Simulation models of an electric-driven smart window: energy and visual performances

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ABSTRACT

The "in-situ" measurements acquired to characterize full-scale electric-driven glasses, able to dynamically switch from opaque to transparent state, were used to develop, calibrate and validate thermal and visual simulation models of these devices. The validated models were then used, in the simulation software TRNSYS, to assess the ability of these dynamic glasses to control the indoor conditions and reduce cooling load.

The analysis was conducted for an office in an historical building, comparing the simulation results associated to the electric-driven glasses with those of the conventional double-glazing ones, from energy and visual points of view. Two different switching strategies were considered: i) Daylight strategy and ii) Thermal strategy. The use of electric-driven glasses allows from the thermal point of view to reduce about 12.5% of the cooling load, while from a visual point of view, to reach the highest values of Useful Daylight Illuminance, if controlled following the Daylight strategy.

KEYWORDS

Smart windows; Electric-driven windows; Thermal comfort; Visual comfort; TRNSYS; Experimental measurements; Numerical model.

INTRODUCTION

The heating and cooling of the building is responsible for around 40% of the total worldwide energy demand [1]. The EU residential building stock is largely composed of buildings with poor energy performance. Thus, the energy refurbishment of the existing building stocks presents a high potential for energy savings and reduction of greenhouse gas emissions in the EU countries [2]. In the Italian scenario, about 4 million of buildings were built before 1920 [3] among these, about 2.1 million of building classified as having an historical value have been occupied [4]. Italian Legislative Decree 192/2005 [5] and Italian Legislative Decree 311/2006 [6] exclude historical and architectural heritage from energy retrofitting actions, if the actions cause a significant change of the building integrity. For these reasons, energy

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saving actions able to improve energy efficiency of buildings without altering their geometric and/or aesthetic aspects represent the only way for refurbishment of historical buildings. With this aim in mind, many researchers have focused their attention to analyse different retrofitting actions applicable to existing buildings and their effects on energy savings [7-9]. Among these actions, the correct use of daylight allows to reduce energy use for lighting in buildings as well as improve visual comfort. In this scenario, smart windows, especially those electrically controlled, can play an important role in controlling the visual and thermal conditions inside a room. Nevertheless, for the best use of these new technologies, in-situ assessments on full scale devices are necessary for understanding their real behaviour upon varying internal and external conditions as well as to develop simulation models able to predict their performance under different operating conditions.

With the aim to evaluate the thermal and visual behaviour of electric-driven (ED) glasses, "in situ" measurements were performed. The experimental data were acquired using a full-scale facility. In the first part of this paper, the "in situ" measurements were used to develop, calibrate and validate thermal and visual simulation models of an electric-driven device, into the simulation software TRNSYS. Then the validated simulation models were used to predict the ability of electric-driven windows, integrated in a typical reference building, to control the indoor environment, upon varying boundary conditions. Energy and visual analyses were carried out considering different control logics.

In particular, the impact of window refurbishment on energy consumption was evaluated for a south oriented office of the Abbey of San Lorenzo ad Septimum located in Aversa (southern Italy) [8]. The analysis was carried out in terms of cooling energy demand reduction and daylight illuminance distributions for the electric-driven window compared with a conventional double-glazing window with the same thermal transmission, by means of the dynamic simulation software TRNSYS [10] during summer.

TEST FACILITY AND MEASUREMENTS SET UP

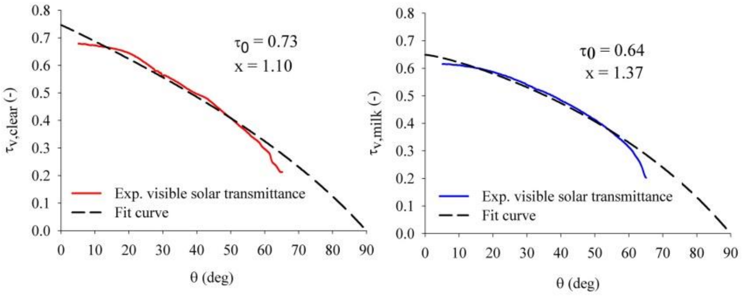
In order to allow experimental studies for assessing in-situ visual performances of full scale smart windows, an experimental station was designed and set-up at the Department of Engineering of the University of Sannio [11,12]. The station consists of a steel structure placed on a turntable, with external size of 6.00 m x 6.00 m and height of 5.50 m. Its envelope consists of three removable vertical test walls (U=0.43 W/m^2), one unremovable vertical technical wall (U=0.05 W/m^2), a floor (U=0.05 W/m^2) and a roof (U=0.06 W/m^2) [11]. The facility is equipped with a double-hang wood frame window with a total size of 2.000 m x 1.200 m, with a ratio between glass area and total window area equal to 0.59; each hang has a glazing with size of 0.785 m x 0.900 m. In order to realize a virtual model of the facility, a comprehensive geometrical and photometrical characterization of internal objects surfaces were carried out [12]. In this paper, the first results of the in-situ visual and thermal characterization of the two full scale double ED glazings, manufactured by Gesimat [13], were used to develop, calibrate and validate thermal and visual simulation models of the ED device. The ED glazing was composed, from outside to inside, of a 4 mm uncoated float glass, a 16 mm gap filled with Argon and an electric-driven layer between two 4 mm uncoated glasses. According to the technical data declared by the manufacturer, the ED glazing is switched from milky to clear state by applying an electric field of about 115 V, within about 1 s. In clear state, ED glazing was characterized by a visible solar transmittance (τ_{vis}) equal to 72.5%, a thermal transmittance (U_g) equal to 2.5 W/m^{2}K, a solar factor (g) equal to 0.72 and a power demand of about 10 W/m^2. In milky state, the ED glazing was characterized by a visible solar transmittance (τ_{vis}) equal to 60.7%, a thermal transmittance (U_g) equal to 2.5 W/m^{2}K and a solar factor (g) equal to 0.67. So as to describe the ED glasses behaviour, in-situ visual and thermal characterizations were carried out. For the characterization, two different measurement set-up were used: (1) for evaluating the visible solar transmittance as a function of light incident angle and (2) for evaluating the internal illuminance daylight distribution as well as the thermal behaviour of the glasses.

