Evaluation of electrochromic windows impact in the energy performance of buildings in Mediterranean climates

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HIGHLIGHTS

- Energy performance analysis of Electrochromic (EC) windows is carried out.
- EC glass and control strategies are modeled and implemented in ESP-r.
- EC windows are evaluated, on a test prototype, as an alternative to shading devices.
- Set-points and measured variables are used to control optical properties of EC glass.
- The most effective results are obtained when EC windows are used in the west façade.

ARTICLE INFO

ABSTRACT

Old buildings refurbishment is essential for the global improvement of building energy indicators. Within this context, the paper focuses on the energy savings that may occur when using electrochromic (EC) windows, an interesting emerging technology alternative to shading devices to control solar gain in buildings located in Mediterranean climates. The EC windows technology is briefly presented and the optical properties adjustments of the glasses are discussed according to the operated range. The EC window dynamic behavior and the different control strategies are modeled and implemented in the ESP-r building simulation program. The EC window impact in the energy needs for heating and cooling is studied, considering different ambient parameters (exterior dry bulb temperature, interior dry bulb temperature and incident radiation) and set points for the EC control. A comparison of several windows solutions (single, double-glazing and EC windows), the type of building, internal gains from occupancy, lighting and equipment and the orientation of windows are considered for discussion through the analysis of the energy needs for heating and cooling. It is concluded that for this climate the best positive results are obtained when the EC are used in the west façade. For the south façade the results show no significant advantages in using EC windows.

1. Introduction

In buildings refurbishment it is necessary to consider three fundamental objectives: to maintain the existing building stock adapting the infrastructures to support the actual economic activity and ensure adequate living standards, protect the environment, safeguarding the historical architecture. From the energy point of view the main purpose of rehabilitation is to obtain rehabilitated buildings as closely as possible to the low energy buildings (Santamouris and Dascalaki, 2002).

In Portugal, buildings to be refurbished have typically single clear glazing. They are commonly replaced by double clear (typical glass used in Portugal, without improved properties, usually known as "current glass" or "conventional glass") and, less frequently, glazing with improved optical characteristics to reduce the solar gains. Therefore, glazing with climate adaptive optical properties may play an important function in the optimization of

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the annual solar gains in order to maximize the gains during winter, preventing the situation of overheating and limiting the solar gains during the summer periods.

In contemporary architecture glass facades have always aroused great interest (Azens and Granqvist, 2003). The architects always wants to have windows and glazed facades with increasing capacities of controlling the amount of light and heat transmitted to the interior of buildings. The glasses that allow this control are designated by chromogenic (Granqvist, 2006a, 2006b). The windows whose optical properties can be regulated in architecture can be considered as "high technology" (Granqvist et al. 2007).

The high performance windows can make use of a variety of chromogenic technologies, wherein the chromogenic term is used to indicate that optical properties can be changed in response to an external stimulus (Granqvist et al., 2010).

The main chromogenic technologies are: electrochromics (EC) (depending on the application of a voltage or electric charge), the termochromics (TC) (depending on temperature), photochromics (dependent on light irradiation, usually in the ultraviolet range), and gasochromics (depending on exposure to reducing or oxidizing gases) (Carmody et al., 2004; Granqvist, 2006a; Granqvist et al., 2009, 2010). It is possible to have more than one of these technologies in the same glass (Granqvist et al., 2010).

The electrochromism can be defined as a reversible change in the optical properties of a material induced by oxidation (loss of electrons) and reduction (gain of electrons) electrochemical due to the passage of an electric current by applying a potential difference between two electrodes (Somani and Radhakrishnan, 2002; Rowley and Mortimer, 2002; Stenzel et al. 2003; Mortimer et al. 2006). This change of the optical properties is reversible, that is, it can always go back to any one state, and lasting (Granqvist, 2012).

This phenomenon allows regulating the transmissivity (τ), the reflectivity (ρ), the absorptivity (α) and emissivity (ε) between two extreme values (Granqvist et al. 2003; Granqvist, 2005). As such, one can define the EC windows as a technology that utilizes an electrical voltage for controlling the amount of light passing through the glass (Sottile, 2002).

The EC technology involves the interaction of basic physics and chemistry, thin film science, device technology, and market opportunities (Granqvist, 2000). There are EC windows that need constant power to maintain a state and EC windows that have memory effect and thus only require power to promote a transition. For the EC with memory effect energy is needed only on an impulse basis to force the transition of the EC window to a different state (Granqvist, 2006b; Kraft and Rottmann, 2006, 2009). These EC windows operate on a "battery-like" mode, with a construction process similar to the laminated glasses made of five layers (Häusler et al., 2004; Kraft et al., 2006; Granqvist et al., 2010). The five layers are illustrated in Fig. 1 (Granqvist, 2000; Lee and DiBartolomeo, 2002; Avendaño et al., 2006; Granqvist et al., 2010).

Layer 1: glass or plastic coated with a transparent conductor (usually FTO—fluorine-doped tin oxide or ITO—tin-doped indium oxide);
Layer 2: one or more electro-active cathodic layers (usually tungsten trioxide WO_3);
Layer 3: ion conductor layer—electrolyte (usually PVB—polyvinyl butyral);
Layer 4: ion storage film or one or more electro-active anodic layers (usually Prussian blue, an inorganic material)—sometimes it is called the counter electrode; and
Layer 5: transparent conductor coating glass or plastic.

The DC voltage needed to change the optical properties of the window is low, typically between 0 and 5 V (Fasano et al., 2002). The process is continuous (it is possible to fix at any state
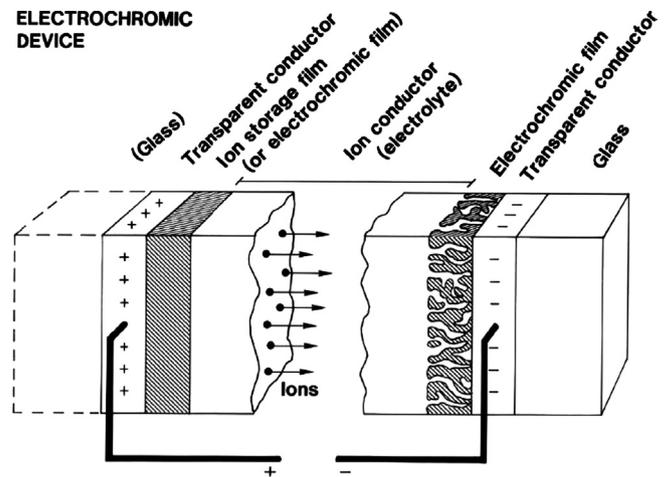
Fig. 1. Schematic representation of an EC device showing the ions displacement under an externally-applied electric field (Avendaño et al., 2006; Granqvist, 2006b).

condition) and reversible through a simple inversion of the electrical polarity (Lee et al., 2004). The transition process velocity decreases with the increase of the ambient temperature and a complete cycle from fully bleached to fully colored is slower than the reversed process. For a window with approximately 1 m^2 it takes 12 min to fully color and 8 min to fully bleach.

The potential of energy saving in buildings for the use of this technology depends on the location, type of building, orientation, lighting and comfort demands. The energy efficiency increases the more the location is sunnier and warmer (Karlsson, 2001).

Although there are several manufacturers worldwide for electrochromic glass, only three have commercially available products in various dimensions (Baetens et al., 2010): SAGE Electrochromics Inc.™ from USA, Gesimat GmbH™ and EControl-Glas™, both from Germany.

According to their durability tests, of about 50,000 cycles, and admitting under normal conditions five cycles per day, all manufacturers indicate that the duration of these windows is between 20 and 30 years.

The study developed in this paper considers the application of EC technology that has memory effect. A comparison of the influence of three types of glazing (single, double and electrochromic) in terms of energy savings with respect to heating and cooling is performed in order to evaluate the usefulness of the EC technology in the energy efficiency of buildings. The energy analysis performed was based on achieving the heating, cooling and annual energy requirements.

