Energy & Buildings 301 (2023) 113705

Contents lists available at ScienceDirect

Energy & Buildings

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

Low-cost gel-polymer electrolytes for smart windows: Effects on yearly energy consumption and visual comfort

Alessandro Cannavale [a,c], Francesco Carlucci [b], Marco Pugliese [c,*], Vincenzo Maiorano [c], Ubaldo Ayr [a], Francesco Fiorito [b,*]

[a] Department of Architecture, Construction and Design, Polytechnic University of Bari, Via Orabona 4, 70125, Bari, Italy
[b] Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Via Orabona 4, 70125, Bari, Italy
[c] National Research Council, Institute of Nanotechnology (CNR-NANOTEC), Via Monteroni, 73100, Lecce, Italy

ARTICLE INFO

Keywords:
Smart windows
Electrochromic materials
Energy efficiency
Visual comfort
Office buildings

ABSTRACT

The experimental analysis of the main figures of merit of an innovative electrochromic (EC) prototype, based on low cost gel-polymer electrolytes, is at the basis of the numerical simulation exposed hereafter, aiming at the assessment of energy and visual comfort benefits deriving from building integration of smart windows in a multi-storey office building. The effectiveness of the dynamic modulation of glazing properties to improve energy efficiency and users' comfort was tested comparing the EC windows with a typical law-compliant static commercial glazing system and with a clear windows. To better understand the performances of the proposed EC film, six different locations – ranging from Seville to Helsinki – were selected throughout the European continent to conduct energy and daylighting analyses on three different exposures (east, south, west). The results obtained show reductions of summer cooling and winter heating as well in all the locations considered. Eventually, the effect of electrochromic switching of transmittance on the indoor visual comfort, is considered using a well-established metric: Useful Daylight Illuminance; with regards to daylight analyses, a significant reduction of hours in which excessive illuminance occurs was observed in all the locations considered, confirming that properly controlled EC devices improve both energy efficiency and visual comfort.

1. Introduction

The compelling acceleration of climate change - as observed by the 6th IPCC Report [1] - and the emerging phenomena related to global warming are forcing us towards a rapid revision of international (and consequently national) regulations on energy saving and on the use of renewable energies. These revisions are especially related to the construction sector, that consumes a large amount of primary energy worldwide each year. European Directive 2018/844 states that buildings are responsible for 36 % of greenhouse gas emissions and that 50 % of final energy consumption in the European Union (EU) is related to HVAC uses [2]. Novel technologies are then required, capable of producing energy by using renewable sources [3–5] or providing control and reduction of energy consumption, just like the so-called "smart windows" do [6–12]. Generally, these devices are based on chromogenic materials, which tune their properties due to precise external physical stimuli (temperature, for thermochromics [13–16]; radiation at give wavelengths in photochromics [17–21] and an external bias, in the case of electrochromics [22–26]). Electrochromic (EC) devices are battery-like systems often embodying two transparent, conductive substrates (coated using Fluorine-doped tin oxide or tin-doped Indium oxide, in most cases), hosting as many EC materials (organic or inorganic), having complementary properties.

The mechanism at the basis of the EC behaviour is well synthesized in a recent work by Tandon et al., [27]. If polaronic coloration takes place – at a reducing potential – the localization of electronic charges creates distortion in the surrounding lattice from the initial equilibrium position and they are balanced by inserted small cations coming from the electrolyte, in a faradaic charging process, giving rise to the creation of bandgap bands, namely polarons, below the conduction band but activating further absorption transitions in the visible region. This mechanism, very frequent in metal oxides, corresponds to reversible redox coloration/bleaching reactions. Cathodic EC materials – like tungsten oxide [28–30] undergo reversible coloration upon intercalation of small

* Corresponding authors at: National Research Council, Institute of Nanotechnology (CNR-NANOTEC), Via Monteroni, 73100, Lecce, Italy (M. Pugliese). Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Via Orabona 4, 70125, Bari, Italy (F. Fiorito).
E-mail addresses: marco.pugliese@nanotec.cnr.it (M. Pugliese), francesco.fiorito@poliba.it (F. Fiorito).

https://doi.org/10.1016/j.enbuild.2023.113705
Received 30 June 2023; Received in revised form 4 October 2023; Accepted 30 October 2023
Available online 1 November 2023

cationic species (H^+, Li^+, Na^+) whereas anodic EC materials – such as nickel oxide [31–34] – colour upon ion deintercalation. Ions can be shuttled within the EC device by applying an external bias, in order to charge the substrates and activate ion migration. EC devices are then completed by an electrolyte standing between the two electrodes. Electrolytes can be in solid, gel or liquid state of aggregation and indeed represent a pivotal element in the design of EC devices, since their intrinsic ionic conductivity strongly influences the device performance [35–41]. The interest in smart windows has increased in the last decades because they may enhance the performance of transparent building envelopes by reducing the energy expenditures for heating, ventilation and air-conditioning (especially cooling loads during summer) or artificial lighting [6,42–46]. In fact, the adaptive tuning of the glazing solar heat gain coefficient (SHGC), with proper control strategies [47–49] according to the external environmental conditions, significantly affects the amount of solar gains, eventually turning into a thermal load for air conditioning systems. A large amount of works [45] have tried to study the energy benefits due to building integration of smart windows, by means of in situ experiments or numerical simulations [50–52]. Beneficial effects on visual comfort have also been observed [53–55]. In a previous experimental activity, some of the authors [56] have proposed an innovative EC device architecture containing a gel polymer electrolyte, based on two cheap and non-toxic commercial resins (a UV-curable urethane-based prepolymer mixed with a vinyl-acetate resin), acting as trapping matrices for liquid constituents (lithium perchlorate in propylene carbonate).

In order to identify a new matrix for the fabrication of gel polymer electrolytes for EC devices, an UV curable polymer resin (Norland Optical Adhesive 65 - NOA65) and Mastek vinyl acetate adhesive (MASTIFLEX) were selected. Consequently, the resulting electrolytes consisted in a mixture of resin with excellent optical characteristics, a solvent (propylene carbonate, PC) and a lithium perchlorate salt ($LiClO_4$) dissolved in it. After investigating the most suitable polymeric host/salt, the best formulation was selected in terms of ion mobility and optical contrast. Eventually, the fabrication process was scaled up to the fabrication of a 10 cm x 10 cm prototype.

Such experimental activity eventually confirmed that these polymer electrolytes may be considered as electrochemically stable alternatives in the role of ion-conducting media. The formulations tested showed conductivities ranging between $4.7 \bullet 10^{-7}$ S/cm and $6.5 \bullet 10^{-4}$ S/cm. In such work, they successfully identified a new matrix for the fabrication of low-cost gel-polymer electrolytes for EC devices, studying the effect of different electrolyte formulations on the performance of devices. They finally proposed a mixture of a UV-curing resin and a vinyl acetate adhesive with good optical properties, propylene carbonate acting as a solvent and a lithium perchlorate salt ($LiClO_4$) dissolved in it.

In this work, optical properties of a 100 cm^2 prototype were collected to assess the modulation of transmittance between the coloured and bleached states, respectively. Such data were at the basis of the numerical simulations reported hereafter, regarding the building integration of smart windows showing the same figures of merit assessed in the fabricated prototype (optical contrast, SHGC, reflectance).

2. Materials and methods

2.1. Fabrication and characterization of the EC prototype

The preparation of 10 cm x 10 cm prototypes was made according to the procedure reported in [57]. The prototype consisted in two transparent conductive substrate (Indium Tin Oxide-covered glasses), hosting – respectively – a 300 nm-thick tungsten oxide layer deposited by thermal evaporation and a 100 nm-thick layer of spin-coated tin oxide nanoparticles. Then, MASTIFLEX-based electrolytes were drop-cast on one substrate and the other one was placed on it, using 80 μm-thick spacers to obtain an electrolyte layer with homogeneous thickness. The prototypes were then exposed to Ultraviolet light, in order to cure the resin.

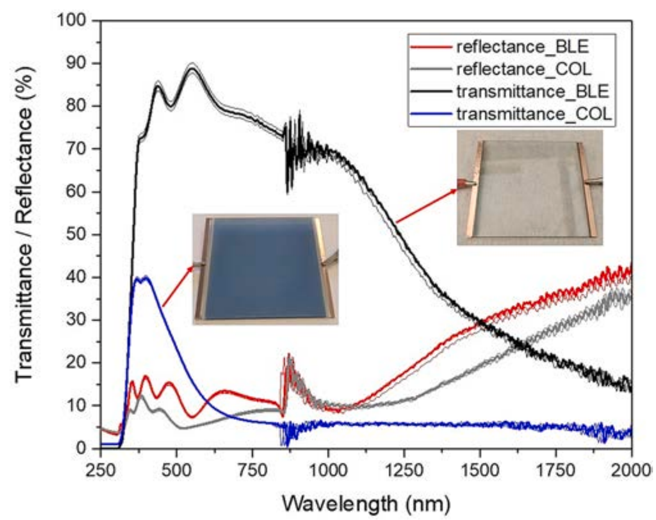

Fig. 1. Optical characterization of prototypes: transmittance and reflectance spectra are reported in the bleached and in the coloured state. In the inset, pictures of the prototype in the two states. The spectra with a continuous thin line represent the measurements with maximum deviation from the average ones, used for the simulations reported in the work.

The experimental measurements required as an input for the numerical simulations carried out in this work were performed on a Perkin Elmer spectrophotometer in a wavelength range between 250 nm and 2000 nm, for both transmittance and reflectance spectra. The latter were collected by means of the same instrument, equipped with an integrating sphere. Such data are reported in Fig. 1 and the inset shows the appearance of the prototype in the bleached and coloured states.

2.2. Simulation methods

Considering the high suitability of chromogenic technologies for office building typologies and their strong dependency on the environmental conditions, the performance of the proposed EC window was tested implementing this technology on the southern, eastern, and western façades of a reference office building located in different climate zones.

The performances were assessed through a yearly dynamic energy and daylighting simulation run with EnergyPlus v.9.4 [57] thanks to its multi-domain nature and its high customization degree [58]. To improve the accuracy of the analyses and to account for the change of state of the windows, the yearly simulations conducted consider six analysis timesteps per hour and update the shading calculation, accordingly.

The medium office model considered for the analyses was selected among the sixteen EnergyPlus reference buildings, which are considered a validated, reliable, and useful starting point for energy efficiency-oriented research [59]. The use of widely adopted building models eases the comparison among different studies allowing to compare the performance of different technologies or the effects of different contexts. From a geometrical point of view (Fig. 2), the building is characterized by three floors above ground with a floor to ceiling height of 2.74 m and a gross floor area of nearly 4980 m^2 each. The total façade surface is 1978 m^2, with a Window-to-Wall-Ratio (WWR) of about 33 %. It follows that the corresponding glazed surface is nearly 653 m^2. In order to properly account for thermal exchanges that happen in different areas of the open-plan floor, each floor is divided into five separate thermal zones, one for each exposure and an inner core. This structure allows to distinguish the results by exposures as each zone has only a single

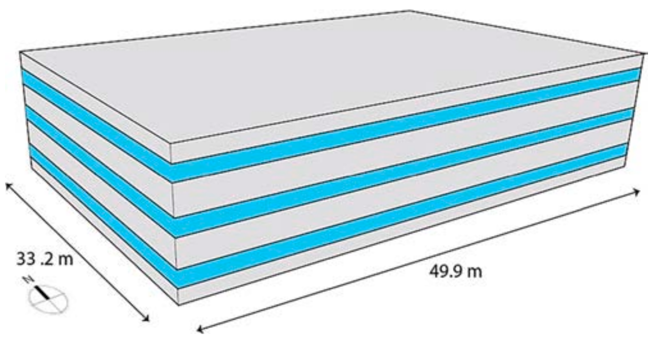

Fig. 2. Medium office reference model.

exposure facing window.

