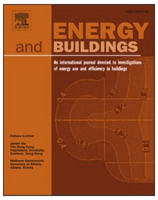
Energy & Buildings 364 (2026) 117625

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb



# Assessing energy, thermal and visual performance of photochromic glazing: From spectrophotometric characterization to building simulations

Henriqueta Teixeira [a,b,c,*], A. Moret Rodrigues [a], Daniel Aelenei [d,e], M. Glória Gomes [a]

[a] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[b] IST-ID, Av. António José de Almeida, 1000-043 Lisbon, Portugal
[c] Laboratório Nacional de Energia e Geologia, Campus do Lumiar 1649-038 Lumiar, Portugal
[d] UNINOVA-CTS, Department of Civil Engineering, Faculty of Science and Technology, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal
[e] LASI, 4800-058 Guimarães, Portugal

## ARTICLE INFO

*Keywords:*
Photochromic glazing
Spectrophotometric tests
Dynamic simulation
Energy performance
Visualcomfort
Thermal comfort

## ABSTRACT

Photochromic (PC) glazing is a promising smart glazing solution for enhancing buildinǵs energy efficiency and indoor comfort through its ability to dynamically adjust its optical properties in response to solar radiation. However, studies assessing the global (energy, thermal and visual) performance of this technology are scarce. This work evaluates the performance of a clear double glazing incorporating a PC film. Spectrophotometric tests were first conducted to determine the thermal and optical properties of the PC film, revealing a dynamic visible transmittance and a low UV and near-infrared transmittance. Subsequently, a previously calibrated dynamic simulation model of an office room was used to assess the impact of the PC film on energy consumption (climatization energy needs and energy use considering an ideal air-conditioning system) and indoor comfort (in accordance with useful daylight illuminance, daylight glare index, predicted mean vote, adaptive thermal comfort model and Portuguese legislation) during working hours (9am-6 pm of weekdays) across the climates of three European cities (Lisbon, Berlin and London). The results show that PC glazing can reduce cooling demand in all studied climates. Total energy use decreased by up to 10% in the warmest of the studied climates, while slight increases were observed in the colder climates. Visual comfort improved significantly, with up to 24% and 74% more working hours with useful illuminance and imperceptible glare levels, respectively. Thermal comfort analysis revealed a negligible change in free-float conditions during working hours, and an improvement of up to 20% when the HVAC system was operating.

## 1. Introduction

Buildings with large glazed façades have been become increasingly common in current architectural design, particularly in commercial buildings. However, conventional glazing systems are usually associated with significant heating and cooling energy needs [1] due to their high thermal and solar transmittances, which can lead to high energy consumptions and thermal discomfort for occupants [2]. In addition, their high visible may also lead to excessive illuminance levels and potential glare problems [3]. These limitations can be mitigated through shading devices, which reduce solar gains [4,5]; although, occupants often perceive the partial or total blockage of light as an inconvenient.

The demand for highly efficient buildings with nearly zero energy needs has encouraged the adoption of smart materials and the development of smart glazing technologies aimed at improving energy performance, visual comfort and overall building sustainability. Smart glazing technologies [6] represent a significant breakthrough in this respect. Some systems can dynamically alter (either autonomously or user-controlled) optical or thermal properties, in response to external stimuli such as solar radiation, temperature or electrical power, while others are capable of transforming energy. Chromogenic smart glazing technologies [7] such as electrochromic, thermochromic, gasochromic and photochromic, achieve different tinting states to better manage solar heat gains and daylight transmission. Electrochromic and gasochromic technologies feature active control, requiring manual or automatic control system to change between states, which requires more

---

* Corresponding author at: CERIS, IST-ID, LNEG, Portugal.
*E-mail addresses:* henriqueta.teixeira@tecnico.ulisboa.pt (H. Teixeira), moret.rodrigues@tecnico.ulisboa.pt (A. Moret Rodrigues), aelenei@fct.unl.pt (D. Aelenei), maria.gloria.gomes@tecnico.ulisboa.pt (M.G. Gomes).

https://doi.org/10.1016/j.enbuild.2026.117625
Received 2 December 2025; Received in revised form 13 April 2026; Accepted 9 May 2026

complex manufacturing and installation processes. In contrast, photochromic and thermochromic technologies operate passively, reacting autonomously to environmental stimuli, without the possibility of externally controlling the switching between states.

Photochromic (PC) glazing [8] is an emerging smart glazing technology that can autonomously and reversibly alter its optical properties in response to solar radiation, particularly in the ultraviolet (UV) range. Due to the presence of photosensitive crystals, the glazing remains clear in the absence of solar radiation, but darkens within minutes when exposed to sunlight, thereby reducing solar gains. Recent reviews [9,10] and research articles [11,12] on the performance of smart glazing technologies highlight the potential of PC glazing as a passive technology, capable of regulating solar control in buildings. However, the scientific literature on this glazing technology is less vast and mature than that of other smart glazing solutions, such as electrochromic and thermochromic glazing, which are established technologies on the market [13].

Despite its potential, research studies focusing on the performance of PC glazing in buildings' façades are still limited and the existing literature remains fragmented. Most studies focus on the energy performance of PC glazing, followed by daylight performance. Tällberg et al. [14] analysed the performance of PC glazing against clear glazing and other chromogenic glazing systems across different climates using dynamic simulations, reporting slightly higher energy use with the PC glazing compared to the clear glazing due to higher heating and artificial lightning energy demand. Cannavale et al. [15] examined the energy and visual performance of a PC glazing against clear and selective glazing systems using dynamic simulations, finding energy savings of up to 20%, an increase of useful illuminance levels of up to 20%, and a reduction of uncomfortable glare levels of up to 37%. Nicoletti et al. [16] employed a simulation model calibrated with experimental data to evaluate the energy and visual performance of a PC glazing against clear and low-emissivity glazing systems, reporting annual energy savings of up to 9%, and improved useful illuminance levels by up to 6%. Khaled et al. [17] assessed the energy and visual performance of five PC films with different spectral modulations installed on clear glazing across multiple climates using a dynamic simulation model, reporting energy consumption reductions of up to 14 kWh/m$^2$ and improved daylight distribution. More recently, Khaled et al. [18] conducted a full-scale experimental study in outdoor test cell facilities to evaluate a PC film, reporting a reduction of 30–50% on overheating, 17% on excessive light, and 9% pf discomfort glare probability. Aste et al. [19] analysed the colour rendering performance of multiple smart glazing technologies, concluding that PC glazing can significantly alter the spectral composition of the daylight transmitted through the window, which can have implications for visual comfort (lower colour fidelity and saturation). A more recent study [20] that examined PC coatings with different colour shades and combinations, showed that PC glazing can improve visual comfort and glare control in office rooms, particularly when considering films with the combination of red, blue and yellow.

Although several studies evaluated the energy and visual performance of PC glazing, the impact of this glazing solution on thermal comfort remains poorly explored. Addressing this research gap is essential for understanding the overall performance of PC glazing. Accordingly, given the promising potential of installation of PC glazing on building façades and the limited literature addressing its overall performance, this study was guided by the following research questions: (i) "What is the energy performance of PC glazing, in terms of climatization and artificial lighting, across different climates?"; (ii) What is the impact of PC glazing on visual comfort, considering the trade-off between daylight availability and glare mitigation, across different climates?"; (iii) "What is the impact of PC glazing on thermal comfort, under both free-float and air-conditioning conditions, across different climates?". To answer these research questions, the aim of this study was to investigate the holistic energy, thermal and visual performance of a clear double-glazing system with and without a commercially available PC film. The analysis adopts as case study an office room under three main European climates. The work comprises (i) spectrophotometric tests to characterize the gradual tinting behaviour of the PC glazing and (ii) dynamic simulation modelling using Energy Management System of EnergyPlus [21] to assess the impact of the film on the energy performance and indoor thermal and visual comfort conditions.

## 2. Materials and methods

The methodology adopted in this study, which combines spectrophotometric tests with dynamic simulations of clear and PC glazing systems, is shown in Fig. 1. It is important to note that although some previous studies by the authors have evaluated PC glazing [22,23], these studies focused on experimental characterisation with less complex spectrophotometric tests without a solar simulator, small-scale testing, or real-occupancy monitoring, being limited in terms of climate representativeness, control strategies, comfort metrics, used equipment and collected variables. In addition, it is worth highlighting that the calibrated simulation model used in this study was originally developed by the authors in a previous study [24], but only the calibration framework was reused, with the glazing technology, optical behaviour and control strategy differing between studies. The present study introduces methodological advances that were not considered in these previous studies.

In the present study, the analysis focused on a double clear glazing used as reference and a double PC glazing consisting of the same clear glazing with a PC film applied. The reference glazing sample (without film) is referred to as "REF" and the photochromic glazing sample as "PC" throughout this work. Spectrophotometric tests were initially conducted over two single clear glass samples, respectively with and without PC film, to obtain the corresponding transmittance and reflectance spectra. During these tests, a solar simulator was used to expose the PC glazing to varying intensities and durations of incident solar irradiance, enabling the achievement of gradual tinted states. The spectral data from both samples were then processed by dedicated software (Optics [25] and Window [26]) to determine the optical properties of the glass panes that were used to compose the two glazing solutions whose performance is analysed and assessed in this study. The relevant performance data for each solution were obtained by running multiple dynamic simulation scenarios, considering different weather input files, with a calibrated model of an individual office room (EnergyPlus [21]). Output variables of temperature, glare, illuminance and energy were selected to assess both the energy performance and indoor thermal and visual comfort with the clear and PC glazing systems.

