impact considering climatization.

4. A Comparative Study of the Performance of Electrochromic Glazing and Other Glazing Technologies

In this section, a comparative study using the same office room is carried out regarding the performance of EC glazing compared to other glazing systems with different types and levels of solar control. This study aims to be comprehensive, meaning that it will be carried out in contexts of use that have a high impact on performance, such as climate variables and solar orientation.

Regarding the glazing systems used for comparison, the following solutions are considered: clear glazing, which is representative of the original glazing of the office room; clear glazing with a solar control film (SCF), which is representative of the existing glazing of the office room; and TC glazing, which increased the percentage of annual working hours with useful illuminance levels and within adaptive thermal comfort by up to 24% and 38%, respectively, and achieved energy savings of up to 50%, compared to the results for clear glazing, as noted by the authors in a previous publication [66]. These glazing options have different optical and solar characteristics and therefore, different levels of solar control. The first two work with constant values of these characteristics, representing a static solar control, while the TC works with variable values within a range, which represents a dynamic type of solar control.

To evaluate the influence of climate variables in this comparative study, the same climates of the three European cities used previously in the EC glazing study are again considered—Lisbon, London, and Berlin. Regarding the influence of solar orientation, the study is conducted assuming that the glazing facade can be exposed to north, east, south, west exposures, which are the directions between which the greatest contrasts in performance can be observed.

Table 6 shows the thermal and optical properties of the clear, with and without SCF, and TC glazing systems, computed using Optics [67] and Window [68] software. The clear glazing without film exhibits high thermal, solar, and visible transmittance values, which can be linked to poor thermal and visual performance [66]. The clear glazing with an SCF provides high solar and visible reflectance values, blocking excessive solar radiation by reflection. The TC glazing, which reacts to a temperature stimulus, presents a dynamic behavior between 5 °C and 95 °C, altering its optical properties to modulate daylight and solar heat gains, reaching low visible and solar transmittance values in the darker states (higher temperature values). Similar to the EC glazing, the clear glazing with SCF and the TC glazing provide a UV protection of 99%. When comparing the EC (Table 3) and TC (Table 6) glazing systems in the fully clear state, the EC glazing exhibits higher visible and solar transmittance values.

Table 6. Main thermal and optical properties of the clear (with and without solar control film) and the thermochromic glazing systems computed with Optics [67] and Window [68] software: thermal transmittance, U-value; solar factor, g; visible transmittance, τ_{vis}; visible front, ρ_{visF}, and back, ρ_{visB}, reflectance; solar transmittance, τ_{sol}; solar front, ρ_{solF}, and back, ρ_{solB}, reflectance; ultraviolet transmittance, τ_{UV}; absorptance of the external, α_1, and internal, α_2, glass panes.

	U-Value [W/m^2·K]	g [-]	τ_{vis} [%]	ρ_{visF} [%]	ρ_{visB} [%]	τ_{sol} [%]	ρ_{solF} [%]	ρ_{solB} [%]	τ_{UV} [%]
Clear glazing without film	2.7	0.8	81	15	15	70	13	13	51
Clear glazing with film	2.6	0.4	27	43	44	17	35	42	1
TC glazing (clear state/dark state)	1.6	0.3/0.1	49/1	9/4	10/8	19/1	36/18	38/37	1/0

Given that solar radiation levels differ between the considered locations (Lisbon, London, and Berlin), the monthly average accumulated solar radiation incident on the facade when oriented north, east, south and west, during the winter and summer months, is presented in Table 7. The winter months comprise December, January, and February. The summer months comprise June, July, and August. For a specific climate, lower solar radiation levels were obtained for the north orientation, as expected. Solar radiation levels are higher during summer than winter months for each solar orientation under all climates, except for the case of the south orientation in Lisbon, with lower values during summer months, which can be explained by the higher solar altitude angle during this time of the year. The minimum, mean, and maximum solar radiation values for each solar orientation under the climate of Lisbon are higher than the ones observed for the other cities. The city of Berlin presents the lowest minimum and mean solar radiation levels for each solar orientation. The maximum solar radiation levels under the climate of London are lower than the ones observed for Berlin. The magnitude of incident solar radiation is directly related to solar gains. As a result, for climates and orientations with higher incident solar radiation, a greater impact of the solar gains on the performance is expected. The largest solar gains are expected to be associated with higher cooling needs and visual discomfort.