This starting reference model was properly adapted to fit the different locations selected and to account for the effects of the EC windows on different energy uses. To that end, considering the high variability of the outdoor conditions in the different locations selected, the HVAC systems were modified to avoid the dependency of the results on the sizing and efficiency of the system. In particular, the original HVAC system – constituted by a furnace for heating generation, a packaged air conditioning for cooling generation, and a multi zone constant volume system for air distribution – was replaced by properly calibrated ideal loads air systems that can directly supply heating and cooling to the thermal zone according to the zone setpoints [60]. Hence, the ideal loads systems were modified with an Energy Management System (EMS) program to account for a multizone air distribution system to behave similarly to the original systems. To account for lighting, heating, and cooling consumptions, the thermal energy demand of the ideal loads system was converted in electrical energy consumption considering common values for packaged direct expansion air conditioning system (Energy Efficiency Ratio (EER) equal to 3 in cooling mode and Coefficient Of Performance (COP) equal to 3 in heating mode). The ideal setpoint temperatures were set to 21 °C and 24 °C for heating and cooling, respectively, in accordance with the starting reference model.

Subsequently, the lighting system of the reference model was properly modified to consider the effect of the change of state of the EC windows. In particular, the lighting system was connected to a sensor grid constituted by illuminance sensors placed in the middle of each thermal zone with a setpoint of 500 lx in accordance with the current technical standard requirements [61]. The same sensors and the same illuminance setpoints were considered to control the EC state; it follows that the EC windows turn from bleached to coloured state when the 500 lx threshold is exceeded and vice versa. This setting allows to account for the use of natural lighting in the thermal zones improving the users comfort while reducing the lighting consumptions.

The operation of the EC system is strictly dependant on climate and location; therefore, 25 different European cities were analysed to select different climate contexts whose main parameters are shown in Table 1. Among these locations, six different European cities – Seville, Brindisi, Rome, Milan, Copenhagen, Helsinki – were selected to represent different possible European climate contexts. This selection aimed to maximize the differences between solar radiation, outdoor air temperature, latitude and longitude, Heating Degree Days (HDD), and Cooling Degree Days (CDD). For example, among hot climates, Seville is characterized by the highest differences between minimum and maximum temperatures while Brindisi is characterized by lower temperature differences and different coordinates which could significantly affect the lighting consumption. Considering Rome and Milan, the former is characterized by higher average solar radiation and dry bulb temperature, while the latter shows higher peak values in both maximum and minimum outdoor air temperatures. Finally, among cold climates, Copenhagen presents medium–low average temperatures coupled with a good variation of the solar radiation while Helsinki is characterized by a large distance between maximum and minimum temperature despite the very high HDD value.

Fig. 3 compares the values of dry bulb temperatures and global horizontal radiation for the selected locations. This figure clearly shows

Table 1
Characteristics of the 25 European cities considered. Data based on long term real observation deducted from Energy Plus Weather (.epw) file.

City	Coordinate		$CDD_{18^{\circ}}$	$HDD_{18^{\circ}}$	Global horizontal radiation [Wh/m^2]			Outdoor air temperature [°C]		
	Latitude	Longitude			Max.	Avg.	Min.	Max.	Avg.	Min.
Larnaca	34.9	33.6	1259	759	998	313	0	36.5	19.0.4	1
Seville	37.4	−6	1063	916	992	297	0	43	18.4	−2
Athens	38	23.7	1076	1112	997	279	0	37.2	17.9	2
Brindisi	40.6	17.9	834	1151	972	264	0	35.8	17.1	−1
Santander	43.5	−3.8	209	1369	955	205	0	31.2	14.8	1.6
Rome	41.9	12.5	649	1444	958	244	0	31.8	15.8	−4
Porto	41.8	8.4	146	1491	976	262	0	32	14.3	0
Madrid	40.4	−3.7	628	1965	997	270	0	40.4	14.3	−4.6
Plovdiv	42.1	24.7	543	2471	945	215	0	36.3	12.7	−11
Milan	45.5	9.2	380	2639	952	216	0	32.6	11.8	−11
Paris	48.9	2.3	142	2644	902	178	0	30	11.1	−6
London	51.5	−0.1	32	2866	893	168	0	31.3	10.2	−5.9
Timisoara	45.8	21.2	365	2896	937	227	0	33.8	11.0	−12
Brussels	50.5	4.2	96	2912	878	153	0	34.9	10.3	−9.1
Geneva	46.2	6.1	193	2965	946	198	0	32.1	10.4	−6.8
Ankara	39.9	32.9	253	3307	1007	248	0	33.8	9.6	–22
Ljubljana	46.1	14.5	168	3383	906	180	0	33.4	9.2	−21
Copenhagen	55.7	12.6	29	3563	827	164	0	26.8	8.3	−9.6
Prague	50.1	14.4	84	3703	890	160	0	32	8.1	−15
Munich	48.1	11.6	79	3738	918	187	0	33.3	8.0	−16.5
Bergen	60.4	5.3	21	3996	774	125	0	27.7	7.1	−8
Moscow	55.7	37.6	99	4655	826	162	0	30.6	5.5	−25.2
Helsinki	60.2	24.9	33	4712	772	158	0	28.7	5.2	−21.7
Reykjavik	64.1	−21.8	0	4917	721	130	0	18.4	4.5	−10.1
Kiruna	67.5	20.13	0	6967	669	125	0	22.7	−1.1	−29.2

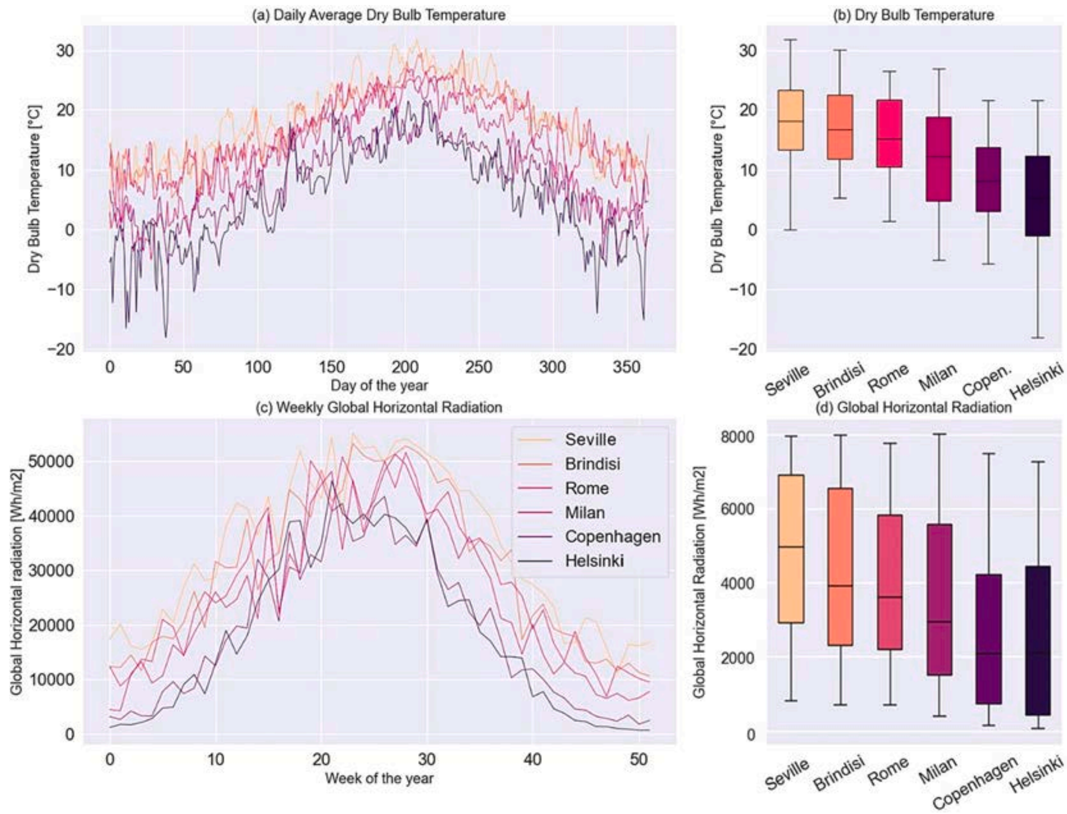

Fig. 3. Climatic characteristics of the selected locations: (a) daily average dry bulb temperatures, (b) statistical distribution of the hourly dry bulb temperatures, (c) weekly cumulative global horizontal radiation, (d) statistical distribution of the daily global horizontal radiation. Data based on long term real observation deducted from Energy Plus Weather (.epw) file.

how the EC windows were tested in a wide range of external conditions, very different from both temperature and solar radiation point of views.

The locations considered affect, on the one hand, the external boundary conditions – as previously described – and, on the other hand, the thermal properties of the envelope itself. Therefore, to properly adapt the reference model to the selected locations, all thermal

Table 2
Characteristics of cities weather and envelope properties.

City	Köppen climate classification	Cooling Degree Days $_{18^{\circ}C}$	Heating Degree Days $_{18^{\circ}C}$	Envelope component	Thermal Transmittance U [W/m^{2}K]
Seville	Csa	1063	916	External wall	0.43
				Slab	0.44
				Roof	0.35
				Window	2.20
Brindisi	Csa	834	1151	External wall	0.34
				Slab	0.38
				Roof	0.33
				Window	2.20
Rome	Csa	649	1444	External wall	0.29
				Slab	0.29
				Roof	0.26
				Window	1.80
Milan	Cfa	380	2639	External wall	0.26
				Slab	0.26
				Roof	0.22
				Window	1.40
Copenhagen	Dfb	29	3563	External wall	0.24
				Slab	0.24
				Roof	0.20
				Window	1.10
Helsinki	Dfb	33	4712	External wall	0.17
				Slab	0.10
				Roof	0.09
				Window	0.80

properties were adjusted to meet different climate requirements starting from the main European energy-containment laws. Hence, a reference thermal transmittance was considered for roofs, walls, slabs, and windows depending on the law requirements and climatic zones, as reported in Table 2.

The EC windows were modelled using the full spectral data of each layer, directly inputted in EnergyPlus. These spectral data were obtained for two different states (bleached and coloured), by considering the same glass composition and changing only the spectrum of the outer layer, according to the defined EC state. Hence, selecting the "switchable" window shading control in EnergyPlus, the software automatically switches between these two constructions to meet the above-described illuminance setpoint. Considering the different climate zones, these two constructions were modelled for each location using the same glazed layers changing only the gaps as described in Table 3 where the adopted double-glazed units (DGU) and triple-glazed units (TGU) are described. The resulting solar heat gain coefficients for the bleached ($SHGC_b$) and coloured ($SHGC_c$) states, together with the values of Visible Light Transmittance of the two states (VLT_b, VLT_c) are also reported.