The PC film, manufactured with nanoceramic technology and made of polyethylene terephthalate (PET) material, has a thickness of 55 μm. This film comprises multiple material layers, from inside to outside: protection release liner, pressure-sensitive adhesive, high optical quality PET, bonding adhesive, high optical quality PET with anti—IR particles deposition, scratch resistant layer. The PC film is intended for installation on the interior surface of glazing systems of building façades and tints in the presence of UV radiation to provide shade, as stated by the manufacturer. The emissivity and spectral optical properties of the fully tinted and fully clear states of the PC film were previously determined by the authors [22], using an UV lamp to tint the film. The methodology adopted in the present study for the spectrophotometric tests represents an improvement by incorporating a solar simulator that allows a more accurate characterization of the dynamic behavior of the film, making it possible to capture the gradual evolution between clear and tinted states and, consequently, enabling a simulation of the performance of the film closer to real-world conditions. The bleaching/recovery kinetics was not assessed in the present study, but according to the findings of a previous study by the authors [22], the chromatic change occurs rapidly during the first minutes and stabilizes after, approximately, 10 min, reaching the fully tinted state after 15 min. The visual and thermal performance of this film was also previously assessed by the authors [23] under real-occupancy conditions, in Lisbon, through an extended field

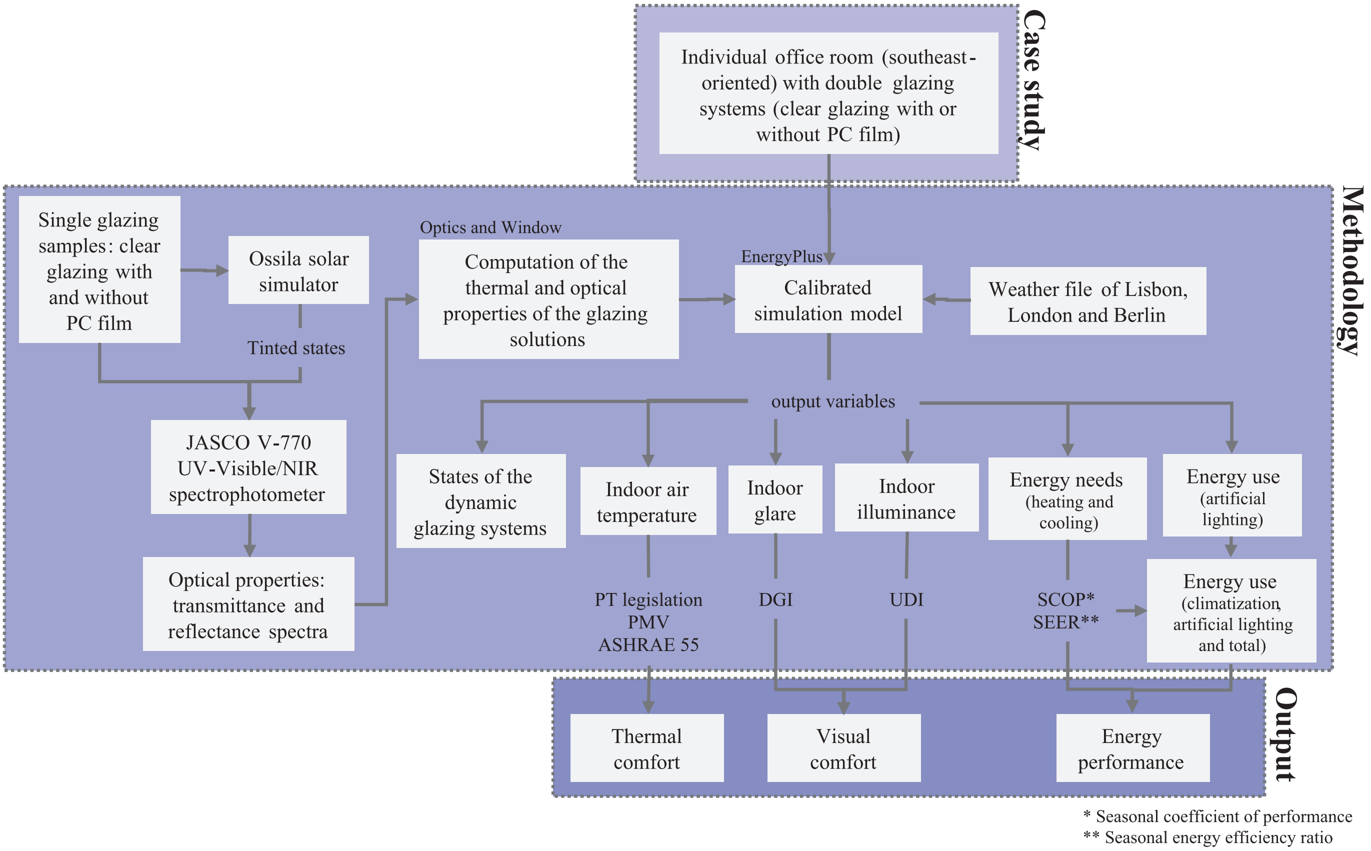


**Fig. 1.** Schematic of the methodology.

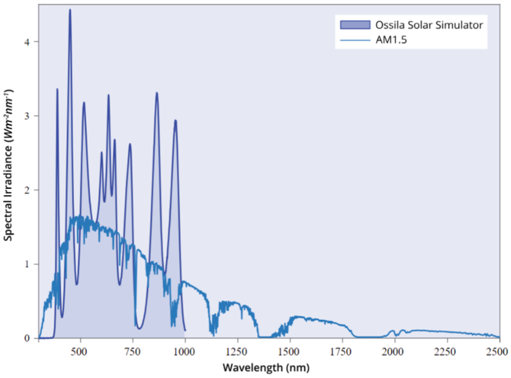
experimental campaign, achieving increases up to 14% and 7% of working hours within thermal comfort and with useful illuminance levels, respectively.

### 2.1. *Spectrophotometric tests*

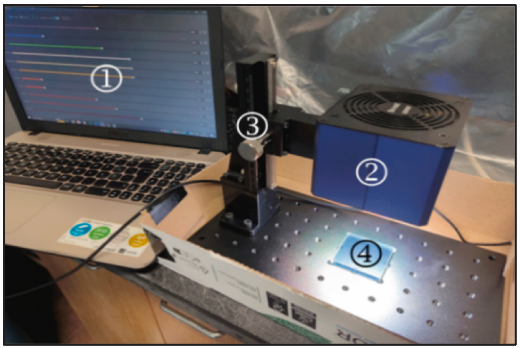
The spectrophotometric tests of this work consisted of measuring the global optical properties (transmittance and reflectance) of glazing samples using a spectrophotometer. Samples of 5x5cm of clear single 6 mm thickness glazing with and without the PC film installed were used, adopting the sample without film as reference. A single sample of clear glazing was tested due to its homogeneous monolithic nature. However, five samples of the PC glazing were tested, making it possible to reduce time consumption of the experimental procedure, while ensuring the full recovery of the clear state between measurements. The optical behaviour of the PC film was considered highly consistent across samples due to a maximum deviation of 3% between samples. Each glazing sample was carefully cleaned with a soft lint free cloth prior to the experimental measurements of the following properties: transmittance, and reflectance of the front and back glazing surfaces.

The Ossila solar simulator (model G2009) [27], which provides a class AAA (spectral match, spatial non-uniformity and temporal instability in accordance with [28]) spectral distribution over a 15 mm diameter area, was used to tint the PC glazing sample before placing it inside the integrating sphere of the spectrophotometer. This solar simulator comprises an array of powerful LEDs to accurately simulate the AM1.5G spectrum over a wavelength range of 350–1050 nm (Fig. 2a). The intensity of each individual LED, as well as the total irradiance output, of the solar simulator can be controlled through the Ossila Solar Simulator Console software [29]. The experimental setup to tint the PC glazing sample before the spectrophotometric tests is shown in Fig. 2b. To obtain different tinted states, the PC glazing was exposed to multiple solar irradiance levels by varying the distance to the solar simulator lamp (range of 5–9 cm with 1 cm intervals) and its total irradiance output (range of 20–100% with 20% intervals at a 10.5 cm distance from the sample). When varying the distance, the irradiance output was kept at 100%. For the largest distance between the sample and the solar simulator, the irradiance output was varied (between 20% and 100%). A CMP3 pyranometer from Kipp&Zonen [30], which has a flat spectral response between 300–2800 nm, was used to measure the multiple solar irradiance levels considering distance and irradiance output variation (Fig. 2c). Solar irradiance levels between, approximately, 55 W/m$^2$ and 1733 W/m$^2$ were obtained. It is important to note that the extreme solar irradiance level (1733 W/m$^2$) does not represent a realistic building exposure, as it was applied exclusively to force the PC film into its fully tinted state, thereby enabling the experimental capture of its limiting spectral condition. This characterization of the dynamic behavior of the PC glazing was necessary to define its full modulation range prior to implementation it in the simulation model. The PC glazing was exposed to each solar irradiance level during different time intervals (1 min, 5 min and 10 min) to investigate the influence of the exposure time on the dynamic behavior of the film. These spectrophotometric measurements were repeated twice, with a variability below 2%, which confirmed the repeatability of the procedure. The variation rate between the measured transmittance values obtained with 1 min versus 5 min exposure and 5 min versus 10 min exposure to the different solar irradiance levels was computed.

The spectrophotometer JASCO V-770 UV–Visible/NIR [32], which features a unique single monochromator design that allows maximum light throughput with excellent absorbance linearity, was used for the spectrophotometric tests. Measuring a wavelength range of 190–700 nm, the spectrophotometer comprises a photomultiplier tube for the UV to visible range and a Peltier-cooled polycrystalline lead sulphide detector for the NIR region. The wavelength accuracy is ± 0.3 nm at

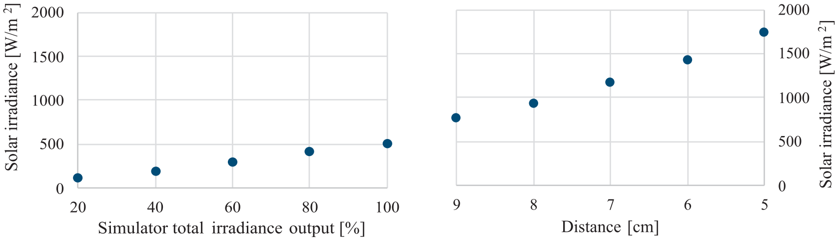


a.



