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Energy savings due to building integration of innovative solid-state electrochromic devices

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Abstract

The next generation of adaptive facades includes dynamic electrochromic (EC) windows: they can dynamically modulate the daylight and solar energy entering buildings by application of an external voltage. Windows play a pivotal role in the definition of the energy balance as well as environmental impacts of buildings. Emerging technologies are focused on the optimization of these building components. We carried out an interdisciplinary study dealing with building integration of an innovative chromogenic technology, consisting in a recently designed single substrate solid-state electrochromic device, developed by some of the authors, with excellent figures and a compact device architecture. The practical implications on the building energy balance were analyzed by means of suitable simulations, carried out in Energy Plus. A reference office building was equipped with different glass technologies on the façade (clear glass, solar control, electrochromic glasses) and located in different cities (Rome, London and Aswan) to also include climatic effects in the analysis. The EC technology here presented outperforms all the others, with overall yearly energy savings as high as 40 kWh/m²yr (referred to window surface) in the hottest climates, assuming the clear glazings as benchmark. Daylighting performances were significantly improved using innovative solid-state EC devices, both in terms of Useful Daylight Illuminance (UDI) and Discomfort Glare Index (DGI). In the best case, 82.7% of hours achieved optimal illuminance conditions on an annual basis.

1 Introduction

Electrochromic (EC) windows, or “smart windows”, can be considered a “green” nanotechnology [1]. As reviewed by C.G. Granqvist, emerging chromogenic technologies (especially thermochromics and electrochromics) can regulate the throughput of visible light and solar energy in dynamic tintable glazings, yielding better energy efficiency than static solutions [2]. Numerous materials show an EC behavior: the most investigated materials are transition metal oxides, but also organic ECs (conjugated polymers or small molecules) have attracted the attention of several research groups worldwide [3]. EC oxides are typically subdivided into two kinds: cathodic and anodic [4]. Cathodic ECs color under ion insertion and cathodic reduction, whereas the anodic ones activate their optical transition due to ion extraction and anodic oxidation. Anodic and cathodic ECs, for this reason, are said to show a complementary fashion. Tungsten oxide (WO_3) is by far the most known and investigated cathodic EC material, whereas a typical anodic inorganic EC oxide is nickel oxide (NiO). The EC coloration/bleaching process is highly reversible and, for the above mentioned inorganic oxides, is finely explained by means of two simple redox reactions [5].

The research field of chromogenic materials has catalyzed the attention of several research groups worldwide, since the 80's. In particular, EC devices [6,7] based on transition metal oxides typically show a multilayered, battery-like architecture [8]. An EC device generally contains transparent conductive substrates, an interposed electrolyte and one or two EC materials. Optical absorption varies when electrons are inserted (extracted, in case of anodic EC materials) into the cathodic EC material from the transparent conductive oxide and charge balancing ions enter from the electrolyte (or exit, respectively, in the case of anodic ECs), simultaneously.

Conventional liquid or gel electrolytes, sandwiched between the two EC materials, represent one of the most critical limitations, since they suffer from poor structural stability, tendency to leak and evaporate, and, then they affect the EC response with irregularities and non-uniform coloration [9–11].

Thus, a substantial effort is in progress, worldwide, to produce innovative solid electrolytes with the aim to overcome these major drawbacks. Solid polymer electrolytes (SPE) are among the most promising materials due to their low processing costs, electrochemical stability, flexibility and easy scalability [12–14]. A clear trend is

currently visible in the design of innovative EC devices, aiming at obtaining solid-state devices, in order to achieve higher duration but also architectural simplification and reduction of impacts and costs [15].

Some of the authors [16,17] reported the performances of a newly designed full solid-state EC device fabricated on a single substrate, made of glass as well as flexible plastic, adopting a Nafion electrolyte film as a suitable solid electrolyte, (8 μm thick) sharing its interfaces with an EC WO_3 layer and a highly transparent and conductive RF-sputtered ITO film, deposited at room temperature (RT). Open issues like electrolyte leakage or solvent evaporation, limited durability and inhomogeneous EC transition were addressed with respect to the more complex sandwich-type architecture, typically containing sticky gel or liquid electrolytes. The best device fabricated showed an optical contrast of 49% (at 650 nm), a switching response time of 30 s and, interestingly, a very low electric energy absorption. Such values are among the best found for solid-state EC devices [18–22]. The electro-optical performances of these devices were adopted as an input for the simulation activities reported hereafter.

It is quite intuitive to envisage the manifold advantages due to building integration of smart glazings in the architectural envelope, nevertheless only a few attempts have been published so far, aiming at a precise report of attainable energy savings on real buildings, on a yearly basis together with the benefits in terms of visual comfort. The dynamic modulation of the energy throughput of glazings has different, interdependent fallouts. First of all, dynamic tintable glazings affect energy consumption in summer, cutting out a large part of undesired solar gains; they also influence visual comfort indoor by maximizing the use of daylighting and, as a consequence, they reduce the use of artificial lighting. According to Lampert [23], the optical switching technology for glazings bears several advantages: they require powering only upon switching, with small voltages; they show durable memory (up to 48 h) and they are quite prone to large-area fabrication.

More recently, DeForest et al. [24] adopted the EnergyPlus software platform to simulate annual energy performance of a dual-band EC glazing in three building types and several US climate regions. They estimated the savings potential of such windows, capable of achieving annual primary energy savings between 6 $\text{kWh/ft}^2\text{yr}$ and 30 $\text{kWh/ft}^2\text{yr}$ per window area, reducing heating, cooling, and lighting demand, if integrated

on windows, with a value strictly depending not only on the device characteristics but also on climatic conditions.

In a previous work [25], they also presented a simulation study of the energy and CO₂ benefits of a transparent, near-infrared switching EC glazing for building applications. They found that the U.S. savings from near-infrared switching EC deployment could be 167 TWh/yr, to show the technical potential a high performance near-infrared EC glazing could have if deployed throughout the U.S. building stock. As predictable, they found that the conventional EC windows outperformed the near-infrared switching EC glazing in “cooling dominated” climates, like the Mediterranean area. DeForest et al. [26] reported the performance of an early prototype EC window controller showing that for a south-facing large-area window, daily lighting energy use savings (between 6:00 and 18:00 h) could reach 8–23% if EC windows were used instead of 50% transmissive windows. Visual comfort and energy implications of EC windows with overhangs were also investigated in hot and cold climates, finding significant reductions of average annual daylight glare index (DGI) and relevant energy savings (10%) with high WWRs. Peak electric demand can be reduced by 14–16% for large-area windows in either climate [27].

Lee et al. [10] reported results from a full-scale demonstration of building-integrated large-area ECs, with a window-to-exterior-wall ratio (WWR) of 0.40. Their lighting, illuminance, and control operations data suggested that EC windows provide greater energy efficiency and improve environmental quality, if compared to conventional window systems generally adopted in buildings. Automated control of EC windows and correct setting of dimmable lighting systems were also investigated in a conference room in Washington, where lighting energy saving reached 91%, compared to the existing lighting system. The authors used Energy Plus platform to estimate annual energy savings (48%) and peak demand savings (35%) [28].

A visual comfort assessment of EC devices smartly activated by means of photogenerated driving force, namely photovoltachromic devices, was carried out by some of the authors [29]. Starting from real devices electro-optical figures of merit, they found that light penetration in office buildings showed that the integration of photovoltachromic devices in traditional windows could dramatically increase indoor visual comfort (useful daylight illuminance increased up to 71.8% and daylight glare probability down to 12%).

Tavares et al. [30] focused on the energy savings attainable using EC windows as an alternative to shading devices to control solar gain in buildings located in Mediterranean climates. They carried out an energy performance simulation of buildings, comparing three glazing options: single glass, conventional double glazing and EC glazing. They found energy savings of 20.28 and 36.94 kWh/m²yr per windows surface in the east/west facades, and a simple payback of 10 years, concluding that the EC glasses are an energy-efficient solution for use in buildings, also in case of refurbishment.

Aldawould [31] compared EC glazings to fixed shading devices in hot dry climate, modeling a typical office building by means of the software DesignBuilder: EC glazing provided the best performance in reducing solar heat gains compared to other tested shading conditions.