To evaluate the benefits of these switchable windows (EC), the responsive models were compared with two different reference models. The first one (REF) is a standard intermediate reference model (SHGC = 0.35, VLT = 0.6) while the second one corresponds to the EC window always in its clear state (CLEAR). To conduct reliable comparisons, six REF and six CLEAR models – one for each location – were created in order to always have the same windows thermal transmittance in the compared models. Hence, reference (REF and CLEAR) and EC models differ only for the SHGC and VLT parameters to understand the effect of the EC modulation.

The latter glazing scenario may also represent the properties of a clear glass with high SHGC value, usually adopted in some existing buildings. For this reason, the comparison between the EC and CLEAR glazing is also relevant in terms of energy uses, not only to assess the effectiveness of EC modulation but also to report the potential advantages deriving from the use of EC glazing in building refurbishment. To avoid dependencies on the thermal properties of the windows, the thermal transmittance of all the windows was considered as reported in Table 3. The use of these two models allows, on the one hand, to compare the responsive technologies with a realistic window and, on the other hand, to highlight the benefits of the modulation of the optical properties in different climates.

The performance of the proposed EC windows was evaluated on both energy and daylighting point of view. In particular, the energy variations were evaluated as variation of the consumptions divided by source while the visual comfort was evaluated considering the Useful Daylighting Illuminance (UDI) developed by Nabil et al., [62]. This parameter considers the absolute daylight illuminance levels on hourly-based meteorological data – over a period of a full year – to define the percentage of time in which the illuminance is within the comfort range. For this study, a range of 300 ÷ 3000 lx was considered as comfortable according to previous scientific studies [63–65]. Hence, depending on the occurrence of the daylight levels, the UDI was classified in: UDI-f (fell-short) when the illuminance is lower than 100 lx and artificial lighting is required, UDI-s (supplementary) when the illuminance is between 100 and 300 lx and supplementary artificial lighting is required to reach the comfort levels, UDI-a (autonomous) when it is between 300 and 3000 lx and no artificial lighting is required, or UDI-e (exceeded) when it is above 3000 lx, in this case no artificial lighting is required but the glare risk is high [66].

To investigate how errors in the measurement of the optical properties of EC glass may affect numerical simulations, we performed a series of measurements on the EC glass. Specifically, transmittance and reflectance spectra have been acquired in the two different operating states (bleached and coloured) at 10 different points on the EC device to assess any changes in the optical characteristics.

In general, the curves may differ by a few percentage points because optical properties of the EC glass may not be identical at each point, but may vary slightly due to small variations in the thickness of each layers (especially the drop-cast electrolytes), or simply due to instrumental error. Fig. 1 shows the spectra of the bleached state with maximum deviation within the set of measurements: such values were assumed at the basis of further numerical simulations, carried out to assess the effect of measurement error on the yearly energy balance obtained in simulations. The discussion of these results are reported in the following Section 3.

3. Results and discussion

3.1. Energy uses

The most significant difference in yearly energy consumption is observed between the building equipped with EC glass and the one equipped with CLEAR glass. Since CLEAR glass shows optical and thermal properties of the EC glass left in bleached conditions, the results observed also confirm the effectiveness of active modulation of this novel technology, compared to glazing compliant with regulations but with non-dynamic optical properties This result is observed in all the considered locations, with some degree of variation mainly due to changes in façade exposure and seasonal differences taken into consideration in the dynamic numerical simulation. Furthermore, the dynamic operation of the EC glass is overridden during the winter season and its glazing properties do not change to maximize solar heat gains: for this reason, in all locations it will be observed that the differences in energy consumption between EC and CLEAR glazing are zero in all the figures reported hereafter.

With reference to energy consumption, in the city of Brindisi, EC glass outperforms REF glass, but with average differences lower than 5 kWh/m^2 per day throughout the year, both in the heating and cooling periods (Fig. 5). On the other hand, the difference in energy consumption observed between EC glass in the coloured conditions and in the

Table 3
Characteristics of the adopted glazing.

	Seville/Brindisi (U = 2.2 W/m^{2}K)	Rome (U = 1.8 W/m^{2}K)	Milan (U = 1.4 W/m^{2}K)	Copenhagen (U = 1.1 W/m^{2}K)	Helsinki (U = 0.8 W/m^{2}K)
Layer 1 (outside)	Bleached / Coloured	Bleached / Coloured	Bleached / Coloured	Bleached / Coloured	Bleached / Coloured
Gap1	Air (8 mm)	Argon (8 mm)	Krypton (8 mm)	Argon (8 mm)	Krypton (8 mm)
Layer 2	Low-e	Low-e	Low-e	Low-e	Low-e
Gap2	–	–	–	Argon (8 mm)	Krypton (8 mm)
Layer 3 (inside)	–	–	–	Low-e	Low-e
$SHGC_b$	0.620	0.620	0.620	0.529	0.529
$SHGC_c$	0.198	0.198	0.198	0.124	0.124
VLT_b	0.720	0.720	0.720	0.610	0.610
VLT_c	0.124	0.124	0.124	0.102	0.102

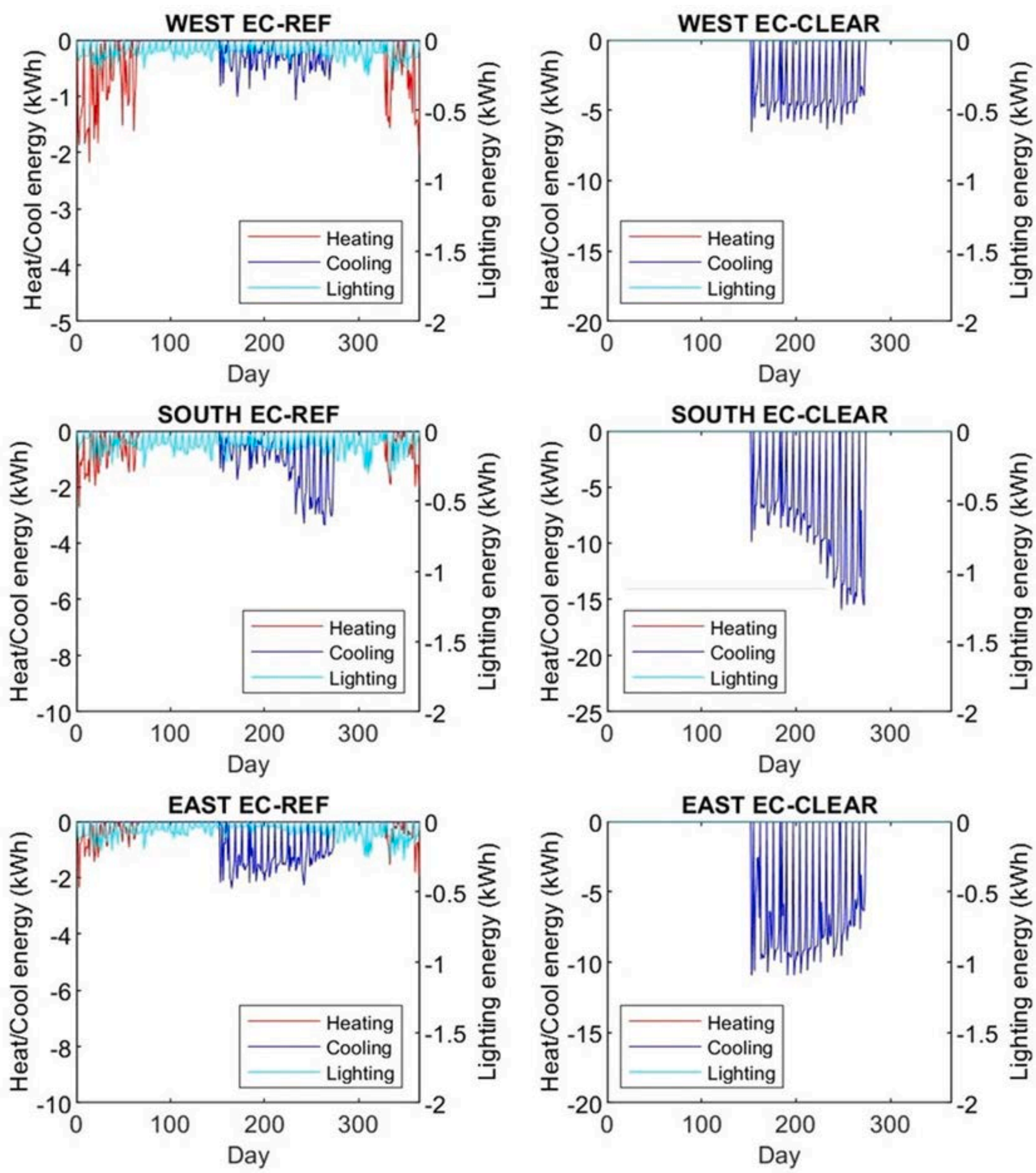

Fig. 4. Daily difference in energy consumption between buildings equipped with EC, CLEAR and REF glazing, respectively. The results shown in the graph concern the city of Seville.

bleached conditions (i.e., the CLEAR glass) are far more significant, particularly in the cooling season. In the summer season, the differences EC-CLEAR are significant on all exposures, with maximum peaks exceeding 20 kWh/m^2 per day on the southern façade exposure, during late summer. On the contrary, both on the west (differences up to 8 kWh/(m^2•day) and on the east (differences up to 11 kWh/(m^2•day) exposures, differences in energy consumption remain almost constant throughout the cooling season.

The results described for the location of Brindisi are very similar, for all the exposures studied, to those observed in the localities of Milan and Rome, albeit with slight differences in terms of absolute values of energy consumption (Fig. 8 and Fig. 9). Trends of diagrams are also similar for these cities. For example, the maximum difference between the EC and CLEAR glazing is roughly 20 ÷ 23 kWh/(m^2•day) in the late summer on the south façade either in Brindisi and in Rome and Milan. Seville also shows similar results (Fig. 4), but with slightly lower energy consumption. In these four locations, it is also observed that the maximum difference (EC-CLEAR) in energy consumption due to the dynamic behaviour of EC glazing observed on the east façade can be noticed at the beginning of the cooling season, with average values of 10 kWh/(m^2•day) in Brindisi and Seville and lower values in Milan and Rome, as the season progresses.

With reference to the differences in energy consumption between the building equipped with EC glass and the one with static glass compliant with the regulations (REF), it can be observed that in all locations (and for all exposures), EC glass shows better performance, with absolute values of this difference strictly dependent on the locality and exposure taken into consideration. In the location of Brindisi as well as for Rome and Seville, this difference is rather contained in the west and east exposures, with values around 5 kWh/(m^2•day). In these three cities also the behaviour on the southern facade is very similar but with an accentuation of the performance difference, detectable mainly at the end of the summer season.