① Solar simulator software ② Solar simulator
③ Height adjustable stage ④ Glazing sample

b.



c.

① JASCO V-770 UV-Visible/NIR spectrophotometer ② Lid of the sample compartment
③ 60 mm UV-Visible/NIE integrating sphere ④ Spectrophotometer software
⑤ Carbon lid tinted black ⑥ Ossila solar simulator ⑦ Solar simulator software

d.

**Fig. 2.** Spectrophotometric tests: a. Spectral irradiance graph of the solar simulator at 1000 W/m$^2$ provided by the manufacturer [31]; b. Experimental setup for tinting the PC glazing sample; c. Solar irradiance incident on the PC glazing sample, in W/m$^2$, measured with the pyranometer, varying the total irradiance output of the simulator (left) and the distance from the lamp (right); d. Experimental setup of the spectrophotometric tests.

651.1 nm and ± 1.5 nm at 1312.2 nm. The scanning speed of the spectrophotometer varies between 10 to 4000 nm/min. The 60 mm UV–Visible/NIR integrating sphere fits directly into the sample compartment and was utilized to measure the hemispheric transmittance and reflectance of the samples by collecting both scattered and direct components of the radiation. The spectrophotometer was operated through the innovative cross-platform molecular spectroscopy software Spectra Manager™ Suite installed in a computer, which is connected to the spectrophotometer. The experimental setup for the spectrophotometric tests is shown in Fig. 2d. When stimulating the dynamic behavior of the PC sample, a carbon lid with the interior painted black was used to cover the solar simulator and avoid exposition from solar irradiance in the room. After placing the sample in the spectrophotometer and before ordering the data scanning, the correct closer of the lid of the sample compartment was carefully verified to avoid the entrance of light.

The transmittance and reflectance (back and front) spectra obtained for the REF glazing and the PC glazing in the clear state and tinted states were used as input in Optics [25] and Window [26] software to compute the optical and thermal properties of the analysed glazing solutions. The spectra obtained from the spectrophotometer were limited to the 300–2500 nm wavelength range and a data interval of 5 nm was applied, as required by the software. An individual glazing file was assembled for each state of the PC glazing. In addition to the spectra, it was also necessary to input the thermal transmittance of the glazing solutions ($\varepsilon_{REF} = 0.84$; $\varepsilon_{PC} = 0.89$), which were previously measured by the authors [22] using the analytical instrument TIR100–2 [33].

### *2.2. Dynamic simulation*

An individual office room (floor area of 19 m$^2$ and window-to-wall ratio of 81% oriented Southeast) located at Instituto Superior Técnico, in Lisbon, was adopted as case study in the dynamic simulation analysis. A simulation model [24] of the office room constructed in EnergyPlus [21], previously calibrated (NMBE: −11.5–0.49%; Cv(RMSE): 4.41–22.60%) with experimental data [34], was used to evaluate the energy, thermal and visual performance of clear glazing versus photochromic glazing during working hours (9 a.m. to 6 p.m.).

The assessed glazing solutions consisted of double clear glazing (6 mm + 12 mm air + 4 mm) with and without the PC film installed on the interior glass surface in accordance with the technical sheet. The dynamic behaviour of the PC glazing was programmed through modelling routines (with actuators, sensors and control logic) in the Energy Management System of EnergyPlus [21], complying with the solar irradiance levels of the spectrophotometric tests. The Energy Management System selects the PC glazing state based on the solar irradiance incident on the window, as derived from the realistic solar radiation levels in the EPW weather files. The extreme irradiance levels used in the laboratory tests were applied solely to determine the fully tinted spectrum and do not correspond to the irradiance levels used in the dynamic simulations.

An ideal HVAC system with a deadband 20-24°C (representative of the existing HVAC system), was considered to be operating during working hours to compute the climatization (heating and cooling) energy needs. The energy performance metrics of the existing HVAC system (seasonal energy efficiency ratio of 7.98 and seasonal coefficient of performance of 4.43) were used to compute the climatization (heating and cooling) energy use. Although an ideal HVAC system was used to compute the heating and energy requirements in the presence of each glazing solution, the performance metrics of the actual HVAC system installed in the office room made it possible to achieve a more realistic energy use in this case study. Thermal comfort was assessed through different metrics: Portuguese legislation (20-25°C comfort range for commercial buildings) [35], ASHRAE 55 adaptive model (80% acceptability range) [36] and predicted mean vote (PMV) (−0.7–0.7comfort range for category B of [37]). Visual comfort was assessed through the useful daylight illuminance (UDI) [38] and daylight glare index [39] metrics.

The weather data files of three cities (Lisbon, London and Berlin), representative of the main European climates, were considered as input in the simulation to evaluate the impact of climate conditions on the performance of the glazing solutions. These weather data files, in EPW format, were retrieved from the EnergyPlus website [40] and represent typical meteorological years for Lisbon (data source: Instituto Nacional de Engenharia, Tecnologia e Inovação; data period: 2005), London (data source: 2001 American Society of Heating, Refrigerating and Air-Conditioning Engineers; data period: 1991) and Berlin (data source: 2001 American Society of Heating, Refrigerating and Air-Conditioning Engineers; data period: 1984). A brief geographical and climatic characterization of these locations is presented in Table 1.

## 3. Spectrophotometric results

The results of the spectrophotometric tests of the clear single glazing with and without PC film are presented in this section.

### *3.1. Transmittance and reflectance spectra*

Fig. 3a illustrates the transmittance and reflectance (front and back) spectra of the REF glazing. As expected, this glazing exhibits high transmittance values across the spectrum, with an average transmittance value of 89% in the range 400–2500 nm. Since this glazing sample does not have any coating or film, the back and front reflectance spectra are equal and appear overlapped in the Fig. 3a.

The transmittance and reflectance (front and back) spectra obtained for the PC glazing in the fully clear state are also shown in Fig. 3a. The PC glazing exhibits low transmittance values across the spectrum, compared to the REF glazing, particularly in the infrared range (800–2500 nm) with average and minimum values of 13% and 6% (at 1674 nm), respectively. Contrary to the REF glazing, the transmittance spectrum of the PC glazing presents extremely low values in the UV range, which can be beneficial for occupants' health and material durability of spaces. The highest transmittance value of 79% in the visible range of the PC glazing spectrum occurred at 490 nm. Due to the lower transmittance spectrum of the PC glazing, compared to the REF glazing, it is possible to state that the PC glazing can provide solar control even in its fully clear state. The back and front reflectance spectra of the PC glazing are similar, with the back reflectance spectrum exhibiting slightly lower values.

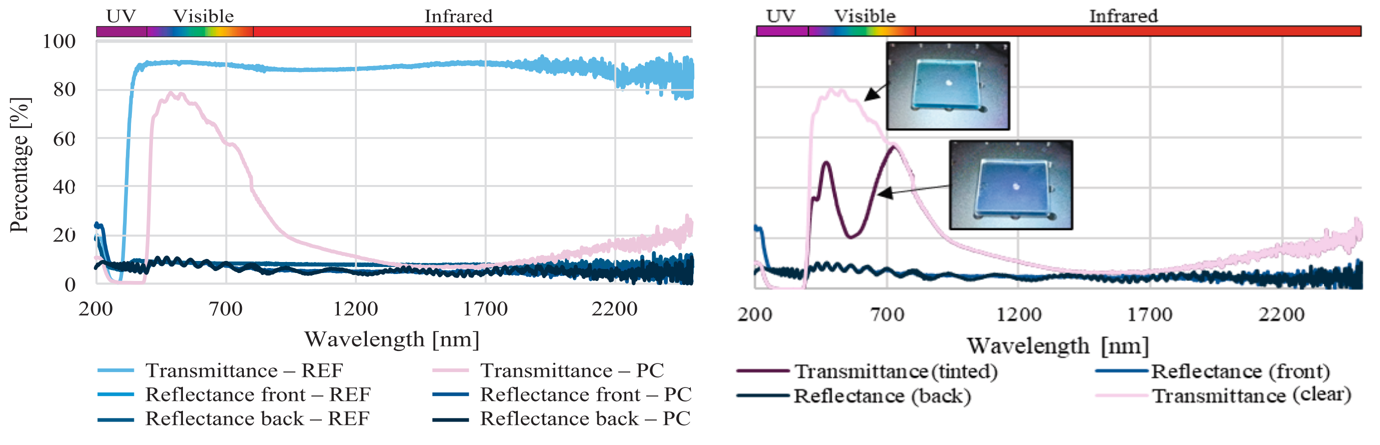
The PC glazing sample was exposed to the highest solar irradiance level (1733 W/m$^2$) for 1 min to assess its impact on the dynamic behaviour of the film. The obtained transmittance and reflectance (front and back) spectra of the tinted PC glazing are shown in Fig. 3b, along with the spectra of the PC glazing in the fully clear state. The back and front reflectance spectra were not influenced by the solar irradiance exposure, appearing overlapped in Fig. 3b. However, a significant change in the transmittance spectrum can be observed in the visible range. The transmittance spectrum of the tinted sample exhibits a low point at 566 nm, with a transmittance value of 21% which is representative of a reduction of 72% compared to the PC glazing in the clear state. Since the reflectance spectra do not change in the presence of incident solar irradiance and a notorious reduction in the transmittance spectrum was observed after irradiance exposure, this dynamic behaviour implies an increase in the solar absorptance of the glazing sample (transmittance + reflectance + absorptance = 1).