Evaluation of the visible solar transmittance as a function of light incident angle

The first set-up was realized for appreciating the variations of visible solar transmittance as a function of the light incident angle. With this aim, the vertical illuminance values both on the external surface of the window E_v^{ext} and just behind the internal surface of each ED glazing E_v^{int} were acquired during days with completely clear sky conditions. In this step, measurements were performed with the window oriented to West as well as with left ED glazing in clear and right ED glazing in milky state. The illuminance values were acquired every 20 s by three Konica Minolta T-10 (accuracy of ± 2 %) when direct sun light strikes on lux-meters, from around 2 p.m. (incident angle of direct light about 65°) to the sunset (incident angle about 5°). The solid lines in Figure 1 show the experimental visible solar transmittance values, for glasses in clear (Figure 1a) and milky (Figure 1b) state. From acquired illuminance values, the experimental visible solar transmittance was calculated as $E_v^{\text{int}} / E_v^{ext}$.

As first approach, the visible solar transmittance value was considered equal to the diffuse-diffuse transmittance $\tau_{\text{dif-dif,fit}}$ and constant for different light incident angles. $\tau_{\text{dif-dif,fit}}$ is defined as $\tau_{dif-dif,fit} = \int_0^{\pi/2} \tau_v(\theta)\sin(2\theta)d\theta$ where θ is the incident angle and $\tau_v(\theta)$ is the empirical angular function [14]. The fitting parameters x and τ_0 were evaluated considering the experimental values of visible transmittance between 5° and 65° (Figure 1a for clear state and Figure 1b for milky state). The dash lines in Figure 1a and Figure 1b show also the fit curves for clear and milk state, respectively. The calculated values of $\tau_{\text{dif-dif,fit}}$ are equal to 43.8% for clear and 42.7% for milk state.

Considering the data displayed in Figure 1, the visible solar transmittance value declared by ED glasses manufacturer (72.5% for clear and 60.7% for milky state) were not take into account for developing the visual simulation model. Indeed, they were considered too high to describe the real behaviour of the ED glasses upon varying of the incident angle of light.

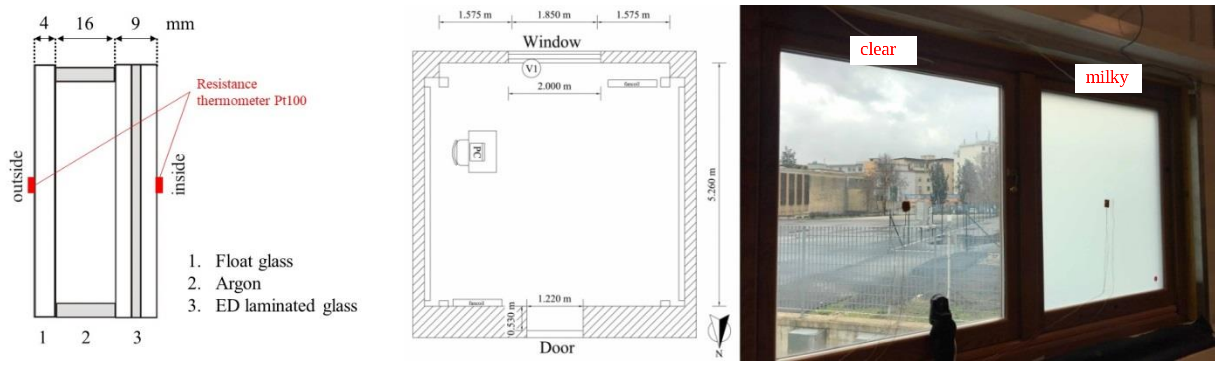


a) b)

Figure 1. Curve fitting for a) clear and b) milk state.

