Energy performance of an electrochromic switchable glazing: Experimental and computational assessments

Energy performance of an electrochromic switchable glazing. Experimental and computational assessments

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Abstract. This paper describes the results of experimental tests and computer simulation modelling aimed at evaluating the performance of an electrochromic (EC) window with respect to solar radiation control and the relative impact on the energy consumption of buildings of the residential type for two typical Italian climates. The research is carried out by a test-cell equipped with a small area EC double glazing unit and by a simulation program of buildings' energy behaviour in transient regime. The experimental results show that EC devices which modulate solar radiation mainly by absorption, like the one investigated in this paper, generate secondary solar heat gains which entails a 20 % decrease of the maximum potential energy flux reduction. Also, this effect could rise the temperature of the internal glass pane of the glazing to levels for which risk of thermal discomfort for the occupants may occur. The computer simulation modelling involves a residential building unoccupied during a large fraction of daytime in weekdays. The savings potential of the investigated EC window are calculated relative to a conventional clear float double glazing unit. Results shows that the EC glazing may lead to a considerable decrease of the cooling energy demand (and of the total building energy consumption) in cooling dominated climates. The energy saving benefits become less marked in heating dominated climates and, for low values of the window-to-wall ratio, can be overcame by the increase in lighting and heating energy requirements that results in an increase of the total building energy demand.

Keywords: Electrochromics, Smart Windows, Solar Energy Control.

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1. Introduction

Smart windows based on electrochromic (EC) technology are currently one of the major research topics in the field of advanced buildings' glazing. These devices are able to regulate the amount of radiant energy that flows inside the buildings through the windows by changing reversibly their optical transmittance under the action of a low electrical voltage [1]. The application of this new class of switchable glazing should result in a reduction of the use of mechanical air conditioning systems, especially in cooling dominated climates, with considerable benefits in terms of energy saving. In addition, they should allow effective control of the levels of daylight and glare for visual comfort management.

Intensive research has been conducted by either full-scale [2-8] and small-scale test cells [9-11] or numerical simulations [12-29] to investigate the effect of EC switchable glazing on buildings' energy performance and indoor visual/thermal comfort conditions. The results of almost all these studies converge on the conclusion that EC windows may constitute an effective energy saving technology in cooling dominated locations and, also, a powerful daylighting control technology for improving indoor visual comfort.

Although the above research spans a wide range of, geographic, building envelope, climate and operating conditions there are still some poorly investigated issues, strictly related to the energy performance potential of these devices, that could draw the attention of researchers.

The first issue is concerned with the assessment of the modulation operated by the EC switchable glazing on the incoming radiant energy flux. This task entails the accurate quantification of the energy flux components released to the indoor envoronmente by an EC glazing when striked by solar radiation. It must be observed, in fact, that for conventional WO_3 based EC devices the change in optical transmittance in response to the applied voltage is light absorption so only a small fraction of the impinging solar radiation is reflected off. This entails that the internal surface of a single-pane EC window – when switched to low transmittance states – releases a great fraction of the absorbed radiation towards the indoor environment via convective and radiative heat transfer. This secondary heat flux may evidently lead to a decrease of the performance of the device in operating as a shading device and to a risk of thermal discomfort originating from radiative exchange between a hot window and the occupants. Furthermore, unwanted damage of the EC layer may occur if the glazing gets much too hot. Investigation on this topic was performed by Klems [2] who measured the heat flows and temperatures affecting the operation of a skylight formed by a low-e double glazed unit (DGU) comprising an EC layer on surface 2. Measurements, made on summer time, showed that in its fully coloured state the EC DGU achieved temperatures as high as 50 and 70°C in the inner (surface 4) and outer (surface 1) glass surfaces respectively. Lee and Di Bartolomeo [3] determined by numerical computations the surface temperatures of a fully coloured EC DGU window and concluded that the inside surface glass temperature should not significantly contribute to thermal discomfort. Fang and Eames [30] simulated by a 3-D finite volume model the thermal behaviour of a three-pane EC vacuum glazing and deduced that the glass pane with the EC layer must face the outdoor environment to prevent the glazing from getting high (damaging) temperatures. Furthermore, a low-e coating [31, 32] could improve the glazing thermal performance as also concluded by Lim et al. [33] and by Jonsson and Ross [20].

The second issue is concerned with the circumstance that most of the computational investigations performed so far considered the impact of EC glazing on the energy consumption of commercial buildings and offices. Only very few simulation studies have analysed the performance of EC windows in residential buildings, although this specific investigation could be worthy of attention since the performance of a shading device is generally influenced, among other factors, by the building's use. Residential buildings were considered in their research by Pal et al. [27] who found that in a townhouse building located at high latitudes (Helsinki) the application of EC windows doesn't bring any energy benefits compared to conventional and other advanced windows. Conversely, Yik and Bojic [16] found that in high-rise residential buildings located at low latitudes (Hong Kong) the application of switchable glazing would lead to a reduction in the annual electricity consumption for space cooling by up to 6.6%. Jonsson and Ross [20] investigated the effect of EC

DGU windows (with and without antireflective coatings) for a wide range of climates in residential buildings and found that conventional uncoated DGU windows are outperformed by the switchable glazing both for the heating and cooling seasons. More recently, De Forest et al. [29] calculated the annual primary energy saving (normalized by window area) deriving from the application of different advanced EC DGU windows in midrise residential buildings relative to the local ASHRARE-compliant window. The energy saving resulted about 130 kWh/m^2y for a cooling dominated climate (Huston) and over 160 kWh/m^2y for a heating dominated climate (Chicago).

The present work try to address the two above discussed issues by both experimental and computational capabilities. The experimental investigation is performed under real weather conditions and involves the use of a small-scale test cell equipped with a small area EC device and instrumented with a number of sensor for quantifying the energy flux entering the test cell through the EC glazing. The computational investigation involves the use of a simulation software of building behavior in dynamic regime for studying the potential of EC windows to reduce energy consumption in a residential building for two typical Italian climates. The results of the present study may constitute useful information for assessing the potential of these devices in reducing buildings' energy consumption when integrated in real building facades.