2. Methodology

Using the energy performance simulation of building the present paper is focused in the analysis of:

- Different types of window glass technologies: single (SG) and double (DGU) glass with static optical properties; double glass with dynamic optical properties—electrochromic (EC) glass;
- various types of EC glass control (solar radiation, outdoor air temperature and indoor air temperature) and different thresholds for state transition;
- different facade orientations of the window location (east, south and west); and
- the effect of the glass area and the influence of the air infiltration rate to consider the increase of the frames tightness in the rehabilitation context.

The objective is to understand how the energy consumption of the spaces will be modified when the building envelope becomes less permeable and how the controlled EC glass can contribute to the energy efficiency of buildings, particularly in the rehabilitation context.

2.1. Simulator

For the present study the ESP-r version 11.10 for Linux™ (Crawley et al., 2005a, 2005b, 2008) was used as the program to perform energy performance simulations. The ESP-r is an energy simulation program on a permanent basis, able to model phenomena involving exchanges of energy and mass inside buildings as well as other auxiliary systems. It also allows simulating real conditions in a building, analyzing its performance in terms of energy consumption, occupant comfort indices, evolution of temperature, air quality, control systems, etc. The ESP-r is a computer program (simulator) available at no cost under an open source license (Open Source), developed by the "Energy Systems Research Unit" (ESRU), University of Strathclyde, Scotland.

The simulators fundamentals (modules, mathematical description, models, etc.) in general and in particular for ESP-r can be found in Clarke (2001). The way the shaders and electrochromic windows could be implemented in ESP-r was based on Strachan (1990) and Haugaard (2003).

2.2. Building test cell model

To perform the simulations a model of a square floor area corresponding to a typical scholar building built during the fifties of the past century was defined.

Three identical blocks were defined (vd. Fig. 2), which differ only in the type of window glass. The main characteristics are:

test cells dimensions ($W \times D \times H$): 7 m $\times$ 7 m $\times$ 4 m;
exterior walls characteristics: limestone coated with plaster with 60 cm of thickness [$U_{value} = 1.90$ W/(m^2 K)];
ceiling and floor characteristics: typical mid-floor construction (plaster, concrete and wood) with 15 cm of thickness [$U_{value} = 2.62$ W/(m^2 K)]; similar boundary conditions (it is admitted during the simulation process that a thermal zone with identical environmental thermal conditions is adjacent to the simulated thermal zone; Clarke, 2001), considering that it is adjacent to another thermal zone;
window dimensions ($W \times H$): 3.0 m $\times$ 1.8 m, placed 1 m from the floor and centered on the façade; and
outside air infiltration: a constant value of 0.6 h^{-1}.

In literature (Rauh, 1999; Syrrakou et al., 2005; Syrrakou et al., 2006; Papaefthimiou et al., 2006a; Papaefthimiou et al., 2006b; Assimakopoulos et al., 2007; Kraft and Rottmann, 2009; Piccolo et al., 2009) it is usual to develop these types of analysis using prototype glasses, not commercially available.

For the present study the data were chosen from SAGE™, since this manufacturer provides the necessary detailed optical properties needed for the simulation. The optical properties of the three studied glass types (single, double and double EC) are listed in Table 1. The data for EC glass corresponds to a laminated type glass and an air gap with 12.7 mm (0.5 in.) filled with air and argon (90%).

As an example, Fig. 2 shows a picture of the model in ESP-r with the glazing area oriented east. The spacing between blocks was set to avoid shadowing between test cells. One test cell is parameterized with single glazing, another with double glazing and another with double EC glazing. Another ESP-r model with the facade entirely glazed (glass area of 25.84 m^2) was defined in order to study the influence of the glass area in the energy performance of the model.
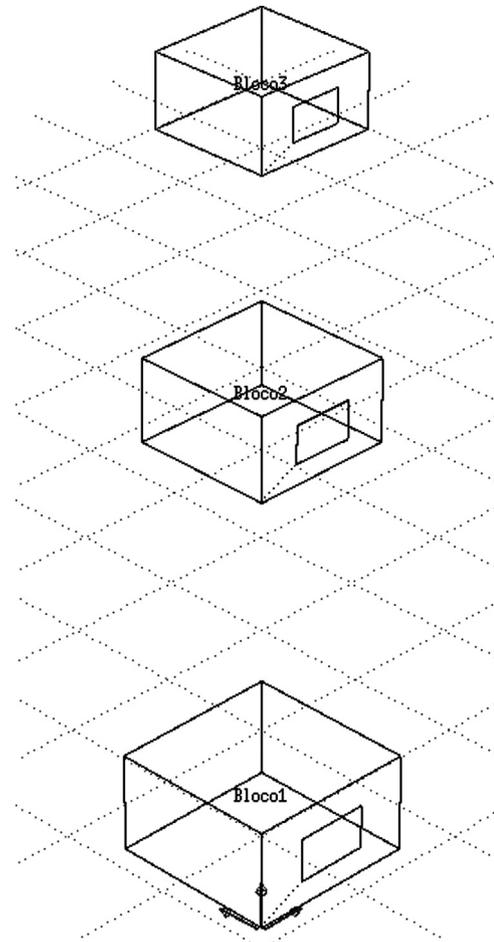
Fig. 2. Example of ESP-r model, with the three test cells and windows in east facade.

Table 1
Physical properties of the three types of glasses analyzed.

Properties	Single Clear 3 mm	Double Clear (4 mm/12 mm/4 mm)	Double EC SAGE™ (4 mm/12 mm/4 mm)	
			Clear	Colored
U (W/(m^2 K)	5.79	2.80	1.60	1.60
$g_{\perp}$	0.86	0.75	0.48	0.090
$\rho_{solar,\perp}$	0.07	0.12	0.20	0.100
$\tau_{solar,\perp}$	0.82	0.67	0.40	0.015
$\alpha_{solar,\perp}$	0.11	0.21	0.40	0.885
$\tau_{v,\perp}$	0.89	0.80	0.62	0.035

The diagrams of occupancy, lighting and equipment were estimated based on the results of an energy audit performed on the building considered, which permitted to estimate the energy consumption breakdown. These diagrams are presented in Figs. 3 and 4. During Sunday, it was not considered occupancy but was considered a constant value of 1% for lighting and equipment.