These results demonstrate not only the effectiveness of dynamic

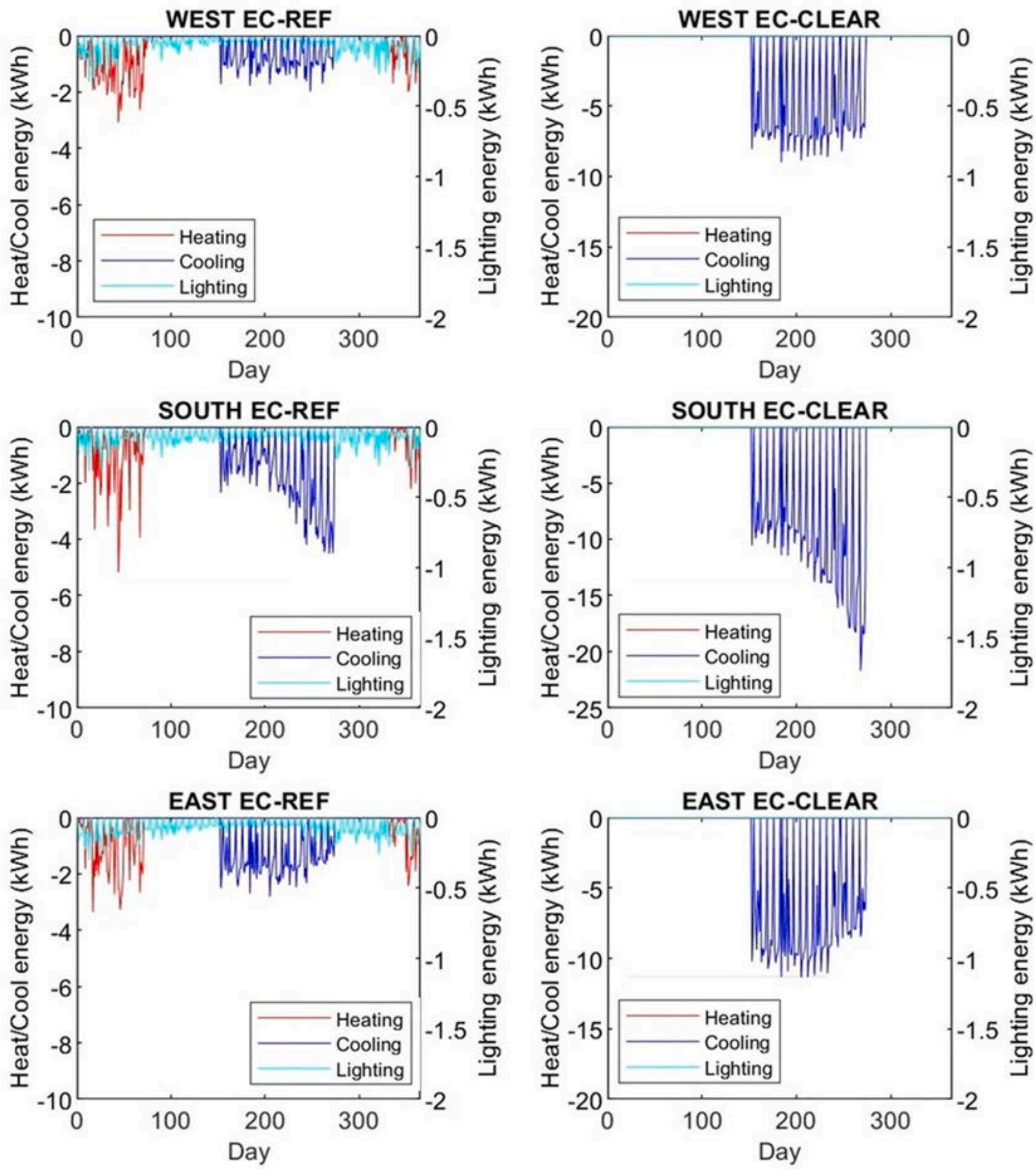

Fig. 5. Daily difference in energy consumption between buildings equipped with EC, CLEAR and REF glazing, respectively. The results shown in the graph concern the city of Brindisi.

modulation for the purpose of containing energy consumption on an annual basis for both summer and winter air conditioning but also show the benefits that can be achieved with respect to a typical static commercial glazing system. Quite unexpectedly, the differences between the energy consumption of EC glass and that of standard glass compliant with regulations (REF) are more significant in Northern Europe, namely in the cities of Helsinki (Fig. 7) and Copenhagen (Fig. 6). On the south façade, the difference in energy consumption during the summer season between EC glass and standard REF glass reaches values of up to 9 kWh/(m^2•day), in the city of Copenhagen and up to 12 kWh/(m^2•day) in the city of Helsinki. In the latter case, peaks exceeding 10 kWh/(m^2•day) are also reached in the difference in energy consumption during the winter season. In both Copenhagen and Helsinki, the differences in energy consumption between EC-REF glazing are smaller both in the summer and winter seasons on the western and eastern exposures. In all the figures, data regarding energy consumption for lighting are not visible due to their lower values compared with heating and cooling.

In Fig. 10, it can be noticed that the amount of cooling degree days and the climatic area strongly influences the performance of HVAC systems throughout the year: in cities with lower values, cooling prevails with respect to heating consumption. In fact, yearly energy consumption profiles in Brindisi, Seville and Rome are indeed similar. At the same time, an inverted similarity can be observed in Copenhagen and Helsinki, located in a "heating dominated" climate. Only Milan shows an intermediate profile of energy consumption, compared with the two groups. It is worth highlighting that cooling consumptions in Brindisi are higher than those obtained in Seville despite the latter is characterized by a warmer climate (834 CDD_{18° in Brindisi and 1063 CDD_{18° in Seville). Hence, further analyses were conducted to check the reliability of the results and their explanation. A detailed analysis of the hourly cooling consumptions, outdoor temperature, and heat gains through the windows confirmed the reliability of the results which can be explained considering the different latitudes and longitudes of the two cities. In particular, both cities belong to the same time zone despite their

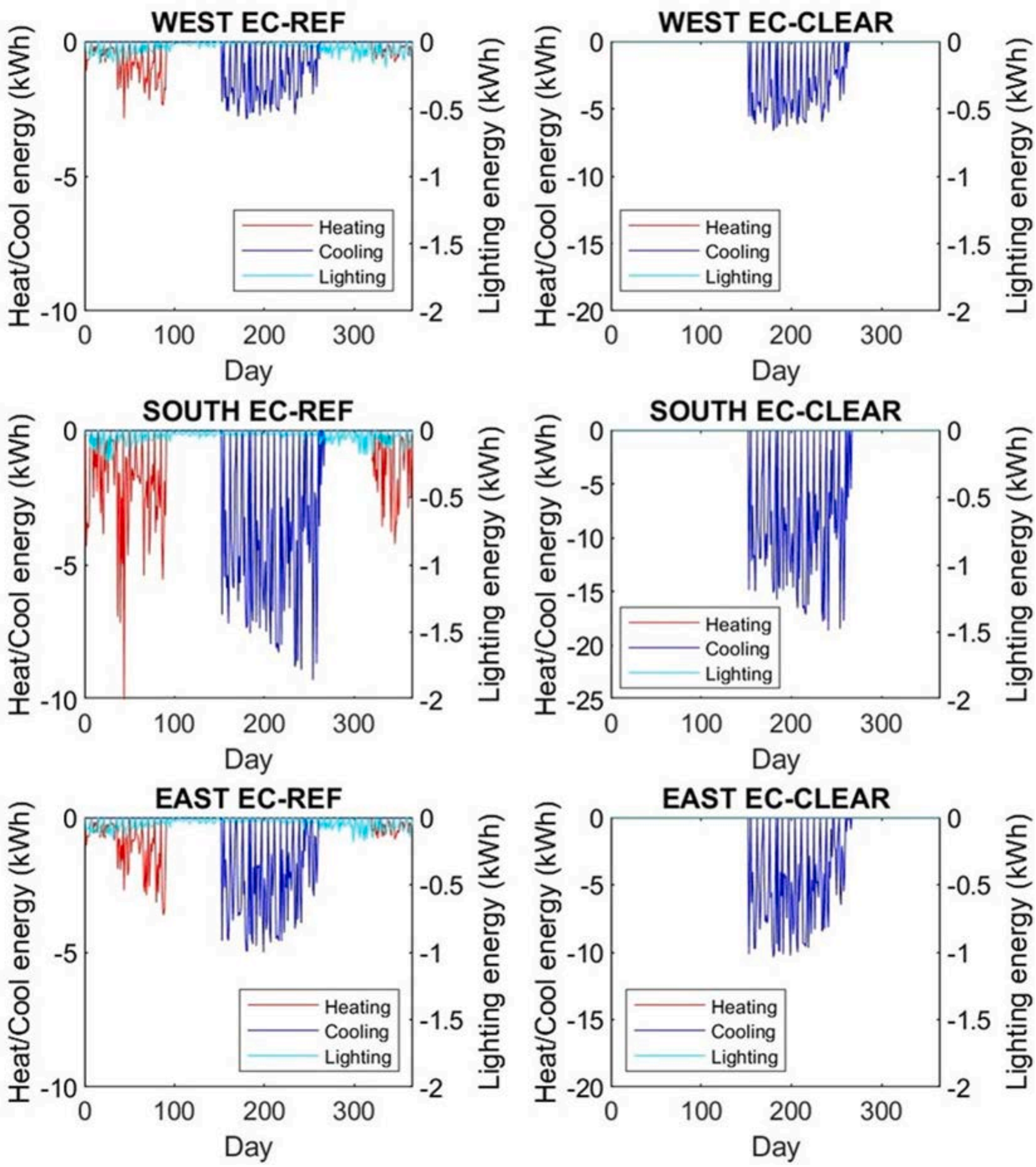

Fig. 6. Daily difference in energy consumption between buildings equipped with EC, CLEAR and REF glazing, respectively. The results shown in the graph concern the city of Copenhagen.

longitudes are different (-5.98 for Seville and + 17.94 for Brindisi); in Brindisi, this difference increases the number of timesteps – during the office opening hours – with direct solar radiation on the façade. Therefore, during summer, the higher outdoor temperatures and solar gains in Seville are concentrated in afternoons and evenings; nevertheless, during these hours – when the cooling system is still on – the internal loads related to occupancy and electrical equipment are lower or nil and, hence, the cooling demand is lower. Moreover, the higher latitude in Brindisi increases the solar gains in the considered thermal zones (thanks to a lower incidence angle) with a consequent increase of the cooling demand. Therefore, to sum up, this unexpected trend is related to the time-shift in outdoor air temperature and solar gains – with respect to the office opening hours – due to the different latitudes and longitudes.

Among the six locations, the ones reporting higher energy consumption are Copenhagen, Helsinki and Milan: the two former cities show a temperate continental climate, whereas Milan has a humid subtropical climate. In all the three cities, energy consumption related to heating is expectedly higher than in the cities having a warm Mediterranean climate: 8699 kWh/yr in Helsinki, 6027 kWh/yr in Copenhagen and 4684 kWh/yr in Milan; such values were observed in the three locations, for the building equipped with REF glazing. Among these cities, Milan is the only one in which the energy required for cooling exceeds the energy expenditures for heating (4887 kWh/yr, for cooling, if the REF glazing is adopted). Such values are lower when EC glazing are used, due to the higher SHGC, allowing higher heat gains in the heating season: differences of about 5 % can be observed in Helsinki and Copenhagen but are much higher in Milan (18 %).