Table 7. Minimum, mean, and maximum monthly average accumulated solar radiation [kWh/m^2] incident on the office facade facing north (N), east (E), south (S) and west (W) during winter and summer months under the climates of the three European cities (Lisbon, London, and Berlin).

		Lisbon				London				Berlin			
		N	E	S	W	N	E	S	W	N	E	S	W
Winter months	Minimum	17.4	45.2	100.2	37.8	7.1	9.6	28.6	11.0	5.6	6.8	17.4	7.9
	Mean	19.2	52.1	104.6	40.1	9.2	15.1	40.1	16.0	8.3	12.5	28.9	12.9
	Maximum	22.2	62.7	109.6	42.7	12.3	22.0	47.8	21.3	12.0	21.0	46.8	20.4
Summer months	Minimum	46.1	128.2	74.9	95.2	41.5	74.6	79.4	79.9	42.4	78.1	83.1	79.0
	Mean	54.3	138.1	89.6	100.4	47.6	77.3	86.9	82.3	48.6	84.0	90.0	83.1
	Maximum	58.8	144.8	106.5	107.0	51.1	82.6	93.2	87.1	52.2	90.1	95.1	85.8

The side-by-side analysis of the impact of solar orientation on the performance of the different glazing systems, considering the clear glazing without film as reference, is presented in the next subsections.

4.1. Energy Performance

Figure 10 shows the annual energy savings (positive values—decreased energy consumption, resulting in energy savings; negative values—increased energy consumption) of the total energy use in the presence of each glazing system when compared to the results for the clear glazing for different solar orientations under the climate of the three cities. When assessing north solar orientation, the EC glazing controlled by glare showed the highest energy savings when compared to the other glazing solutions under the climates of Lisbon (9%) and London (2%). Still assessing north solar orientation, the EC glazing controlled by temperature showed a lower energy increase than the EC glazing controlled by glare and the clear glazing with film under the climate of Berlin, being surpassed by the TC glazing, which reached a neutral energy savings. The negative impact of the glazing systems with solar control, considering the north orientation, is more significant during winter months, when solar radiation levels are lower, and the reduction of solar heat gains and daylighting through the glazing are relatively higher, compared to their results during the summer months. When focusing on the results for the east solar orientation, the EC glazing with glare control presented similar energy savings (24%) to those for the clear glazing with film (26%) for the city of Lisbon, and the highest energy savings for the cities of London (6%) and Berlin (9%), along with the TC glazing (London—6%; Berlin—11%). The EC glazing with glare control showed the highest energy savings when compared to that of the EC glazing with temperature control and the clear glazing with film for a south orientation under the climates of the cities of London and Berlin. The EC glazing with glare control presented the highest energy savings (between 14% and 36%) when compared to the other glazing solutions for the west solar orientation, under all climates. Contrary to other glazing solutions, the EC glazing controlled by glare achieved positive energy savings for all solar orientations under the climates of Lisbon and London. Except for the south orientation under the climate of Lisbon, the EC glazing with temperature control showed negative energy savings.

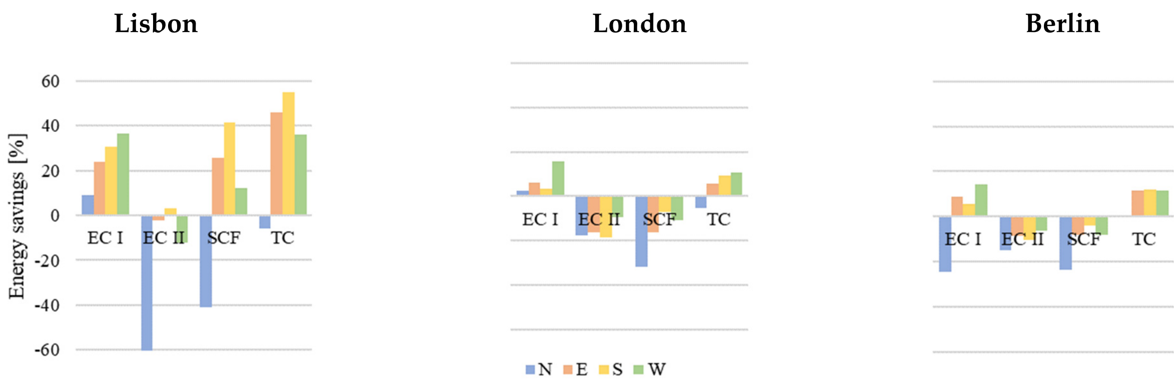


Figure 10. Annual energy savings, in % (positive values—decreased energy consumption, which resulted in energy savings; negative value—increased energy consumption), of the total energy use (climatization and artificial lighting) by the office room in the presence of each glazing system (electrochromic glazing with control I, electrochromic glazing with control II, clear glazing with film, thermochromic glazing) compared with the results for the clear glazing, for different solar orientations (N—north, E—east, S—south, W—west) under the three European climates.