From the energy audit walk-through and equipments and systems characterization, the maximum values for occupancy, lighting and equipment were estimated and considered for the simulation:
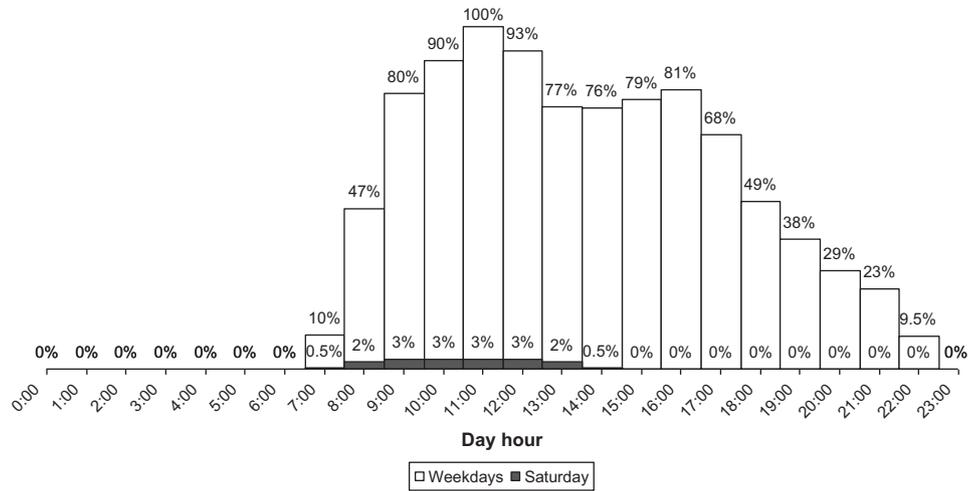
Fig. 3. Occupancy diagrams for weekdays and Saturday.
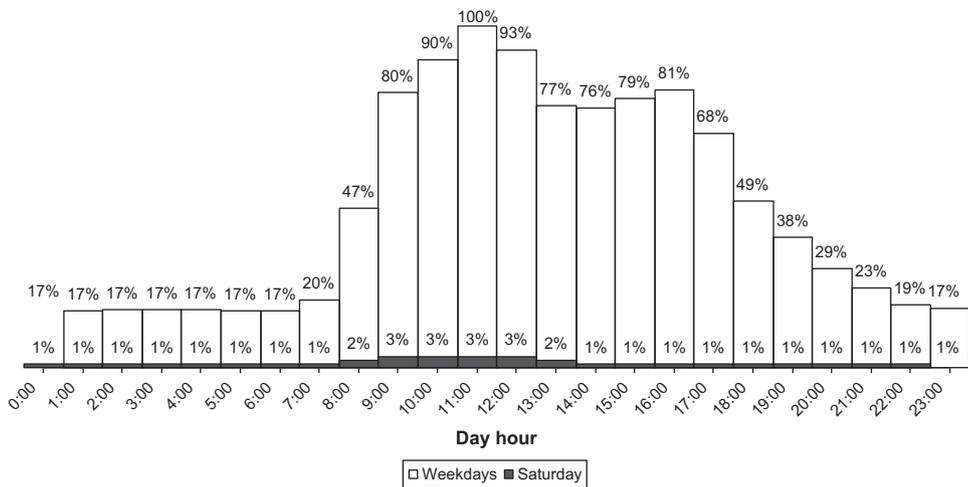
Fig. 4. Lighting and equipment diagrams for weekdays and Saturday.

- 15 m²/occupant—three occupants (240 W—sensible heat, 120 W—latent heat);
- 10 W/m² for lighting (490 W); and
- 5 W/m² for equipment (245 W).

These parameters are difficult to predict, so it must have adopted reference standards for use in buildings, such as those described in RSECE (2006).

Regarding the level of occupancy of a building, the release of sensible and latent heat inherent to each person must be taken into consideration, a value that varies according to the degree of activity.

2.3. Control of the electrochromic glass

The modulation of the electrochromic glass was achieved by the adaptation of a module designed for ESP-r and intended to simulate the use of shutters, entitled "Black Box Model" (Frontini et al. 2009).

The parameterization of the EC Glass in the "Black Box Model" consists in the creation of a file with the optical properties of the glass for a set of six possible states of coloration, including the

clear state (State 1) and full-color (Condition 6). However, in reality, the control of the state of the EC glass can be done continuously. These six states were defined with the list of properties listed in Fig. 5.

As the solar factor (g), the solar transmittance (τ_{solar}) and solar reflectivity (ρ_{solar}) of the glasses are a function of the angle of solar incidence, to prepare the text file with the optical properties of each of the states for the entire solar spectrum, it was necessary to use the equations that permit to calculate the optical properties (τ_{solar}, g, ρ_{solar}) for each solar height and solar azimuth that will be used in the text file. The formulation used (see Eqs. (1)–(4)) is based on the equations from Rosenfeld (1996), Roos et al. (2000, 2001), Kuhn (2006), and Kuhn et al. (2011), validated by Platzer (2000), Rosenfeld et al. (2000), Karlsson and Roos (2000), Roos et al. (2000), and Karlsson et al. (2001). Thus, it was possible to calculate, based on the values presented in Table 2, the values of τ_{solar}, g and ρ_{solar}, for the solar azimuth range of $[-90°, 90°]$ and solar height range of $[-90°, 90°]$, with increments of 5°.

$$g_{glass}[\alpha_{in}] = g_{glass}[0°]\left(1 - a_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\alpha_{roos}} - b_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\beta_{roos}} - c_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\gamma_{roos}}\right) \quad (1)$$
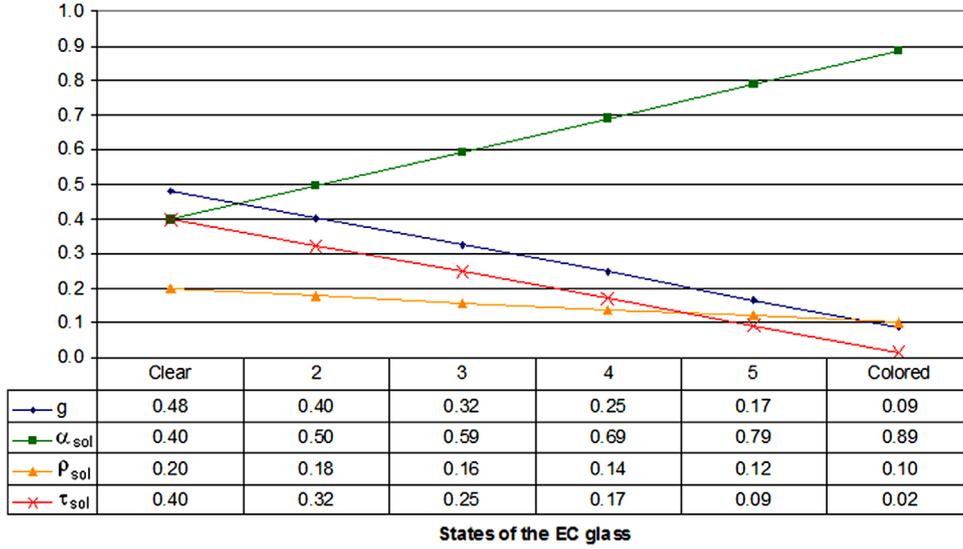
Fig. 5. Optical properties, for normal incidence, of the six states of the EC glass.

Table 2
Parameters used to calculate ($\tau_{sol,\perp}$, $g_\perp$, $\rho_{sol,\perp}$).

Parameters	Value	Notes
p_{roos}	2.00	Number of glass panes separated by an air layer
q_{roos}	1.00	Fixed parameter
a_{roos}	8.00	Fixed parameter
b_{roos}	0.25	Fixed parameter
c_{roos}	−7.25	Fixed parameter
α_{roos}	5.90	Fixed parameter
β_{roos}	2.00	Fixed parameter
γ_{roos}	6.19	Fixed parameter
$g\ (\alpha=0°)$	0.48	Variable parameter
$\tau_{sol}\ (\alpha=0°)$	0.40	Variable parameter
$\rho_{sol}\ (\alpha=0°)$	0.20	Variable parameter
$\alpha_{sol}\ (\alpha_{in}=0°)$	0.40	Fixed parameter (α_{in}: solar incidence angle)
ϕ	0.00	Orientation of the facade (0°=south, positive west)
ϕ_s	–	Variable parameter: solar azimuth angle (0°=south, west positive)
ϕ_f	–	Variable parameter: $\phi_f=\phi_s-\phi$ (façade azimuth angle, 0° parallel to facade normal)
α_s	–	Variable parameter: solar altitude angle

$$\tau_{sol,glass}[\alpha_{in}]\approx\tau_{sol,glass}[0°]\left(1-a_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\alpha_{roos}}-b_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\beta_{roos}}-c_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\gamma_{roos}}\right) \quad (2)$$

$$\rho_{sol,glass}(\alpha_{in})\approx\begin{cases}1-\tau_{sol,glass}(\alpha_{in})-\underbrace{\left[1-\rho_{sol,glass}(\alpha_{in}=0°)-\tau_{sol,glass}(\alpha_{in}=0°)\right]}_{\text{absortivity for normal incidence}\alpha(\alpha_{in}=0°)}\text{if}\alpha_{in}\le 75°\\1-\tau_{sol,glass}(\alpha_{in})-\alpha(\alpha_{in}=0°)\frac{\alpha_{in}-90°}{15°}\text{if}\alpha_{in}> 75°\end{cases}$$

$$(3)$$

$$\tau_{sol,glass}[\alpha_{in}]\approx\tau_{sol,glass}[0°]\left(1-a_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\alpha_{roos}}-b_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\beta_{roos}}-c_{roos}\left(\frac{\alpha_{in}}{90°}\right)^{\gamma_{roos}}\right) \quad (4)$$

In these equations the parameters a_{roos}, b_{roos}, c_{roos}, α_{roos}, β_{roos} and γ_{roos} correspond to constants defined by:

α_{roos}	$5.2+0.7\times q_{roos}$
β_{roos}	2
γ_{roos}	$(5.26+0.06\times p_{roos})+(0.73+0.04\times p_{roos})\times q_{roos}$
a_{roos}	8
b_{roos}	$0.25/q_{roos}$
c_{roos}	$1-a_{roos}-b_{roos}$
q_{roos}	1 (for EC glasses)
p_{roos}	2 (number of glass panes separated by an air layer)

As the determination of the sets of optical properties is a function of the orientation of the facade, it is necessary to create a file for each of the geographical orientations studied with EC (east, south and west), in a format recognized by the simulator (Frontini et al., 2009).