As mentioned, the PC glazing sample was exposed to different solar irradiance levels (Fig. 2c) during 1, 5 and 10 min to assess its dynamic behaviour. Since the tinting response of the PC film is limited to the visible range, transmittance measurements were performed for wavelength between 350–800 nm. This narrower wavelength range also ensures that the PC glazing does not reverse to its clear state during the spectrophotometer readings.

The transmittance spectra of the PC glazing exposed to the multiple solar irradiance levels for the different times (1, 5 and 10 min), along with the transmittance spectra of the PC glazing in the clear state and the REF glazing, between 350–800 nm, are shown in Fig. 4a. It is possible to observe that, as expected, for higher incident solar irradiance levels, lower transmittance values were obtained for the tinted PC glazing. The spectra obtained after 1-min exposure to 1424 W/m$^2$ and 1733 W/m$^2$ solar irradiance levels are similar. The obtained transmittance values of the tinted PC glazing with 5-min exposure were significantly lower than the ones measured with 1-min exposure. Large discrepancies of transmittance values were obtained between the PC glazing in the clear state

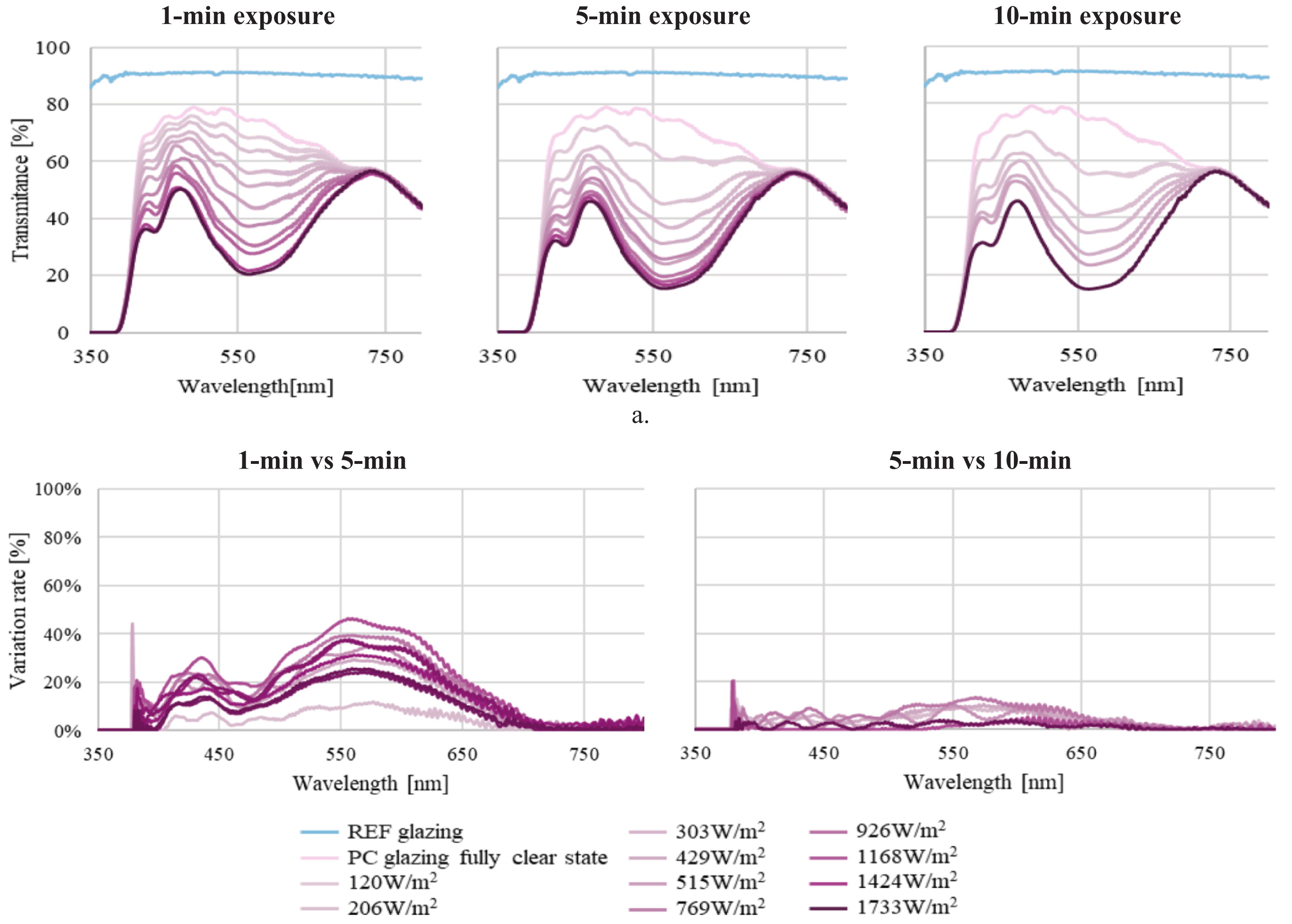
**Table 1**
Geographical information and climatic characteristics of the three cities (Lisbon, London and Berlin).

| City | Latitude [°] | Longitude [°] | Köppen-Geiger climate classification [41] | Monthly average global solar radiation [Wh/m$^2$] | | Dry-bulb temperature [°C] | |
|---|---|---|---|---|---|---|---|
| | | | | Minimum | Maximum | Minimum | Maximum |
| Lisbon | 38.7 N | 9.2 W | Mediterranean (Csa) | 1947 | 7348 | 4.1 | 36.0 |
| London | 51.2 N | 0.2 W | Marine west coast (Cfb) | 549 | 5020 | −5.9 | 31.3 |
| Berlin | 52.5 N | 13.4E | Warm-summer humid continental (Dfb) | 406 | 5109 | −9.1 | 32.8 |



a. b.

**Fig. 3.** A. transmittance and reflectance (front and back) spectra, from 200 to 2500 nm, of the REF glazing and the PC glazing in the fully clear state; b. Transmittance and reflectance (front and back) spectra, from 200 to 2500 nm, of the PC glazing clear and tinted states.



a.

b.

**Fig. 4.** A. transmittance spectra, from 350 to 800 nm, of the PC glazing exposed to different solar irradiance levels during 1 min, 5 min and 10 min, along with the transmittance spectrum of the REF glazing and the PC glazing in the fully clear state: b. Variation rate between the transmittance spectra, from 350 to 800 nm, of the PC glazing when exposed to different solar irradiance levels during 1 min versus 5 min and 5 min versus 10 min.

and when exposed to the minimum solar irradiance level, with 5-min exposure, and again between this tinted state and the one that resulted from exposure to 206 W/m$^2$ solar irradiance. The spectra of the PC glazing that resulted from the 5-min exposure to solar irradiance levels between 769 and 1424 W/m$^2$ are similar to the spectrum associated to the highest solar irradiance level. Since the spectra obtained for the PC glazing with 5-min exposure to solar irradiance levels of 769–1424 W/m$^2$ were similar to the spectrum that resulted from the exposure to the highest solar irradiance level, these solar irradiance levels were not tested for the 10–min exposure. Once more, the obtained transmittance values of the tinted PC glazing are lower with 10-min exposure, compared to the results of the 5–min exposure. However, the spectrum associated with the highest solar irradiance is similar between these two exposure times (5-min and 10-min).

Fig. 4b presents the computed variation rate for wavelengths between 350 nm and 800 nm. Focusing on the variation rate between the 1–min and 5–min exposure transmittance, larger variation rates can be observed for wavelengths between 400 nm and 650 nm, with values up to 47%. The high values obtained in the ultraviolet range can be explained by the extremely low transmittance values in this range. Regarding the variation rate between the 5-min and 10-min exposure transmittance, the obtained values are significantly low, compared to the variation rate between 1 and 5-min exposures. Disregarding the ultraviolet range, values up to 13% were obtained. Lower variation rates were computed for spectra associated with higher incident solar irradiance levels. Since the variation rates are significantly low, spectrophotometric tests covering longer exposure times were not conducted and the transmittance and reflectance spectra obtained with the 10-min exposure (Fig. 4a) were considered representative of the clear, intermediate and tinted states of the PC glazing. A 10-minute interval is also advised as the minimum timestep for dynamic simulations.