4.2. Visual Comfort

Figure 11a shows the increase (positive percentage values) and decrease (negative percentage values) in annual working hours with useful illuminance levels (UDI metric [77,78]) in the presence of each glazing system when compared with the results for the clear glazing for different solar orientations under the climate of the three cities. Positive percentage results are desirable, since they represent an increase in the indoor visual comfort. Focusing on the results for a north solar orientation, which is exposed to significantly low daylight levels, the EC glazing controlled by glare had the lowest decrease (between −1% and −2%) of working hours with useful illuminance levels for all climates, when compared to the other glazing systems because of the high visible transmittance of its clear state. For the east orientation, the EC glazing controlled by glare promoted an increase (5%) in working hours with useful illuminance in Lisbon (similar to the glazing with SCF—6%) that was surpassed by the TC glazing (10%); however, the EC showed the lowest decrease (up to 1%) in working hours with useful illuminance, comparing to the other glazing solutions, under the cold climates of London and Berlin. The EC glazing controlled by glare always showed an increase in working hours with useful illuminance when installed in a west-oriented façade, being surpassed by the TC glazing under all climates. The EC glazing controlled by temperature had a negative impact on illuminance levels for all solar orientations under the three climates, particularly in Lisbon.

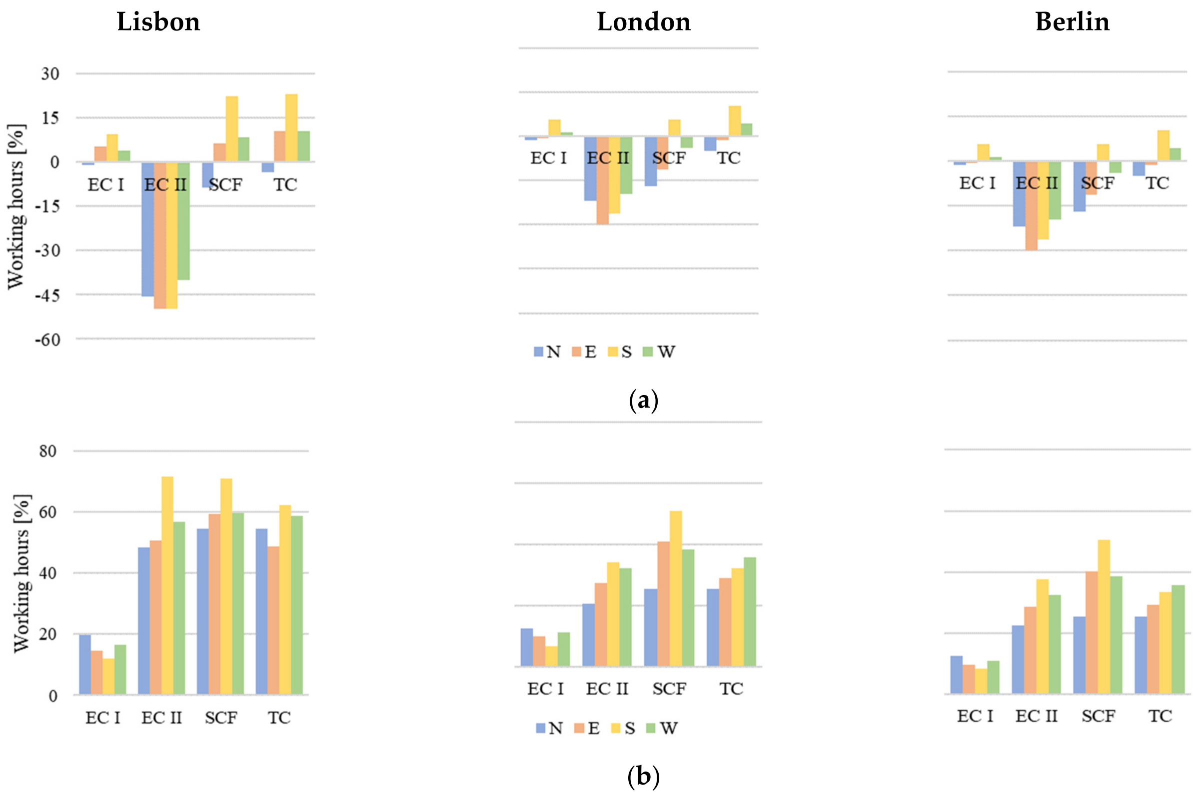


Figure 11. Increase (positive percentage values) and decrease (negative percentage values) in annual working hours with (**a**) useful illuminance levels and (**b**) imperceptible glare levels in the presence of each glazing system (electrochromic glazing with control I, electrochromic glazing with control II, clear glazing with film, thermochromic glazing) compared with the results for the clear glazing for different solar orientations (N—north, E—east, S—south, W—west) under the three European climates.

Figure 11b shows the increase (positive percentage values) and decrease (negative percentage values) in annual working hours, with imperceptible glare levels (DGI [79]), in the presence of each glazing system against the clear glazing for different solar orientations under the climate of the three cities. Positive percentage results are desirable, since they represent an increase in the indoor visual comfort. Due to the constant reduction of indoor illuminance levels in the presence of the EC glazing controlled by temperature, as previously stated, the percentage of working hours with imperceptible glare significantly increased with this glazing solution for all solar orientations under the different climates, particularly in Lisbon. Focusing on east and west solar orientations, the EC glazing controlled by temperature showed a very similar performance to that of the TC glazing, under all climates. The EC glazing controlled by temperature promoted the highest glare reduction (72% of working hours with imperceptible glare) when oriented south, compared to the other glazing solutions, under the climate of Lisbon. For the cold climates of London and Berlin, the EC glazing controlled by temperature showed high percentages of working hours with imperceptible glare (London—34%; Berlin—38%) for the south solar orientations, being only surpassed by the clear glazing with SCF (London—51%; Berlin—51%).