Brindisi, Rome and Seville show a warm Mediterranean climate, according to the Köppen climate classification and, accordingly, the profiles of energy expenditures are similar, with prevailing energy use for cooling. In Brindisi, the building equipped with a CLEAR glazing shows the highest energy use for cooling, 10,075 kWh/yr (76 % of total energy required yearly for HVAC and artificial lighting). Such value is

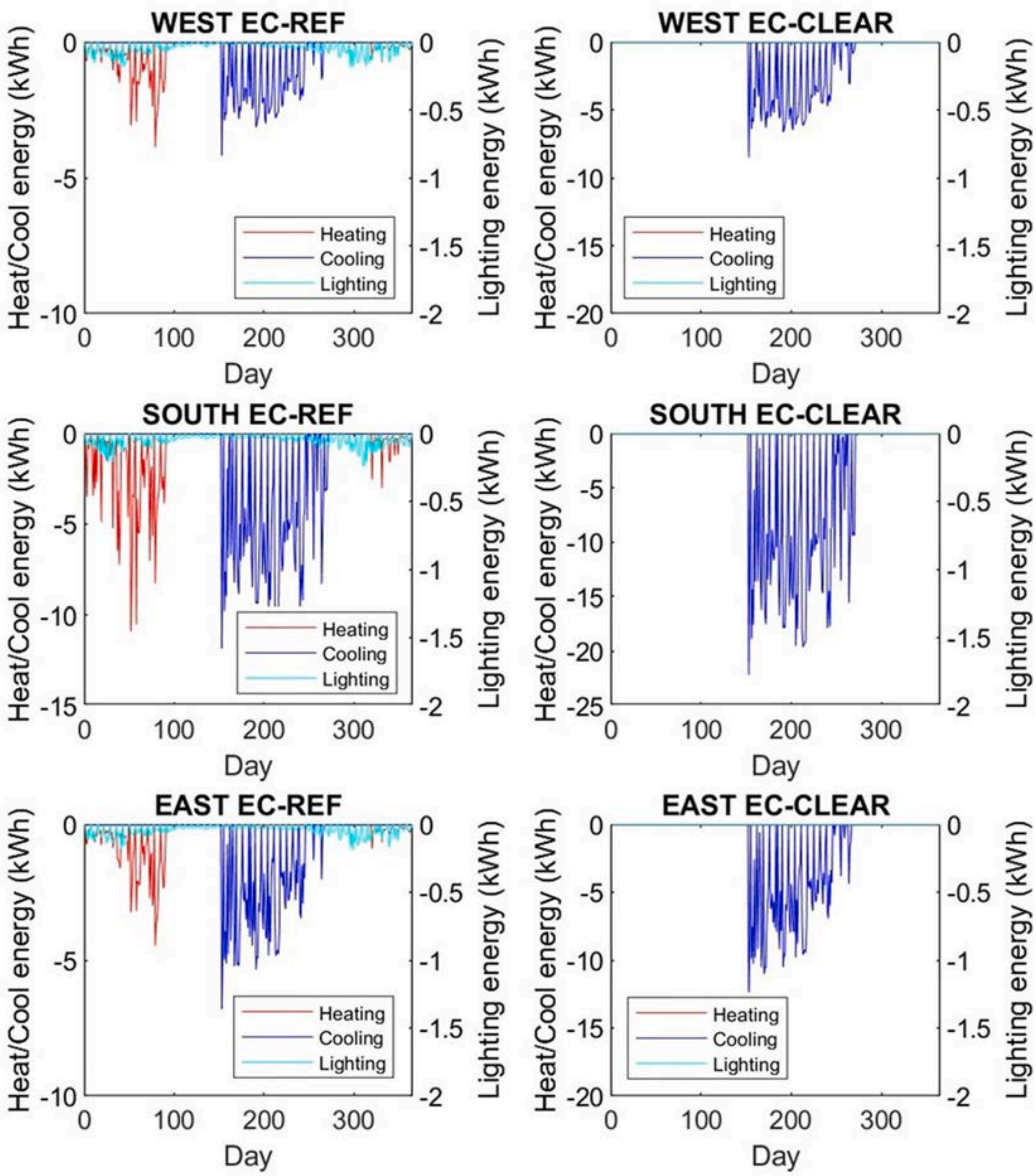

Fig. 7. Daily difference in energy consumption between buildings equipped with EC, CLEAR and REF glazing, respectively. The results shown in the graph concern the city of Helsinki.

reduced by 20 % if the building is equipped with EC glazing. Cooling energy is reduced by 26 % using EC glazing and by 21 % using the REF glazing. The low impact of heating demand in warm climates is related to the specific model and building type considered. Indeed, the office model is characterized by high internal gains related to electrical equipment and people; moreover, the model was simulated without considering the urban context increasing the solar gains. Hence, the high solar and internal gains coupled with a highly insulated envelope (compliant with the latest laws) reduce the impact of heating demand on the overall consumptions.

In Milan, the use of EC glazing reduces energy uses for cooling by 39 %, compared to CLEAR glazing (by 13 % compared to REF glazing). On the other hand, total energy consumption is reduced by 19 % and 13 %, compared to CLEAR and REF glazing, respectively. Seville shows the lowest energy consumption for heating, ranging from 144 kWh/yr (for EC and CLEAR glazing) to 336 kWh/yr, for REF glazing. Such values decrease by 42 % when the EC glazing is used because the SHGC of the REF glazing is higher. The profile of energy consumption is very similar to the one observed for Rome.

Furthermore, results reported in Fig. 10 show that the yearly amount of energy consumed for cooling, heating and artificial lighting is always lower when building envelopes embody EC glazing. This fact can be observed in each location, regardless of the climatic area. Moreover, these results show the effectiveness of this novel technology in reducing energy uses for cooling and heating, compared to commercial glazing with static optical and thermal properties. In absolute terms, if one analyses the difference in energy uses due to the use of EC glazing, compared to the results obtained using the REF glazing, it may be observed that the energy saved in each location is somewhat proportional to the total amount of yearly energy consumed for each use. In fact, the highest differences in energy use are reported in Milan (1698 kWh/yr), Helsinki (1409 kWh/yr) and Copenhagen (1325 kWh/yr). Total savings will be lower in the Mediterranean cities: Rome (1144 kWh/(m^2yr), Brindisi (830 kWh/yr) and Seville (606 kWh/yr).

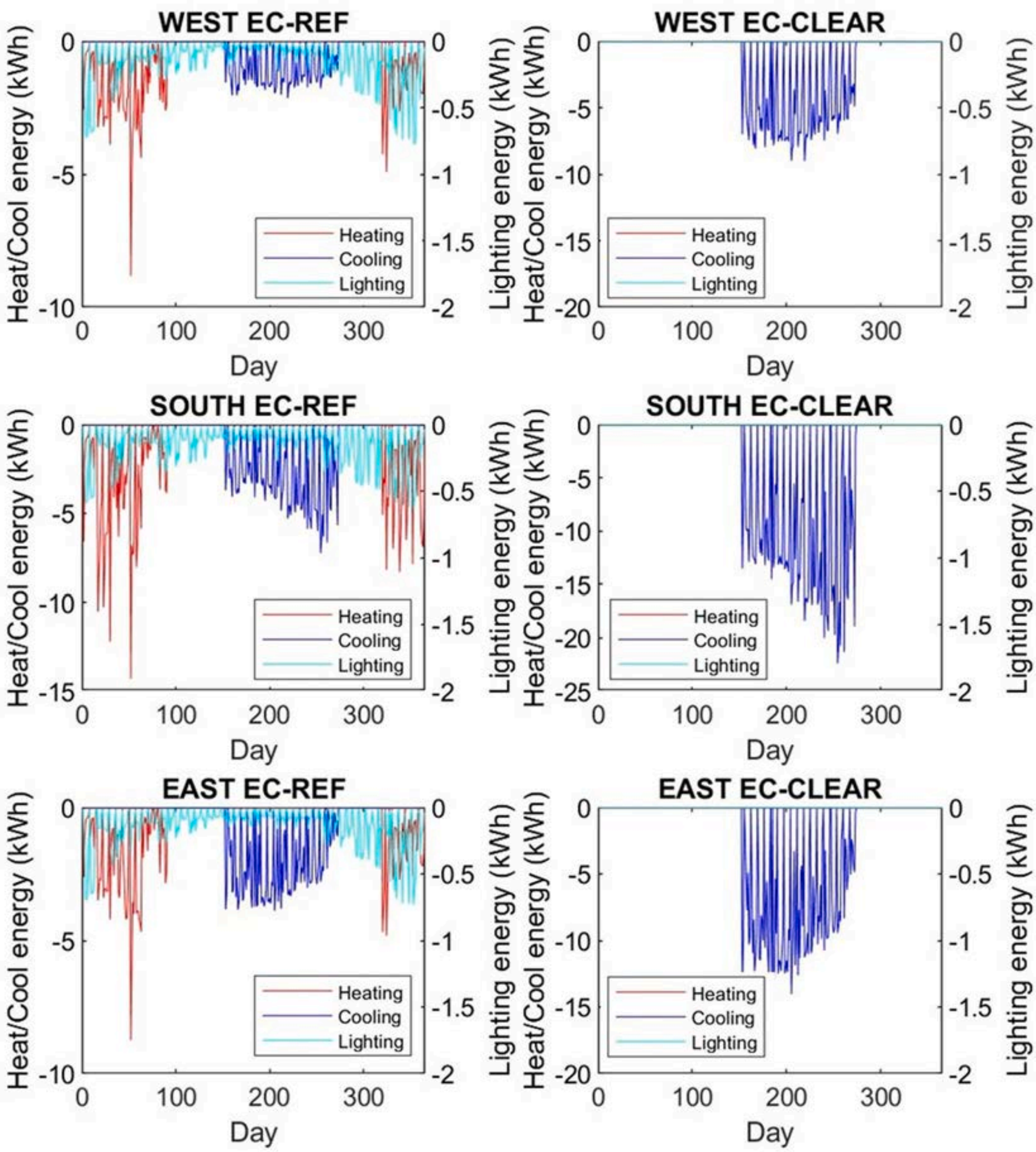

Fig. 8. Daily difference in energy consumption between buildings equipped with EC, CLEAR and REF glazing, respectively. The results shown in the graph concern the city of Milan.