2. Methodology

The EC glazing considered in this study is a home-made fully solid state EC device. It is based on the complementary electrochromism of WO_3 (the "active" layer) and NiOH:Li (the "ion storage" material) electrically interacting through a Li^+ ion conducting polymer (PEO-PEGMA:Li). The layers are deposited on two glass substrates covered by fluorine doped tin oxide ("K glass"[34]) according to the scheme illustrated in Fig.1. A sample of area 12×12 cm^2 switches reversibly from a transparent state to a dark blue with a low value of applied potential ± 2.5 V. The typical switching time for the colouring process, is about 5, 6 min (from about 70 to 30 % visible transmittance) while the bleaching process takes a shorter time. Considerable lower transmittances (~7 %) are attainable anyway by switching the device for longer times but at expense of its reversibility behaviour. In Fig. 1 The UV-VIS-NIR (near) normal transmittance spectra, measured by a Perkin-Elmer Lamda 2 spectrophotometer in the 300-1000 nm range and by a Perkin-Elmer system 2000 FT-IR in the 1000-3500 nm range is illustrated for the fully bleached and fully coloured states.

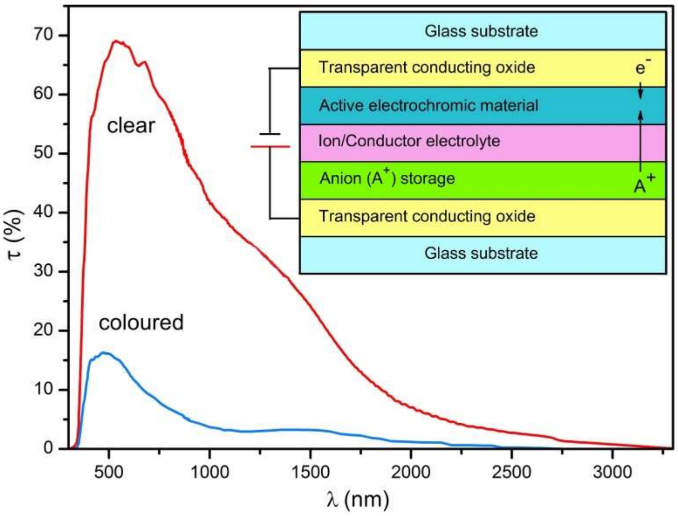

Figure 1. Optical transmittance spectra of the EC device in the full bleaching (red line) and full colouring (blue line) states. In the insert the multilayer structure of the EC device is shown.

Additional information on the optical, electrical and dynamic behaviour of the device can be found in [35, 36].

Table 1. Climatic parameters of the selected towns

	Bolzano	Messina
Min yearly temperature (°C)	-11.6	5.0
Max yearly temperature (°C)	34.6	34.9
Heating degree-days (°C gg)	2913	758
Cooling degree-days (°C gg)	254	1085
Climate [37]	Moist continental	Mediterranean

The thermal performance of this device is investigated by both experimental and computational capabilities in two Italian locations characterized by different climatic conditions. The first selected centre, Messina (latitude: 38° 12′, elevation: 51 m), exhibits a typical Mediterranean climate, with cooling periods prevalent with respect to heating ones. The second selected centre, Bolzano (latitude: 46° 28′, elevation: 241 m), is characterized by a moist continental climate typical of Alps and Apennines, with cold winters and marked yearly thermal excursions. The climatic parameters of the selected towns as reported in Table 1.

2.1 Experimental apparatus

The experimental apparatus employed in this work is the same as that used in previous studies [9-11]. However its description is repeated here for the reader convenience. A prototype of the above described EC device of area 12×12 cm^2 and thickness 8 mm is installed in a wood frame 22 mm thick together with a 4 mm thick clear float glass (visible transmittance ~ 90 %) to form a double glazing EC unit (EC DGU) with about a 10 mm air gap. The surrounding edges are sealed with insulating silicon glue. The whole structure is then placed as a wall (the "front wall") of a test-cell 43 cm wide, 42 cm deep and 44 cm high. It is considered representative of the scale model (1:10) of an unfurnished room approximately cubic in shape. In this configuration the EC device, whose bottom edge is at a distance of 22 cm from the floor, is in contact with the external air which is introduced from the ceiling by a diffuser and expulsed by an air-outlet located at the bottom of a side wall. Caorse regulations of the air exchange rate of the cell can be done through a fan. All the internal walls of the cell (floor and ceiling included) are colored with matt white paint of reflectance ~0.8. The area-weighted mean solar absorbance of all indoor surfaces is estimated to be 0.25±0.05. Additional insulation was wrapped around the cell to enhance its adiabatic behaviour. From the thermophysical properties of the constituent materials, the thermal transmittances of the front-wall and of the side-walls are estimated to be 2.4 and 1.2 Wm^{-2}K^{-1} respectively. The thermal and optical properties of the EC DGU, namely the glass emissivity (ε), solar and visible normal transmittance (τ_{sn}, τ_{vn}), solar and visible normal reflectance (ρ_{sn}, ρ_{vn}), overall thermal transmittance (U), solar heat gain coefficient (g) are reported in Table 2. The methodologies used to determine these parameters are described in [9, 11].

The cell is equipped with a number of sensors for monitoring the microclimate parameters affecting its thermal behaviour. Specifically:

– Two photosensors placed 0.5 m above the top of the cell measure:

- the external global (direct plus diffuse) horizontal irradiance $I_{H,out}$;
- the external global vertical irradiance $I_{V,out}$;

– Two photosensors placed inside the cell measure:

• the vertical irradiance just behind the EC-DGU (close to its middle point) at a distance of 1 cm from the glass surface $I_{V,in}$;

• the horizontal illuminance $E_{H,in}$ on a 11×8.0 cm^2 work-plane located 19 and 15 cm from the front-wall and from the floor respectively.

– Two shielded digital temperature (accuracy 0.1 %) sensors placed outside the cell measure:

• the surface temperature of the external glass pane $T_{g,out}$ (near the edge of the EC DGU);

• the external air temperature and relative humidity ($T_{a,out}$) near the air-inlet;

– Three shielded digital temperature sensors placed inside the cell measure:

• the surface temperature of the internal glass pane $T_{g,in}$ (near the edge of the EC-DGU);

• the internal air temperature and relative humidity ($T_{a,in}$) near the air-outlet;

• the surface temperature of the wall facing the EC DGU $T_{w,in}$.