Syrarakou et al. [32] carried out an eco-efficiency analysis on an EC prototype and showed that, with the right premises (reduction of the purchase cost to 200 €/m² lifetime increase above 15 years), cost and environmental efficiency could be achieved at the same time. They stated that EC glazings theoretically reduce the building energy requirements by 52%, in cooling dominated areas.

2 Methods

2.1 Solid-state ECs: fabrication methods and characterization of devices

The energetic implications deriving from the building integration of a monolithic solid-state EC fabricated by some of the authors [33] were investigated in the paper. The EC devices (later on referred as CNR-EC) were fabricated on a single substrate, made of glass or flexible plastics, with a simplified architecture based on substrate/ITO/WO₃/Nafion/ITO configuration, in which a Nafion film (with a thickness of 8 µm) tightly shares its interfaces with the WO₃ layer and the highly transparent and conductive RF-sputtered ITO film [10]. Fig.1 reports a cross section of the device, obtained by scanning electron image.

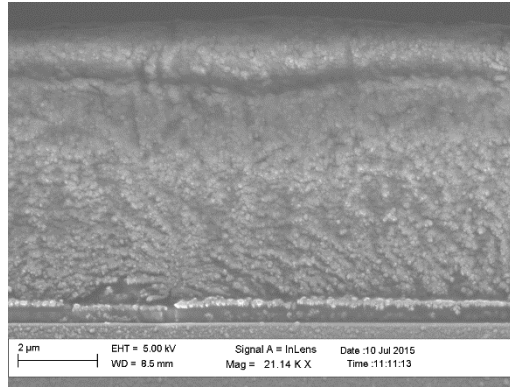


Figure 1. A cross section scanning electron microscopy image of EC device based on solid Nafion film with a thickness of 8 μm .

The whole process was carried out at room temperature (RT) condition without any lamination step with a secondary electrode. This point is quite relevant in terms of costs of fabrication process and environmental impacts. In particular, transparent and conductive ITO thin films (300 nm thick) having a sheet resistance of 20 Ω/square and an optical transmittance above 50% in the visible range were deposited at RT on solid Nafion film by non-reactive RF sputtering, without affecting the structural and functional properties of the polymer electrolyte. A solid Nafion film with a thickness of 8 μm was deposited on the WO_3 layer by spin-coating since the investigation of the influence of polymer electrolyte film thicknesses on the EC response demonstrated that this thickness value was crucial to obtain highly performing solid-state devices. The WO_3 layer (300 nm thick) was deposited by electron beam on commercial conductive substrates, both glass and plastic. Table 1 summarizes the thickness of the materials and the fabrication methods adopted for EC devices under investigation.

Table 1: Thicknesses and fabrication process of the materials constituting the monolithic solid-state EC devices

Materials	Thickness	Fabrication process
PEN	0.125 mm	Commercial
ITO	150 nm	
WO_3	300 nm	Physical vacuum deposition: Electron-beam
Nafion- H^+	8 μm	Solution processing: Spin-coating
ITO	300 nm	Physical vacuum deposition: RF magnetron sputtering

The electro-optical and electrochemical properties of the devices were assessed by spectrophotometry (transmittance and kinetic spectra), cyclic voltammetry and chronoamperometry measurements, respectively.

This EC system showed as high coloration efficiency as $139 \text{ cm}^2/\text{C}$, an optical contrast of 49% (at 650nm) (Figure 2a), a switching response time of 30s (Figure 2b) and a very low electric energy absorption (of about $80 \text{ mJ}/\text{cm}^2$) required to achieve a complete and homogeneous coloration (90% of optical modulation). In addition, these devices exhibited a strong enhancement in terms of interface properties, robustness, environmental stability (one year of storage), cyclability (300 cyclovoltammetry cycles) and long-term durability of at least 1000 chronoamperometric cycles.

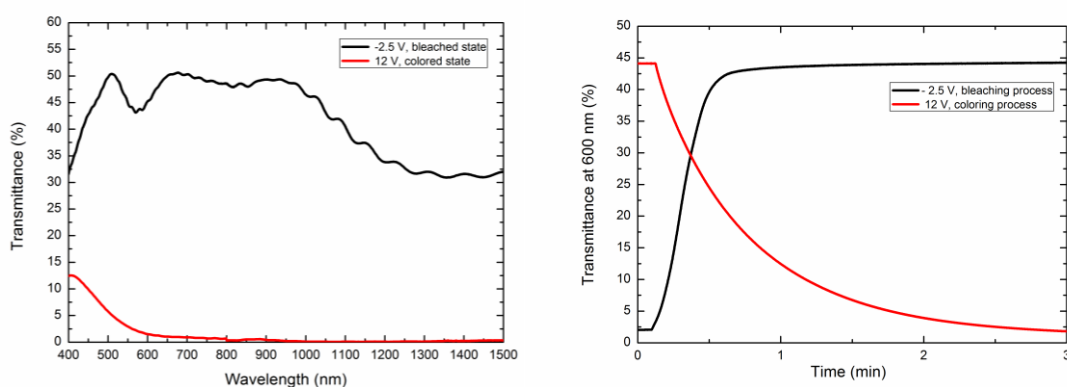


Figure 2. (a) Transmittance spectra of device under bleached and colored conditions in the range wavelength between 400 nm and 1500 nm. (b) Color switching time of EC films measured at wavelength of 600 nm with applied potentials of -2.5 V (bleached) and $+12 \text{ V}$ (colored).

As a result, a very compact and lightweight device was obtained, which was very manageable, safe and easy to use and, not negligible, with an ultra-thin aesthetics and a simple architectural design. Furthermore, this organic-inorganic hybrid EC device assembled in a cheap and facile process without any lamination step and fully at RT condition led to the possibility of “growing” the active layers on glass as well as on plastic substrates (Fig. 3). In the end, thanks to its low power and robust operation (wide electrochemical window and high durability) due to ideal chemo-physical properties of solid Nafion film, together with optimal interface characteristics between electrolyte and counter electrode, this novel monolithic architecture stands out of conventional EC devices.



Fig. 3. Pictures in bleached and colored conditions of flexible EC devices fabricated on polyethylenenaphthalate (PET) substrate.

2.2 Building model description

The building model used in this study (Figure 4) was taken from the archive of the reference buildings available from the US Department of Energy [34]. The selected reference building was a medium-sized office building with three floors and five thermal zones consisting of one core area and four external spaces (one for each exposure) in each floor. In this study, only three thermal zones for each floor were considered, corresponding to the Southern exposure (ZN_1 – Surface area 621 m²), the Eastern exposure (ZN_2 - Surface area 394 m²) and the Western exposure (ZN_4 - Surface area 394 m²). Total conditioned floor area was then 4230 m², approximately. The wall window ratio is 33% of external wall and the total window area is 652 m². Envelope thermal resistance is 0.46 m²K/W for ground floor, 2.74 m²K/W for roof, and 1.42 m²K/W for walls. Daily internal load condition and pattern fraction of occupants, lighting, and equipment were left unchanged according to “reference building” specifications, with 10.76 W/m² for both lighting and equipment loads in the office building and an occupancy rate of 18.58 m²/person.

Fenestration was assumed to have thermal–optical properties of a simple double-pane glazing system (6mm-clear glass/16mm-air gap/6mm-clear glass) as a baseline model, ideally representing existing building conditions. Clear glass pane was a 6 mm Optifloat Clear, with $T_{vis} = 0.884$. However, as the use of this kind of glazing is being discouraged

by energy saving regulations in many countries, a spectrally selective glazing (SGG Cool-Lite KN-155) was considered as representative of new buildings. A further option which is commonly adopted to prevent unwanted solar radiations to enter the indoor space is that of using solar control glazings. As reported by Ebisawa [35], soda-lime-silicate glazings are substantially transparent over the entire solar radiation wavelength and slight absorption and reflections occur. Solar control glazings contribute to reduce undesired heat gain, especially in "cooling dominated climates", by reflecting solar infrared radiation, while transmitting as high as possible visible transmittance. This is obtained by means of a coating that can be fabricated by an accurate design of a multilayer interference coating, consisting in a stack of high index dielectric (e.g. TiO_2) coupled with a low index dielectric (SiO_2 , MgF_2). Each layer is typically 275 nm, which is a quarter of the solar infrared wavelength. On the other hand, as reported by Kennedy et al. [36], selective coatings show both high solar absorptance and low thermal emittance, typically deposited on face 2. In the present case a commercial 6 mm SGG Cool-Lite ST 136 pane was used to replace the outer pane of the reference window.