Each text file has the values of $\tau_{solar,\perp}$, $g_\perp$ and $\rho_{solar,\perp}$ for solar incidence range in each of the six discrete states defined for EC glass. During the simulation process, the state of the EC glass is determined according to the value of the control variable. Based on the instant height and solar azimuth, in each step of the simulation, the optical properties of the EC glass are obtained from the text file.

The current "Black Box Model" has five possible glazing control options (Frontini et al., 2009), namely by the air temperature zone, the outside air temperature, the incident radiation on an outside surface, the level of zone illuminance and the air temperature of another zone.

Following the criterion of Roos et al. (2005) an hourly time step for the dynamic simulations was adopted, which is considered adequate for typical the operation and control conditions of the EC windows. In fact, Kraft and Rottmann (2009) state that for 1 m² the transition duration from clear to colored and back to clear is about 20 min. According to the scarce data available in the literature it is foreseeable

that the alteration of the EC glasses state does not occur with a high frequency. In addition, the time constant of older buildings which require rehabilitation is usually very high, and thus, from the viewpoint of the thermal response of the building or indoor thermal conditions it is not useful to consider frequent variations of the EC glass state (Roos et al., 2005).

2.4. Simulations

Table 3 lists the 24 simulations that were performed for each window orientation (east, south and west). The simulations code corresponds to a sequential numbering. The index "e" and "w" refer to the glass on the east and west facades, respectively, and the number without index refers to the glass on the south façade. The description field complete the information about the simulation criteria, namely the considered setpoint (20/25 °C), the conditioning period (for example, 8–20 h), the EC control parameter (indoor temperature, outdoor temperature, incident solar radiation) and the transition conditions for each of the states of the EC glass. If no information is presented the parameter is not considered in the parameterization of the simulation.

The simulation exercises were conducted with the perspective to evaluate both the passive behavior and the energy performance for space heating and cooling. In accordance with the Portuguese building regulation (RSECE, 2006) for the condition of space air-conditioned, during the building occupation period an air temperature set point value of 20 °C was used for heating and of 25 °C for cooling. This criterion creates a dead band between 20/25 °C, wherein the indoor air temperature is not controlled. During the non-occupancy periods the air temperature in the zone is not controlled, thus varying consistently with the heat losses and gains of the thermal zone.

In Portugal and south European regions the south facade of buildings is the one that receives more solar radiation throughout the year. Contrary to this, the North facades only receive diffuse radiation during wintertime and during the cooling period they receive direct solar radiation during a short period at the early morning and late afternoon. Therefore, the North facades were not considered for the study with EC glasses, because their control certainly does not result in significant energy savings. The east and west facades although they receive low solar radiation during the heating season, by the fact that during the cooling season the sun presents an apparent path close to perpendicular of the east (during the morning) and west (during the afternoon) facades, the solar radiation incidence in this facades is intense and therefore these oriented spaces present overheating problems. Therefore, the east, south and west orientations were considered for the study.

In the situation of double glazing with improved physical properties it has the following characteristics $U = 1.50$ W/(m² K) and for an angle of incidence of 0°, $g_{\perp} = 0.46$; $\rho_{sol,\perp} = 0.12$; $\tau_{sol,\perp} = 0.38$; $\alpha_{sol,\perp} = 0.50$. We have two double glazings (PLANITHERM—outdoor/PLANI-LUX—interior) with 4 mm each and a box with 12 mm air filled with air (6%) and argon. The properties of this glass were calculated using the program that calculates the optical properties of glasses known as "WINDOW 5.2a v5.2.17a". The results of the properties obtained with "WINDOW" were introduced in the ESP-r database so they can be used. The results of "WINDOW" are imported directly to the ESP-r without any additional treatment.

Some of the works based in simulation (for example, Karlsson (2001)) present results only for the cooling season, assuming that during the heating season the glass is always in the clear state, not contributing to the increased need for heating energy. Nevertheless, the study developed here was based on a seasonal and annual base, assuming the year divided into heating and cooling seasons.

The weather file from Coimbra was used for the simulations. Coimbra is a city in the center of Portugal mainland at latitude of 40.210° N, longitude of 8.430° W and elevation above sea level of 140 m. Table 4 presents monthly statistical meteorological data for Coimbra extracted from the weather file used for the building energy simulations.

3. Results and discussion

The single glass solution is the current status of the majority of service buildings constructed in the middle of the last century, corresponding to the principal building stock candidate to be subject to rehabilitation during the next decade in Portugal and in many

Table 3
Simulations identification and description.

Simulation	Description
1e/1/1w	Interior temperature of the test cell; 25/24/23/22/21/1 (°C)
2e/2/2w	Incident radiation on the test cell glass; 100/80/60/40/20/–10 (W/m²)
3e/3/3w	20/25 °C; 8–20 h; interior temperature of the test cell; 25/24/23/22/21/1 (°C)
4e/4/4w	20/25 °C; 8–20 h; incident radiation on the test cell glass; 100/80/60/40/20/–10 (W/m²)
5e/5/5w	The same as simulation 1, the EC glass always in the clear state
6e/6/6w	The same as simulation 1, the EC glass always in the colored state
7e/7/7w	The same as simulation 3, the EC glass always in the clear state
8e/8/8w	The same as simulation 4, the EC glass always in the clear state
9e/9/9w	The same as simulation 4, the EC glass always in the colored state
10e/10/10w	The same as simulation 4, 250/200/150/100/20/–10 (W/m²)
11e/11/11w	20/25 °C; 8–20 h; outside temperature; 27/26/25/24/23/1 (°C)
12e/12/12w	The same as simulation 1, with glass on the entire facade (east/south/west)
13e/13/13w	The same as simulation 3, with glass on the entire facade (east/south/west)
14e/14/14w	The same as simulation 4, with glass on the entire facade (east/south/west)
15e/15/15w	The same as simulation 3, the EC glass always in the colored state
16e/16/16w	20/25 °C; 8–20 h; incident radiation on the test cell glass; 250/200/150/100/20/–10 (W/m²)
17e/17/17w	The same as simulation 16, with glass on the entire facade (east/south/west)
18	The same as simulation 2, with infiltrations air rate of 0.3 h⁻¹
19	The same as simulation 4, with infiltrations air rate of 0.3 h⁻¹
21e/21/21w	The same as simulation 3, the double glazing has improved physical properties
22e/22/22w	The same as simulation 4, the double glazing has improved physical properties
23	The same as simulation 21, the EC glass is always in the clear state
24	The same as simulation 22, the EC glass is always in the clear state
25	The same as simulation 1, the double glazing has improved properties

Table 4
Monthly statistical meteorological data for Coimbra.