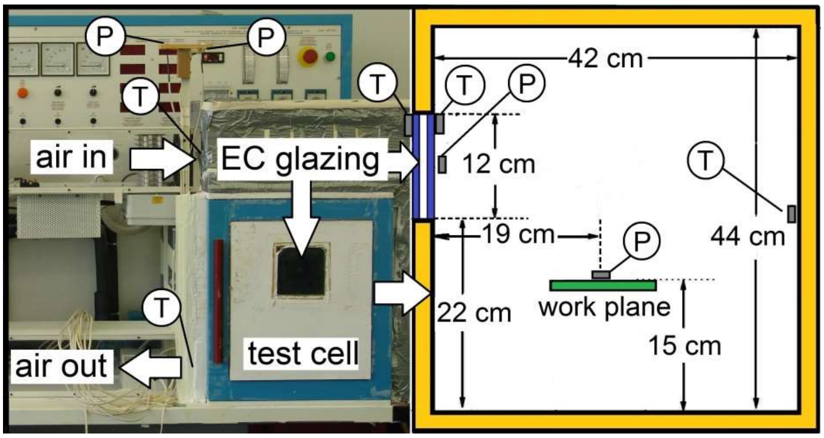

Figure 2. photographic view of the test rig (left side). Schematic cross section of the test-cell (right side). Labels "P" and "T" stand for photosensor and temperature sensor respectively.

The photodiodes employed for measuring the solar irradiance have a 190-1100 nm sensitivity spectral range while the one recording luminance levels on the work plane has a 350-820 nm sensitivity spectral range and a spectral response curve adapted to human eye sensitivity. Both types of phototosensors have been previously calibrated in situ respectively with a pyranometer and a luxmeter and a maximum error of 5 % was found in the measurement range investigated.

Data recorded by the sensor are acquired by a low-cost home-made data-logger comprising (1) the BASIC Stamp 2 Microcontroller [38], (2) an interface circuit for connecting five digital temperature sensors; (3) a 8-channel 12-bit A/D converter provided with an interface circuit for connecting eight photosensors. A photographic view of the test rig together with a schematic cross section of the test-cell is shown in Fig. 2.

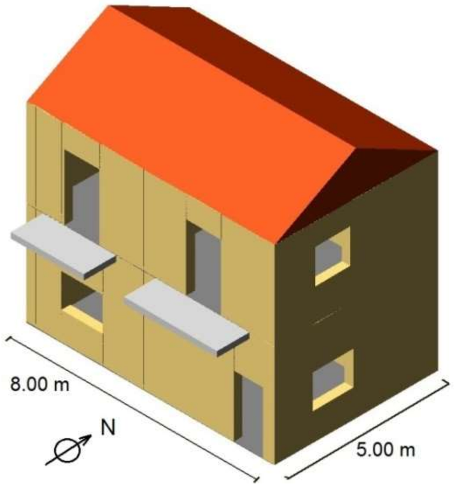

Figure 3. The two-storey building modelled in simulations.

2.2 Computational modelling

In order to assess the impact of EC glazing in improving the energy performance of residential building types the thermal performance of a model building is investigated by computational tools. The case study selected for simulations is a uni-familiar two-storey building with an attic room, as shown in Fig. 3. It comprises an air conditioning system consisting of a gas heating coil (burner efficiency equal to 0.85) and a direct expansion cooling coil (gross rated COP equal to 3) both controlled by a zone thermostate. The gross conditioned floor area amounts to about 80 m^2. The heating and cooling set-points were considered respectively equal to 20°C and 26°C all over the year during occupied periods. The house is equipped with an artificial lighting system (installed electric power density equal to 5.5 W/m^2) consisting of fluorescent lamps with an efficiency of 90 lm/W. The operation hours of both the air conditioning and artificial lighting systems have been selected adopting a building use profile typical of dwellings, i.e., 06:00-09:00 and 17:00-23:00 from Monday to Friday and 07:00-23:00 on Sunday and Saturday. Occupants are supposed to contribute a total heat load of 6 W/m^2. The thermophysical properties of the envelope opaque components expressed in terms of the global wall transmittance (U), aeral mass density (m) and aeral heat capacity (C) are reported in Table 2.

The thermal and daylighting behaviour of the building is simulated in transient regime for different values of the window-to-wall ratio (WWR) as specified in Fig. 4. The calculus procedure makes use of the formula [39]:

$$Q_T = \sum_i Q_i \cdot f_i \tag{1}$$

Table 2. Thermophysical properties of the opaque and transparent components of the model building envelope. The optical and thermal properties of the EC DGU also refer to the home-made EC device.

Envelope opaque structures				
	External wall	Ground floor	Roof	External door
U (W/m^{2}K)	0.424	0.423	0.410	0.726
m (kg/m^2)	501.50	482.90	789.75	37.75
C (kJ/m^{2}K)	419.22	394.20	734.61	20.83
Glazing components				
	DGU reference	EC DGU bleached	EC DGU coloured	
ε	0.840	0.840	0.84	
τ_{sn}	0.74	0.460	0.033	
ρ_{sn}	0.12	0.099	0.083	
τ_{vn}	0.80	0.610	0.036	
ρ_{vn}	0.15	0.099	0.075	
U (W/m^{2}K)	2.8	2.2	2.2	
g	0.79	0.53	0.12	

where f_i, the primary energy factor of the i-th energetic carrier, is assigned with the values f_i=2.37 (for electricity) and 1.10 (for natural gas). The annual consumption of each energetic carrier, Q_i, is derived from building energy simulations performed by EnergyPlus, developed in 2001 at the Lawrence Berkeley Laboratory by combination of the two software DOE-2 e BLAST [40]. The software performs integrated simulations of the environment and of the air conditioning system and consists of three basic components: a heat and mass balance simulation module solving the thermal zone balance, a building system simulation module modelling the HVAC system and a simulation manager, controlling the entire process. The heat flows exchanged through the building envelope components are calculated by means of the "response factor" technique, based on transfer functions.

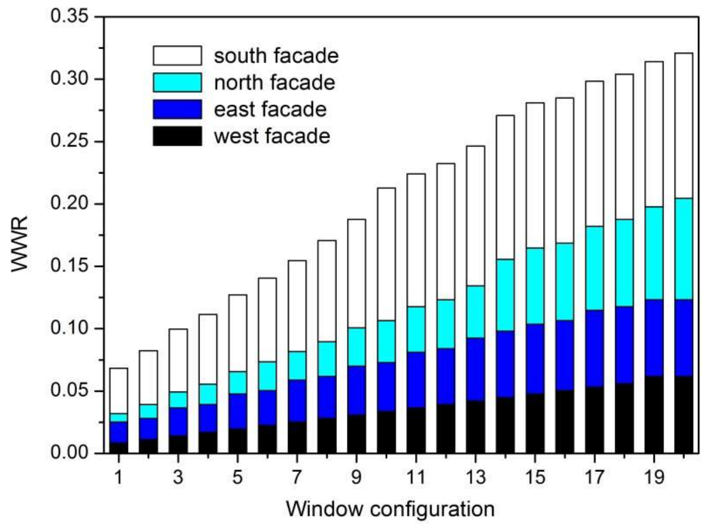

Figure 4. Values of the window-to-wall ratio (WWR)of the building façade.