### 3.2. *Computation of the optical and thermal properties*

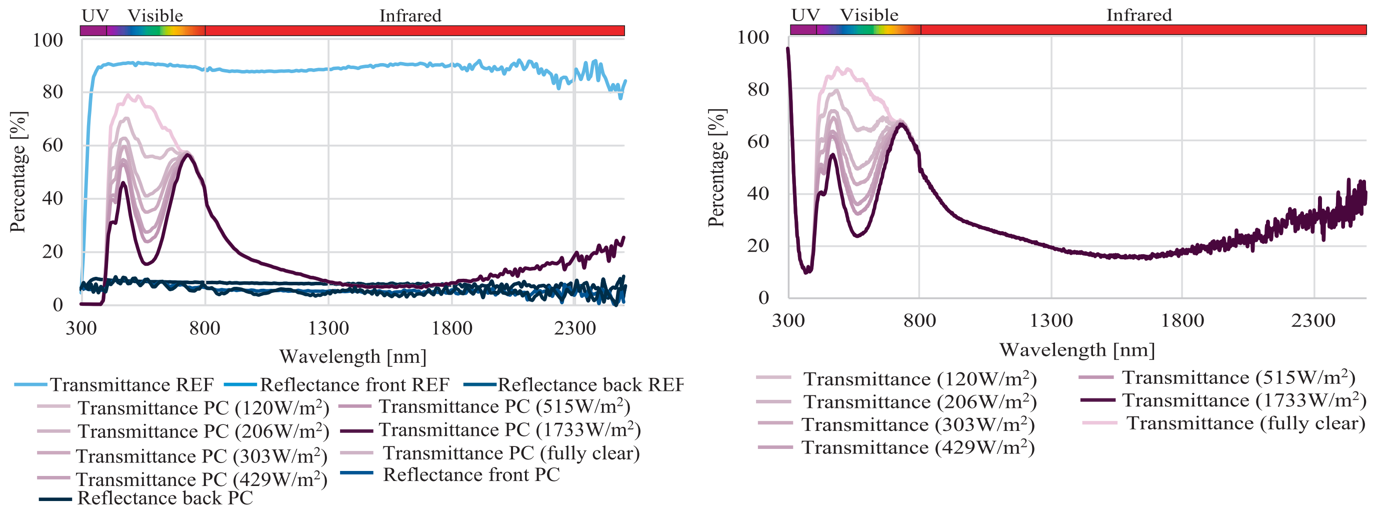
The transmittance and reflectance (front and back) spectra of the clear glazing and the PC glazing (10-min exposure time) were used as input in Optics [25] and Window [26] software. The adopted transmittance and reflectance spectra complying with the software spectra requirements referred in section 2.1 are shown in Fig. 5a. Using these spectra, the transmittance spectrum of the PC film without the glass substrate was computed by the software for each solar irradiance level (Fig. 5b). These computed spectra make it possible for Optics to apply the PC film to other glass substrates and create multiple filmed glazing solutions.

The computed optical and thermal properties of the REF glazing and the PC glazing in the different states, resulting from the input of the spectra and the thermal emissivity, are presented in Table 2. The presence of the PC film resulted in a significant change of the solar factor, transmittance and solar absorptance of the glazing. The solar factor reduced to 0.58–0.47 with the PC film. As expected from the previously measured transmittance spectra, a large variation of the visible transmittance (22–74%) between states was obtained for the PC glazing. A strong variation of the solar transmittance (25–41%) was also obtained, but with a narrower range compared to the visible transmittance. The PC film totally reduced the transmittance of ultraviolet radiation. A variation of the solar absorptance of the PC glazing between 53%, in the clear state, and 68% in the fully tinted state was obtained.

## 4. Simulation results

The results of the energy performance and visual and thermal comfort in the office room with clear double glazing, with and without the PC film, under the climates of the three European cities (Lisbon, London and Berlin), are presented in this section. The results of the glazing without film (adopted as reference) are referred to as “REF”, and the results of the glazing with photochromic film are referred to as “PC”.

As previously mentioned, the dynamic behaviour of the PC glazing depends on its exposure to sun radiation. Fig. 6a shows the dynamic behaviour (evolution of tinted states) of the PC glazing throughout the year, under the different climates. Since the glazed area of the office room is oriented southeast, higher tinted states were obtained during the morning period, as expected. It can be observed that under the hot climate of Lisbon, the PC glazing remains more time in the fully tinted state, compared to the results of the other cities. The dynamic behaviour is similar under the climates of London and Berlin. Fig. 6b shows the percentage of annual working hours with each tinted state of the PC glazing. Under the climate of Lisbon, which has the highest solar radiation levels (Table 1), the PC glazing was at the fully tinted state during 22% of working hours and at the fully clear state during only 2% of working hours. The intermediate states 3 to 5 have similar percentage values for Lisbon. The intermediate state 1 has the highest occurrence under the three climates, with values of 31%, 49% and 51% of working hours for Lisbon, London and Berlin. The percentage distribution of the tinted states is similar under the cold climates of London and Berlin, as expected from what was observed in Fig. 6a, with the intermediate states 1 and 2 having slightly higher percentage values for Berlin. The PC glazing exhibited its totally tinted state only during 9% of working hours under the colder climates.



a. b.

**Fig. 5.** A. transmittance and reflectance (front and back) spectra, from 300 to 2500 nm, of the REF glazing and the PC glazing used as input in Optics software; b. Transmittance spectrum, from 300 to 2500 nm, of the PC film without glass substrate.

**Table 2**
Thermal and optical properties of the glazing solutions analysed in the spectrophotometric tests, computed using Optics [25] and Window [26] software: thermal transmittance, $U$; solar factor, $g$; visible transmittance, $\tau_{vis}$; visible front, $\rho_{visF}$, and back, $\rho_{visB}$, reflectance; solar transmittance, $\tau_{sol}$; solar front, $\rho_{solF}$, and back, $\rho_{solB}$, reflectance; ultraviolet transmittance, $\tau_{UV}$; absorptance of the glass pane, $\alpha$.

| Single glazing | $U$[W/m$^2$K)] | g[-] | $\tau_{vis}$ [%] | $\rho_{visF}$ [%] | $\rho_{visB}$ [%] | $\tau_{sol}$ [%] | $\rho_{solF}$ [%] | $\rho_{solB}$ [%] | $\tau_{UV}$ [%] | α [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| Clear | 5.81 | 0.87 | 91 | 9 | 9 | 90 | 8 | 8 | 60 | 8 |
| Clear with PC film | 5.81 | | | 8 | 8 | | 6 | 6 | 0 | |
| Fully clear | | 0.58 | 74 | | | 41 | | | | 53 |
| Intermediate 1 | | 0.55 | 60 | | | 37 | | | | 57 |
| Intermediate 2 | | 0.52 | 47 | | | 33 | | | | 61 |
| Intermediate 3 | | 0.51 | 41 | | | 32 | | | | 62 |
| Intermediate 4 | | 0.50 | 35 | | | 29 | | | | 64 |
| Intermediate 5 | | 0.49 | 32 | | | 28 | | | | 65 |
| Fully tinted | | 0.47 | 22 | | | 25 | | | | 68 |

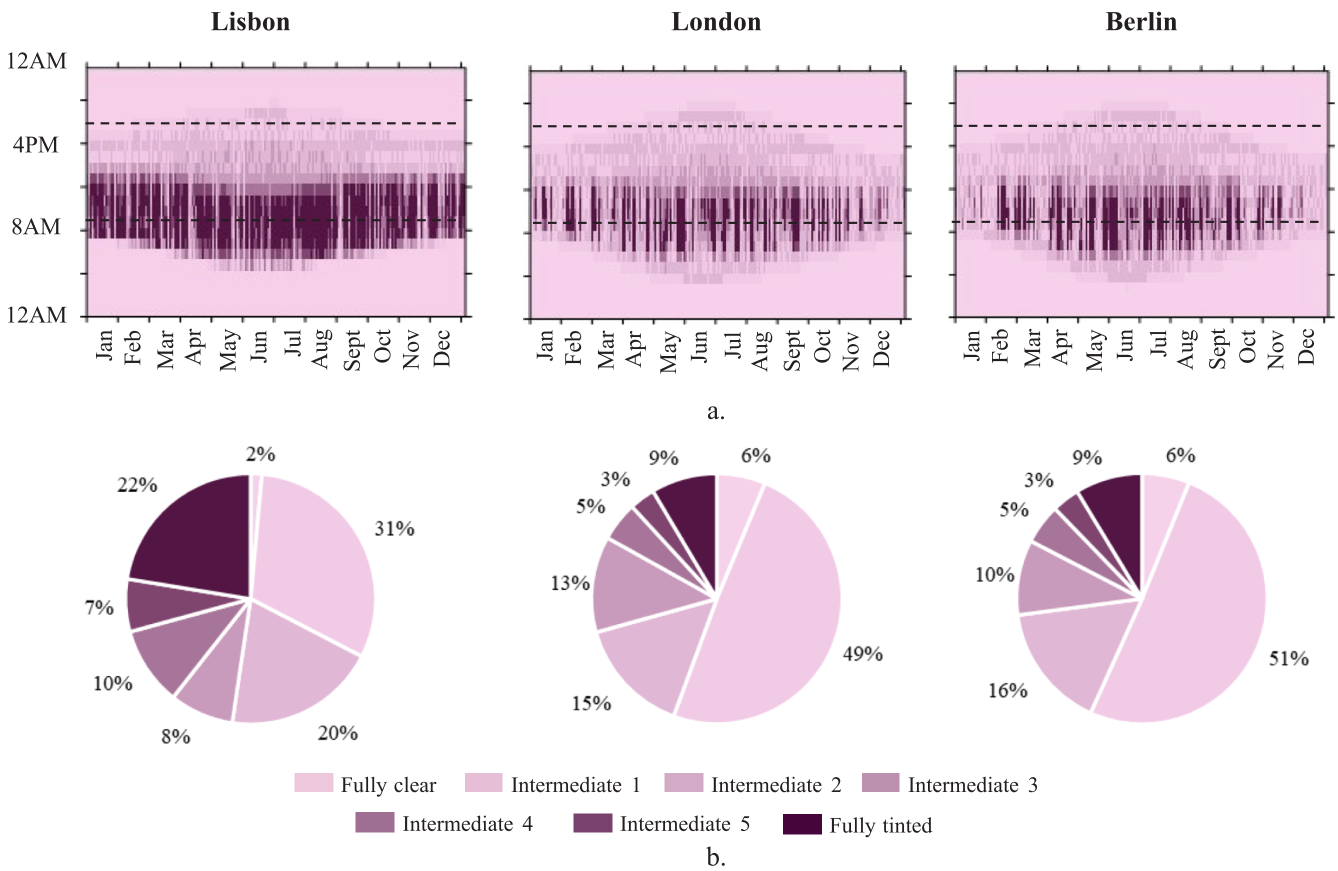


**Fig. 6.** Simulated tinted states of the photochromic film, under the climate of the three European cities: a. Tinted states throughout the year (working hours limit with dashed lines); b. Percentage of annual working hours with each tinted state.