EC devices were supposed to be applied only on South, East, and West windows and were assumed to be located on the inside face of the outside glass, they consequently affected both solar heat gain coefficient and the overall T_{vis} . To compare the performance of the EC glazing under investigation with a commercial product, the EC glazing a SageGlass Clear was used. The resulting properties of the glazings, including those of the CNR-EC glazing, based on actual measurements of transmissivity and reflectance, were calculated using LBNL Window 7.5, and given in Table 2.

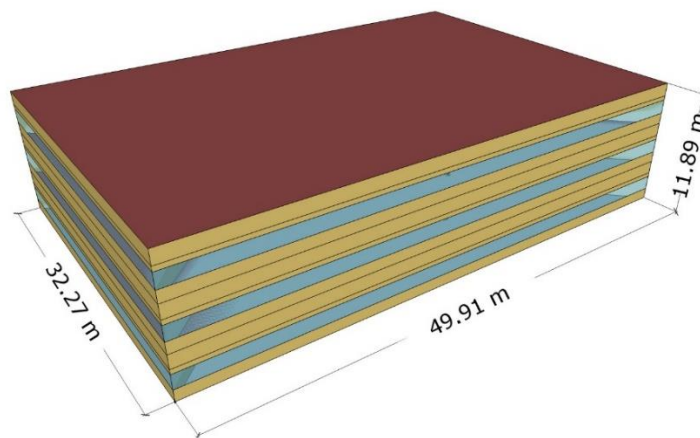


Figure 4. 3D model of the reference building

Table 2. Glazing features as modelled. Parameter values were calculated using LBNL Window 7.5 software starting from glazing features. For Electrochromic glazings values pertaining to bleached and fully tinted configuration are given.

Window type	U factor [W/m ² K]	Tvis	SHGC
Clear glass	2.720	0.787	0.716
Selective glass	1.900	0.470	0.360
Solar Control	2.698	0.329	0.345
Commercial EC	1.947	0.622, 0.015	0.470, 0.100
CNR-EC	1.980	0.409, 0.027	0.439, 0.113

Table 3. Summary of geographic and meteorological characteristics of the selected locations, together with the yearly average temperature and rainfall (source climate-data.org), the average sky cover and overall radiation on horizontal surface (source IWECC dataset).

City	Lat. [°]	Koppen-Geiger Climate Class		Avg. Temp. [°C]	Avg. Rainfall [mm]	Avg. Sky Cover [0-10]	Horiz. Radiation [kWh/m ² yr]
London	51.15	Temperate oceanic	Cfb	11.1	621	6.7	1001
Rome	41.90	Warm mediterranean	Csa	15.7	798	2.5	1461
Aswan	23.97	Hot desert	Bwh	26.8	1	0.9	2294

Detailed simulations were carried out with reference to Rome (Mediterranean climate, Csa according to Koppen-Geiger classification). In addition, to get more information about the location dependence, two more cities were included in the analysis: London (North-Europe climate, Cfb according to Koppen-Geiger classification) and Aswan (Desertic climate, BWh according to Koppen-Geiger classification). A summary of the main climatic variables is given in Table 3.

All the analyses were carried out using EnergyPlus v. 8.8. EnergyPlus is a free simulation tool, developed by the U.S. Department of Energy's Building Technology Office, for modeling thermal loads and performing energy analysis of whole buildings or single building zones. EnergyPlus models are defined by building geometry, envelope characteristics, mechanical system characteristics, and occupancy and setpoint schedules.

In order to determine the heating and cooling energy consumptions in a simple and straightforward way, and also avoid making assumptions on more detailed plant characteristics, an "IdealLoadAirSystem" with no outdoor air was considered. This EnergyPlus object provides both the heating and cooling energy required to meet the temperature set-points that have been provided by the relevant schedules. As the purpose

of the analysis was that of determining the influence on energy consumptions for heating and cooling due to different glazing types, no restrictions were applied to the maximum sensitive heating capacity. As the IdealLoadAirSystem returns exactly the thermal energy that must be provided, to convert such value into electrical energy, a constant COP of 3 was assumed for both heating and cooling modes. Heating was assumed to be turned on during working hours and off during nights and holydays and limited to a period from November 1st to March 31st, while cooling was turned on from June 1st to September 30th for both Rome and London, while in Aswan the cooling period was extended from April 1st to November 30th to account for the more extreme climate conditions.

Although climate zones are significantly different, envelope thermal resistance was also the same. However, a comparison of the envelope characteristic of reference buildings designed for different cities in the USA, normally adapted to climate conditions according to ASHRAE Standard 90.1-2004, confirmed that no significant change in thermal resistance was found when the same climate zones were considered. With reference to the weather conditions, data taken from a large and homogeneous dataset were preferred. Consequently, the IWEC (International Weather for Energy Calculations) database developed by ASHRAE within the Research Project 1015 was used.

In order to maximize energy savings, artificial lighting was controlled by means of the Daylighting:Controls object which allowed a continuous dimming of overhead artificial lighting as a function of the illuminance value calculated at a given reference point. Reference points were located at the center of each zone, so that lighting levels could be modulated independently as a function of floor and exposure. A minimum illuminance of 500 lx on the work surface was taken as a reference, that is a value prescribed for offices by international standards [35]. However, as the visual task in most office activities is turning to be computer screen-based rather than paper based, 300 lux is becoming the de facto standard. Consequently, as the use of this setpoint value may have significant implications on energy savings, the analysis was carried out using both values as a reference.

Finally, to model the electro-chromic behavior of glazings the WindowProperty:ShadowControl object was used. The shading type was set to “Switchable glazing” which allows to linearly change the optical properties of the glazing (p) between two extreme values corresponding to the bleached (p_{bleached}) and tinted (p_{tinted})

state (given in Table 2 for the devices under analysis). The linear variation depends on a switching factor (f_{switch}) according to the following equation:

$$p = (1 - f_{\text{switch}})p_{\text{bleached}} + f_{\text{switch}}p_{\text{tinted}}$$

The control strategy that varies the switching factor, in the present case, was based on maintaining the same minimum illuminance levels as discussed before, in the same reference points used to control artificial lighting. Consequently, the switching factor is different for each zone. Considering that, as shown in Fig. 2, the bleaching process takes less than a minute, while the coloring takes about three minutes, in both cases the process may be considered completed within one of the EnergyPlus timesteps, which are considered to be equal to 10 minutes. No particular assumption was consequently needed to handle EC response. As reported in the literature [37,38], the coloration time is independent of the area of devices.

2.3 Daylighting analysis

EC glass has the advantage of providing dynamic energy throughput control of the glazing, resulting in multiple energy and visual comfort benefits. In this work, as already explained, the control strategy has been set by first imposing a minimum illuminance of 500 lx on the work surface, that is a value prescribed for offices by international standards [39], and then a value of 300 lx corresponding to the de-facto standard for screen-based office tasks. This indeed allows to enhance the use of natural lighting, resulting in energy savings compared to solutions showing fixed shielding (such as solar control films) or opaque and external (venetian blinds and other shades).

Two comfort parameters chosen for assessing the visual comfort benefits of building integrated EC glazings were Useful Daylight Illuminance (UDI) and Discomfort Glare Index (DGI), employing the output from EnergyPlus software. This supplementary analysis can be considered a preliminary study, useful to give a full overview of the manifold impacts of EC technology on energy balance and comfort. More detailed analyses are being carried out for an exhaustive daylighting analysis. Useful Daylight Illuminance (UDI) parameter, developed by Nabil et al. [40], considers absolute daylight illuminance levels on hourly-based meteorological data, over a period of a full year. UDI are defined as percentages of time in which sensors' illuminances fall within a range of

values that is considered comfortable by the users. According to previous literature reviews (based on occupants' preferences and behaviors) [41,42], a range of 300–3000 lx has been considered suitable. Daylight illuminances lower than 300 lx are generally considered insufficient; daylight illuminances higher than 3000 lx are likely to produce visual or thermal discomfort. On the other hand, glare indeed represents a critical factor affecting the level of visual comfort in daylit office spaces. DGI was then estimated at each reference point as reported in the Engineering reference Manual of EnergyPlus [43], Chapter 7, paragraph 7.3.4. Recommended value here adopted for maximum allowable DGI, referred to activity and zone type, was 22 for daylit offices, as reported in Table 1.28 of the Input Output Reference Documentation of EnergyPlus [43] .