3. Results and discussion.

3.1 Experimental investigation

Measurements were carried out in summer time on the roof at the Department of Engineering of the University of Messina, Italy. The site is characterized by a quite unobstructed background and is therefore suited for the conceived experiment.

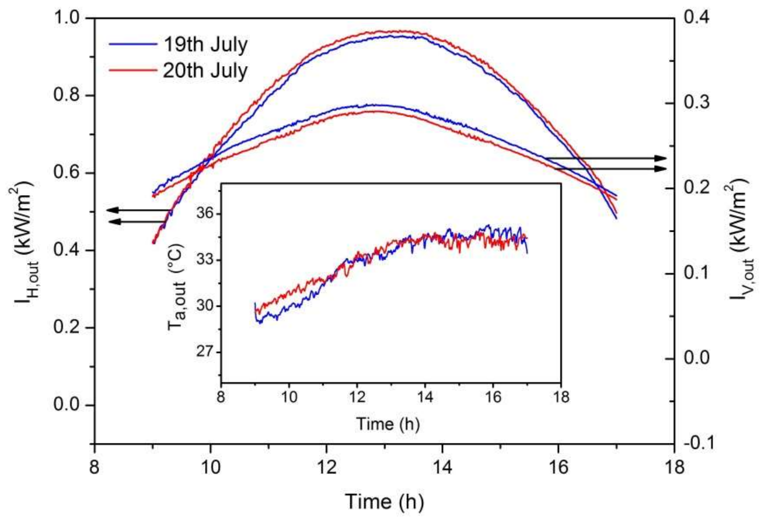

Figure 5. The time variation of the external global horizontal irradiance $I_{H,out}$ and of external global vertical irradiance $I_{V,out}$ on the 19th of July (blue line) and 20th of July (red line). In the insert the time variation of the external air temperature during the same days is shown.

Data here reported, referring to completely clear sky conditions, are collected for test cell oriented toward the south and west directions when the EC glazing is fully coloured or fully bleached. Due to the availability of only a single test-cell, comparative tests are performed on following days characterized by almost identical weather conditions. The selected couple of days satisfying this requisite are the 11th and 12th of June, the 3rd and 4th of July and the 19th and 20th of July as far as the south direction is concerned while the 15th and 16th of July are considered for the west direction. The accuracy involved in this measurement methodology can be inferred from Fig. 5 where the time variation of the outdoor environmental variables (horizontal irradiance, I_H, vertical irradiance, I_V, and temperature, $T_{a,out}$, collected on the 19th and 20th of July is reported. The mean difference in the I_H, I_V and $T_{a,out}$ data recorded in these different days is within 1.8%, 3% and 1.5% respectively. Deviations of the same magnitude are found in the other representative couple of days.

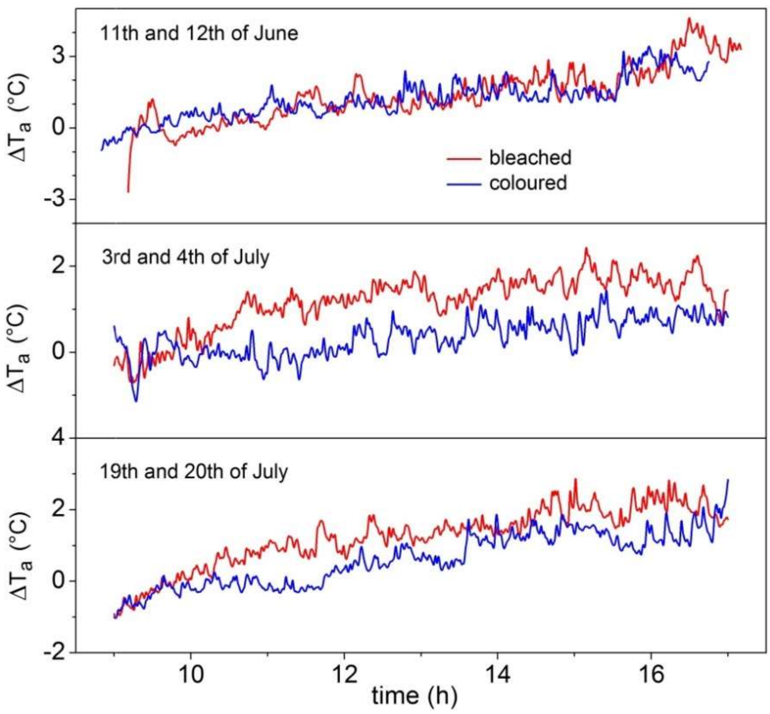

Figure 6. The time variation of the difference ΔT_a between the internal $T_{a,in}$ and external $T_{a,out}$ air temperatures for the case of EC device fully bleached (red lines) and fully coloured (blue lines). Test cell is oriented toward the south direction.

Information on the performance of the EC DGU in reducing overheating effects for south facing windows can be inferred from Fig. 6. Here the time variation of the difference between the internal $T_{a,in}$ and external $T_{a,out}$ air temperatures ($\Delta T_a = T_{a,in} - T_{a,out}$) is reported for the case of EC device fully bleached and fully coloured for an air exchange rate of about 70 air-exchanges/h.

In all the analysed cases the curves exhibit positive values over almost the entire measurement time (about 8 h) meaning that internal air temperature gets hotter than the external one. The graph clearly shows how the temperature difference is lower for the EC-DGU fully coloured (blue lines). The mean value of the temperature differences (evaluated on the three representative couple of days), in fact, are 1.3 and 0.7 °C for the fully bleached and fully coloured case respectively.