	January	February	March	April	May	June	July	August	September	October	November	December
Monthly mean dry bulb temperature (°C)	9.6	11.0	12.7	13.1	15.6	19.0	20.8	21.1	20.6	16.9	12.2	11.2
Daily monthly mean dry bulb temperature range (°C)	7.1	7.4	9.4	9.3	9.6	10.4	11.6	11.9	11.1	8.6	6.9	6.0
Heating degree days, base 18.3 °C (°C/day)	259	206	162	136	77	18	2	2	11	63	146	216
Daily monthly mean horizontal global solar radiation (Wh/m²)	2093	2606	4084	5330	5802	6687	6819	6273	4787	3328	2043	1679
Daily monthly mean horizontal diffuse solar radiation (Wh/m²)	902	1474	1936	2298	2833	2866	2356	2120	1981	1482	1217	959

Mediterranean cities. Therefore, the single glass was considered the reference solution for the results presentation and discussion.

The analysis of energy performance is based on the differences to the reference case (single glass) of the energy needs for heating, cooling and annual (heating+cooling). It was determined that the positive variations correspond to an increase in the energy needs and a negative variation corresponds to energy reductions.

The results for the heating and cooling needs considering glazing areas of 5.4 m² and 25.84 m² (simulations 12e/12/12w, 13e/13/13w, 14e/14/14w and 17e/17/17w) are presented in Tables 5 and 6. In Table 5 it is considered that the useful floor area is 49 m². The glazing area of 5.4 m² corresponds to a WWR (Window to Wall Ratio) of 19.3% and a WFR (Window to Floor Ratio) of 11%. The glazing area of 25.84 m² corresponds to a WWR of 92.3% and a WFR of 52.7%.

The results of Table 5 show that, regardless of geographic orientation of the glazed area, space heating needs are higher than the energy requirements for cooling. Moreover, the higher overall energy needs are obtained when the glazing is located on the west facade and the lower result observed for the south facade. The increase of the south glazing area results in a decrease of the specific energy needs for heating and an increase of energy needs for cooling. For east and west facades both heating and cooling needs increase with the increasing of glazing area.

The problem related with the control of solar heat gains in the east and west facades, particularly to avoid excessive direct gains during the cooling season, is underlined by the higher cooling needs of these when compared with the south facade.

With 25.84 m² glazed area at south the annual energy needs for heating with single glass are reduced and the energy needs for cooling increases. The results in terms of energy needs are also reflected in the number of hours needed for heating or cooling. For the case of west glazing facade both the energy requirements and the number of hours for heating and cooling increase.

For the east orientation, the energy requirements for heating and cooling increase with the increasing of glass area. One fact to be noted to this particular orientation is the decrease of the number of hours for heating when the glass area increases. Although this decrease can be considered marginal it may be explained by the higher solar heat gains. However, if the glass area will be larger, higher thermal losses will occur, requiring higher thermal power (and energy) to achieve comfort conditions at the beginning of the building occupancy.

As noted by the analysis of the above results, the test cell energy requirements for cooling and heating with the window south-facing are lower than when it is on the east or west facades, with the worst results observed for the west facade. These results confirm and quantify the more difficulty to control the direct solar gains in these orientations.

Table 7 presents the results obtained when considering a lower air infiltration rate of 0.3 h^{-1}, tested for the south facade and for a glazing area of 5.4 m².

Table 5
Energy needs for the base situation with single glass (kWh/m² yr).

Area →	5.40 m²			25.84 m²		
Orientation → Energy for ↓	East	South	West	East	South	West
Heating	43.59	39.02	44.66	48.37	34.24	53.06
Cooling	22.85	22.16	24.50	30.21	29.33	37.63
Annual	66.45	61.18	69.17	78.58	63.58	90.68

Table 6
Single glass results (h/yr).

Window orientation	East		South		West	
Window area (m²)	Heating	Cooling	Heating	Cooling	Heating	Cooling
5.4	2120	1469	2095	1452	2144	1477
25.84	2072	1511	1837	1572	2168	1551

Table 7
Results of simulation 19 for the base situation with single glass (5.4 m²).

Heating – kWh/m².year (hours/year)	Cooling – kWh/m².year (hours/year)
31.61 (1904)	24.89 (1583)

3.1. East facing glazing

The results of energy needs for the double (DGU) and EC glass, relatively to the reference single glass (SG) solution, are presented in Figs. 6 and 7 for the east facade.

From the presented results it is possible to conclude:

(1) The DGU and EC glass always results in improvements of the energy needs, with better results for the EC glazing. For the heating season the results with DGU glass is always better than the solution considering EC glass, presenting both solutions better energy consumptions results than the reference single glass. For the cooling season the EC glass solution is always better than the other two glass technologies. DGU glazing always has lower performance results for the cooling season, except when the solar factor of the double glazing (improved double glass) is similar to the real EC glass.

(2) Simulation results 21e and 22e in Fig. 6 show that DGU with a solar factor similar to the EC SAGE™ glass in the transparent (clear) state performs worse than EC.
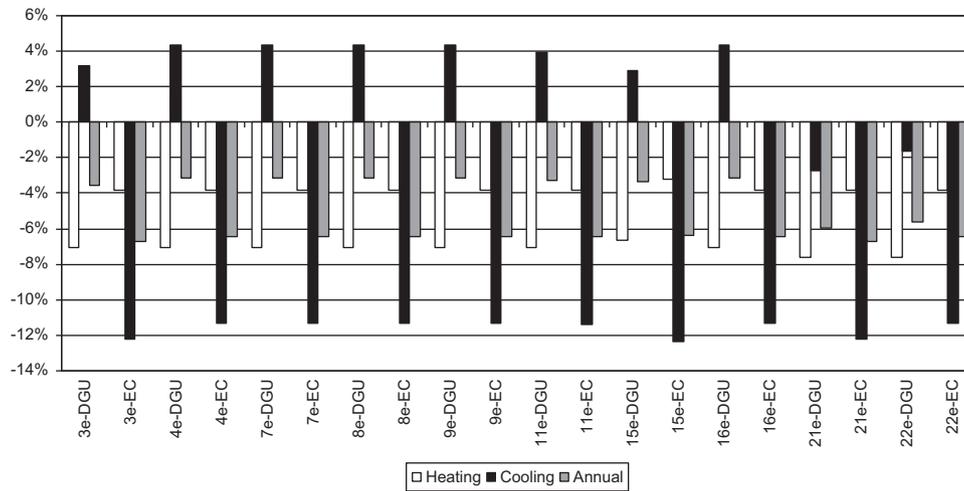
Fig. 6. Differences of the energy needs for heating, cooling and annual by the use of DGU and EC glass, 5.4 m² glass area in east facade (SG as reference solution).
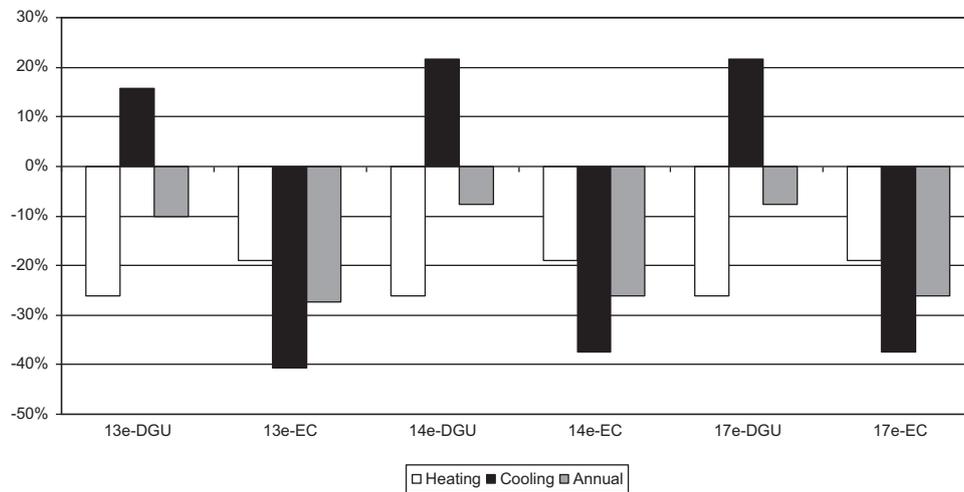
Fig. 7. Differences of the energy needs for heating, cooling and annual by the use of DGU and EC glass, 25.84 m² glass area in the east façade (SG as reference solution).
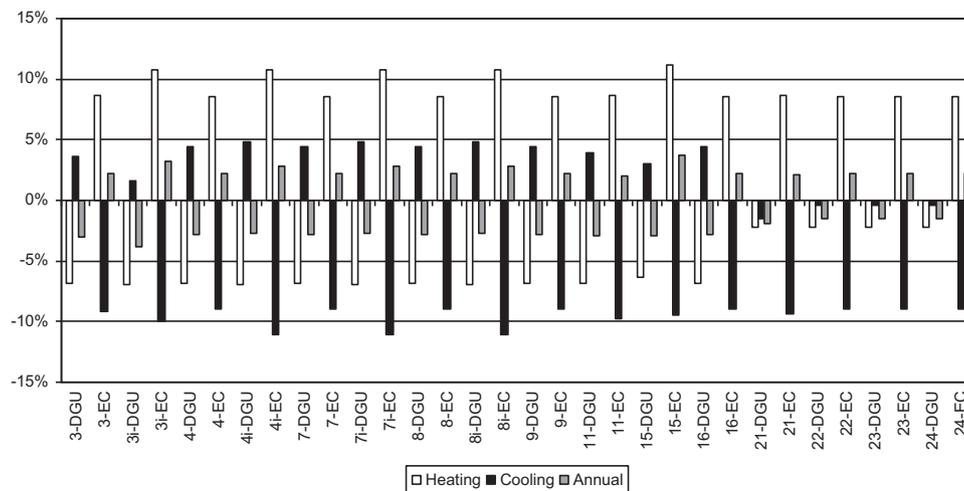
Fig. 8. Differences of the energy needs for heating, cooling and annual by the use of DGU and EC glass, 5.4 m² glass area in south façade (SG as reference solution).