Evaluation of internal illuminance daylight distributions as well as the thermal behaviour of the glasses

The second set-up was realized for acquiring of the external daylight illuminances as well as the internal daylight illuminance distributions. All monitored quantities were acquired at the same time, with the test room oriented to South. The measurements were collected in sunny days from 9:00 to 17:00, local time, with a time step of 2 minutes, on 12th, 13th and 18th July in milky state and on 8th, 11th, 15th and 16th July in clear state. The external weather conditions were evaluated acquiring the global and diffuse horizontal illuminance values on the roof of the facility, by using two illuminance-meters LP PHOT 03 [15], with accuracy <4%. For the diffuse horizontal illuminance, one illuminance-meter was equipped with a black painted shadow-ring, with a diameter of 0.574 m and thickness equal to 0.052 m. So as to highlight the potential benefit on thermal comfort associated to the use of the ED windows, the glasses surface temperature as well as the indoor air temperature were also measured. The temperatures were monitored by using a resistance thermometer Pt100 with a range of -40÷80 °C and an accuracy equal to ±0.1 °C at 0 °C, as shown in Figure 2a. The sensors on the external surface of glasses were installed with appropriate shielding to consider the effect of direct solar radiation. Each parameter was logged every 10 seconds by means of a Fluke NetDAQ Data Logger. In order to evaluate the visual behaviour of the electric-driven device, the simulation results were compared with the experimental values acquired by an illuminance-meters Konica Minolta T-10 placed in vertical position just behind the glass (V1, as reported in the Figure 2b). Figure 2c shows the window equipped with the ED glasses in the clear (left pane) and milky (right pane) state.



a) b) c)

Figure 2. a) Schematic layout of the ED double glazed unit, b) layout of the room with position of the sensor and c) the ET device in the two states with some sensors.

VIRTUAL MODELS OF THE ED GLASSES

A virtual model of the test facility was realized in the dynamic simulation software TRNSYS 17 [10]. This software is widely used in literature to evaluate the energy performance of buildings upon varying the operating scenarios [8,16,17].

The daylight analysis was conducted by means of the TypeDLT developed by the Institute for Renewable Energy EURAC research [18], within the EU FP7 Project CommONEnergy. The TypeDLT is a climate-based tool that allows to perform daylight analysis of Complex Fenestration Systems (CFS) by using the Bidirectional Scattering Distribution Function (BSDF). The TypeDLT implements the simulation software RADIANCE [19], in particular the so called Three-Phase Method (3PM) [20], inside TRNSYS. Experimental data about the thermo-physical characteristics of the building envelope [11] as well as the photometrical characteristics of internal surfaces [12] were set in the virtual model of the facility.

Thermal simulation model

The whole ED window was modelled by means of the software WINDOW 7.5, considering the schematic layout of the ED double glazed unit reported in Figure 2a. In particular, two different window models were realized, one for the ED window in the clear state and another one for the ED window in the milky state. The output file of the software WINDOW 7.5 was then used in software platform TRNSYS 17 by means of the Type 56 to compare the experimental thermal performances with those obtained through simulations. A simulation time step equal to 10 seconds was used. During the simulations, the same outdoor boundary conditions measured during the experimental tests were considered.

In particular, taking into account that only one test-room was available, a first comparison between the boundary conditions during the days with the ED window in clear state and those with the ED window in milky state was carried out in order to effectively compare the performance recorded in the clear state with those associated to the milky state in the same outdoor conditions. This preliminary comparison was performed in terms of percentage difference of external air temperature, percentage difference of global solar radiation on the horizontal and wind velocity. The comparative test was considered acceptable in the cases of the difference in the outdoor environmental variables never exceeded 5%. The days July 8th (ED window in clear state) as well as July 12th (ED window in milky state) are comparable with one another.

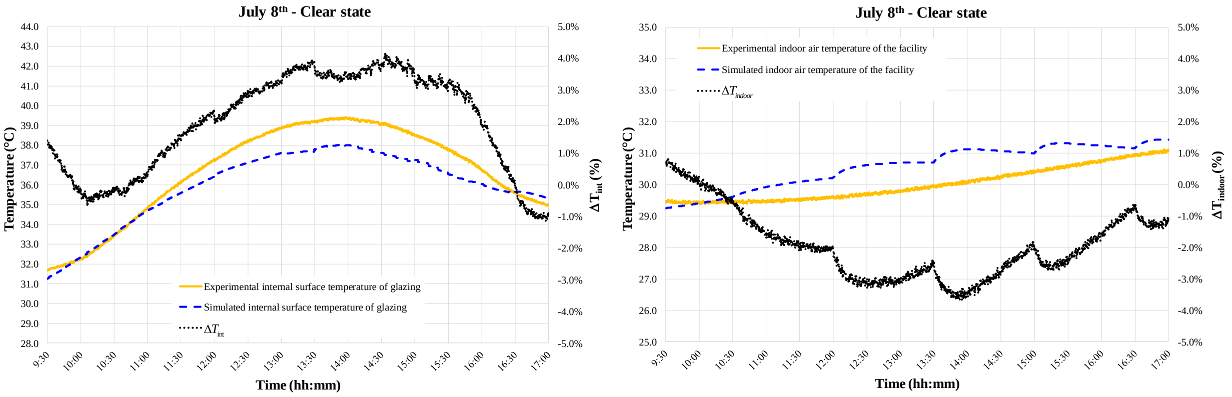
The simulation results were compared to the experimental data in order to assess the model reliability. The comparison was performed in terms of internal surface temperature of the glazing as well as indoor air temperature for both July 8th (ED window in clear state) as well as July 12th (ED window in milky state). In order to verify the accuracy of the modelled ED window, the following indices were calculated:

$$\Delta T_{\mathrm{int}} = \frac{T_{\mathrm{int,exp}} - T_{\mathrm{int,sim}}}{T_{\mathrm{int,exp}}} \times 100 \tag{1}$$

$$\Delta T_{\mathrm{indoor}} = \frac{T_{\mathrm{indoor,exp}} - T_{\mathrm{indoor,sim}}}{T_{\mathrm{indoor,exp}}} \times 100 \tag{2}$$