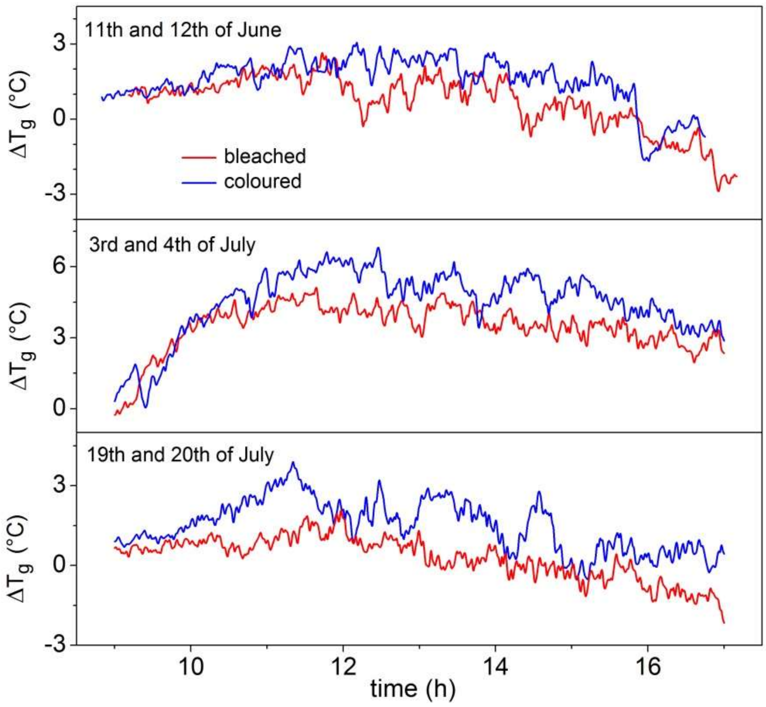

Figure 7. The time variation of the difference ΔT_g between the internal $T_{g,in}$ and external $T_{g,out}$ glazing surface temperatures for the case of EC device fully bleached (red lines) and fully coloured (blue lines). Test cell is oriented toward the south direction.

The time variation of the difference between the external $T_{g,out}$ and internal $T_{g,in}$ glass surface temperatures ($\Delta T_g = T_{g,in} - T_{g,out}$) is reported in Fig. 7 for the case of EC device fully bleached and fully coloured. In all the analysed cases the curves exhibit positive values over almost the entire measurement time meaning that the temperature of the outer pane (the EC device) gets hotter than the inner one. The mean value of the temperature differences (evaluated on the three representative couple of days), in fact, are 1.5 and 2.5 °C for the fully bleached and fully coloured case respectively. The higher temperature difference found in the dark state is due to the EC effect that involves mainly absorption of radiation rather than reflection. The peak values of $T_{g,in}$ and $T_{g,out}$ are measured, in fact, for the EC DGU fully coloured and amount to 38.2 and 40.8 °C respectively. When the peak value of

$T_{g,in}$ is registered the temperature of the internal air ($T_{a,in}$) and of the wall facing the EC DGU ($T_{w,in}$) are 36.0 and 35.7 °C respectively.

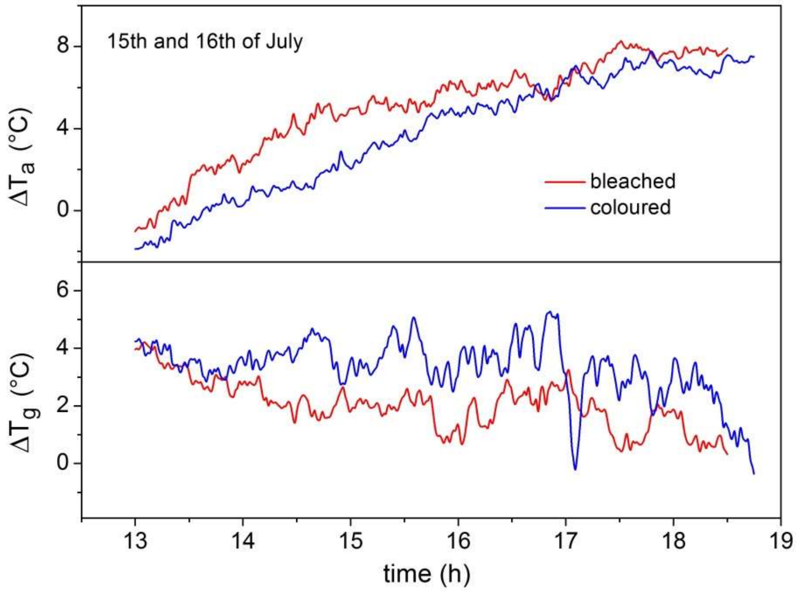

Figure 8. The time variation of the difference ΔT_a between the internal $T_{a,in}$ and external $T_{a,out}$ air temperatures (upper half) and of the difference ΔT_g between the internal $T_{g,in}$ and external $T_{g,out}$ glazing surface temperatures (lower half) for the case of EC device fully bleached (red lines) and fully coloured (blue lines). Test cell is oriented toward the west direction.

Analogue comments yield for the temperature differences relative to the west direction shown in Fig. 8. In this case the mean value of ΔT_a amounts to 5.0 and 3.8 while the mean value of ΔT_g amounts to 2.0 and 3.3 for the fully bleached and fully coloured case respectively. The peak values of $T_{g,in}$ and $T_{g,out}$ are measured also in this case for the EC devices fully coloured and amount to 41.5 and 46.7 °C respectively. When the peak value of $T_{g,in}$ is registered it results $T_{a,in}$=36.1 and $T_{w,in}$=35.7. The higher temperature differences found for this orientation compared to the south one are easily explained observing that in this case the fraction of direct sunlight entering the test cell is much larger. For south orientation the incoming radiation comes mainly from diffuse sunlight because of the considerable solar height in the measurement period (~ 70°).

The measured temperature differences demonstrate the ability of the investigated switchable device in reducing heat loads during the summer season. An estimate of the thermal load reduction can be deduced from the measured data of $I_{V,in}$, $T_{g,in}$, $T_{w,in}$, $T_{a,in}$ and $T_{a,out}$ observing that the heat flux entering the test cell through the window comprises the fraction of the vertical irradiance directly transmitted through the glazing ($Q_{irr,d}$), the net thermal radiation emitted by the internal surface of the glazing ($Q_{irr,th}$) and the heat flux released via convection by the internal surface of the glazing to the internal air (Q_c). Considering the test cell as an enclosure with uniform wall temperature $T_{w,in}$, we can write

$$Q = Q_{irr,d} + Q_{irr,th} + Q_c = AI_{V,in} + \varepsilon\sigma_0 A[(T_{g,in})^4 - (T_{w,in})^4] + hA(T_{g,in} - T_a) \tag{2}$$

where A is the EC DGU area, ε is the glazing surface emissivity, σ_0 the Stefan-Boltzman constant, h (7.1±0.3 W/m^{2}K [11]) the convection coefficient and T_a the mean value between $T_{a,in}$ and $T_{a,out}$.