3.2. South facing glazing

Figs. 8 and 9 and Table 8 show the comparative results of the simulations, based on the situation described in Tables 5 and 7,

when the glass is placed on the south facade. By analyzing these results one may conclude:

(1) For the glass area of 5.4 m², regardless of the electrochromic glass control, the annual results of overall electrochromic glass
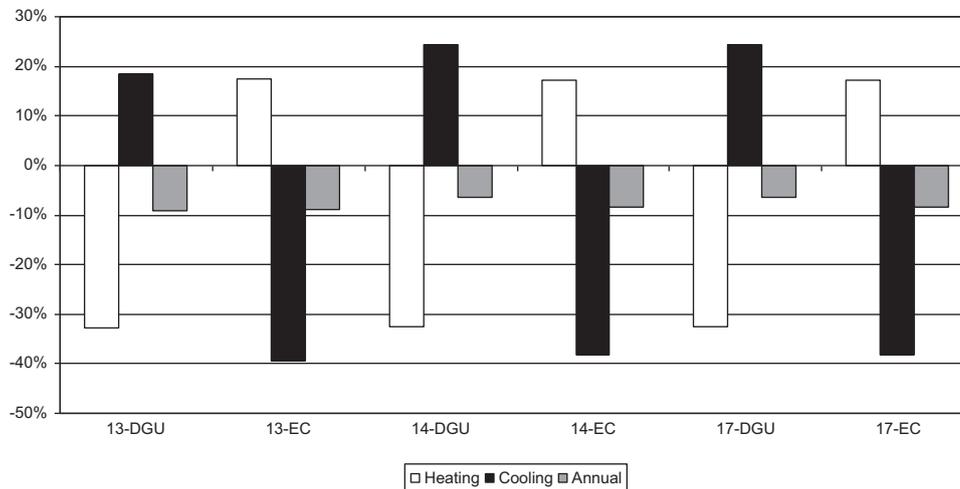
Fig. 9. Differences of the energy needs for heating, cooling and annual by the use of DGU and EC glass, 25.84 m² glass area in south façade (SG as reference solution).

Table 8
Differences in the energy needs of simulation 19 (%).

	Heating	Cooling	Annual
Simulation 19			
Double glass	−8	5	−2
EC double glass	10	−7	2

always has lower performance than for the single or double conventional glass. However, the results with double glass are better than with single glass. Considering only the annual energy need for heating, double glazing has a better performance and EC glazing a lower performance. Considering only the cooling needs, the electrochromic glazing presents energy improvements when compared with the single and double current glass.

(2) For window area of 25.84 m², the annual results (heating+cooling) of overall electrochromic windows are always better than for the single glass. When compared to the double glazing the results are dependent of the control type (see Fig. 8). Focusing on the annual heating needs, double glazing shows a significant improvement as regards to the base case while electrochromic glazing has slightly lower performance. Considering the cooling needs electrochromic glazing shows a significant improvement as regards to the base case while double glazing has slightly lower performance.

(3) If the air infiltration rates decrease the overall results are similar to those referred in comment (1) above. The annual energy needs for heating will reduce with double glass (−7%) and increase with the solution of EC glass (+13%). However, considering only the cooling needs the EC glass solution presents better results (−8%) than the double glass (+4%). By reducing the rate of infiltration of outside air to $0.3\,h^{-1}$, the conclusions remain the same in relation to the initial situation ($0.6\,h^{-1}$). As such, it can be said that the high uncertainty that exists regarding the rate of air infiltration in buildings does not have effect on the general conclusions of the energy savings achieved by the use of EC glass in the test cell.

(4) If the solar factor of the double glazing would be equal to the solar factor of EC glazing in clear state, the double glazing improves the overall energy performance over single glazing and the EC glass solution is less efficient than the single and double glazing. The double glass has positive energy performance influence in both seasons, while the use of EC glass presents the reduction of energy for cooling, however with an increase of the energy for heating.

3.3. West facing glazing

Figs. 10 and 11 present the results of comparison with the base solution (Table 5), considering the glazing on the west facade. By analyzing these results one may conclude:

(1) When the window is located in the west facade the EC glass always contributes to improve the room energy performance and is more effective than the current double glazing. Also, EC glass was shown to be more useful in the west facade than in the east facade (compare with Figs. 6 and 7). When considering only the east and west facades, for the configuration with larger window area the savings on annual energy needs (heating plus cooling) are more than three times higher (≈100 kWh/yr→≈350 kWh/yr), when considering the replacement of single glass with double glass, and about five times higher (≈200/300 kWh/yr→≈1000/1500 kWh/yr) when admitting the application of EC glass.

(2) The EC glass always has higher influence in the energy performance improvement compared to the option of double glazing. It is also observed that the positive energy performance influence is higher in the west orientation than in the east orientation.

(3) Both current DGU and EC glazing show energy advantages for the heating season when compared to the single glazing solution. When the lower glass area is considered the energy savings are higher for the current DGU glass solution (see Fig. 10). For the larger glass area the energy savings for heating with EC glass are higher than with the DGU glass solution. During the cooling season the EC glass reduces the energy needs for cooling and the double glass increases the need of energy for cooling with the exception of the use of double glazing with improved physical properties (21w and 22w).

The results show that to a larger glazing area in east and west facades (about five times), the reductions in annual energy requirements (heating plus cooling) is about 66% when considering double glazing, and about 80% when it is used EC glass.