### 4.1. *Energy performance*

The monthly and annual energy needs (heating and cooling) in the presence of the clear glazing with and without the PC film, under the different climates, is shown in Fig. 7a. The PC glazing reduced the cooling energy needs throughout the year in the three cities, particularly during summer months, compared to the clear glazing. However, heating energy needs increased during winter months in the cold climates of London and Berlin with the PC glazing. No heating needs were obtained in the hot climate of Lisbon, meaning all glazing solutions were responsible for excessive solar heat gains even during winter months. The PC glazing reduced by 19–22% the annual cooling energy needs, particularly in Lisbon (22%), compared to the clear glazing.

Fig. 7b shows the monthly and annual energy use (heating, cooling and artificial lighting) in the presence of the clear glazing with and without the PC film, under the different climates. For all cities, the artificial lighting energy use increased with the PC glazing throughout the year, compared to the clear glazing. The PC glazing reduced the total energy use in the city of Lisbon by 11% but increased the total energy use in London and Berlin by 13% and 9%, respectively, due to the increase of the artificial lighting and heating energy use.

### 4.2. *Thermal comfort*

Fig. 8a shows the percentage of monthly and annual working hours within thermal comfort (Portuguese legislation ranges) in the presence of the glazing system with and without PC glazing, under the three European climates. The PC glazing had a low impact on thermal comfort conditions for all locations, slightly increasing the percentage of working hours within thermal comfort during January in Lisbon and during

a.

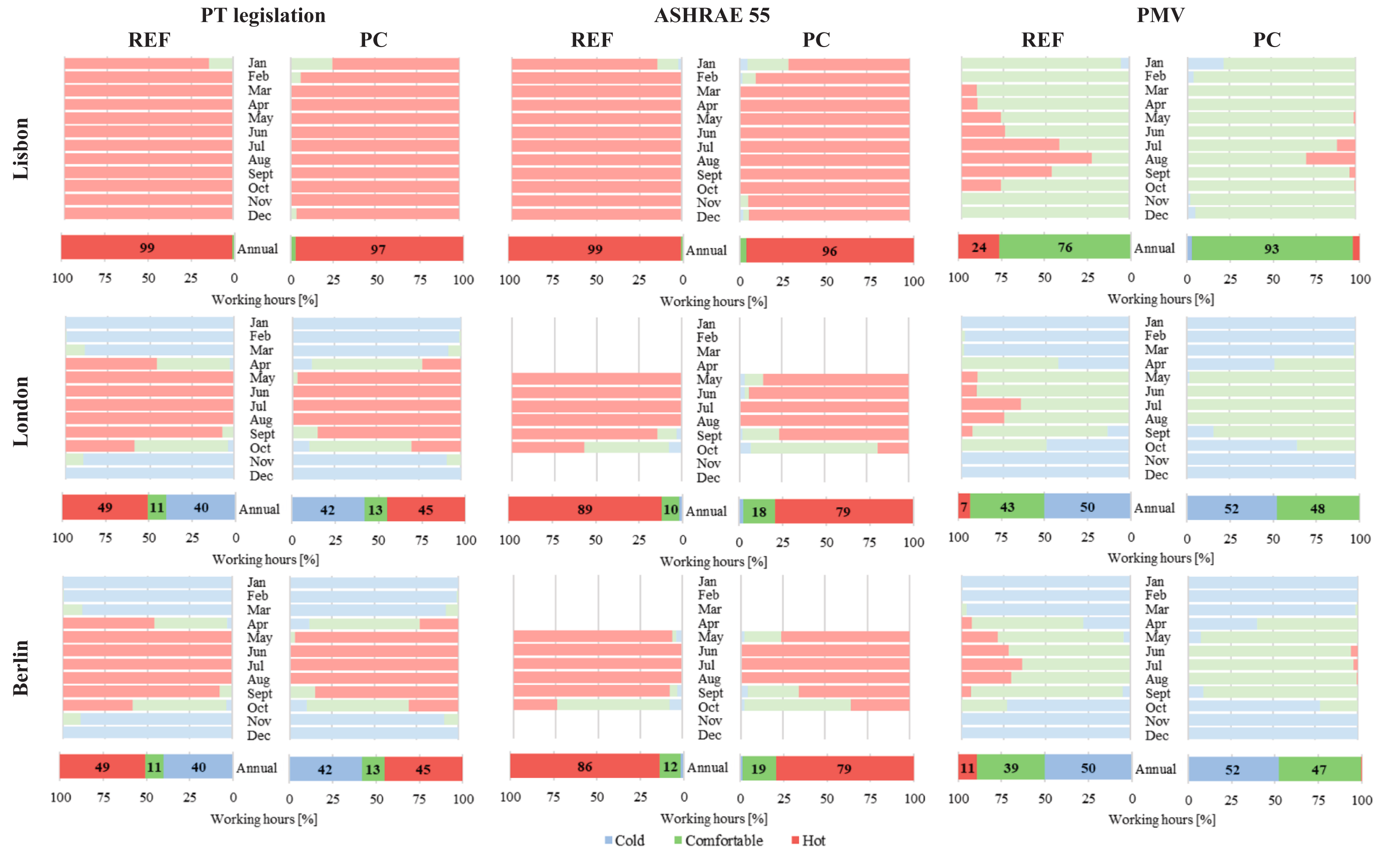
b.

**Fig. 7.** Simulated energy performance of the office room in the presence of each glazing system, under the climate of three European cities: a. Monthly and annual energy needs, in kWh/m$^2$; b. Monthly and annual energy use, in kWh/m$^2$.

April-May in London and Berlin. The PC glazing slightly increased the percentage of annual working hours within thermal comfort by 1–2%, for all locations, compared to the clear double glazing.

The percentage of monthly and annual working hours within thermal comfort (ASHRAE 55 adaptive model ranges) in the presence of the clear and PC glazing systems, under the three European climates, is shown in Fig. 8b. The PC glazing had a low impact on promoting thermal comfort conditions, increasing the percentage of working hours within thermal comfort during winter months in Lisbon and mid-season months in London and Berlin. The PC glazing increased the percentage (3–19%) of working hours within thermal comfort by reducing hot temperature levels, for all cities, particularly in London (18%) and Berlin (19%), compared to the clear double glazing (1–12%).

Fig. 8c shows the percentage of monthly and annual working hours within thermal comfort (PMV ranges) in the presence of each glazing system, under the three European climates. The percentage distribution of working hours in the different comfort ranges throughout the year, in accordance with this index, is very different from the one obtained with the two previous standards due to the operation of the HVAC system. The PC glazing significantly reduced the occurrence of hot temperature levels, for the three cities, achieving approximately 100% of working hours within thermal comfort throughout the year in Lisbon (except from July to September) and from May to August in London and Berlin. The PC glazing was effective on promoting thermal comfort, for all climates, achieving high percentage values of working hours with comfortable temperature levels (47–93%), particularly in the city of Lisbon (93%) where an increase of 30% was obtained compared to the clear double glazing.



a.

b.

c.

**Fig. 8.** Simulated thermal comfort conditions of the office room in the presence of each glazing system, under the climate of three European cities: a. Percentage of monthly and annual working hours within specific Portuguese legislation thermal comfort ranges, in %; b. Percentage of monthly and annual working hours within specific ASHRAE 55 adaptive model (80% acceptability) thermal comfort ranges, in %; c. Percentage of monthly and annual working hours within specific predicted mean vote thermal comfort ranges, in %.

### 4.3. *Visual comfort*

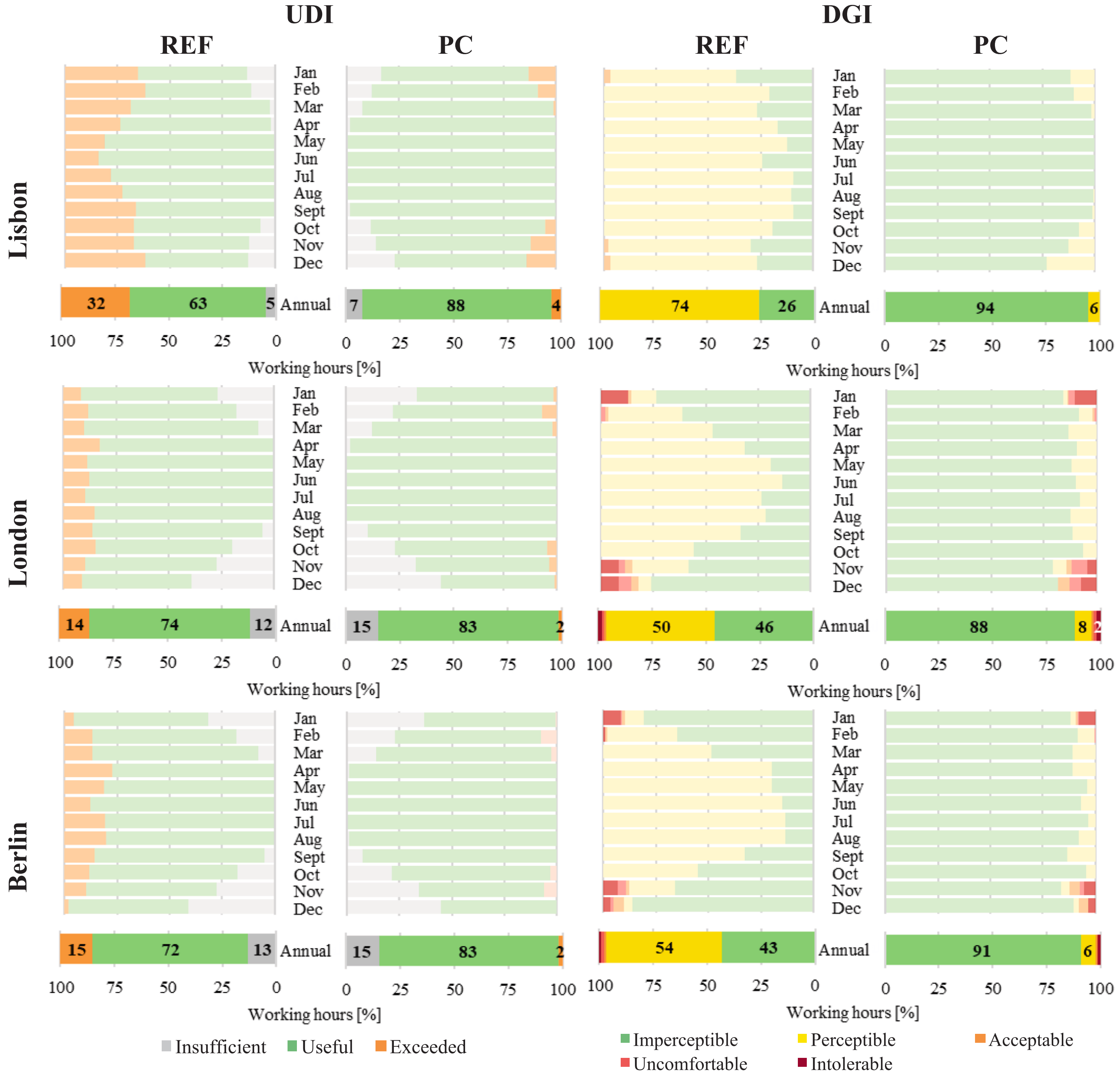
Fig. 9a shows the percentage of monthly and annual working hours within specific UDI levels in the presence of each glazing system, under the three climates. The PC glazing promoted useful illuminance levels throughout the year, for all locations, by reducing excessive illuminance levels, compared to the clear double glazing. Insufficient illuminance levels slightly increased with the PC glazing, compared to the clear double glazing. During summer months almost 100% of working hours had useful illuminance with the PC glazing, in the three cities. The PC glazing was effective on promoting useful illuminance levels in all locations, achieving high percentage values of 83–88%, against 63–74% with the clear double glazing. The slight increase of insufficient illuminance levels with the PC glazing resulted in an additional 2–3% of working hours with low illuminance compared to the clear double glazing.