To evaluate the extent of the error in the measurement of the transmittance spectrum on the yearly energy balance resulting from numerical simulations, further numerical simulation activities were carried out, using the spectra with maximum deviation from the average value within the experimental set of measurements. The latter was considered as the reference measurement, at the basis of the simulations reported in this work. Such further simulations confirmed the reliability of the data presented in the manuscript. In general terms, global annual energy consumption never differs by more than 1 % from the data presented. Such maximum difference is achieved only in the cities of Copenhagen and Helsinki: the other locations show lower deviations. In fact, if the bleached conditions of the EC glass show lower transmittance, increases in consumption during the winter season can be observed (+1.01 %). The change in light transmission directly affects the SHGC value and this leads to a change of solar gains during the winter season (and an increase of cooling load, respectively, in the summer season). By referring only to the values of the solar factor of the windows, it can be observed how a variation of g-factor of about 1.3 % impacts percentage deviations by approximately 1 % in locations with predominant energy consumption in the winter season, like Copenhagen. In all the locations covered by this study, the variation in total energy consumption resulting from the adoption of different transmission spectra present in the set of measurements does not exceed of 0.5 %, confirming the reliability of the simulation activities presented. The column of EC glazing in Fig. 10 reports the extent of percentage variation in energy balance observed assuming transmittance spectra with maximum deviation from the average spectrum in the set of measurements.

Regarding the comparison of these outcomes with other studies and technologies, previous analyses [67] tested EC windows and automated dynamic blinds in different contexts. The results, despite non-identical locations and control strategies, highlighted slightly higher benefits for the EC devices thanks to the reduction of the heating consumption when compared with a low-transmitting glazing. The main drawback is related to the significant increase of the lighting consumption which could be overcome thanks to the revised control strategy proposed in this paper. Moreover, beyond the energy point of view, EC systems do

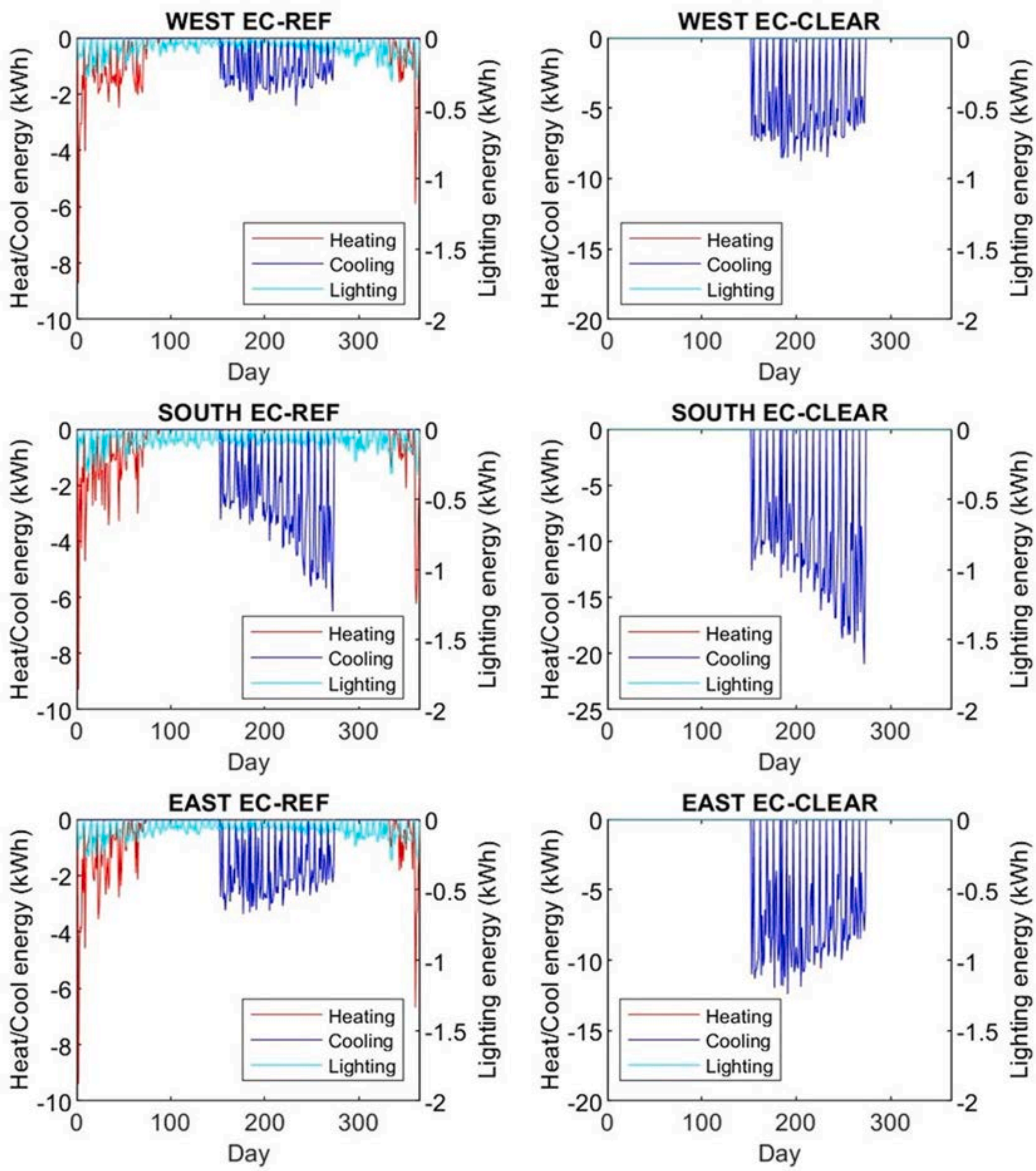

Fig. 9. Daily difference in energy consumption between buildings equipped with EC, CLEAR and REF glazing, respectively. The results shown in the graph concern the city of Rome.

not reduce the view out as no physical obstacle are needed to reduce the incoming solar radiation unlike the automated venetian blinds. Considering this comparison [67], traditional EC windows could be less cost-effective when compared with automated shading systems; nevertheless, the proposed device could merge both the energy, functional, and cost effectiveness thanks to the use of low-cost gel polymers. Indeed, the electrolyte layer has a significant impact on the overall cost of an electrochromic device. If we wanted to compare the cost of our electrolyte with other types, we could analyse the cost of other gel-like or solid-state electrolytes. For example, polymethylmethacrylate (PMMA) and polyvinylalcohol (PVA) are among the most commonly used polymers for the formulation of gel-like electrolytes. The cost of these materials is a few hundred euros per kilogram. Instead, among solid polymer electrolytes, Nafion, a perfluorosulfonic acid polymer used in both fuel cells and EC devices, is the best alternative, but it costs a few thousand euros per litre. Alternatively, some inorganic oxides (SiO_2, Ta_2O_5, etc.) appear to be a cost-effective choice in terms of raw material cost, but they require vapour deposition techniques (thermal evaporation, sputtering, e-beam deposition) which significantly affect the overall cost. The proposed gel electrolyte, on the other hand, has the advantage of being easily processed by solution techniques and costs a few tens of euros per kg.

3.2. Visual comfort

The investigation of indoor visual comfort based on the UDI metrics also demonstrated the potential benefits deriving from building integration of EC glazing in the office building acting as a case study for this work. In a similar way to what was done for the energy performance simulations, comparisons were made regarding all the locations previously considered. Table 4 shows the results of comparisons of daylighting performance, with reference to UDI, comparing the

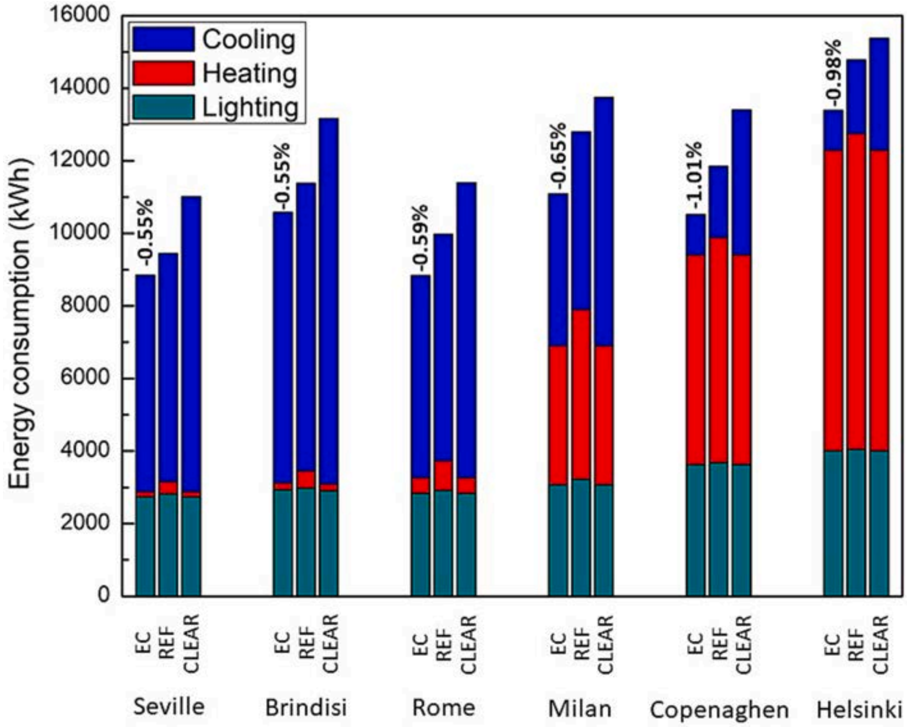

Fig. 10. Column diagram that represents the detail of global energy consumption by type of use (heating, cooling, artificial lighting) on an annual basis for each location. Results of simulations for EC glazing report the maximum change in energy balance obtained when spectra with maximum deviation were used as inputs for numerical simulations.

Table 4
UDI values in each location for EC (coloured) and CLEAR (bleached) conditions (the maximum errors derived from the EC spectra measurements are expressed in brackets).

	EC				**CLEAR**			
	UDI-f (0-100)	**UDI-s (100-300)**	**UDI-a (300-3000)**	**UDI-e (>3000)**	**UDI-f (0-100)**	**UDI-s (100-300)**	**UDI-a (300-3000)**	**UDI-e (>3000)**
Seville	4.48% (±0)	4.00% (±0.06)	66.44% (±0.52)	25.08% (±0.55)	4.48%	3.96%	63.32%	28.24
Brindisi	5.43% (±0.06)	2.99% (±0.03)	66.89% (±0.45)	24.69 (±0.55)	5.43%	2.99%	62.90%	28.68
Rome	4.65% (±0.06)	3.83% (±0.03)	68.84% (±0.42)	22.68 (±0.42)	4.65%	3.80%	62.02%	29.53
Milan	7.34% (±0.13)	4.97% (±0.06)	68.71% (±0.16)	18.98 (±0.26)	7.34%	4.94%	59.81%	27.91
Copenhagen	13.45% (±0.06)	7.44% (±0.23)	69.33% (±0.03)	9.78 (±0.26)	13.45%	7.44%	64.17%	14.94
Helsinki	18.45% (±0.06)	9.49% (±0.10)	63.71% (±0.32)	8.35 (±0.39)	18.45%	9.42%	55.13%	17.00

daylighting performance of the glazing in coloured (EC) and bleached conditions (CLEAR) only with regards to the south façade of the office building. It turned out that the number of working hours in which the test room with dynamic glazing was in UDI-a conditions always higher than those reported for the static glass.

Also in the evaluation of the UDI metric, to define the conditions of internal visual comfort, it is noted that in all locations, albeit to different extents, the EC technology allows good control of daylighting, by means of dynamic EC switching, effectively reducing the number of hours in which users are exposed - on an annual basis - to conditions of excessive lighting (UDI-e), generally considered compatible with glare effects.