A comparative analysis of results obtained with three different ways of controlling the EC glass (indoor air temperature of the test cell, outdoor air ambient temperature and incident solar radiation on the EC glass) concluded that the control by the outside temperature and the inside temperature of the cell test, have less effective results (simulations 3e/3/3w and 11e/11/11w) than when considering the incident solar radiation (simulations 4e/4/4w).
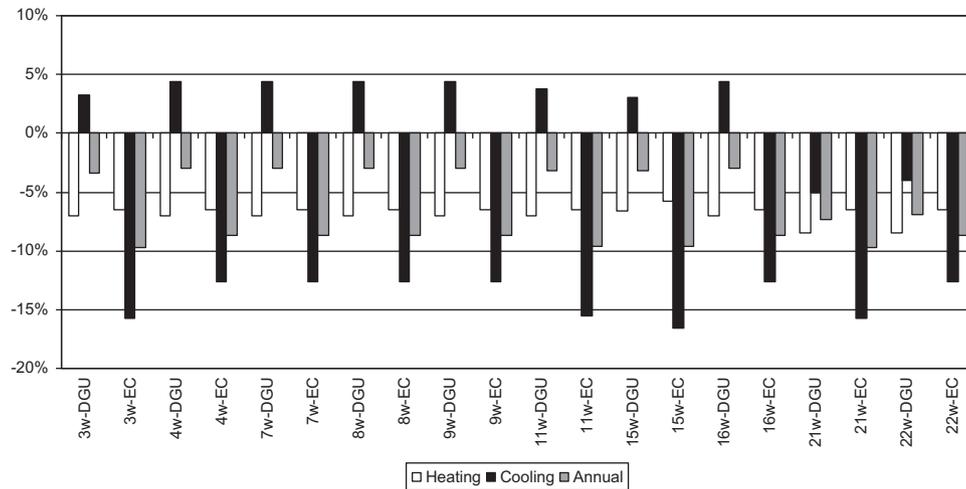
Fig. 10. Differences of the energy needs for heating, cooling and annual by the use of DGU and EC glass, 5.4 m² glass area in west façade (SG as reference solution).
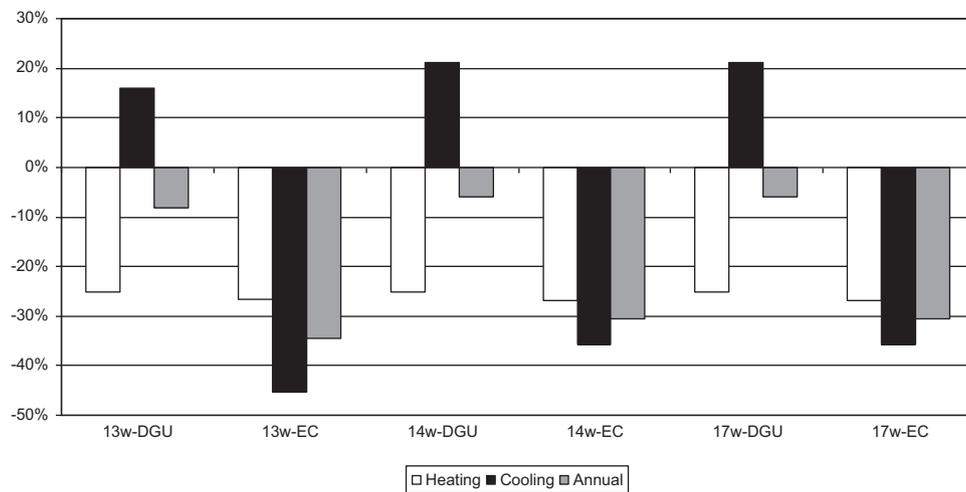
Fig. 11. Differences of the energy needs for heating, cooling and annual by the use of DGU and EC glass, 25.84 m² glass area in west façade (SG as reference solution).

For all orientations, in the heating season EC glasses should be almost always in the transparent state, and effective control being achieved for the intermediate and cooling seasons.

Table 9 shows the obtained peak load for heating and cooling for simulations 3e/3/3w and 4e/4/4w. Independently of the glazing type the peak load for heating occurs at beginning of January, 11th. For all situations the peak load for cooling occurs during August, 12th at different hours, as can be seen in Fig. 12. The results show slightly lower values of the maximum heating and cooling load when the EC glass is considered.

Fig. 12 shows that regardless of the orientation of the facade where the glass is admitted the values of the maximum cooling power for the situation of single and double-glazing are close (differences less than 1%).

Evaluating the results with the use of EC glass, it may also be concluded that the values of maximum cooling are almost independent of the control variable. The differences are between 2% and 5%. The lowest value of the maximum cooling load corresponds to control the EC glass according to the inside temperature of the test cells.

When comparing the use of EC glass with single glass, the reduction on the maximum cooling power is 15% for the east facade, 9% for the south facade and 16% for the west facade.

Regarding the use of single glass, the maximum cooling load with the use of double glazing in the east orientation is

anticipated. This phenomenon is due to the lower energy losses by the double glazing due to the lower U-value (2.80 W/m² K for double glass and 5.79 W/m² K for the single glass). The action(s) of the EC glass in the reduction of the space solar gains, results in a delay in the maximum cooling demand. Regarding the use of single or double glass, in the west facade the occurrence of maximum cooling load is advanced when using EC glass. In the south facade the time of maximum cooling load occurrence is independent of the glass type.

The maximum cooling demand for double glass solution in the east facade occurs within one hour earlier than the situation of single glass, a phenomenon related with the difference of glass U-values. The higher U-value of the single glass promotes higher energy losses from the interior space to the exterior than with the double glazing during the morning hours, when the outdoor air temperature is below the reference space temperature of 25 °C (see Fig. 13). The higher losses by single glass delay and reduce the heat accumulation within the building thermal mass, also contributing to the delay and reduction of the space thermal load.

3.4. Simplified economic analysis

The nonexistence of large-scale EC production and thus a competitive market result in actual high cost of the EC glass technology. For example, the cost of commercially available products from SAGE™ and

Gesimat is around 1000 €/m². However, important cost depreciation could happen with the maturation of the technology and the production process, and market demand for use in new and rehabilitated buildings. In this context and for the purpose of conducting an economic study a simplified analysis is developed with the perspective to determine the costs that will make the technology viable.

Considering that the EC glass has "memory effect", i.e., it is only necessary to provide energy to stimulate a transition from one sate to another and not to maintain the state, and that the energy required to this stimulus is negligible, the supply electrical energy is ignored in this analysis.

Investment decisions on technology replacements depend strongly on the discount rate assumed by each decision maker, which translates directly into the time span for full investment recovery. In order to facilitate the assessment of the EC option, admissible extra cost values of the EC option as compared to DGU were calculated for various time periods. Considering only the building energy operational cost and assuming an unitary coefficient of performance (COP) for heating and an energy efficiency ratio (ERR) of 2 for cooling, Table 10 presents the exercise for EC glass in east façade and Table 11 for EC glass in the west façade, considering in both cases a window area of 5.4 m².

Additional to this operational cost analysis, other savings components could be discussed in a more detailed analysis. Namely, the reduction of the installed HVAC system capacity, there is no need for additional blinds, increase thermal and visual comfort (no glare), increased productivity, possible energy savings in the artificial lighting system, decrease the installed electrical power of the building and maximum power demand to the electrical grid (Sanders and Podbelski, 2009, 2010; Sanders, 2010).

The cooling energy savings will be higher in buildings in warmer climates than the Portuguese case. It is likely that the achieved energy savings can contribute to mitigate the high cost of current commercially available EC glass (1000 €/m²), and thus contributing to increased the use on a large scale, and consequently to reduce the production cost.

Several authors reported results of annual energy savings above 100 kWh/m²_glass.year by the use of EC glass. For example, admitting a solar radiation incidence on a south oriented window of 1000 kWh/m² yr, Granqvist (2001), Azens and Granqvist (2003), Azens et al. (2005), Niklasson and Granqvist (2007), Granqvist (2007) and Granqvist (2008) reported annual savings of 170 kWh/m²_glass.year. Syrrakou et al. (2005) refer typical values for energy savings by the use of EC glass in the order of 120–340 kWh/m²_glass.year. Karlsson (2001) analyzed three different climates (Stockholm, Sweden, Denver and Miami, USA) and obtained annual energy savings between 0 and 150 kWh/m²_glass.year, and indicates an average value for annual energy savings of 100 kWh/m²_glass.year. From the present study the operational energy savings are in the range 20–37 kWh/m²_glass.year (see Tables 9 and 10), showing less favorable results for the use of EC windows.