3 Results

3.1 Energy balance due to lighting, heating and air conditioning

A full comparison among specific yearly electric energy consumption data was carried out in order to assess the energy savings attainable in the reference building, equipped with different glazing technologies on three facades (South, East and West). To this aim, we assessed the yearly energy performances adopting clear glass as a reference technology for existing buildings and selective glazings as representative of new buildings. In order to normalize results and make them easily comparable, energy consumptions were represented in terms of specific yearly consumptions (for lighting, heating, and cooling) per unit floor area averaged over the three exposures. Energy demand for equipment was not included in the analysis because it is a constant term, not affected by glazing type.

Detailed analysis was carried out for Rome (Figs. 5-10), while for other cities a summary of the performances for selected technologies is given in Tables 4-7. With reference to clear glass the cooling energy demand (averaged over the three exposures) was 20.3 kWh/m²yr, one order of magnitude higher than heating demand (1.4 kWh/m²yr) and more than double compared to the electric energy required to operate artificial lighting (7.4 kWh/m²yr). The thermal zones on the three facades showed similar results except for cooling energy demand, that was higher on the Southern exposition (22.6 kWh/m²yr).

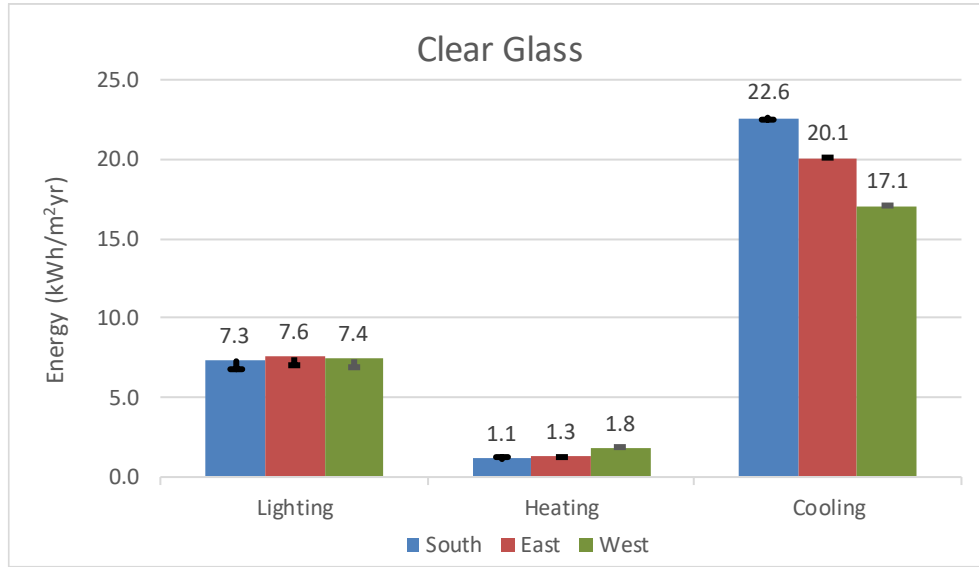


Figure 5. Specific yearly energy consumptions for lighting, heating and cooling according to the façade exposure, adopting windows equipped with clear glass. Error bars represent the variation resulting from the adoption of a 300 lx for workplace illuminance.

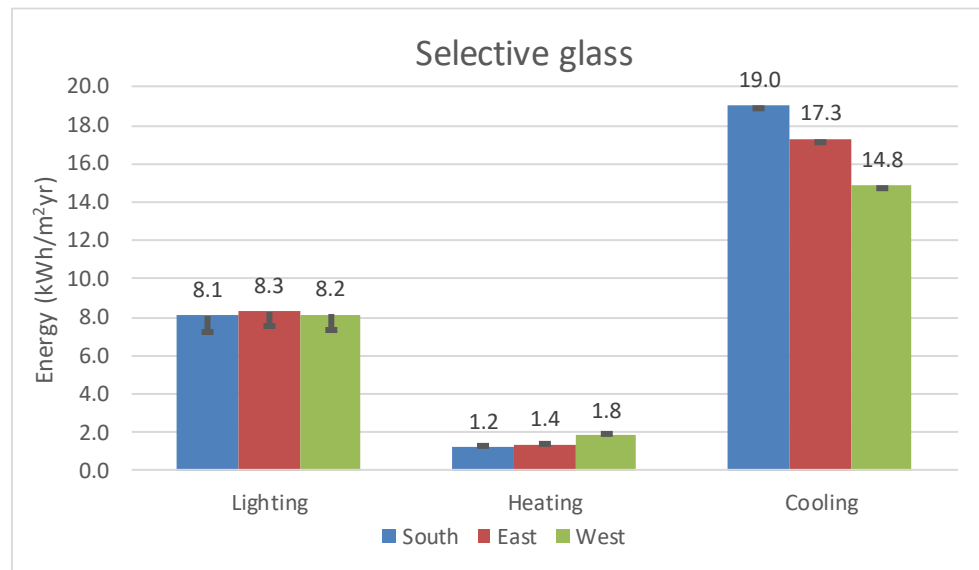


Figure 6. Specific yearly energy consumptions for lighting, heating and cooling according to the façade exposure, adopting windows equipped with selective glass. Error bars represent the variation resulting from the adoption of a 300 lx for workplace illuminance.

The use of selective glazings (Figure 6) caused a significant reduction in electric energy for cooling (dropped to 17.4 kWh/m²·yr), while energy demand for heating remained mostly the same (1.4 kWh/m²·yr) and lighting energy showed a slight increase up to 8.2 kWh/m²·yr, as expected considering that T_{vis} is lower for this kind of glazing. As already observed, the Southern façade required more cooling energy than the others.

The use of solar control films in double pane windows caused a notable reduction of energy consumption for cooling. Annual overall energy uses were 27.1 kWh/m²yr, 26.1 kWh/m²yr, and 24.5 kWh/m²yr, on South, East, and West façades respectively. On the Southern exposure, the global energy saving (considering all electric energy uses: cooling, heating and lighting) compared to CG was 13%, while it reduced to 4% when referred to SG, (Figure 7). Extending the analysis to all the facades the overall savings dropped to 10%. The observed 25% increase in energy consumption for lighting, compared to the basic clear glass technology was clearly due to the non-adaptive transparency of solar control glazings, resulting in an increase of hours when artificial lighting occurs. Anyway, such increase was largely offset by significant savings in cooling.

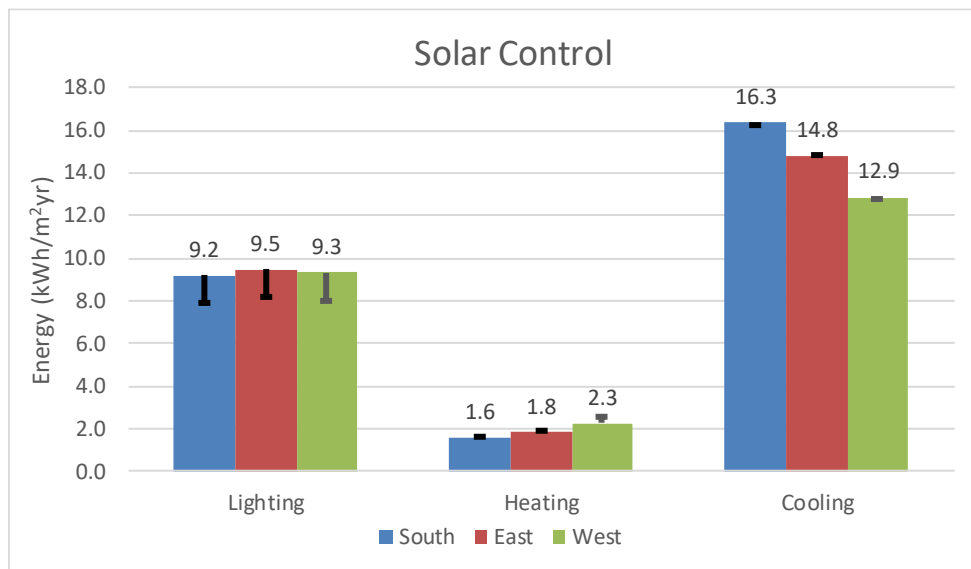


Figure 7. Specific yearly energy consumptions for lighting, heating and cooling according to the façade exposure, adopting windows equipped with solar control glazings. Error bars represent the variation resulting from the adoption of a 300 lx for workplace illuminance.