4.3. Thermal Comfort

Figure 11a shows the increase (positive percentage values) and decrease (negative percentage values) in annual working hours within thermal comfort in accordance with the Portuguese legislation standards [59], in the presence of each glazing system compared with the clear glazing, for different solar orientations under the climate of the three cities. Positive percentage results are desirable, since they represent an increase in the indoor thermal comfort. Focusing on the east solar orientation, the EC glazing controlled by temperature showed the highest increases in working hours within thermal comfort (between 6% and 9%), under all climates, when compared with the remaining glazing solutions. The EC glazing controlled by temperature showed the best performance (between 9% and 17% of working hours within thermal comfort) for a south orientation, when comparing to the other glazing solutions, under all climates, being only surpassed by the TC glazing in Lisbon (22%). Under the climate of Lisbon, the EC glazing is the only glazing solution that made it possible to increase working hours within thermal comfort, helping to achieve an increase of 3%. Under the cold climates, the performance of this glazing system also surpassed the performance of the other glazing solutions when oriented west.

Figure 12b shows the increase (positive percentage values) and decrease (negative percentage values) in annual working hours within thermal comfort, in accordance with the ASHRAE 55 adaptive model [75], in the presence of each glazing system compared to the results for the clear glazing, for different solar orientations under the climate of the three cities. Positive percentage results are desirable, since they represent an increase in the indoor thermal comfort. The EC glazing controlled by temperature showed the highest increase in working hours within thermal comfort for the north (between 10% and 26%) and west (between 14% and 33%) solar orientations compared to the other glazing solutions, under all climates. Focusing on the south solar orientation, the EC glazing controlled by temperature made it possible to significantly increase (between 22% and 38%) the percentage of working hours within thermal comfort, under all climates, being only slightly surpassed by the TC glazing under the climates of Lisbon (26%) and London (40%).

Figure 12c shows the increase (positive percentage values) and decrease (negative percentage values) in annual working hours within thermal comfort in accordance with the PMV [76], in the presence of each glazing system compared with the results for the clear glazing, for different solar orientations under the climate of the three cities. Positive percentage results are desirable, since they represent an increase in the indoor thermal comfort. The EC glazing controlled by glare is the only glazing solution that increased the percentage of working hours within thermal comfort when assessing the south (9%) and west (2%) solar orientations, under the climate of Lisbon. The EC glazing controlled by temperature showed the highest increase when oriented east (12%), when compared to the other glazing solutions, under the climate of Lisbon. In accordance with this standard, all the glazing solutions decreased the percentage of working hours within thermal comfort for the different solar orientations under the cold climates of the cities of London and Berlin. For a specific solar orientation, this decrease was smaller in the presence of the EC glazing controlled by glare.