The best results, with active EC glazing, were observed in Copenhagen, with 69,33 % working hours in the range 300 ÷ 3000 lx (UDI-a) and in Rome, with 68.84 %.

Copenhagen shows the highest values of UDI-a either in the EC and in the CLEAR conditions (69.33 % and 64.17 %, respectively) and – consequently - very low UDI-e values. The highest increase in UDI-a values (+8.9 %) is reported in Milan. It ranges from 59.81 % in the bleached conditions, to 68.71 % when the glass is coloured.

The maximum percentage decrease in UDI-e hours, when switching the glazing from the CLEAR (i.e., bleached) conditions to the EC conditions (i.e., colored), can be observed in Milan (from 27.91 % to 18.97

%), Rome (from 29.53 % to 22.68 %) and Helsinki (from 16.99 % to 8.35 %). In these cities, data reported in the table show only slight variations of the percentages regarding UDI-f (0 ÷ 100) and UDI-s (100 ÷ 300), while significant changes are reported in the column containing the UDI-a (300 ÷ 3000): from 55.13 % to 63.71 % in Helsinki or from 59.81 % to 68.71 % in Milan. This circumstance occurs in all locations – though with different values – and is due to the modulation provided by the dynamic contrast of EC glazing: it makes it possible to reduce the number of hours in which extra illuminance occurs (UDI-e), bringing a good part of it back within the optimal range (UDI-a).

The measurement error of the transmission spectra does not produce significant effects in the evaluation of the UDI figure of merit, in all the locations studied.

4. Conclusions

In this work, we have reported the results of numerical simulations based on experimental data measured after fabricating a 100 cm^2 EC prototype embodying a low-cost gel-polymer electrolyte, with a novel formulation. Although it is now clear that EC smart window technology helps to significantly reduce energy consumption in buildings, the actual use of this type of device is struggling to catch on, and often remains confined to isolated applications in specific settings. The main cause lies in the high cost of production, which makes EC windows uncompetitive in the market, compared to other cheaper though less energy-efficient solutions. Therefore, the development of low-cost materials and deposition techniques acquires crucial importance for the diffusion of EC technology. This paper aims not only to emphasize the importance of EC technology in next-generation buildings, but suggests an approach toward reducing production costs by focusing on one of the main components of an EC device, namely the electrolyte. Commercially available solutions use inorganic solid-state electrolytes deposited by expensive vacuum processes. Replacing inorganic electrolytes with polymer electrolytes (which can be processed by solution techniques) is proposed to lower production costs, related to both the cost of the raw material and the deposition technique. In the specific case, the electrolyte used in the here discussed device can be processed by the most common wet-processing techniques (dip coating, doctor blade, slot casting, screen printing, etc.). In addition, its very low cost (a few euros/litre) makes it competitive with other heat- or UV-hardening polymers widely used for the same purpose.

To test the performances of this low-cost EC film energy and daylighting simulations were carried out using a validated multi-storey office building, located in several European locations, representing as many climatic conditions as possible, from Helsinki to Seville. This experimental/simulation activity was useful to find out the effectiveness of this novel technology, both with regard to yearly energy saving (cooling, heating, lighting) and to daylighting, in several European locations. The results obtained show that this kind of device not only reduces fabrication costs but may also be effective both in cooling dominated and cold climates. The results reported and just commented demonstrate the effectiveness of the innovative EC technology proposed in all the locations taken into consideration, although the cities studied fall within somewhat different climatic zones. From an energy point of view, EC devices always show energy demand lower than both law compliant and clear windows in all the analysed models. Thanks to a wide modulation of the SHGC (0.62 – 0.2 for DGUs and 0.53 – 0.12 for TGUs) and to a proper activation criterion, the benefits of these systems include reduction of heating, cooling, and lighting demand in all the considered locations when compared to the law compliant reference model. The highest differences in energy use are reported in Milan (1698 kWh/yr), Helsinki (1409 kWh/yr) and Copenhagen (1325 kWh/yr) thanks to significant enhancement on both heating and cooling consumptions, while total savings are lower in the Mediterranean cities: Rome (1144 kWh/(m^2yr), Brindisi (830 kWh/yr) and Seville (606 kWh/yr). Similar results can be found comparing the EC device with clear windows; in this case, the enhancements on energy efficiency are related only to the cooling consumptions and, therefore, the highest benefits are registered in the Mediterranean area. From a daylighting point of view, the use of the proposed EC film improves the UDI in all the locations considered thanks to a reduction of the UDI-e and a consequent increase of the UDI-a. Hence, the modulation of the optical properties of the EC windows allows to increase the percentage of time in which the illuminance is within the comfort range. This result confirms that EC devices improve on the one hand, the users' comfort and, on the other hand, reduces the energy consumption related to the artificial lighting. Moreover, the results obtained from the comparison with clear glass highlight that using these EC devices for retrofitting intervention can significantly improve both energy efficiency and visual comfort of existing buildings.

To sum up, the results obtained in this study show that the novel formulation of the proposed low-cost gel-polymer electrolyte – implemented in EC windows – allows to reduce the cost of the device improving, at once, energy demand and daylighting of office buildings located in different climate zones. Further building uses (residential, educational, etc.) could be considered in future studies to test the performance of these devices in different contexts where the occupancy and the internal loads are different in magnitude and temporal distribution. Despite the high potential of chromogenic technologies, EC systems are still not widespread; therefore, this study aims to be a starting point to ease the spread of these technologies thanks to the low-cost of the device adopted and to the comprehensive energy and daylighting analyses conducted.

CRediT authorship contribution statement

Alessandro Cannavale: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Francesco Carlucci:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Marco Pugliese:** Writing – review & editing, Methodology, Data curation. **Vincenzo Maiorano:** Writing – review & editing, Supervision. **Ubaldo Ayr:** Writing – review & editing, Supervision. **Francesco Fiorito:** Conceptualization, Methodology, Writing – review & editing, Supervision, Data curation.

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.

Data availability

Data will be made available on request.

References

[1] IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., 10.1017/9781009325844.

[2] E. Parliament, Directive (EU) 2018/844 of the european parliament and of the council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, (2018). https://eur-lex.europa.eu/eli/dir/2018/844/oj.

[3] N. Armaroli, V. Balzani, Solar electricity and solar fuels: status and perspectives in the context of the energy transition, Chem. A Eur. J. 22 (2016) 32–57, https://doi.org/10.1002/chem.201503580.

[4] A. Modi, F. Bühler, J.G. Andreasen, F. Haglind, A review of solar energy based heat and power generation systems, Renew. Sustain. Energy Rev. 67 (2017) 1047–1064, https://doi.org/10.1016/j.rser.2016.09.075.

[5] M. Erdiwansyah, H. Husin, M.Z. Nasaruddin, Muhibbuddin,, A critical review of the integration of renewable energy sources with various technologies, Protection and Control of Modern Power Systems. 6 (2021), https://doi.org/10.1186/s41601-021-00181-3.

[6] A. Azens, C.G. Granqvist, Electrochromic smart windows: Energy efficiency and device aspects, J. Solid State Electrochem. 7 (2003) 64–68, https://doi.org/10.1007/s10008-002-0313-4.

[7] C.G. Granqvist, Electrochromics for smart windows: oxide-based thin films and devices, Thin Solid Films 564 (2014) 1–38, https://doi.org/10.1016/j.tsf.2014.02.002.

[8] Y. Wang, E.L. Runnerstom, D.J. Milliron, Switchable Materials for Smart Windows (2016) 1–22, https://doi.org/10.1146/annurev-chembioeng-080615-034647.

[9] Y. Ke, J. Chen, G. Lin, S. Wang, Y. Zhou, J. Yin, P.S. Lee, Y. Long, Smart windows: electro- thermo-, mechano-, photochromics, and beyond, Adv Energy Mater. 9 (2019) 1–38, https://doi.org/10.1002/aenm.201902066.

[10] M. Feng, X. Bu, J. Yang, D. Li, Z. Zhang, Y. Dai, X. Zhang, Review: smart windows based on photonic crystals, J Mater Sci. 55 (2020) 8444–8463, https://doi.org/10.1007/s10853-020-04460-6.

[11] F. Xu, X. Cao, H. Luo, P. Jin, Recent advances in VO2-based thermochromic composites for smart windows, J Mater Chem C Mater. 6 (2018) 1903–1919, https://doi.org/10.1039/c7tc05768g.

[12] B.P. Jelle, Electrochromic smart windows for dynamic daylight and solar energy control in buildings, in: R.J. Mortimer, D.R. Rosseinsky and P.M.S. Monk (Ed.), Electrochromic Materials and Devices, 2015: pp. 419–502.

[13] C.G. Granqvist, Electrochromics and thermochromics: towards a new paradigm for energy efficient buildings, Mater Today Proc. 3 (2016) S2–S11, https://doi.org/10.1016/j.matpr.2016.01.002.

[14] M.A. Chowdhury, M. Joshi, B.S. Butola, Photochromic and thermochromic colorants in textile applications, J Eng Fiber Fabr. 9 (2014) 107–123, https://doi.org/10.1177/155892501400900113.

[15] Y. Cui, Y. Ke, C. Liu, Z. Chen, N. Wang, L. Zhang, Y. Zhou, S. Wang, Y. Gao, Y. Long, Thermochromic VO2 for energy-efficient smart windows, Joule. 2 (2018) 1707–1746, https://doi.org/10.1016/j.joule.2018.06.018.

[16] T. Wu, T. Yin, X. Hu, G. Nian, S. Qu, W. Yang, A thermochromic hydrogel for camouflage and soft display, Adv Opt Mater. 8 (2020) 1–8, https://doi.org/10.1002/adom.202000031.

[17] F. Ortica, The role of temperature in the photochromic behaviour, Dyes Pigm. 92 (2012) 807–816, https://doi.org/10.1016/j.dyepig.2011.04.002.

[18] L. Wu, S. Zhang, J. Gao, P. Qiang, J. Lei, Preparation of a spirooxazine grafted PMMA and its photochromic properties, Synth Commun. 46 (2016) 818–830, https://doi.org/10.1080/00397911.2016.1178296.

[19] L.Y.L. Wu, Q. Zhao, H. Huang, R.J. Lim, Sol-gel based photochromic coating for solar responsive smart window, Surf Coat Technol. 320 (2017) 601–607, https://doi.org/10.1016/j.surfcoat.2016.10.074.

[20] C. Bechinger, M.S. Burdis, J.G. Zhang, Comparison between electrochromic and photochromic coloration efficiency of tungsten oxide thin films, Solid State Commun. 101 (1997) 753–756, https://doi.org/10.1016/S0038-1098(96)00703-X.

[21] A.G. Lvov, A.M. Kavun, Structural and spectral properties of photochromic diarylethenes: size effect of the ethene bridge, J. Org. Chem. 82 (2017) 1477–1486, https://doi.org/10.1021/acs.joc.6b02665.

[22] P. Cossari, M. Pugliese, S. Gambino, A. Cannavale, V. Maiorano, G. Gigli, M. Mazzeo, Fully integrated electrochromic-OLED devices for highly transparent smart glasses, J Mater Chem C Mater. 6 (2018) 7274–7284, https://doi.org/10.1039/c8tc01665h.