The use of commercial electrochromic glazings showed a further reduction in energy consumption compared to solar control glazings. As it can be observed in Figure 8, improvement in energy savings was dominated by cooling performances: an impressive energy saving of 35% was obtained with reference to CG, while it dropped to 25% when referred to SG. On the other hand, the expected, slight increase in heating (+11%) was easily explained in terms of mitigated solar heat gains in winter, due to lower solar and visible transmittance of electrochromic glazings, even in the “bleached” conditions, compared to clear glass. Also, the energy uses for lighting were almost coincident with

those observed in the building equipped with clear glass and 7% lower compared to the SG case, confirming the usefulness of the variable transparency. The overall yearly energy saving in the building achieves the value of 23% with respect to CG, and 17% with respect to SG.

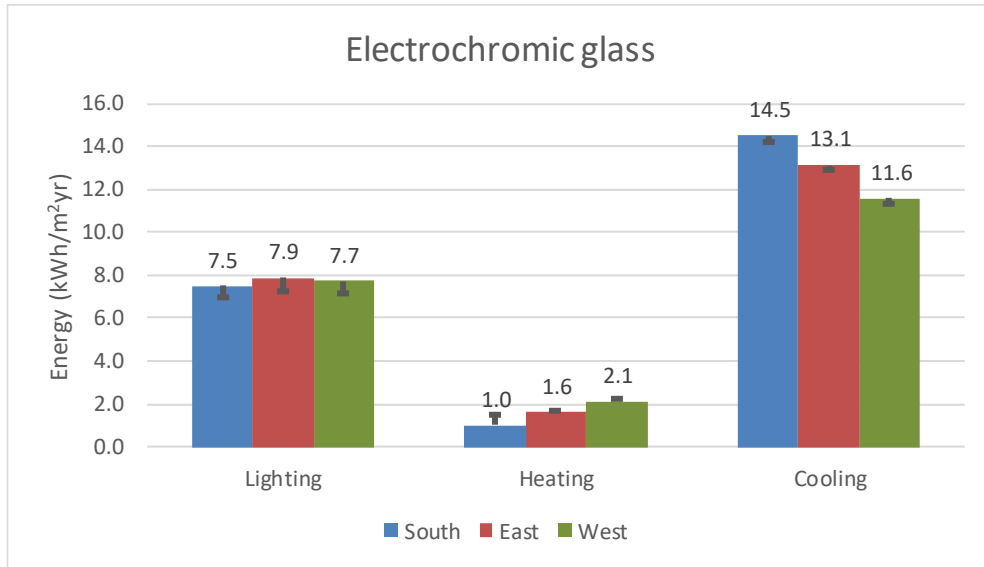


Figure 8. Specific yearly energy consumptions for lighting, heating and cooling according to the façade exposure, adopting windows equipped with commercial EC glazings. Error bars represent the variation resulting from the adoption of a 300 lx for workplace illuminance.

Figure 9 reports electric energy uses in the building zones equipped with the innovative solid-state electrochromic technology developed by CNR (CNR_EC). In this case, overall energy savings for cooling increase to 38% (if compared to CG) and to 28% if compared to SG, while on the Southern façade savings raise up to 40%. However, the lower transmittance in bleached conditions compared to commercial electrochromic glazings caused an increase of the energy consumptions both for heating (+29% overall) and for lighting (+32%), especially in winter seasons and on Eastern and Western facades. However, in absolute terms the first one determines a negligible effect on the overall result, while the increase in energy demand for lighting reduces the overall energy saving due to this technology to 17%. When compared to SG the overall reduction in electric energy demand drops to 10%.

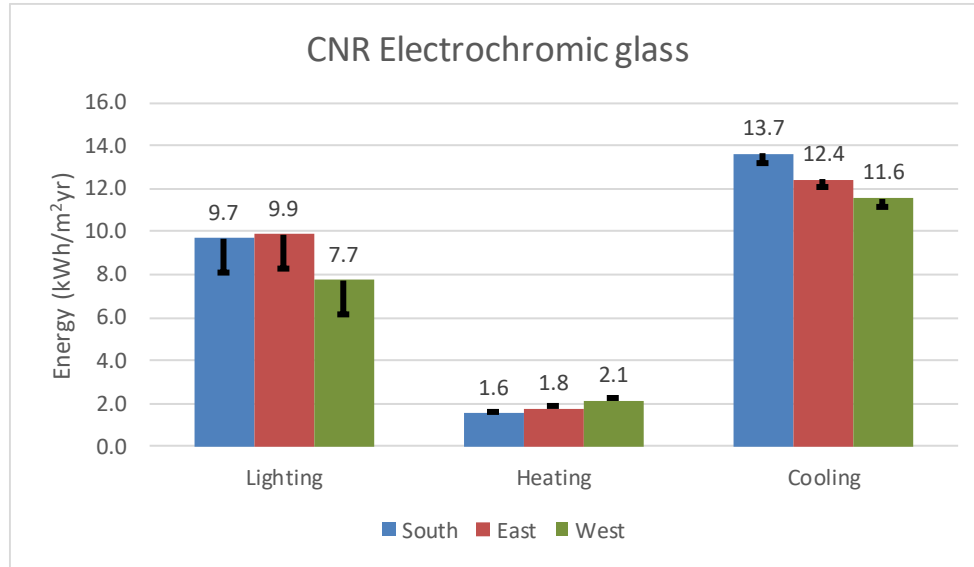


Figure 9. Specific yearly energy consumptions for lighting, heating and cooling according to the façade exposure, adopting windows equipped with CNR electrochromic glazing. Error bars represent the variation resulting from the adoption of a 300 lx for workplace illuminance.

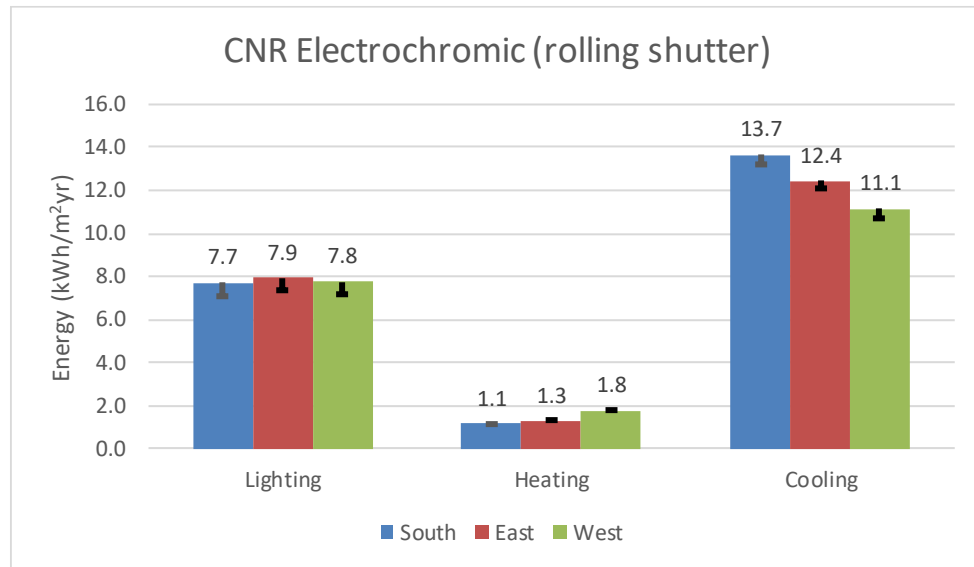


Figure 10. Specific yearly energy consumptions for lighting, heating and cooling according to the façade exposure, adopting windows equipped with CNR electrochromic device applied as rolling shutter. Error bars represent the variation resulting from the adoption of a 300 lx for workplace illuminance.