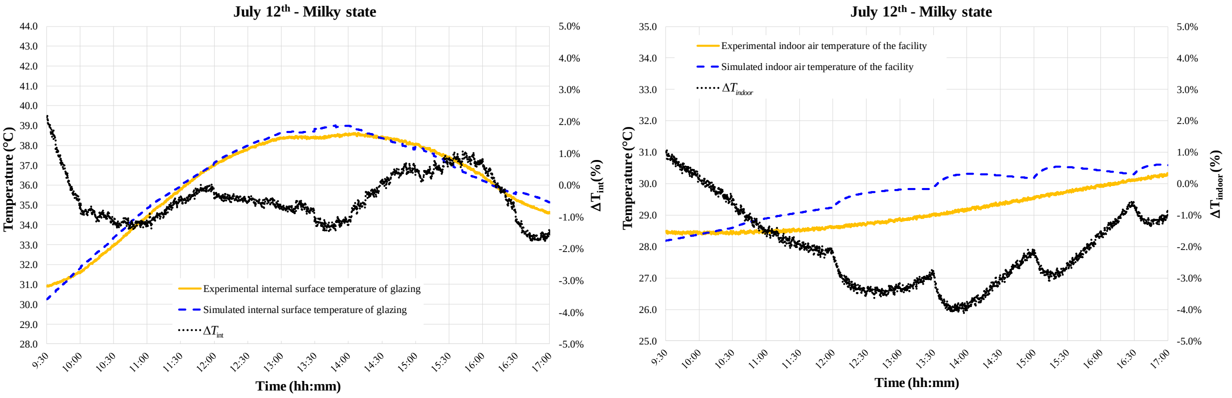
where $T_{\mathrm{int,exp}}$ and $T_{\mathrm{int,sim}}$ are the experimental and simulated internal surface temperature of the glazing, respectively; $T_{\mathrm{indoor,exp}}$ and $T_{\mathrm{indoor,sim}}$ are the experimental and simulated indoor air temperature of the test-room, respectively.

Figures 3a and 3b compare the simulation results with the experimental data in terms of T_{int} and T_{indoor} as a function of the time for the clear state (July 8th). These figures highlight how the modelled clear ED window predicts quite well the measured values. In particular, the values of ΔT_{int} range from -1.13% to 4.14%, while the values $\Delta T_{\mathrm{indoor}}$ during July 8th range from -3.67% to 0.82%. Figures 4a and 4b compare the simulation results with the experimental data in terms of T_{int} and T_{indoor} as a function of the time for the milky state (July 12th). These figures highlight a good model reliability. In particular, the values of ΔT_{int} range from -1.79% to 2.19%, while the values of $\Delta T_{\mathrm{indoor}}$ range between -4.14% and 1.08%.



a) b)

Figure 3. Comparison between simulation results and experimental data in terms of: a) internal surface temperature of the glazing, b) indoor air temperature.



a) b)

Figure 4. Comparison between simulation results and experimental data in terms of: a) internal surface temperature of the glazing, b) indoor air temperature.

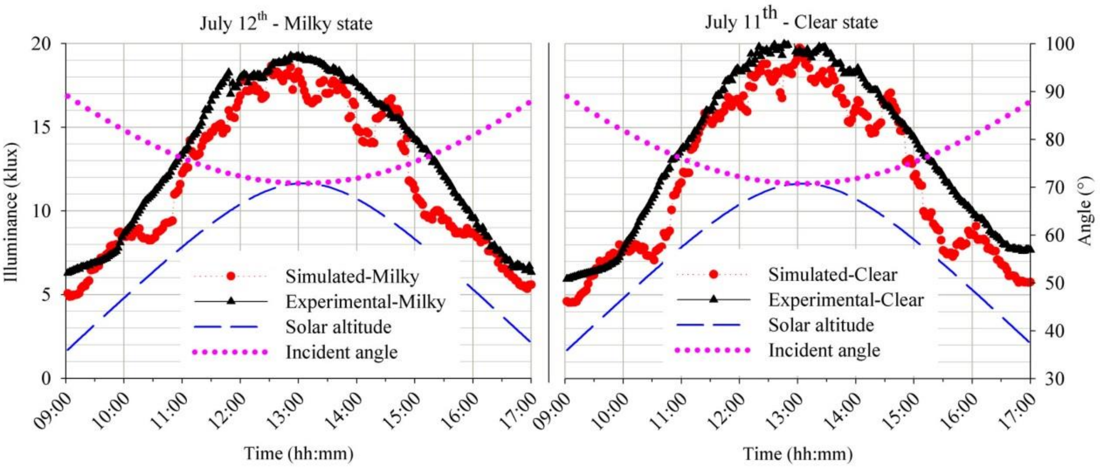
Visual simulation models

So as to describe the visual behaviour of the ED glasses, two different simulation models of the ED glasses, one for clear end one for milky state, were modelled by using programs OPTICS 6 and WINDOW 7.5. At first, the ED layer was modelled considering a diffusing interlayer between two clear glasses. Then, the modelled ED layer was used in WINDOW 7.5 to build the double glazing and obtain the preliminary BSDF file. Finally, the BSDF file was modified to scale the visible solar transmittance to values specified above and the modified BSDF files were used in the simulation software.