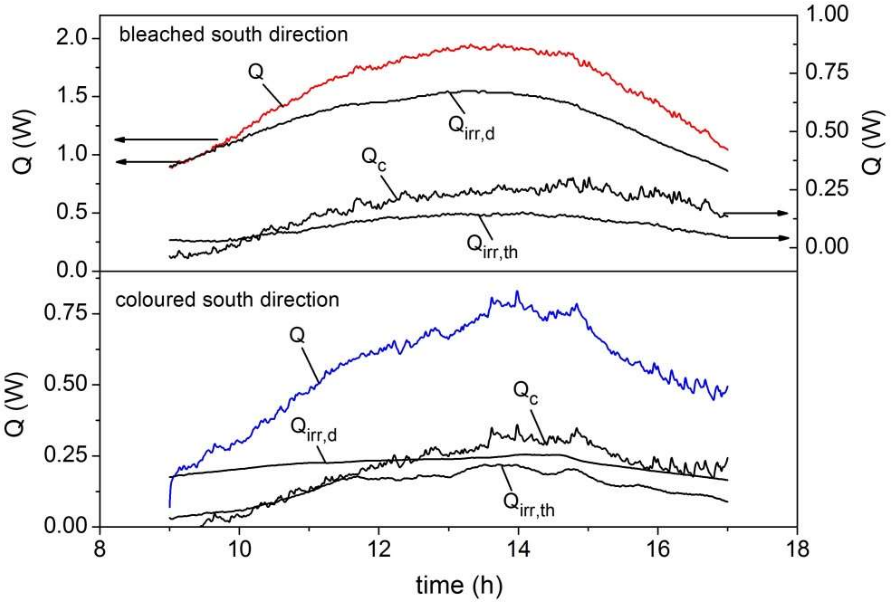

Figure 9. The time variation of the total instantaneous heat flux and of its components through the glazing for the fully bleached case (upper half) and fully coloured case (lower half). Test cell is oriented toward the south direction.

Results of this calculation are shown if Fig. 9 and 10 where Q and its components ($Q_{irr,d}$, $Q_{irr,th}$ and Q_c) are reported as a function of time for the two considered switching states and orientations. Areas subtended by the curves represent the total heat load over the measurement period

$$Q_{load} = \sum_i Q^i \Delta t = \sum_i Q^i_{irr,d} \Delta t + \sum_i Q^i_{irr,th} \Delta t + \sum_i Q^i_c \Delta t \tag{3}$$

where superscript i means "measured value" and Δt refers to the sampling time (about 64 sec). Applying the above equation we find that in the case of south direction switching the EC device to its darkest state produces an abatement of the direct irradiance through the window (the first term on the right side of the above equation) by about 83% (from 37.2 to 6.3 kJ), an increment of the thermal irradiation (the second term on the right side of the above equation) by about 46 % (from 2.8 to 4.1 kJ) and an increment of the convective heat transfer (the third term on the right side of the above equation) by about 14% (from 4.9 to 5.6 kJ). The net effect is a decrease of the total heat load by about 64 % (from 44.9 to 15.9 kJ).

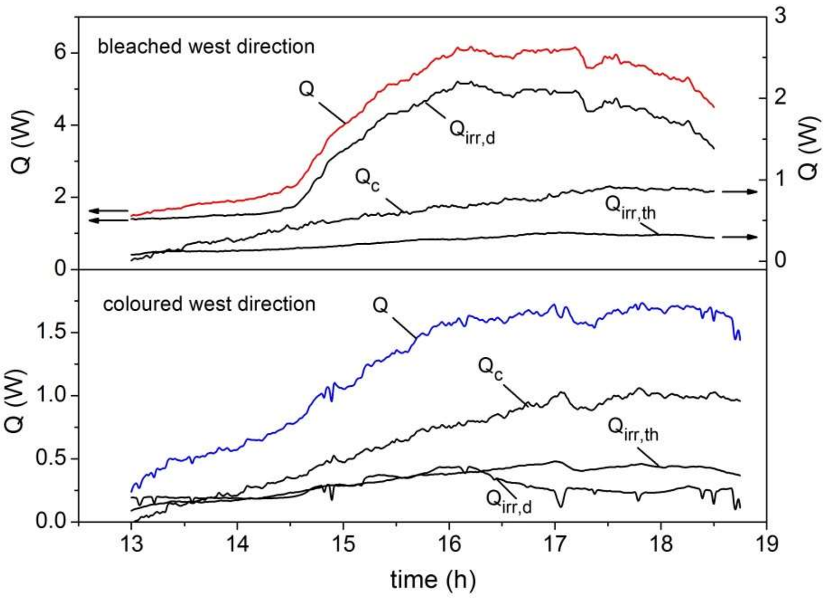

Figure 10. The time variation of the total instantaneous heat flux and of its components through the glazing for the fully bleached case (upper half) and fully coloured case (lower half). Test cell is oriented toward the west direction.

Analogously, in the case of west direction switching the EC device to its darkest state produces an abatement of the direct irradiance through the window by about 92% (from 68.9 to 5.5 kJ), an increment of the thermal irradiation by about 48 % (from 4.6 to 6.8 kJ) and an increment of the convective heat transfer by about 16% (from 11.5 to 13.3 kJ). The net effect is a decrease of the total heat load by about 70 % (from 85.0 to 25.6 kJ).

For both the considered orientations, therefore, the absorbing behaviour of the investigated EC device diminishes its effective dynamic transmittance control on solar radiation by about 20%.

Moreover, the inner pain can reach temperatures near/above 40 °C so risk of thermal discomfort may occur for the occupants. To overcome this effect a low-emissivity coating may be placed on the inner pane (surface 3 counting from the outside) to increase the rejection of the absorbed heat to the external environment. [41]. Alternatively, the use of ventilated glazing units could be an effective option [42].

When evaluating these results it must be underlined that the test cell used for the experimental measurements is a demonstration facility for air conditioning so its shape, dimensions and window position as well as other features (air exchange rates, walls material and structure, etc.) are not very typical for today's design of residential/office rooms. Furthermore, application of scale models is often questioned because may lead to over-estimation in daylighting levels [43, 44]. Anyway, the results outlined in fig. 9 and 10, concerning the evaluation of the energy flux components entering the test cell through the EC DGU, are reasonably deemed to be unaffected by the quite high value of the air exchange rate used in the experimental tests. Air velocity measured by a hot wire anemometer at a distance of 1 cm from the internal wall surfaces, in fact, resulted lower than 0.05 m/s. That led to values of the internal heat transfer coefficient *h* typical of laminar free convection on vertical surfaces.