The above-mentioned results and some considerations about the innovative technology at the basis of this study led us to consider a specific hypothesis to override the inherent optical limitation of the CNR-EC glazing and take full advantage of its innovative characteristics. As reported by Favoino et al. [44,45], a correct strategy for adaptive chromogenic glazings has relevant fallouts on energy and visual comfort performances.

As explained above (Methods section), unlike commercial EC glazings, this technology requires only one substrate, even flexible, if conductive PEN is adopted [46].

We have therefore hypothesized to use a rolling EC device, fabricated on a PEN film, to be conveniently dropped into the glass only during the same period in which the cooling is turned on, so that in the winter season all the solar gains can be exploited, so as to reduce heating loads and limit artificial lighting. Under this configuration (Fig. 10), the building outperforms all the other technology configurations, on an annual basis. The total energy savings achievable with the latter solution reached 25% compared to the CG reference configuration and 19% compared to SG reference. In both cases results outperformed both solar control glazings (savings of 10% and 3% respectively) and commercial ECs (savings of 23% and 17% respectively).

This allowed the electrochromic film to be potentially used in the summer season, as a rolling shutter, thus maximizing the beneficial effects on energy balance. As it can be noticed, Figure 11 reports the best figures of merit in terms of average energy consumptions per unit area. Overall electricity uses for cooling, heating and lighting were reduced, in the best case scenario (CNR-EC with rolling shutters), from 29.1 kWh/m²yr to 21.7 kWh/m²yr, with a net saving of 7.4 kWh/m²yr, corresponding to a 25%. If the CNR-EC technology was employed to make a conventional glazing energy savings dropped to 4.9 kWh/m²yr, slightly lower than the value resulting from the application of the commercial EC glazing which yielded 6.6 kWh/m²yr savings. Thus, when using the CNR-EC technology, the use of the “rolling shutter” is recommended in order to maximize the energy savings. Adopting the selective glass as a reference reduced energy savings to 5.3 kWh/m²yr for the rolling shutter case, to 2.8 kWh/m²yr for the CNR-EC glass case, and to 4.5 kWh/m²yr for the commercial EC glass.

As anticipated in Sec. 2.3, the conventional illuminance value of 500 lx to be ensured on the working plane is being reconsidered in the light of a substantial transition to a screen-based visual task. Consequently, a 300 lx is considered as suitable and this might affect the results of the previous analyses. In fact, in addition to a reduction in lighting energy demand, this may also imply a reduction in cooling loads, which are largely dominant in the analyzed building, at the expense of a slight increase in heating energy demand. As shown by error bars in Figs. 5-10, the largest improvement (both for lighting and cooling energy) was observed for the EC glass configuration which, being darker

than the others in bleached state, required an extensive use of artificial lighting, particularly in winter. The reduction in cooling energy resulted from both a reduction of heat dissipated by lighting and the possibility to more effectively take advantage of EC glazings. In fact, the second technology showing the largest improvements was that based on solar control galzings, but this time the improvement was mostly observed on lighting energy demand, while no effect was observed on cooling energy demand (as expected, having a constant transparency coefficient).

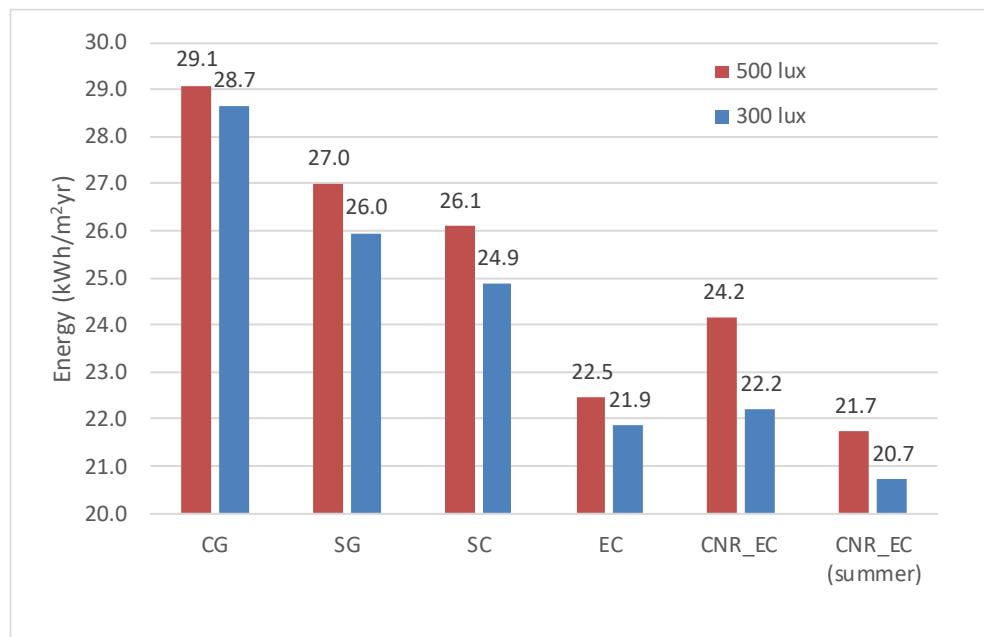


Figure 11. Specific yearly electric energy consumption for lighting, heating and cooling in buildings equipped with different glazings technologies.

As anticipated in Sec. 2.3, the conventional illuminance value of 500 lx to be ensured on the working plane is being reconsidered in the light of a substantial transition to a screen-based visual task. Consequently, a 300 lx is considered as suitable and this might affect the results of the previous analyses. In fact, in addition to a reduction in lighting energy demand, this may also imply a reduction in cooling loads, which are largely dominant in the analyzed building, at the expense of a slight increase in heating energy demand. As shown by error bars in Figs. 5-10, the largest improvement (both for lighting and cooling energy) was observed for the EC glass configuration which, being darker than the others in bleached state, required an extensive use of artificial lighting, particularly in winter. The reduction in cooling energy resulted from both a reduction of heat dissipated by

lighting and the possibility to more effectively take advantage of EC glazings. In fact, the second technology showing the largest improvements was that based on solar control glazings, but this time the improvement was mostly observed on lighting energy demand, while no effect was observed on cooling energy demand (as expected, having a constant transparency coefficient).

In absolute terms, as shown in Fig. 11, the best performing technology remains the CNR-EC with the rolling shutter strategy, with 8 kWh/m²yr less than CG and 5.3 kWh/m²yr less than SG. Commercial EC reduces the energy demand by 6.8 kWh/m²yr when compared to CG, and by 4.1 kWh/m²yr when compared to SG. Under these conditions, the CNR-EC technology applied to glazings showed increased consumptions by only 0.3 kWh/m²yr compared to commercial EC, thus providing a substantially equivalent performance.

3.2 Effect of building location on overall energy balance

In order to evaluate the variation of the obtainable benefits according to the latitude at which the building is located, the comparison was extended to different cities but, for the sake of brevity, limited to reference cases and CNR-EC technology. As anticipated, London and Aswan, representative for North-European and desertic climates respectively, were included in the analysis. The results, summarized in Tables 4-5 for the 500 lx setpoint, and Tables 6-7 for the 300 lx setpoint, showed that, moving from locations with lower solar radiation and higher sky cover rating to locations with higher radiation and lower sky cover rating the benefits deriving from building integration of CNR-EC technologies in glazings changed significantly. In London, cooling demand was reduced by 62% but it started from relatively low absolute values, so the 43% increase in lighting energy demand and 9% more for heating reduced the overall advantage to just a 3%. As the use of SG technology reduced cooling demand at the expense of lighting and heating, with an overall figure which remained nearly the same as CG, the two reference cases nearly coincided. Under these conditions the use of EC glazings seemed of little advantage from the energy point of view. Conversely, the use of the rolling shutter strategy provided a 16% reduction in the overall specific energy use. When the 300 lx setpoint was used to control artificial lighting and EC state, the overall energy use reduced to 22.4 kWh/m²yr for CG and to 21.1 kWh/m²yr for SG, while for EC-CNR it dropped to 20.0 kWh/m²yr when used as glazing, and to 17.2 kWh/m²yr when used as rolling shutter.