In order to perform simulations with the real sky conditions under which the daylight distributions were acquired, the recorded external illuminance values were used as input of the simulation software. A simulation time step equal to 2 min, from 9:00 to 17:00 local time, was used. The reliability of the ED simulation models was assessed comparing the experimental values with those simulated. The comparison was carried out in terms of vertical illuminance values acquired behind the ED devices (measurement point V1) on July 12th, 13th and 18th (milky state) and on July 11th, 15th and 16th (clear state). The Figure 5 shows the comparison between experimental data, acquired on July 11th (clear state) and July 12th (milky state), as well as the simulated illuminance values. In the figures, the solar altitude and the incident angle of light were also plotted. The figures underline that both visual simulation models are able to predict experimental data with a good degree of accuracy, except for error that occur at around 10:30 a.m. and 15:30 p.m, corresponding to an incident angle of about 78°.

The assessment was also based on statistical indices, evaluating the relative mean bias error (rMBE) and the relative root mean square error (rRMSE) with respect experimental data. In the Table 1, the rMBE and the rRMSE, calculated taking into account the measurement carried out during all the three days in clear and milky state, were listed. Considering the results reported in [21,22], the simulation results were considered in good agreement with the experimental ones if the rMBE is less than ±15% and the rRMSE is less than +35%. From the values in the table, it is possible to deduce that i) the simulation values overestimate the experimental data and ii) the error associated to the visual model for milky state is lower than that for clear state.

The Figure 6 display the frequency distribution of percentage relative error in experimental data for ED glazing in clear and milky state with respect to: a) the illuminance values on the sensor V1, b) the internal surface temperature of the glazing and c) the indoor air temperature. The figures highlight that: (i) the simulation model for milky state predicts the experimental data better than the simulation model for clear state (Figure 6a); (ii) with respect to the internal surface temperature of the glazing (Figure 6b), the error associated to the thermal model for milky state is lower than that for clear state; while (iii) in terms of the indoor air temperature (Figure 6c) no significant differences were observed.

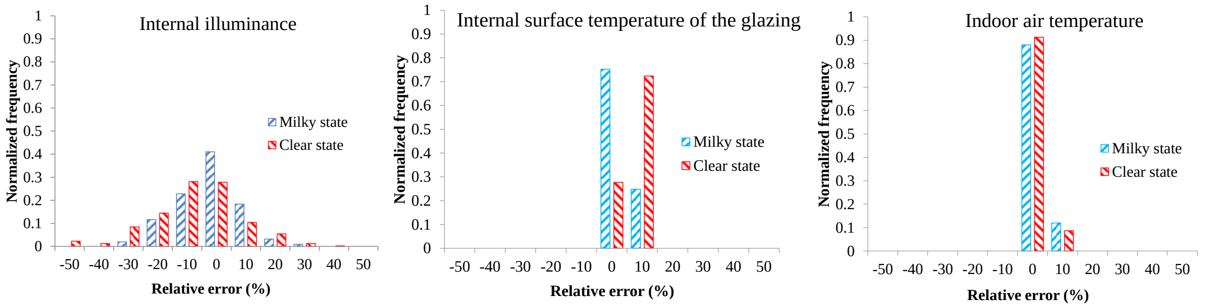


a) b)

Figure 5. Measured and simulated illuminance value for the sensor V1 in a) milky and b) clear state.

Table 1. Relative mean bias error (rMBE) and relative root mean square error (rRMSE) for sensor V1.

State	rMBE (%)	rRMSE (%)
Clear	-11.5	17.4
Milky	-6.8	11.4



a) b) c)

Figure 6. Frequency distribution of relative percentage error using simulation models for ED glazing in clear and milky state for a) internal illuminance predictions, b) internal surface temperature of the glazing and c) indoor air temperature.

SIMULATIONS

Finally, the visual and the thermal simulation models developed for the ED glasses were used to evaluate the ability of ED glazing to improve visual and thermal comfort inside of existing buildings.

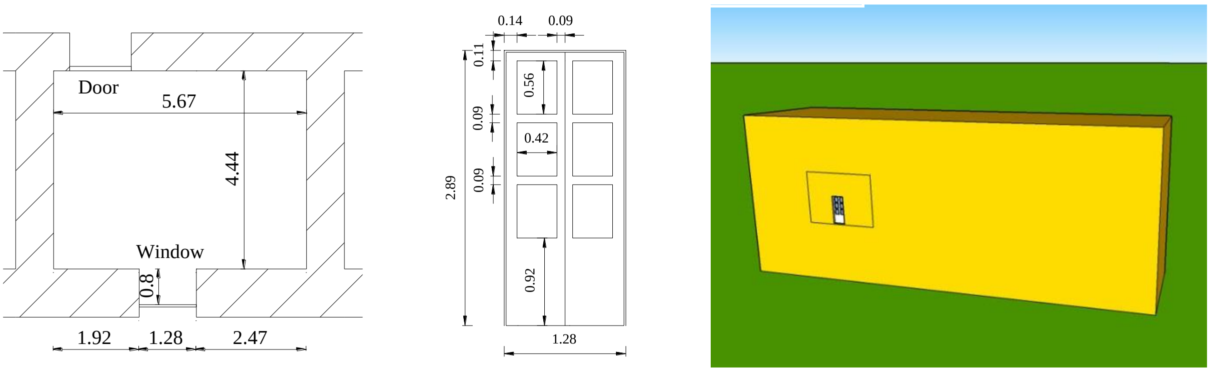
For this purpose, a south oriented office of the Abbey of San Lorenzo ad Septimum was chosen as case study. The Abbey is located in Aversa (southern Italy) and houses the Department of Architecture and Industrial Design of the University of Campania “Luigi Vanvitelli” [8]. The objects of this analysis are both to assess the ability of the ED glazing to control internal conditions as well as to evaluate the impact of window refurbishment on energy consumption in historical buildings. The evaluations were carried out in terms of cooling energy demand reduction and daylight illuminance distributions for the ED window compared with a conventional double-glazing window, with the same thermal transmission. The office was considered located in Naples (latitude = 40°51′46″80 N; longitude = 14°16′36″12 E). Simulations were performed by using the dynamic simulation software TRNSYS [10] during summer time, for three months (from June 1st to August 31st) and with a simulation time step equal to 1 hour.