Although several studies (Karlsson, 2001; Lee et al., 2004; Jonsson and Roos, 2010a, 2010b) show the feasibility of using EC windows also on the south facade, the present results show that the use of EC glass is only interesting on the east and west facades. A justification for the results differences between this study and the findings of the major studies in the literature is related to the physical characteristics of the EC glasses considered. While in the present work it was adopted the physical characteristics of a

Table 9
Maximum heating and cooling power for simulations 3e/3/3w e 4e/4/4w.

		Heating		Cooling	
		(kW)	11th January	(kW)	12th August
East					
3e					
	Single	3.12	10 h30 min	2.54	11 h30 min
	Double	3.01	10 h30 min	2.53	10 h30 min
	EC	2.97	10 h30 min	2.16	12 h30 min
4e					
	Single	3.12	10 h30 min	2.58	11 h30 min
	Double	3.00	10 h30 min	2.59	10 h30 min
	EC	2.97	10 h30 min	2.22	12 h30 min
South					
3					
	Single	3.10	10 h30 min	2.47	13 h30 min
	Double	3.00	10 h30 min	2.44	13 h30 min
	EC	3.02	10 h30 min	2.24	13 h30 min
4					
	Single	3.10	10 h30 min	2.50	13 h30 min
	Double	3.00	10 h30 min	2.48	13 h30 min
	EC	3.02	10 h30 min	2.28	10 h30 min
West					
3w					
	Single	3.13	10 h30 min	2.62	16 h30 min
	Double	3.01	10 h30 min	2.59	16 h30 min
	EC	2.96	10 h30 min	2.18	15 h30 min
	Single	3.13	10 h30 min	2.66	16 h30 min
	Double	3.01	10 h30 min	2.63	16 h30 min
	EC	2.96	10 h30 min	2.28	15 h30 min

Fig. 12. Maximum cooling power for simulations 3e, 4e, 3, 4, 3w e 4w.
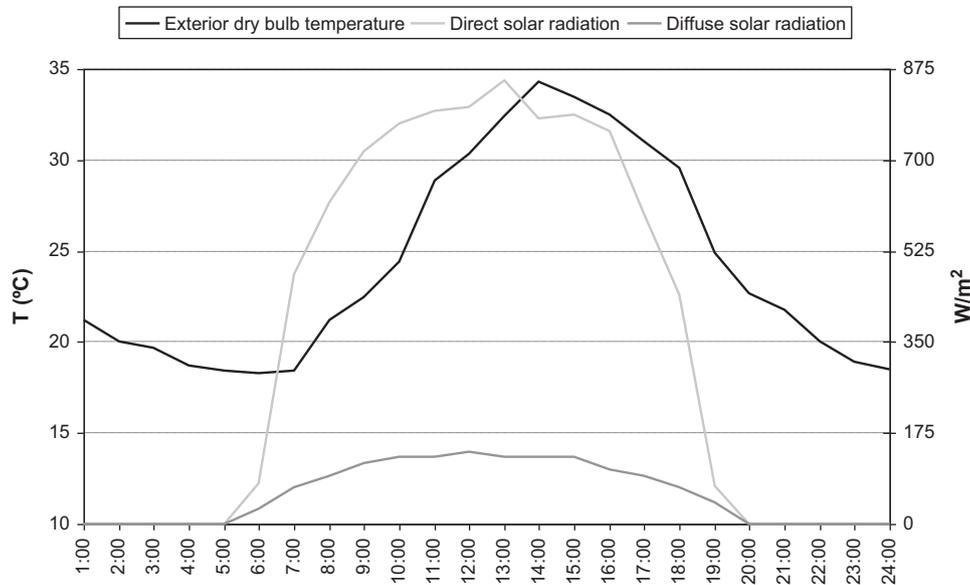
Fig. 13. Outdoor air temperature, direct solar radiation and diffuse solar radiation, August 12th (Coimbra).

Table 10
Simplified economic analysis: Admissible extra cost values for several time periods; EC glass in east facade.

Energy for heating saved by the use of EC glass		39	kWh
Energy for cooling saved by the use of EC glass		71	kWh
Annual energy saved by the use of EC glass		110	kWh
EC glass area		5.4	m^2
Annual energy saved per unit area		20.28	kWh/m^2 EC glass yr
kWh price		0.14€	
(excluding taxes and power rate)			
Maximum permissible costs (€/m^2) to amortize the investment in EC windows in:	1 year	2.84€	
	5 years	14.19€	
	10 years	28.39€	
	15 years	42.58€	
	20 years	56.78€	

Table 11
Simplified economic analysis: Admissible extra cost values for several time periods; EC glass in west facade.

Energy for heating saved by the use of EC glass		98	kWh
Energy for cooling saved by the use of EC glass		102	kWh
Annual energy saved by the use of EC glass		200	kWh
EC glass area		5.4	m^2
Annual energy saved per unit area		36.94	kWh/m^2 EC glass yr
kWh price		0.14€	
(excluding taxes and power rate)			
Maximum permissible costs (€/m^2) to amortize the investment in EC windows in:	1 year	5.17€	
	5 years	25.86€	
	10 years	51.72€	
	15 years	77.58€	
	20 years	103.44€	

commercially available EC glass, the other studies usually admitted EC glass prototypes with better physical characteristics not yet commercially available. Also, the studies only calculate the savings for the cooling season, omitting the possible negative effect of the EC glass in the heating season.

4. Conclusions

In this work, the comparison between three glazing options (single glass, conventional double glazing and electrochromic glazing) is performed. Through building energy simulation with

the ESP-r program the energy needs for heating and cooling are evaluated. The energy savings, regarding the situation of using single glass (baseline), were calculated by difference of the energy requirements for heating, cooling and annual.

The results show advantages of glasses with controllable properties (EC windows) on east and west facades. The best results of the application of EC glass from the energy performance perspective are obtained for the western facade, with a reduction of the annual energy needs of about 62% higher than for the east facade. For south facades the use of conventional double glazing shows better results in the annual building energy needs and, therefore, the application of EC glass presents no advantage.

The results also clearly show the advantage of EC glass for the cooling season and suggest that the EC glass may not be useful for the heating season. As the results are mainly valid for the latitude used and Mediterranean climate, specific simulations must be performed using the applicable climate files in order to corroborate or distinguish the conclusion of this work for other climates. Particularly, careful analysis must be taken into account for climates where the energy needs for heating are dominant.

Considering the obtained energy savings of 20.28 and 36.94 kWh/m^2_glass.year for windows in the east/west facades, and a simple payback of 10 years (the usual manufacturers warranty period), the economical attractiveness is achieved if the extra cost is less than 28.39/51.72 €/m^2 glass. Nevertheless, investment decisions should be informed by additional considerations on other types of benefits of the use of EC glass.

It is concluded that the EC glasses are an energy-efficient solution for use in buildings. Nevertheless, the adoption of this technology in rehabilitation strategies of building fenestration should taking into account each facade orientation, giving priority to east and west facades, where the control of solar gains are more difficult. Nevertheless, the present results clearly show that the application of this type of glazing in the rehabilitation of buildings should always be preceded by careful study.

The use of building energy simulation tools that can be adapted to accommodate these types of technological solutions with dynamic properties (e.g. EC glass) are of high importance to help building designers to forecast the influence of such new technological elements for building construction, both in the design phase of new or rehabilitated buildings. In fact, there are nowadays several building energy simulation tools that permit the energy performance comparison of different technological solutions with confidence. Therefore, it is high recommended that the policy makers will require the use of this kind of tools in the national building regulations context.

Acknowledgments

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