Fig. 9b shows the percentage of monthly and annual working hours within specific DGI levels in the presence of each glazing solution, under the three European climates. Imperceptible glare levels significantly increased throughout the year with the PC glazing, for all cities. For the city of Lisbon, approximately 100% of working hours had imperceptible glare from April to September in the presence of the PC glazing. Due to the lower solar radiation levels incident on the PC glazing to promote the tinting of the film, this glazing was less effective under the cold climates, particularly in the city of London. The acceptable, uncomfortable and intolerable glare levels obtained in London and Berlin with the PC glazing, during winter months when the sun elevation angle is lower, were similar to the ones computed in the presence of the clear double glazing. The most significant impact of the PC glazing on glare levels was obtained for Lisbon, with an increase of 68% of working hours with imperceptible glare. For London and Berlin, the performance of the PC glazing (88% and 91%) in terms of glare reduction was also good but the results are closer to the ones obtained for the REF glazing. Extremely low percentage values of working hours of 3–4% were obtained for the occurrence of acceptable, uncomfortable and intolerable glare levels in the presence of all glazing solutions under the climates of Berlin and London.

## 5. Discussion

The added value of this study lies on the combination of experimental spectrophotometric data and dynamic simulations (including modelling routines in the energy management system of EnergyPlus [21]), enabling a more accurate representation of the PC glazing performance. By characterizing the optical properties of the glazing when exposed to different solar irradiance levels, the dynamic behaviour of the film is represented more realistically. Furthermore, by integrating energy, visual and thermal performance analyses across different climates, the results contribute to a comprehensive assessment of the installation potential of this glazing technology in real-world applications.

The cooling energy needs were reduced in the presence of the PC glazing, particularly in the hot climate of Lisbon where the higher solar radiation levels enhanced the darkening process of the film. The increase of the artificial lighting energy use with the PC glazing, due to its lower visible transmittance, resulted on a slight reduction of the total energy



a.

b.

**Fig. 9.** Simulated visual comfort conditions of the office room in the presence of each glazing system, under the climate of three European cities: a. Percentage of monthly and annual working hours within specific UDI levels, in %; b. Percentage of monthly and annual working hours within specific DGI levels, in %.

use in Lisbon but a slight increase under the colder climates. The obtained energy use savings are consistent with those reported in previous studies [16,17], considering the same climate types.

The occurrence of useful illuminance and imperceptible glare levels significantly increased with the PC glazing, particularly for Lisbon, due to its dynamic behaviour in the visible range. The results of the visual comfort are also in agreement with those reported by previous studies [16,17].

The PC glazing promoted thermal comfort conditions either under a free-float regime or with the operation of the HVAC system. Although previous studies [16,17] did not explicitly assessed the impact of PC glazing on thermal comfort conditions, they evaluated the climatization (heating and cooling) energy use, reporting a somewhat significant increase of the heating energy needs. However, the occurrence of too low temperature levels in the present work was similar for PC glazing and clear double glazing.

It is noteworthy to mention that hysteresis, cyclic repeatability and temperature dependence of the chromatic change of the PC film were not assessed in the present study and may affect real building operation. It is important to note that the results and conclusions of this study are also influenced by the following modelling choices, which act as constrains on the generalization of the research findings: the geometry of the office room and glazing systems; the configuration and properties of opaque and transparent materials; the selected climates and solar orientation; the definition and scheduling of occupancy, equipment, and artificial lighting; the definition and operation of the climatization system; and the software and performance metrics used.

Future research is planned to extend this work by applying its methodology to other building typologies and climates, considering additional static and dynamic glazing solutions, as well as alternative climatization systems and artificial lighting control systems. Studies on the improvement of the experimental characterization of the film are also strongly advised, including hysteresis, cyclic repeatability and temperature dependence. Additional efforts should also focus on: longer-term and in-situ/field validation of performance results; sensitivity analysis on control strategies of the energy management system and switching kinetics; evaluation of durability performance (aging tests); and assessment of environmental impacts of PC glazing against other glazing solutions [42].

## 6. Conclusions

This study combines an experimental-simulation approach, including spectrophotometric tests to obtain the optical properties of a PC glazing to gradually characterize its dynamic behaviour under different irradiance levels, and the use of these properties as input in a dynamic simulation (with dedicated modelling routines in the Energy Management System of EnergyPlus [21]) of an office room. The aim was to assess its energy, thermal and visual performance under the climate of three European cities (Lisbon, London and Berlin), comparing PC glazing against a conventional clear double glazing.

Regarding the findings of the spectrophotometric tests, it can be concluded that the PC glazing presented low transmittance values in the UV and near infrared radiation ranges, a dynamic behavior in the visible radiation range and constant reflectance spectra regardless of the incident solar irradiance. In addition, its solar factor, visible and solar transmittance values were reduced to 0.58–0.47, 74–22% and 41–25%, respectively (clear-tinted states). The spectrophotometric tests enabled the determination of the optical properties of the PC film for 7 tinted states (from fully clear to fully tinted), which were then used in the dynamic simulation through modelling routines in the energy management system of EnergyPlus [21] that controlled the different glazing states and respective properties in response to incident solar radiation levels.

Regarding the simulation-based performance of the PC glazing, compared to the clear double glazing, the dynamic glazing was able to reduce cooling energy needs and mitigate excessive illuminance, glare and temperature levels. The PC glazing reduced the cooling energy needs up to 22% but resulted in a slight increase of the heating energy needs in cold climates. The artificial lighting energy use also increased with the PC glazing due to its lower transmittance. A lower total energy with the PC glazing was only obtained for the climate of Lisbon (reduction of 10%). The percentage of working hours with useful illuminance and imperceptible glare increased to 24% and 74%, respectively, with the PC glazing. In terms of thermal comfort, the percentage of working hours within thermal comfort increased slightly (up to 2%) in the presence of the PC glazing under a free-float regime, and more significantly (up to 20%) when considering HVAC operation system.

These findings highlight the potential of installation of PC glazing in office rooms to optimize energy use and improve indoor environmental quality, with the performance varying by climatic region showing best performances under hot climates with high solar radiation levels.

## CRediT authorship contribution statement

**Henriqueta Teixeira:** Writing – original draft, Methodology, Investigation. **A. Moret Rodrigues:** Writing – review & editing, Supervision, Methodology, Investigation. **Daniel Aelenei:** Writing – review & editing, Supervision, Methodology, Investigation. **M. Glória Gomes:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

This research was funded in part by the Fundação para a Ciência e a Tecnologia, I.P. (FCT, https://ror.org/00snfqn58) under Grant UID/6438/2025 (https://doi.org/10.54499/UID/06438/2025) of the research unit CERIS and the PhD Grant PD/BD/150576/2020 (DOI: 10.5449/PD/BD/150576/2020). For the purpose of Open Access, the authors have applied a CC-BY public copyright license to any Author's Accepted Manuscript (AAM) version arising from this submission. The first and last authors would like to acknowledge the Project BE.Neutral—Agenda de Mobilidade para a neutralidade carbónica nas cidades, contract number 35, funded by the Resilience and Recovery Plan (PRR) through the European Union under the Next Generation EU, and Fundo Ambiental, through Protocol 49—"Plataforma de Apoio à Rede de Cidades Portuguesas climaticamente neutras e inteligentes 2030". The authors thankfully appreciate the technical support given by the IMPERSOL Company. The authors also thank the occupant of the office room (DME of IST) for supporting the study.

## Data availability

Data will be made available on request.

## References

[1] W.J. Hee, et al., The role of window glazing on daylighting and energy saving in buildings, Renew. Sustain. Energy Rev. 42 (2015) 323–343, https://doi.org/10.1016/j.rser.2014.09.020.