Figure 12. Increase (positive percentage values) and decrease (negative percentage values) in the annual percentage of working hours within thermal comfort, in accordance with (**a**) the Portuguese legislation [43], (**b**) the ASHRAE 55 adaptive model [44], and (**c**) the predicted mean vote [45] in the presence of each glazing system (electrochromic glazing with control I, electrochromic glazing with control II, clear glazing with film, thermochromic glazing) compared with the results for the clear glazing, for different solar orientations (N—north, E—east, S—south, W—west) under the three European climates.

5. Critical Discussion and Limitations

The added value of this study lies on the assessment of different performance aspects of an EC glazing, covering energy performance and indoor thermal and visual comfort, thus providing a holistic approach. The evaluation of the impact of climate and solar orientation on the performance of the glazing, comparing it with other glazing systems with different types and levels of solar control, are also key aspects of this study.

Even though the EC glazing controlled by temperature levels showed lower cooling and heating energy requirements, this glazing increased the artificial lighting energy use because of the low visible transmittance of its intermediate and fully tinted states, resulting in higher annual total energy use values.

The EC glazing controlled by glare showed high percentages regarding annual working hours (74–80%) with useful illuminance levels for all climates. In addition, uncomfortable and intolerable glare levels were reduced in the presence of this glazing system. The EC controlled by temperature significantly reduced indoor glare, achieving 80–93% of annual working hours with imperceptible glare; however, this control was less efficient in regards to blocking uncomfortable and intolerable glare levels. This can be explained by the fact that during the winter months, the solar altitude is lower, increasing indoor glare levels, but the temperature is insufficient to trigger the chromatic change to darken the EC glazing.

The thermal comfort assessment covering different standards made it possible to consider different requirements, parameters, and comfort conditions. Under free-float conditions, the EC glazing controlled by temperature showed higher percentages of working hours (up to 43%) within thermal comfort. Contrary to the results under free-float, this glazing did not show high percentages of working hours within thermal comfort when assessed using the PMV index. This could be due to the reduction of solar gains through the glazing, which increased the percentage of working hours with too cold temperature levels. As a result, the EC glazing controlled by glare showed a better thermal performance, when considering the operation of the HVAC system, with up to 93% of working hours within thermal comfort.

The comparative analysis of the performance of the EC glazing compared with that of the other glazing solutions (clear glazing with SCF and TC glazing), for different solar orientations, made it possible to better measure the evolution of the different performance aspects assessed and to evaluate the installation potential of the considered glazing solutions, using a clear glazing as the reference.

It was only possible to obtain energy savings for all solar orientations in the presence of the EC glazing controlled by glare under the climates of Lisbon (9–36%) and London (2–16%). The highest energy savings (14–36%) for a west solar orientation were also obtained with this glazing. Nevertheless, for east and south solar orientations, the energy savings obtained with the EC glazing controlled by glare were surpassed by the TC glazing. These finds are not in agreement with those obtained in the simulation study by Tällberg et al. [27], where energy consumption with the EC glazing was lower than with the TC glazing for south-oriented windows under temperate and continental climates, considering the real thermal and optical property values. This discrepancy of results can be explained by the lower WWR adopted by Tällberg et al. [27] and by the difference between the TC glazing properties used in the studies.

As expected, the percentage of annual working hours with useful illuminance levels, for a north orientation, suffered a negative impact in the presence of the glazing solutions with solar control (clear glazing with SCF, TC glazing, and EC glazing). However, it is worth mentioning that the EC glazing with glare control resulted in the lowest decrease in the useful illuminance levels (1–2%) for a north orientation. For south and west solar orientations, the TC glazing made it possible to achieve between 10–23% and 3–11% of annual working hours with useful illuminance levels, respectively. Even though the EC glazing controlled by temperature showed significant increases (34–72%) in annual working hours with imperceptible glare, considering the south solar orientation, its performance was surpassed by the clear glazing with SCF in London (51%) and Berlin (51%), which promoted a static/continuous type of solar control.

When assessing thermal comfort under a free-float regime, the EC glazing with temperature control presented the highest increases in annual working hours (6–33%) within thermal comfort, for a west orientation. With the HVAC system operating, all glazing systems were found to decrease the percentage of working hours within thermal comfort under the cold climates of the cities of London and Berlin.