Office

The office, located at the first floor of the Abbey, has a floor area of about 26.0 m^2 and a height of about 5.45 m. The window, with a total surface of about 3.70 m^2 and a ratio glass area/total window area equal to 0.38, is placed on the external side of the perimeter wall that has a thickness of about 1.00 m. The Figure 7 shows a) the layout of the office, b) the layout of the window and c) the Abbey model in the simulation software TRNSYS.

In-situ measurements were performed in order to evaluate the thermal behaviour of the external walls, showing an average value of the thermal transmittance equal to about 1,09 W/m^{2}K. For the energetic analyses, the office was modelled by using the Type 56. The thermal gains associated to the presence of one person, the lighting system and one PC with monitor were considered.

The photometrical characterization of the room surfaces was achieved by means of a spectro-photometer Minolta CM – 2600d (spectral reflectance standard deviation within 0.1%), utilizing the standard illuminant D65. The experimental reflectance values were used to characterize the RADIANCE model of the office. For the daylight analyses, the office was modelled by using the TypeDLT.



a) b) c)

Figure 7. a) office layout, b) window layout and c) abbey model.

Simulation conditions

The simulations were carried out considering operational both cooling plant and lighting system during the office time, from 9:00 to 18:00 in weekdays. The cooling plant was considered ON if the indoor temperature reaches the value of 26 °C, while the lighting system was considered ON if the daylight average illuminance value is lower than 300 lx. The ED glasses were controlled following two different switching strategies: i) Daylight strategy and ii) Thermal strategy.

Daylight strategy: the ED glasses were considered in the milky state without sun radiation. With sun radiation, if the average illuminance value inside the room was lower than 300 lx the ED glasses were considered in clear state, otherwise in the milky state.
Thermal strategy: the ED glasses were considered in the milky state without sun radiation. With sun radiation, if the temperature inside the room was lower than 26 °C the ED glasses were considered in clear state, otherwise in the milky state.

RESULTS AND DISCUSSION

The simulations were performed for conventional double-glazing window as well as for the two switching strategies for the ED window. The simulation results were compared from the energy point of view in terms of cooling energy demand reduction, while from the visual point of view in terms of Useful Daylight Illuminance (UDI) [23] and Spatial Daylight Autonomy (sDA) [24]. The UDI represents the fraction of the time in a year in which the horizontal daylight illuminance at a given point fall in a given range. Three ranges are defined to identify the time with too little ($UDI_{Underlit}$), appropriate (UDI_{Useful}) or too high daylight ($UDI_{Overlit}$) illuminance values. The sDA represent the percent of an area in which is guaranteed a minimum daylight illuminance level for a specified fraction of the operating hours. In this paper, the daylight was considered fulfilled if illuminance values meet or exceed 300 lx for at least 50% of the office hours ($sDA_{300/50\%}$).
The Figure 8 shows the cooling energy demand for the simulation period upon varying the window typology and the control strategy. From the figure it is possible to notice that:

- whatever the month is, the cooling load with the conventional double-glazing is greater than that with ED window;
- the cooling load with the ED window is almost the same for the two switching strategies;
- the percentage cooling load reduction range from about 17.0% in June to about 11.6% in August;
- the use of ED window allows a cooling load reduction of about 12.5%.