This resulted in a reduction of 23% and 18% in overall specific energy consumptions, respectively referred to CG and SG.

In Aswan, when using clear glass the heating energy demand was, as expected, nearly zero, cooling energy demand was the highest (about twice than in Rome), while lighting demand was 8.2 kWh/m²yr, in between the values observed in Rome and London (likely because the Sun is nearly at Zenith during Summer, thus letting less light enter the southern facade). Increased cooling energy demand resulted from higher outdoor temperatures (reaching 45° C maxima), and from an extended operational interval which spanned from April 1st to November 30th. The use of selective glass caused a slight increase in energy use for lighting, largely balanced by a reduction of 5.6 kWh/m²yr in cooling demand. Application of CNR-EC glazing caused an increase in lighting energy demand (9.2 kWh/m²yr), balanced by a further drop in cooling energy demand (33.1 kWh/m²yr), corresponding to a variation of 23% and 15% if compared to CG and SG, respectively. When the rolling shutter strategy was used, the variations affected only lighting energy demand, and when compared with the reference cases variations were almost negligible (as it was expected, considering that in Aswan cooling is turned on for a longer period). Finally, when the 300 lx setpoint was assumed, for both the reference conditions lighting energy was reduced by 1.4 kWh/m²yr, while for EC-CNR the reduction was 1.9 kWh/m²yr, resulting in a 22% variation compared to CG, and in a 14% variation compared to SG.

Table 4 Specific yearly energy consumptions assuming a 500 lx setpoint for artificial lighting. L=lighting, H=heating, C=cooling, O=overall. Values given in brackets are obtained using the “rolling shutter” strategy.

	Energy use per area [kWh/m ² yr]				Energy use per area [kWh/m ² yr]				Energy use per area [kWh/m ² yr]			
	Clear Glass				Selective Glass				CNR Electrochromic			
	L	H	C	O	L	H	C	O	L	H	C	O
LON	9.2	5.4	8.6	23.2	11.9	6.0	5.4	23.3	13.2 (10.8)	5.9 (5.4)	3.3	22.4 (19.6)
ROM	7.4	1.4	20.3	29.1	8.2	1.4	17.4	27.0	9.8 (7.8)	1.8 (1.4)	12.6	24.2 (21.7)
ASW	8.2	0.0	46.7	54.9	8.4	0.0	41.1	49.6	9.2 (8.4)	0.0 (0.0)	33.1	42.3 (41.5)

Table 5 Relative variations in energy consumptions resulting from use of CNR electrochromic glass compared against clear glass (CG) and selective glass (SG) configurations assuming a 500 lx setpoint for artificial lighting. L=lighting, H=heating, C=cooling, O=overall. Values given in brackets are obtained using the “rolling shutter” strategy.

	Variations from CG to CNR-EC [%]				Variations from SG to CNR-EC [%]			
	L	H	C	O	L	H	C	O
LON	43% (17%)	9% (0%)	-62%	-3% (-16%)	11% (-9%)	-2% (-10%)	-39%	-4% (-16%)
ROM	32% (5%)	29% (0%)	-38%	-17% (-25%)	20% (-5%)	29% (0%)	-28%	-10% (-20%)
ASW	12% (2%)	n.a. n.a.	-29%	-23% (-24%)	10% (0%)	n.a. n.a.	-19%	-15% (-16%)

Table 6. Specific yearly energy Consumptions assuming a 300 lx setpoint for artificial lighting. L=lighting, H=heating, C=cooling, O=overall. Values given in brackets are obtained using the “rolling shutter” strategy.

	Energy use per area [kWh/m ² yr]				Energy use per area [kWh/m ² yr]				Energy use per area [kWh/m ² yr]			
	Clear Glass				Selective Glass				CNR Electrochromic			
	L	H	C	O	L	H	C	O	L	H	C	O
LON	8.2	5.6	8.6	22.4	9.1	5.6	6.4	21.1	10.7 (8.6)	6.2 (5.6)	3.1	20.0 (17.2)
ROM	6.9	1.4	20.4	28.7	7.4	1.5	17.4	26.0	8.2 (7.2)	1.9 (1.4)	12.2	22.2 (20.7)
ASW	6.8	0.0	46.7	53.4	7.0	0.0	41.0	48.0	7.3 (7.0)	0.0	34.4	41.7 (41.4)

Table 7 Relative variations in energy consumptions resulting from use of CNR electrochromic glass compared against clear glass (CG) and selective glass (SG) configurations assuming a 300 lx setpoint for artificial lighting. L=lighting, H=heating, C=cooling, O=overall. Values given in brackets are obtained using the “rolling shutter” strategy.

	Variations from CG to CNR-EC [%]				Variations from SG to CNR-EC [%]			
	L	H	C	O	L	H	C	O
LON	30% (5%)	11% (0%)	-64%	-11% (-23%)	18% (-5%)	11% (0%)	-52%	-5% (-18%)
ROM	19% (4%)	36% (0%)	-40%	-23% (-28%)	11% (-3%)	27% (-7%)	-30%	-15% (-20%)
ASW	7% (3%)	n.a. n.a.	-26%	-22% (-22%)	4% (0%)	n.a. n.a.	-16%	-13% (-14%)

3.3 Daylighting implications

The effects of all the above mentioned glazing technologies on the visual comfort of the occupants was evaluated in terms of UDI and DGI. The results for all the different technologies are shown in Table 8 with reference to Rome. It can be seen that using clear glass minimized under illuminance ($UDI_{<300}$) but maximized over-illuminance and glare problems (GI being below 22% only in 56% of the time). Using selective glazings halved over-illuminance problems, with a small increase in under-illuminance conditions. Use of solar control glazings corrected most of the problems, minimizing $UDI_{>3000}$ while $UDI_{<300}$, increases up to 18.3, with the already observed consequences on artificial lighting. However, glare problems are mostly removed. Use of commercial EC glazings provided results in between the previous, with more over-illuminance cases ($UDI_{>3000}=14.8\%$) and acceptable figures for both $UDI_{300-3000}$ and GI.

Innovative CNR-EC windows maximized the percentage of hours in which the building's occupants were in UDI conditions, nearly eliminating over-illuminance ($UDI_{>3000}=0.1\%$) and glare problems. The percentage of hours in UDI varied from 42.4% in the case of clear glass to 80.4% in the case of CNR-EC glazings when used during the whole year. As expected, considering the increased request for artificial lighting, application of CNR-EC glazings also maximized the percentage of under-illuminated hours, equal to 19.4%, slightly higher than that resulting from the use of solar control glazings. Adopting a 300 lx setpoint turned out to slightly increase under-illuminance, while decreasing $UDI_{300-3000}$. From the visual comfort point of view the use of the “rolling shutter” strategy was less effective than observed in purely energetic terms. In fact, the use of clear glass during most of the year reduced the $UDI_{300-3000}$ to 63.1%, while keeping $UDI_{<300}$ sufficiently low (comparable to commercial EC glazings). Similar figures were obtained when to 300 lx setpoint was used. However, it was in terms of over-illuminance and glare that the performance was worsened, thus suggesting that rather than using the “rolling shutters” only during Summer, an extension to Spring and Autumn (or, in any case, to periods in which the heating system is turned off) might improve visual comfort without affecting energy consumptions. In fact, when using the shutters from April 1st to November 30th the resulting figures show significant improvements, with over illuminance limited to 7.8% of the cases and GI under the maximum limit in 93.6% of the cases.