[2] T. Ashrafian, N. Moazzen, The impact of glazing ratio and window configuration on occupants' comfort and energy demand: the case study of a school building in Eskisehir, Turkey, Sustain. Cities Soc. vol. 47, no. January (2019) 101483, https://doi.org/10.1016/j.scs.2019.101483.

[3] J. Li, Q. Ban, X. Chen, J. Yao, Glazing sizing in large atrium buildings: a perspective of balancing daylight quantity and visual comfort, Energies (basel) 12 (4) (2019) 13–15, https://doi.org/10.3390/en12040701.

[4] M.G. Gomes, A.J. Santos, A.M. Rodrigues, Solar and visible optical properties of glazing systems with venetian blinds: Numerical, experimental and blind control study, Build. Environ. 71 (2014) 47–59, https://doi.org/10.1016/j.buildenv.2013.09.003.

[5] W. O'Brien, K. Kapsis, A.K. Athienitis, "Manually-operated window shade patterns in office buildings, A Critical Review" (2013), https://doi.org/10.1016/j.buildenv.2012.10.003.

[6] S.D. Rezaei, S. Shannigrahi, S. Ramakrishna, A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment, Sol. Energy Mater. Sol. Cells 159 (2017) 26–51, https://doi.org/10.1016/j.solmat.2016.08.026.

[7] A. Cannavale, "Chromogenic Technologies for Energy Saving," 2020. doi: 10.3390/cleantechnol2040029.

[8] Y. Ke, et al., Smart Windows: Smart Windows: Electro-, Thermo-, Mechano-, Photochromics, and beyond, Adv. Energy Mater. 9 (39) (2019) 1902066, https://doi.org/10.1002/aenm.201970153.

[9] M. Michael, F. Favoino, Q. Jin, A. Luna-Navarro, M. Overend, A Systematic Review and Classification of Glazing Technologies for Building Façades, Energies (basel) 16 (14) (Jul. 2023) 5357, https://doi.org/10.3390/en16145357.

[10] H. Teixeira, A. Rodrigues Moret, D. Aelenei, and M. G. Gomes, "Literature review of solar control smart building glazing: Technologies, performance, and research insights," *Build. Environ.*, vol. 274, p. 112784, Apr. 2025, doi: 10.1016/j.buildenv.2025.112784.

[11] M. A. Hassan, S. Alaa, and F. Sherief, "Assessment of retrofitting smart glass on office building Façade to enhance thermal comfort and energy consumption in hot arid climates (Case study in Egypt)," *Ain Shams Engineering Journal*, vol. 16, no. 5, Apr. 2025, doi: 10.1016/j.asej.2025.103333.

[12] M.H. Jahangir, R. Aboutorabi, Comparison of energy consumption and life cycle assessment in a building equipped with smart windows (electrochromic, thermochromic and photochromic): Case study in Tehran, Results Eng. 29 (Mar. 2026), https://doi.org/10.1016/j.rineng.2025.108878.

[13] S. Wijewardane, M. Santamouris, Smart glazing systems: an industrial outlook, Sol. Compass 14 (Jun. 2025) 100114, https://doi.org/10.1016/j.solcom.2025.100114.

[14] R. Tällberg, B.P. Jelle, R. Loonen, T. Gao, M. Hamdy, Comparison of the energy saving potential of adaptive and controllable smart windows: a state-of-the-art review and simulation studies of thermochromic, photochromic and

electrochromic technologies, Sol. Energy Mater. Sol. Cells (2019), https://doi.org/10.1016/j.solmat.2019.02.041.

[15] A. Cannavale, et al., Energy and daylighting performance of building integrated spirooxazine photochromic films, Sol. Energy (2021), https://doi.org/10.1016/j.solener.2021.10.058.

[16] F. Nicoletti, D. Kaliakatsos, V. Ferraro, M.A. Cucumo, Analysis of the energy and visual performance of a building with photochromic windows for a location in southern Italy, Build. Environ. 224 (2022) 109570, https://doi.org/10.1016/j.buildenv.2022.109570.

[17] K. Khaled, U. Berardi, A cross-climate assessment of the visual and energy performance of flexible photochromic films for in-situ window retrofits, Energy Build. 300 (2023) 113664, https://doi.org/10.1016/j.enbuild.2023.113664.

[18] K. Khaled, U. Berardi, Full-scale assessment of a liquid CsWO3-SnO2 near-infrared shielding coating and a nanoceramic WO3 photochromic window film for in-situ window retrofits, Build. Environ. 269 (Feb. 2025), https://doi.org/10.1016/j.buildenv.2024.112447.

[19] N. Aste, F. Leonforte, A. Piccolo, Color rendering performance of smart glazings for building applications, Sol. Energy 176 (Dec. 2018) 51–61, https://doi.org/10.1016/j.solener.2018.10.026.

[20] N. H. Matin, A. Eydgahi, and P. Matin, "The Effect of Smart Colored Windows on Visual Performance of Buildings," *Buildings*, vol. 12, no. 6, Jun. 2022, doi: 10.3390/buildings12060861.

[21] "EnergyPlus." Accessed: Apr. 23, 2020. [Online]. Available: https://energyplus.net/.

[22] H. Teixeira, A. Moret Rodrigues, D. Aelenei, I. Ferreira, M.G. Gomes, Solar-optical and thermal behavior of photochromic glazing: Small-scale testing under real sky conditions, Constr. Build. Mater. 456 (2024) Dec, https://doi.org/10.1016/j.conbuildmat.2024.139309.

[23] H. Teixeira, M. G. Gomes, A. Moret Rodrigues, and D. Aelenei, "Solar responsive building glazing: Experimental analysis of the impact of photochromic glazing on indoor thermal and luminous conditions," *Journal of Building Engineering*, vol. 92, p. 109812, Sep. 2024, doi: 10.1016/j.jobe.2024.109812.

[24] H. Teixeira, M.G. Gomes, A.M. Rodrigues, D. Aelenei, Assessment of the visual, thermal and energy performance of static vs thermochromic double-glazing under different European climates, Build. Environ. 217 (2022) 109115, https://doi.org/10.1016/j.buildenv.2022.109115.

[25] "Optics | Windows and Daylighting." Accessed: Jan. 24, 2020. [Online]. Available: https://windows.lbl.gov/software/optics.

[26] C. Curcija, S. Vidanovic, R. Hart, J. Jonsson, and R. Mitchell, *WINDOW Technical Documentation*. Lawrence Berkeley Natl. Lab., 2018.

[27] Accessed: May 21 (2024) [Online]. Available: https://www.ossila.com/products/solar-simulator.

[28] "IEC 60904-9:2020 Photovoltaic devices - Part 9: Classification of solar simulator characteristics," 2020.

[29] "Software and Drivers | Ossila." Accessed: Jul. 10, 2025. [Online]. Available: https://www.ossila.com/pages/software-drivers#Solar-Simulator.

[30] "CMP3 spectrally flat Class C pyranometer - Kipp & Zonen." Accessed: May 22, 2024. [Online]. Available: https://www.kippzonen.com/Product/11/CMP3-Pyranometer.

[31] "Solar Simulators: Interpreting Spectral Irradiance Graphs | Ossila." Accessed: May 21, 2024. [Online]. Available: https://www.ossila.com/pages/what-is-your-spectral-match-graph-telling-you.

[32] "V-770 UV-visible/NIR spectrophotometer | JASCO." Accessed: Nov. 18, 2020. [Online]. Available: https://jascoinc.com/products/spectroscopy/uv-visible-nir-spectrophotometers/models/v-770-uv-visible-nir-spectrophotometer/.

[33] "TIR100 – INGLAS." Accessed: Apr. 18, 2024. [Online]. Available: https://inglas.org/tir100/.

[34] H. Teixeira, M. da Glória Gomes, A. Moret Rodrigues, J. Pereira, In-Service thermal and Luminous Performance monitoring of a Refurbished Building with Solar Control Films on the Glazing System, Energies (basel) 14 (5) (2021) 1388, https://doi.org/10.3390/en14051388.

[35] "Order 349-B/2013 of 29 of November 2013," *Diário da República*, vol. 232, pp. 6624-(18)-6624-(29), 2013.

[36] ASHRAE, *ASHRAE Standard 55-2017: Thremal Environmental Conditions for Human Occupancy*. Atlanta, GA, USA: Am. Soc Heating Refrig. Air-Conditioning Eng., 2017.

[37] B.S. En, 16798, "BS EN 16798 - Energy performance of buildings, Ventilation for Buildings" (2019).

[38] J. Mardaljevic, M. Andersen, N. Roy, J. Christoffersen, "Daylighting metrics: I there a relation between useful daylight illuminance and daylight glare probability?," in *first Building simulation and Optimization Conference*, UK, Loughborough, 2012, pp. 189–196.

[39] R. G. Hopkinson, "Glare from daylighting in buildings," *Appl. Ergon.*, vol. 3, no. 4, 1972, doi: 10.1016/0003-6870(72)90102-0.

[40] "EnergyPlus." Accessed: Apr. 12, 2026. [Online]. Available: https://energyplus.net/weather.

[41] H. E. Beck, N. E. Zimmermann, T. R. Mcvicar, N. Vergopolan, A. Berg, and E. F. Wood, "Data Descriptor: Present and future Köppen-Geiger climate classification maps at 1-km resolution," 2018, doi: 10.1038/sdata.2018.214.

[42] J. Pereira, C.C. Rivero, M.G. Gomes, A.M. Rodrigues, M. Marrero, Energy, environmental and economic analysis of windows' retrofit with solar control films: a case study in Mediterranean climate, Energy (2021), https://doi.org/10.1016/j.energy.2021.121083.