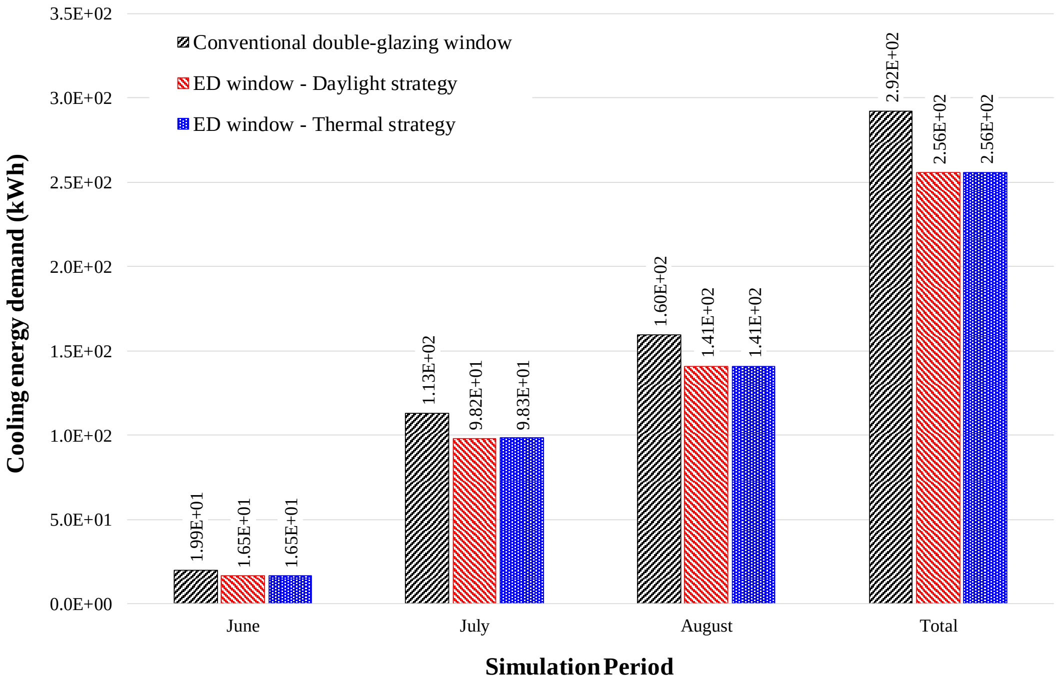


Figure 8. Cooling energy demand during summer time upon varying the window typology and the control strategy.

The Figure 9 shows the UDI values in the office for a) the conventional double-glazing window as well as the ED window controlled following b) the Daylight strategy and c) the Thermal strategy, considering a comfort range between 100 lux and 2000 lux [23] and calculated during office hours from June 1st to August 31st. From figures it is possible to notice that the UDI_{Useful} ranges from about 69% to 100% with conventional double-glazing window, while with ED window the UDI_{Useful} ranges from about 98% to 100% if controlled following the Daylight strategy and from about 88% to 93% if controlled following the Thermal strategy. In addition, the analysis reveal that the use of ED window allows to avoid to exceed the upper illuminance comfort threshold (2000 lux).

In the Table 2, the $sDA_{300/50\%}$ vales calculated for the conventional double-glazing window and the ED window controlled following both strategy were listed. The values reported in the table highlight that:

- with the conventional double-glazing, it is possible reach the highest $sDA_{300/50\%}$;
- the Daylight strategy allows to achieve higher $sDA_{300/50\%}$ than the Thermal strategy.

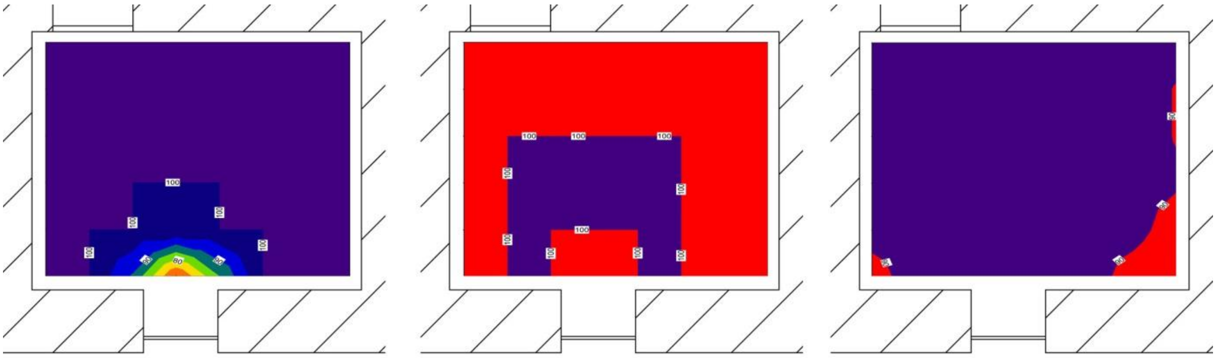
CONCLUSION

In this paper, an electric-driven window was characterized in a full-scale facility by “in situ” measurements. The considered ED window is able to switch from opaque to transparent state by applying an electric field. At first, the thermal and visual simulation models of the ED device, two for milky and two for clear state, were modelled by means of the software WINDOW 7.5. Then, the simulation software TRNSYS 17 was used to calibrate and validate the ED models on the base of experimental data, showing a good agreement between numerical and experimental data for all ED models.

The validated simulation models were used in the simulation software TRNSYS for both to predict the ability of ED windows to control the thermal and visual comfort and to evaluate the impact of window refurbishment on energy consumption in historical buildings.

The evaluations were carried out for an office in an historical building located in Aversa, considering two different switching strategies for the ED window: i) Daylight strategy and ii) Thermal strategy.

The simulation results obtained for the ED window were compared with those performed by means of a conventional double-glazing window from an energy and visual points of view. In particular, a cooling energy demand reduction deriving from the integration of ED windows in the historical office building of about 12.5% was assessed for both switching strategies. From a visual point of view the Useful Daylight Illuminance (UDI) and the Spatial Daylight Autonomy (sDA) were calculated. With respect UDI, ED window allowed to avoid the presence of points in which the illuminance values exceed 2000 lux. Controlling the ED window following the Daylight strategy, it was been possible to guarantee highest values of $\mathrm{UDI}_{\mathrm{useful}}$, ranging between 98% and 100%. In terms of sDA, the highest values (equal to 0.975) were reached with the conventional double-glazing window, while comparing the two switching strategies, the Daylight strategy proves to be the best.



a) b) c)

Figure 9. Useful UDI values in the office for a) the conventional double-glazing window as well as the ED window controlled following b) the Daylight strategy and c) the Thermal strategy.