[23] C.G. Granqvist, Oxide electrochromics: an introduction to devices and materials, Sol. Energy Mater. Sol. Cells 99 (2012) 1–13, https://doi.org/10.1016/j.solmat.2011.08.021.

[24] C.G. Granqvist, İ. Bayrak Pehlivan, G.A. Niklasson, Electrochromics on a roll: Web-coating and lamination for smart windows, Surf Coat Technol. 336 (2018) 133–138, https://doi.org/10.1016/j.surfcoat.2017.08.006.

[25] D.R. Rosseinsky, R.J. Mortimer, Electrochromic materials and devices, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2013. 10.1002/9783527679850.

[26] C.G. Granqvist, Handbook of Inorganic Electrochromic Materials (1995), https://doi.org/10.1016/B978-044489930-9/50014-3.

[27] B. Tandon, H.C. Lu, D.J. Milliron, Dual-band electrochromism: plasmonic and polaronic mechanisms, J. Phys. Chem. C 126 (2022) 9228–9238, https://doi.org/10.1021/acs.jpcc.2c02155.

[28] H. Zheng, J.Z. Ou, M.S. Strano, R.B. Kaner, A. Mitchell, K. Kalantar-Zadeh, Nanostructured tungsten oxide - properties, synthesis, and applications, Adv Funct Mater. 21 (2011) 2175–2196, https://doi.org/10.1002/adfm.201002477.

[29] A. Subrahmanyam, A. Karuppasamy, Optical and electrochromic properties of oxygen sputtered tungsten oxide (WO3) thin films, Sol. Energy Mater. Sol. Cells 91 (2007) 266–274, https://doi.org/10.1016/j.solmat.2006.09.005.

[30] C.G. Granqvist, Chapter 3 - Tungsten oxide films: preparation, structure, and composition of evaporated films, in: C.G.B.T.-H. of I.E.M. Granqvist (Ed.), Elsevier Science B.V., Amsterdam, 1995: pp. 29–53. https://doi.org/10.1016/B978-044489930-9/50003-9.

[31] G.A. Niklasson, C.G. Granqvist, Electrochromics for smart windows: thin films of tungsten oxide and nickel oxide, and devices based on these, J. Mater. Chem. 17 (2007) 127–156, https://doi.org/10.1039/B612174H.

[32] S.I. Cordoba-Torresi, A. Hugot-Le Goff, S. Joiret, Electrochromic behavior of nickel oxide electrodes, J Electrochem Soc. 138 (1991) 1548–1553, https://doi.org/10.1149/1.2085831.

[33] H. Liu, W. Zheng, X. Yan, B. Feng, Studies on electrochromic properties of nickel oxide thin films prepared by reactive sputtering, J. Alloy. Compd. 462 (1–2) (2008) 356–361, https://doi.org/10.1016/j.jallcom.2007.08.066.

[34] S.J. Lee, T.G. Lee, S. Nahm, D.H. Kim, D.J. Yang, S.H. Han, Investigation of all-solid-state electrochromic devices with durability enhanced tungsten-doped nickel oxide as a counter electrode, J. Alloys Compd. 815 (2020), 152399, https://doi.org/10.1016/j.jallcom.2019.152399.

[35] M.B. Armand, Polymer Electrolytes, Annu. Rev. Mater. Sci. 16 (1986) 245–261, https://doi.org/10.1146/annurev.ms.16.080186.001333.

[36] C.A. Nguyen, S. Xiong, J. Ma, X. Lu, P.S. Lee, Toward electrochromic device using solid electrolyte with polar polymer host, J. Phys. Chem. B. 113 (2009) 8006–8010, https://doi.org/10.1021/jp900875y.

[37] W. Liu, S.W. Lee, D. Lin, F. Shi, S. Wang, A.D. Sendek, Y. Cui, Enhancing ionic conductivity in composite polymer electrolytes with well-aligned ceramic nanowires, Nat Energy. 2 (2017) 1–7, https://doi.org/10.1038/nenergy.2017.35.

[38] C.O. Avellaneda, D.F. Vieira, A. Al-Kahlout, S. Heusing, E.R. Leite, A. Pawlicka, M. A. Aegerter, All solid-state electrochromic devices with gelatin-based electrolyte, Sol. Energy Mater. Sol. Cells 92 (2008) 228–233, https://doi.org/10.1016/j.solmat.2007.02.025.

[39] I.B. Pehlivan, R. Marsal, E. Pehlivan, E.L. Runnerstrom, D.J. Milliron, C. G. Granqvist, G.A. Niklasson, Electrochromic devices with polymer electrolytes functionalized by SiO 2 and In2O3: Sn nanoparticles: rapid coloring/bleaching dynamics and strong near-infrared absorption, Sol. Energy Mater. Sol. Cells 126 (2014) 241–247, https://doi.org/10.1016/j.solmat.2013.06.010.

[40] P. Cossari, C. Simari, A. Cannavale, G. Gigli, I. Nicotera, Advanced processing and characterization of Nafion electrolyte films for solid-state electrochromic devices fabricated at room temperature on single substrate, Solid State Ion. 317 (2018) 46–52, https://doi.org/10.1016/j.ssi.2017.12.029.

[41] K. Tajima, Y. Yamada, S. Bao, M. Okada, K. Yoshimura, Solid electrolyte of tantalum oxide thin film deposited by reactive DC and RF magnetron sputtering for all-solid-state switchable mirror glass, Sol. Energy Mater. Sol. Cells 92 (2008) 120–125, https://doi.org/10.1016/j.solmat.2007.01.022.

[42] K. Allen, K. Connelly, P. Rutherford, Y. Wu, Smart windows—dynamic control of building energy performance, Energy Build. 139 (2017) 535–546, https://doi.org/10.1016/j.enbuild.2016.12.093.

[43] M. Casini, Smart windows for energy efficiency of buildings, Int. J. Civil Struct. Eng.– IJCSE. 2 (2015) 230–238, https://doi.org/10.5593/SGEM2015/B62/S26.040.

[44] Z. Xie, X. Jin, G. Chen, J. Xu, D. Chen, G. Shen, Integrated smart electrochromic windows for energy saving and storage applications, Chem. Commun. 50 (2014) 608–610, https://doi.org/10.1039/C3CC47950A.

[45] A. Cannavale, U. Ayr, F. Fiorito, F. Martellotta, Smart electrochromic windows to enhance building energy efficiency and visual comfort, Energies (basel). 13 (2020), https://doi.org/10.3390/en13061449.

[46] R. Baetens, B.P. Jelle, A. Gustavsen, Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review, Sol. Energy Mater. Sol. Cells 94 (2010) 87–105, https://doi.org/10.1016/j.solmat.2009.08.021.

[47] J.M. Dussault, M. Sourbron, L. Gosselin, Reduced energy consumption and enhanced comfort with smart windows: comparison between quasi-optimal, predictive and rule-based control strategies, Energy Build. 127 (2016) 680–691, https://doi.org/10.1016/j.enbuild.2016.06.024.

[48] M.N. Assimakopoulos, A. Tsangrassoulis, M. Santamouris, G. Guarracino, Comparing the energy performance of an electrochromic window under various control strategies, Build Environ. 42 (2007) 2829–2834, https://doi.org/10.1016/j.buildenv.2006.04.004.

[49] A. Jonsson, A. Roos, Evaluation of control strategies for different smart window combinations using computer simulations, Sol. Energy 84 (2010) 1–9, https://doi.org/10.1016/j.solener.2009.10.021.

[50] A. Piccolo, Thermal performance of an electrochromic smart window tested in an environmental test cell, Energy Build. 42 (2010) 1409–1417, https://doi.org/10.1016/j.enbuild.2010.03.010.

[51] A. Piccolo, F. Simone, Performance requirements for electrochromic smart window, Journal of Building, Engineering 3 (2015) 94–103, https://doi.org/10.1016/j.jobe.2015.07.002.

[52] A. Piccolo, F. Simone, Energy performance of an all solid state electrochromic prototype for smart window applications, Energy Procedia 78 (2015) 110–115, https://doi.org/10.1016/j.egypro.2015.11.123.

[53] A.D. Tenner, L. Zonneveldt, Switchable Facades and Visual Comfort the SWIFT Test Rooms in Eindhoven (2002) 1–6.

[54] E.S. Lee, D.L. Dibartolomeo, J.H. Klems, S.E. Selkowitz, Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visual Comfort (2006) 1–23.

[55] A. Piccolo, F. Simone, Effect of switchable glazing on discomfort glare from windows, Build Environ. 44 (2009) 1171–1180, https://doi.org/10.1016/j.buildenv.2008.08.013.

[56] V. Primiceri, M. Pugliese, C.T. Prontera, A.G. Monteduro, M. Esposito, A. Maggiore, A. Cannavale, R. Giannuzzi, G. Gigli, V. Maiorano, Low-cost gel polymeric electrolytes for electrochromic applications, Sol. Energy Mater. Sol. Cells 240 (2022), https://doi.org/10.1016/j.solmat.2022.111657.

[57] US Department of Energy, EnergyPlus Version 9.4 Documentation: Getting Started, Energyplus^{TM}. (2020).

[58] R.C.G.M. Loonen, F. Favoino, J.L.M. Hensen, M. Overend, Review of current status, requirements and opportunities for building performance simulation of adaptive facades†, J. Build. Perform Simul. 10 (2017) 205–223, https://doi.org/10.1080/19401493.2016.1152303.

[59] K. Field, M. Deru, D. Studer, Using Doe Commercial Reference Buildings for Simulation Studies. Proceedings of the SimBuild 2010 Fourth National Conference of IBPSA-USA, 2010.
[60] US Department of Energy, EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations, US Department of Energy. (2021) Available online: https://energyplus.net/documenta.
[61] C.E.D.N. [CEN], EN 12464-1, Light and lighting - Lighting of work places - Part 1: Indoor work, European Standard. (2002).
[62] A. Nabil, J. Mardaljevic, Useful daylight illuminance: a new paradigm for assessing daylight in buildings, Light. Res. Technol. 37 (2005) 41–59, https://doi.org/10.1191/1365782805li128oa.
[63] A. Nabil, J. Mardaljevic, Useful daylight illuminances: a replacement for daylight factors, Energy Build. 38 (2006) 905–913, https://doi.org/10.1016/j.enbuild.2006.03.013.
[64] J. Mardaljievic, Validation of a lighting simulation program under real sky conditions, Lighting §res, Technol. 27 (1995) 181–188.
[65] J. Mardaljevic, R.K. Waskett, B. Painter, Electrochromic materials and devices, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2013. 10.1002/9783527679850.
[66] J. Mardaljevic, M. Andersen, N. Roy, J. Christoffersen, Daylighting metrics: is there a relation between useful daylight illuminance and daylight glare probability?, 1 (2012) 189–196. https://publications.ibpsa.org/conference/paper/?id=bso2012_3B1 (accessed February 22, 2023).
[67] F. Carlucci, F. Fiorito, Methodological approach and comparative analyses for smart envelopes assessment in three different temperate climates, Rivista Tema. 8 (2022). 10.30682/TEMA0801M.