It is noteworthy to mention that the findings that resulted from the methodology of this work (Section 2) were influenced by limitations that can act as constrains when generalizing the research findings, such as, specifically: office room and glazing system geometry; glazing solutions with characteristic thermal and optical properties; climates; specific occupation and equipment operation schedules; comfort conditions imposed; solar orientation; type and energy efficiency of the climatization system; and software used. The same opaque elements of the envelope were adopted for the different locations/climates to allow a direct glazing performance comparison between the different climate conditions. However, it is important to note that this decision can negatively affect the glazing performance results under the cold climates of London and Berlin, since the regulatory requirements were not taken into account, and high heat exchanges are expected to occur due to low temperature levels. Even though EnergyPlus [70] is a well-established energy simulation program commonly used by engineers, architects and researchers, its ability to compute the visual performance of the assessed glazing systems can be considered limited because of its difficulty in solving for the internal reflectance of solar radiation, which results in an overestimation of the computed illuminance. A co-simulation strategy between EnergyPlus and Radiance could be more appropriate to assess the visual performance; nevertheless, for small square office rooms, such as the one used as the case study, the difference between the computed illuminance values of EnergyPlus and Radiance is less than 20% [86]. Still, regarding the visual performance assessment, the glare metric chosen (DGI) can act as a limitation, since it is based on the effect of contrast between adaptation luminance and a bright element in the field of view, and this metric is considered to have a less robust performance in daylight-dominated spaces [87,88].

6. Conclusions

This study comprises a multiple performance assessment of an EC glazing, controlled by indoor glare or temperature levels. Both energy performance and indoor (visual and thermal) comfort were evaluated under the main European climates, through a calibrated simulation model of an office room for a refurbishment scenario. The impact of solar orientation on the performance of the EC glazing was also assessed and compared to the performance of a clear glazing with a solar control film and a TC glazing, considering a clear glazing without film as the reference.

Regarding performance of the EC glazing oriented to the southeast, the following conclusions can be drawn:

- The EC glazing controlled by temperature levels reduced climatization needs. However, its negative impact on artificial lighting and higher control energy use resulted in higher annual total energy use. The lowest annual total energy use was achieved with glare control under the climate of London.
- Annual working hours (74–80%) with useful illuminance levels increased with glare control. Even though indoor glare levels were significantly reduced with temperature control, annual working hours with insufficient illuminance (48–79%) suffered a considerable increase.
- Even though temperature control showed a better performance (21–43%) under free-float, glare control showed a better performance (46–93%) when considering the operation of the HVAC system.

Regarding the comparative analysis of the impact of solar orientation on the performance of the different glazing solutions, the following conclusions can be drawn:

- The EC glazing controlled by glare was the only glazing solution that achieved energy savings for all solar orientations under the climates of Lisbon (9–36%) and London (2–16%). Even though it achieved the highest energy savings for a west orientation (up to 36%), it was surpassed by the TC glazing for the east (up to 46%) and south (up to 55%) orientations.
- The EC glazing with glare control had the lowest negative impact (−2%) on useful illuminance levels for a north orientation. The TC glazing was more efficient in regards to illuminance control for a south (10–33%) and west (3–12%) orientation. The EC glazing controlled by temperature significantly increased imperceptible glare levels when oriented south (34–72%), only being surpassed by the SCF glazing in London (51%) and Berlin (51%).

- Considering free-float regime, the EC glazing with temperature control was the most effective at promoting thermal comfort for a west orientation (3–33%). With the HVAC system operating, all glazing systems were found to decrease thermal comfort under cold climates.

This study has provided important insights regarding the potential for implementing EC glazing in largely glazed buildings for refurbishment scenarios, under different European climates. Further studies on the performance of EC glazing could be conducted to complement the research findings on the topic, such as: a parametric analysis to help understand the impact of construction aspects and glazing properties on performance; economic and environmental analyses; and comparing its performance with other dynamic glazing technologies, such as photochromic glazing.

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CO_2	carbon dioxide
Cv(RMSE)	coefficient of variation of the root mean square error
DGI	daylight glare index
DGP	daylight glare probability
EC	electrochromic
HVAC	heating, ventilation, and air conditioning
NMBE	normalized mean bias error
PMV	predicted mean vote
SCOP	seasonal coefficient of performance
SEER	seasonal energy efficiency ratio
TC	thermochromic
UDI	useful daylight illuminance

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