Table 2. $\mathrm{sDA}_{300/50\%}$ vales during office hours from June 1st to August 31st.

	Conventional double-glazing	ED window Daylight strategy	 Thermal strategy
$\mathrm{sDA}_{300/50\%}$	0.975	0.734	0.570

REFERENCES

1. http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (accessed May 2018).
2. Ballarini, I., Corgnati, S. P., Corrado, V., Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project, *Energy Policy*, , Vol. 68, pp 273-284, 2014.
3. de Rossi, F., Scuto, V., Tino, S., Vanoli, G. P., Risparmio energetico come elemento qualificante nel recupero di palazzine anni ’30, *Proceedings of The 61th ATI National Conference*, Perugia, 2006.

4. ISTAT. Paesaggio e patrimonio culturale. https://www.istat.it/it/files/2014/06/09_Paesaggio-patrimonio-culturale-Bes2014.pdf (accessed May 2018).
5. Italian Government, Attuazione della Direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia, Legislative Decree n. 192, 2005.
6. Italian Government, Disposizioni correttive ed integrative al decreto legislativo 19 agosto 2005, n. 192, recante attuazione della direttiva 2002/91/CE, relativa al rendimento energetico nell'edilizia, Legislative Decree n. 311, 2006.
7. Ciampi, G., Rosato, A., Scorpio, M., Sibilio, S., Retrofitting Solutions for Energy Saving in a Historical Building Lighting System, *Energy Procedia*, Vol. 78, pp 2669–2674, 2015.
8. Ciampi, G., Rosato, A., Scorpio, M., Sibilio, S., Energy and Economic Evaluation of Retrofit Actions on an Existing Historical Building in the South of Italy by Using a Dynamic Simulation Software, *Energy Procedia*, Vol. 78, pp 741-746, 2015.
9. Bellia, L., d'Ambrosio Alfano, R., Giordano, J., Ianniello, E., Riccio, G., Energy requalification of a historical building: A case study, *Energy Build.*, Vol. 95, pp 184-189, 2015.
10. Solar Energy Laboratory. TRNSYS, A transient system simulation program. Tech. rep. Madison, USA: University of Wisconsin, 2004.
11. Ascione, F., De Masi, R. F., de Rossi, F., Ruggiero, S., Vanoli, G. P., MATRIX, a multi activity test-room for evaluating the energy performances of 'building/HVAC' systems in Mediterranean climate: Experimental set-up and CFD/BPS numerical modelling, *Energy Build.*, Vol. 126, pp 424–446, 2016.
12. Sibilio, S., Rosato, A., Scorpio, M., Iuliano, G., Ciampi, G., Vanoli, G. P., de Rossi, F., A Review of Electrochromic Windows for Residential Applications, *Int. J. Heat Technol.*, Vol. 34, pp S481-S488, 2016.
13. Gesimat. http://www.gesimat.de/elektrotrop.html (accessed May 2018).
14. Reinhart, C.F., Andersen, M., Development and validation of a Radiance model for a translucent panel, *Energy Build.*, Vol. 38, pp 890–904, 2006.
15. Delta-OHM. http://www.deltaohm.com/ver2012/ (accessed May 2018).
16. Sibilio, S., Rosato, A., Ciampi, G., Scorpio, M., Akisawa, A., Building-integrated trigeneration system: Energy, environmental and economic dynamic performance assessment for Italian residential applications, *Renewable Sustainable Energy Rev.*, Vol. 68, No. 2, pp 920-933, 2016.
17. Ciampi, G., Rosato, A., Scorpio, M., Sibilio, S., Energy performance of a residential building-integrated micro-cogeneration system upon varying thermal load and control logic, *Int. J. of Low-Carbon Technol.*, Vol. 11, pp 75-88, 2016.
18. Michele, G. D., Oberegger, U. F., Baglivo, L., Coupling dynamic energy and daylighting simulations for complex fenestration systems, *Proceedings of BSA 2015 – Building Simulation Applicatio*, 2015.
19. http://radsite.lbl.gov/radiance/framew.html (accessed May 2018).
20. https://www.radiance-online.org/learning/tutorials (accessed May 2018).
21. Reinhart, C. F., Breton, P. F., Experimental Validation of Autodesk 3ds Max Design 2009 and Daysim 3.0, Leukos, Vol. 6, No. 1, 2009.
22. McNeil, A., Lee, E. S., A validation of the Radiance three-phase simulation method for modelling annual daylight performance of optically complex fenestration systems, *J. Build. Perform. Simul.*, Vol. 6, pp 24-37, 2013.
23. Nabil, A., Mardaljevic, J., Useful daylight illuminances: A replacement for daylight factors, *Energy Build.*, Vol. 38, No. 7, pp 905-913, 2006.
24. Illuminating Engineering Society, IES, Approved Method: IES Spatial Daylight Autonomy(sDA) and Annual Sunlight Exposure (ASE), 2012.