Table 8. Visual comfort assessment in terms of Useful Daylight Illuminance and Glare Index for the different technologies with reference to Rome

	UDI_{<300}	UDI₃₀₀₋₃₀₀₀	UDI_{>3000}	Glare Index < 22
CG	10.7	42.4	46.8	56.5
SG	14.9	63.9	21.2	83.5
SC	18.3	79.1	2.6	95.9
EC@500 lx	13.7	71.6	14.8	88.0
EC@300 lx	16.0	69.2	14.8	87.3
CNR-EC @ 500lx	19.4	80.4	0.1	99.9
CNR-EC @ 300lx	21.2	78.6	0.1	99.3
CNR-EC (roll. shut.) @ 500 lx	13.8	63.1	23.1	79.3
CNR-EC (roll. Shut.) @ 300 lx	15.7	63.8	20.5	81.2
CNR-EC (roll. shut. Extended)	16.8	75.4	7.8	93.6

With reference to other locations, the comparison was carried out between the reference conditions and the CNR-EC glazing used during the whole year. Table 9 shows that the reference conditions in London were characterized by higher UDI_{<300} and lower UDI_{>3000}, with two-thirds of the hours having GI below 22. Use of the CNR-EC glazing set to zero any over-illuminance and glare problem, independent of the chosen setpoint, but increased to about one third the number of hours with UDI_{<300}, with the already observed implications on artificial lighting. Thus, in such cases the rolling shutter strategy might certainly yield better results. With reference to Aswan it is interesting to point out that the CG reference conditions showed the highest UDI₃₀₀₋₃₀₀₀ equal to 63.5%, with the minimum UDI_{<300} equal to 9.6%. This resulted from the Sun position during the year which, with an altitude spanning between 42° and 89° was less likely to penetrate the room and create over-illuminance and glare problems. Using the CNR-EC glass during the whole year consequently resulted in complete control of glare and over-illuminance, with the lowest observed UDI_{<300} equal to 17.3%, and the highest UDI₃₀₀₋₃₀₀₀ equal to 82.7%. When the 300 lx setpoint was used, very small variations appeared, with a slight increase in UDI_{<300}, and a decrease in UDI₃₀₀₋₃₀₀₀, coherently with the fact that this control strategy supports lower illuminance levels.

Table 9. Visual comfort assessment in terms of Useful Daylight Illuminance and Glare Index for clear glass (CG) and CNR EC glazing with reference to London and Aswan

	Location	UDI _{<300}	UDI ₃₀₀₋₃₀₀₀	UDI _{>3000}	Glare Index < 22
CG	LON	16.9	48.2	34.9	66.7
	ASW	9.6	63.5	27	63.0
SG	LON	23.0	59.1	17.9	87.2
	ASW	13.9	85.9	0.2	87.1
CNR-EC @500 lx	LON	31.8	68.2	0	100
	ASW	17.3	82.7	0	100
CNR-EC @300 lx	LON	33.4	66.1	0.4	99.4
	ASW	18.8	81.2	0	100

In support of the above considerations, the analysis of the CNR-EC glazing state (and its corresponding transparency) showed (Figure 12) that, using the 500 lx setpoint, in Aswan the fully tinted state is rarely reached, but conversely the glass works for about 50% of the time at 3/4 of its potential. In London, the glazing is in bleached state for 36% of the time, but to compensate for cases when the Sun altitude is low, it is fully tinted in 22% of the cases. Finally, in Rome the fully tinted condition and that at 3/4 potential cover more than half of the cases, confirming the usefulness of the devices as already demonstrated by visual comfort data.

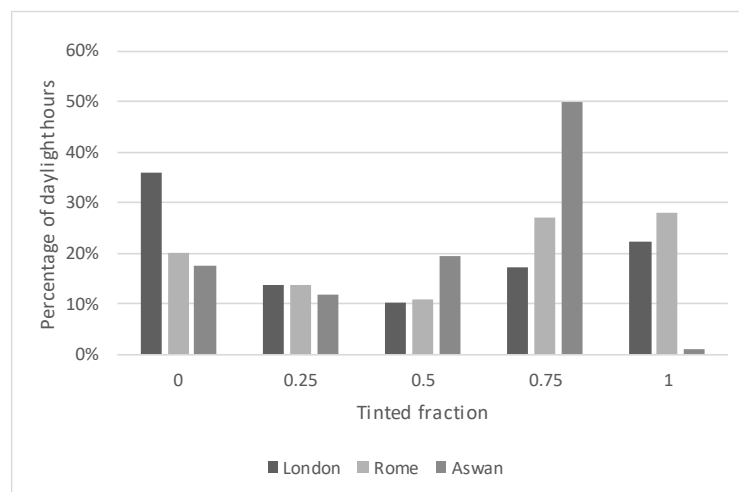


Figure 12. Frequency distribution of the CNR-EC state (0=bleached, 1=fully tinted) calculated for Southern exposure over daylight hours with reference to the three locations under investigation and assuming a 500 lx setpoint.

4 Discussion

Electricity consumption for artificial lighting, heating and cooling have been considered for the South, East and West facades of a reference building, on an annual basis at the latitude of Rome, at first, and then extended to London and Aswan. The highest electricity consumption was found to occur on the South facade, whereas on the Eastern and Western facades lower but comparable results were observed. The most relevant point was represented by the influence of cooling loads on the yearly energy balance compared to winter heating (the difference was about one order of magnitude). Artificial lighting also had a role on the annual electric energy balance, and, quite predictably, was influenced by the optical properties of glazings, but the net fluctuations among different facades were less relevant than those observed in cooling loads. The all-year use of CNR-EC glazings determined an increase (estimated with reference to clear class condition) varying between 12% (in Aswan) and 43% (in London) in lighting energy demand, but this value dropped to values between 2% and 17% if the “rolling shutter” strategy was used. The latter strategy also offered significant advantages in terms of solar gains during the Winter season which, conversely, would be greatly reduced by using glazing with low T_{vis} .

All proposed solutions involved a significant reduction in summer air-conditioning costs, compared with the reference case (clear glass). This was due to the varying shielding capacity of the different proposed solutions. In Rome, the energy consumption for cooling passed from 20.3 kWh/m²yr (clear glass) to 17.4 kWh/m²yr when adopting selective glass. Such results were further improved when using commercial ECs (13.0 kWh/m²yr), and using CNR solid-state ECs with the “rolling shutter” strategy (12.2 kWh/m²yr).

Considering the overall energy demand, the use of CNR solid state EC implied savings varying between 0.8 kWh/m²yr in London to 12.6 kWh/m²yr in Aswan, assuming clear glass as a reference. The use of the rolling shutter strategy could further increase savings to 3.6 kWh/m²yr in London, 8.0 kWh/m²yr in Rome, and to 13.4 kWh/m²yr in Aswan. In relative terms, the best performance was found in Rome where 25% savings were obtained by using the rolling shutter strategy. It is important to point out that such figures were obtained by normalizing energy demand with reference to floor surface. If values were normalized with reference to window surface [24,30] savings varied between 11 kWh/m²yr and 40.2 kWh/m²yr, in line with values given by Tavares [30].

The adoption of a 300 lx setpoint for both EC control strategy and artificial lighting switching proved to be very effective in increasing energy savings, particularly in favor of EC-CNR which, being darker than commercial EC in bleached mode, inherently increased energy demand for artificial lighting. However, under these conditions, energy savings up to 28% could be obtained in comparison to clear glass, and up to 20% in comparison to selective glass.

As to visual comfort benefits in daylit offices, the best results were achieved using CNR-EC glazings, which minimized both glare problems and the number of hours, on annual basis, in which excessive illuminance occurred.

Further improvements in savings could be obtained adopting other use strategies for the control of EC glazings' transmittance transitions. These results may help inform decision-making about the possible development of this innovative technology.

5 Conclusion

Following a previous study dealing with innovative solid-state EC devices, fabricated using a highly compact and simplified device architecture on a single substrate, we studied the effects on the annual energy balance, as well as on visual comfort, deriving from the integration of glass facades equipped with different glazings technologies. The study was first conducted assuming that the reference building, an office building on three levels, was located in Rome. Then it was extended, to achieve a useful comparison, to other cities representative of different climatic conditions: London and Aswan. The results of the analyses clearly showed that glasses with adaptive transparency (EC) offered better performances than the other technologies (clear glass and solar control glazings), with particular reference to energy consumption for summer cooling, which were a predominant item of the annual energy balance in "cooling dominated" climatic conditions. The annual energy saving for cooling reached 38% compared to a building with windows made of common glass. The overall energy saving using innovative solid-state EC devices was found to be 25%. The results in terms of increased visual comfort were quite similar, evaluated in terms of UDI and DGI, proving that the technology under investigation may offer promising developments.

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