3.2 Computational investigation

The energy performance of the EC glazing prototype is assessed by making a comparative analysis between the annual primary energy consumption of the model building described in sect. 2.2 when equipped, in one case, by a standard DGU without coatings (reference window) and, in the other one, by EC glazing. The reference DGU is constituted by two clear float glasses 4 mm thick enclosing an air space 12.7 mm wide while the EC glazing has the same structure of the home-made EC DGU device used in the experimental measurements and described in section 2.1. The thermo-physical properties of the two kind of glazing, are reported in Table 2.

In order to assess the impact of different climate conditions on the EC glazing performance the model building is supposed to be located in two different urban centres representative of outdoor conditions typical of Italian climates: Messina (the same location of the experimental tests) and

Bolzano. As already outlined in sect. 2 (and Tab. 1) the two centres have quite different climatic conditions and are here considered as case studies of a typical cooling dominated and heating dominated Italian climate.

As for the control strategy of the EC DGU, a simple strategy based on illuminance control is adopted. Specifically, the optical transmittance of the window is varied continuously between the fully bleached and fully coloured levels in response to the value of the indoor daylight horizontal illuminance evaluated at the ground floor at a height of 0.85 m (referred thereafter as the illuminance control point) in the center of the perimeter zone. Both in summer and winter and during occupied hours the EC window is dynamically coloured to maintain in correspondence of the control point an illuminance level not exceeding 600 lux. The illuminance value on the control point also drives, using an on/off strategy, the switching of the artificial lighting system which is set to an *on* state when the illuminance is equal or lower than 300 lux. The above set point levels meet the general recommendations of lighting standards for indoor spaces [45, 46]. During the winter season and in unoccupied hours, i.e., when glare risk for the occupants cannot occur, the control strategy of the EC glazing is modified setting it in a fully transparent condition in order to increase solar gains as much as possible. This should has the positive effect of realizing a preheating of the indoor environment which turns out in a decrease of the energy consumption of the heating system when activated to restore comfort conditions. Conversely, during the summer season and in unoccupied hours the EC glazing is switched to its fully coloured state in order to decrease solar gains as much as possible. This should has the positive effect of preventing (or at least limiting) overheating of the indoor environment which turns out in a decrease of the energy consumption of the cooling system when activated to restore comfort conditions. Therefore, although during unoccupied hours the air conditioning system is simulated to be not working, energy saving benefits are reasonably attended from the above described preheating and overheating-reduction effects accomplished by the EC device.

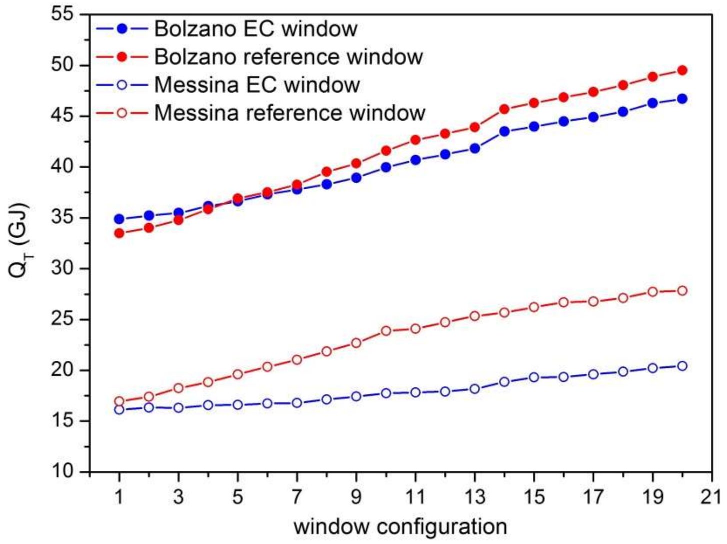

Figure 11. The total yearly primary energy demand of the building equipped with the two kind of glazing as a function of WWR.

In Fig. 11 the total yearly primary energy of the building equipped with the two kind of glazing is reported as a function of WWR for the two considered climatic situations. In Fig. 12 and 13 the same parameter is reported, but separating the different contributions due to artificial lighting, heating and cooling. The graphs show how in the case of Messina the use of EC glazing leads to a remarkable decrease of the energy consumption for each value of WWR.

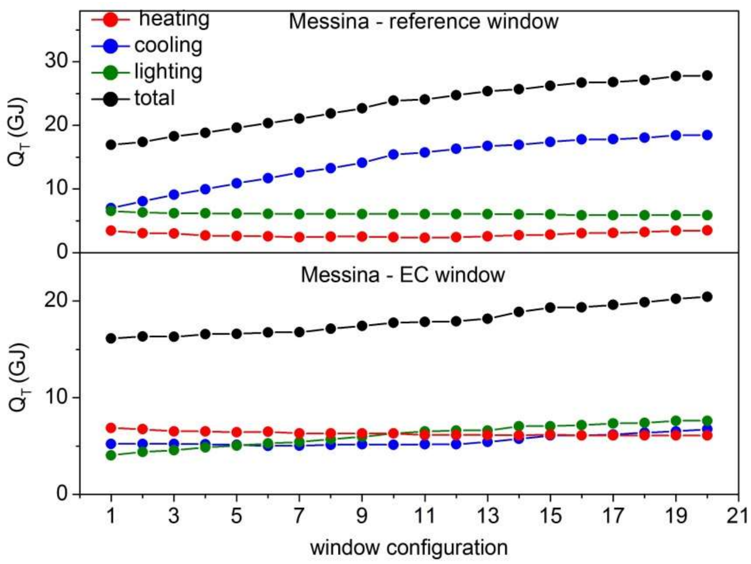

Figure 12. The heating, cooling and lighting contributions to the total yearly primary energy consumption of the building as a function of WWR for Messina.

In the case of Bolzano the decrease of the energy consumption is evidently less marked and occurs only for WWR>0.16, while for lower WWR values the building energy consumption is found to increase. This circumstance reflects the different climatic characteristics of the two towns. In Messina, where the greatest energetic demand is due to cooling, the EC windows are able to effectively reduce excessive solar heat gains in the summer season [47]. This effect compensates for the increase of the heating and lighting energy consumption due to the lower transmittance in the transparent state (compared to the reference window case) which reduces solar gain and indoor daylight availability in the winter season. The net effect is a marked reduction of the total energy consumption.

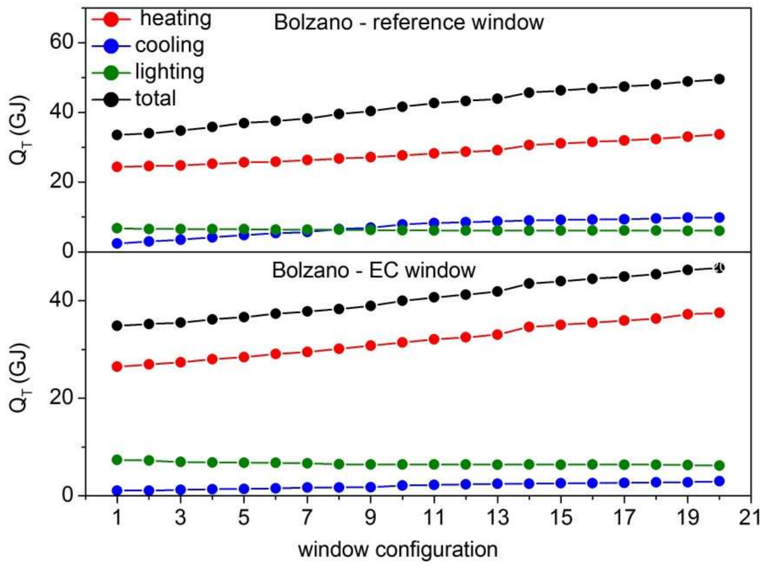

Figure 13. The heating, cooling and lighting contributions to the total yearly primary energy consumption of the building as a function of WWR for Bolzano.

In Bolzano, instead, where the dominant energy demand is associated to heating, the solar gain control operated by the EC glazing determines less benefits in the energy saving due to cooling. And, for low values of WWR (< 0.16), this reduction is overcame by the increase in the winter heating and lighting energy consumption caused by the lower transmittance in the transparent state compared to the reference window case. The net effect is an increase of the total energy consumption.

The influence of the EC glazing on each energetic contribution, Q_i, is more effectively quantified in Fig. 14, where the relative deviations between the yearly primary energy demands obtained adopting the two typologies of glazing is reported as a function of WWR. Such parameter is defined as:

$$\Delta Q_i = \frac{Q_{i,EC} - Q_{i,R}}{Q_{TOT,R}} \tag{4}$$

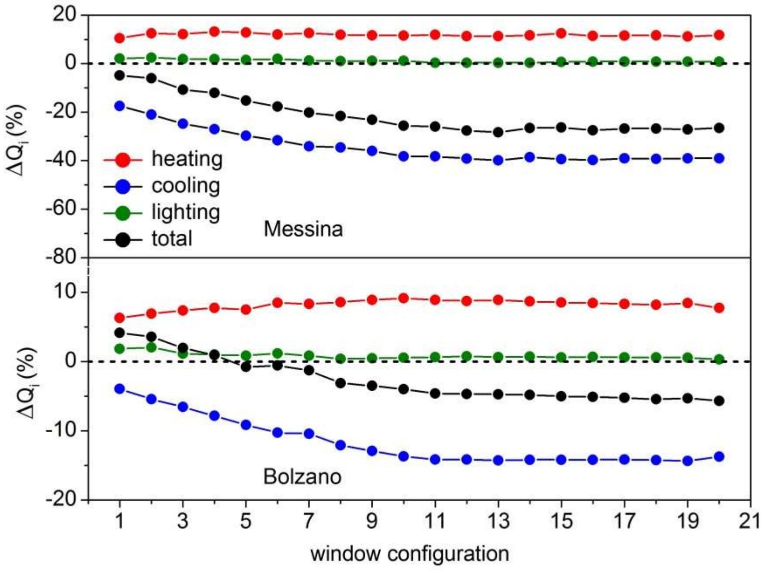

Figure 14. Relative deviations of each contribute to the total the energy demand obtained using EC glazing from the ones obtained using the reference glazing as a function of WWR.

where subscripts "EC" and "R" stand for "electrochromic" and "reference" respectively. The graphs show how the EC glazing performance is optimal when the cooling demand is dominant over the heating/lighting demand. In Messina, in fact, deviations varying from -20% to -40%, even for low values of WWR (<0.10), are found in the cooling contribution while, in more rigid climates (like Bolzano), the deviations is always smaller than -15%. However, for both towns the deviations concerning the heating and lighting contributions are always positive (+10% in Bolzano and +2% in Messina) evidencing how the use of EC glazing leads to an increase of these energy contributions.

When considering these results it must be underlined that the adopted control strategy doesn't take into account possible glare risk for the occupants. Since EC windows are generally unable to fully block glare effects from direct sunlight, even in their lower transmittance state [10], additional shading systems (overhangs, etc.) [18] could be required. This would probably modify to a certain extent the results here presented although the results obtained by one of the authors in previous works [9-11] suggest that, at least in the case of Messina, the general trend above outlined should remain essentially unaffected.

4. Conclusions

In the present work the heat and light transfer control performance of an EC window is assessed by both experimental and computational approaches for two typical Italian climates. The experimental tests, conducted by a small-scale test cell, evidences that the investigated EC device is effective in reducing heat loads in a cooling dominated climate during the summer season. The other major finding – concerned with the analysis of the heat flux components entering the test cell – is that EC devices which modulate solar radiation mainly by absorption, like the one investigated in this paper, generate secondary solar heat gains which entail a 20 % decrease of the maximum potential energy flux reduction. Also, this effect could rise the temperature of the internal glass pane of the glazing to levels for which risk of thermal discomfort for the occupants may occur.

As for the numerical investigation, the results presented here are referred to a residential building with a standard use profile characterized by unoccupied periods during a large fraction of daytime (from 09:00 to 17:00 from Monday to Friday). In this context, the noteworthy result is that for cooling dominated climates the investigated EC device could be very effective (in accordance with the experimental finding) in producing appreciable benefits in terms of heat load reduction. This reduction may lead, in turn, to a marked decrease of the total building energy consumption. This is due to the fact that the benefits on cooling energy demand in the summer season (associated to solar heat gain reduction) exceeds the increase of heating and lighting in the winter season. However, for heating dominated climates it turns out that the cooling load reduction benefits could be exceeded by the increase in heating and lighting requirements for relatively low values of the glazed surface area of the building. This leads to an unwanted growth of the total building energy demand.

Further experimental investigation (currently in progress) is required to assess the effect of additional low-e coatings (on surface 3 of the EC DGU) and/or EC ventilated glazing units on the secondary heat fluxes associated to the absorptive behaviour of the EC layer. Additional computational analysis (currently in progress) is needed to investigate the energy performance of the

EC glazing for climate conditions different from the ones here investigated and when driven by control strategies which take also into account visual comfort requirements (glare control, luminance control, etc.).

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