The energetic characterization of solar-control environments

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Highlights

The energy consumption associated with maintaining thermal comfort in buildings remains a significant and partially unjustified share, accounting for 30-40% of total energy consumption. The windowed components, often with thermal insulation performances even higher than the minimum requirements, still lack design and characterization in terms of the incident solar radiation control, a particularly delicate topic for achieving indoor wellness conditions and more generally for a higher energy efficiency in buildings.

Abstract

Despite the increasingly pressing regulations in the energy sector (EPBD recast, law 90/2013 and the consequent decree 162 of 2015), which push towards policies and financial measures to promote buildings with almost zero energy, the quality of the internal environment remains one of the critical parameters on which to pay more attention in view of a consistent evaluation of the NZEB building. The authors show, in the present paper, the results related to the energetic characterization of two test rooms, identical for surface and opaque envelope, but with different typologies of windows on the South-East and South-West wall.

Keywords

Electrochromic glazing, Internal comfort, Dynamic simulation

1. INTRODUCTION

Energy consumption by both residential and commercial buildings in developed countries account for 20–40% of total energy used [1]. Approximately 60% of all used energy in building sector is consumed for space heating and cooling (residential), lighting and ventilation (mainly commercial buildings). Windows are often one of the most energy inefficient components of buildings, for about 20–40% energy loss [2]. The most significant parameters influencing the heat transfer through windows include outdoor conditions, shading, building orientation, type and area of window, glass properties and glazing characteristics [3]. Though thermal insulation of windows is already well addressed in products widely available on the market [4], the control of
incident solar radiation, in order to optimize incoming thermal and lighting flows, is still particularly delicate and a key element for the achievement of internal comfort and more generally of greater energy efficiency in buildings. An ideal window should be able to transmit enough visible light, and to control transmitted Infrared radiation (IR) in the meantime [5]. Five main approaches can be hypothesized for this purpose: 1) to realize highly insulating windows (U-value < 0.35 W/m²K); 2) to reduce Solar Heat Gain (SHG) but admit daylight; 3) to use dynamic glazing (with variable transmittance); 4) to realize daylight/sunlight redirecting systems; 5) to integrate and to optimize lighting and HVAC via smart, integrated façades, with the use of low-U, low-E plus switchable SHG glazing [6]. The last one is by far the most ambitious approach, aspiring to obtain a new generation of advanced transparent closures, able to fully adapt to the environmental conditions in a dynamic way, ensuring, in full synergy with the systems and equipment, an efficient continuous and automatic management of all matter and energy flows in accordance to climate, user behaviour, and market conditions of energy. The authors in this paper present the results related to the energy characterization of two test rooms, identical in surface and type of envelope, but with different glazed elements on the SOUTH-EAST and SOUTH-WEST wall: one with traditional frames with high thermal performance, the other but with different glazed elements on the SOUTH-EAST and SOUTH-WEST wall: one with traditional frames with high thermal performance, the other with low emissivity electrochromic glass appropriately controlled remotely. Both test chambers have been instrumented to measure the main thermo-hygrometric and climatic parameters necessary in order to verify the real comfort conditions and to estimate the energy requirements associated with the use of electrochromic glazing.

2. STATE OF THE ART

Neglecting the mechanical shading systems (manual or automated), widely dealt with in the scientific literature [7,8], the possibilities to associate energy saving, lighting control and users comfort are inevitably entrusted to dynamic systems (switchable) integrated into the glass (SPD, LCD, thermochromic, EC, etc.), able to save up to 60% of the needs of artificial lighting, to reduce the cooling load up to 20% [9,10], with a good users’ acceptance of this technology mainly because of the reduction of glare, reflections and discomfort near the windows [11]. The switchable devices are categorized into passive and active systems. In passive devices, the switching process is activated automatically in accordance with the environmental conditions (e.g. light in case of photochromic windows, or temperature and heat in thermochromic windows). Alternatively, the active systems require an external triggering mechanism.
to perform the modulation (e.g. electricity in electrochromic windows). The active switchable glazing systems offer supplementary options compared to the passive systems whereas their dependency on power supply and wiring should be reckoned with as a drawback [2]. The most common active-controlled intelligent windows use suspended particle windows, liquid crystals and chromic materials. A Suspended Particle Device (SPD) consists of a polymer layer, containing a large number of light absorbing and polarizable particles (less than 200 nm in size), between two sheets of glass or plastic coated with transparent and electrically conducting thin films facing the polymer layer. Applying a sufficient electric voltage to the polymer layer, via the transparent conducting films, makes the particles align and become parallel to the electric field thereby yielding a higher transmittance. In the “off” state, when no voltage is applied, the particles are randomly dispersed and therefore absorb light and create a dark appearance; conversely, in the “on” state the particles align and the character of the glass changes from dark to clear. Nowadays, energy efficiency and lifetime not yet proven. Liquid Crystal Windows are switchable glass panes with a liquid crystal layer changing light transmission properties in order to control light and heat intake. The use of switchable dyes, hosted in liquid crystals, allow more or less radiation to permeate, depending on their alignment, making the window appear darker or brighter. Nowadays, mainly used for privacy control, but not yet recognized as an energy savings device or proven to have wide-angle, low glare properties. Chromic materials are classified into four types: gasochromic, photochromic, thermochromic (TC) and electrochromic (EC). In gasochromic devices a hydrogen gas (H2) is applied to switch a thin layer of tungsten oxide (WO3), covered by a very thin layer of platinum between colored and bleached states. This process can be reversed by introducing diluted oxygen. The hydrogen and oxygen are produced by an electrolyser. These are generally cheaper and simpler devices than the other chromic ones, not requiring the ion conductor and storage layers. Although, gasochromic devices exhibit some merits such as better transmittance modulation, lower required voltage, staying lucid in the swap period, and adjustability of any middle state between transparent and entirely opaque; only a few numbers of EC materials can be darkened by hydrogen. Furthermore, strict control of the gas exchange process is another issue. The best transmittance values obtained for a coated double-glazed unit, with a moderate film thickness, and hydrogen concentrations below the combustion limit are 76% and 77% for solar and visual transmittance, respectively, in the bleached state and 5% and 6% for solar and visual transmittance, respectively, in the coloured state. Darker states can be obtained by applying thicker films associated all'isolamento termico, a miglioramento energetico.
of tungsten oxide without reducing the transmittance in the bleached state [12].

Photochromic materials change their transparency in response to light intensity. They found success in eyeglass that change from clear in the dim indoor light to dark in the bright outdoors. Since photochromic materials are responsive to light intensity, but remain unchanged with temperature changes, windows made from these materials darken when exposed to light irrespective of the temperature level outside. The promising approach is the development of hybrid systems that integrate some type of active smart windows technology with photochromic materials to address the problem of automatic darkening during cold, sunny days [13]. Thermochromic (TC) materials change color in response to temperature variations. The TC interlayer thin film (within 0.3-1 mm) is extruded through the draw plate onto unadhereable underlying material or directly on the glass. As the temperature becomes higher than the transition point, the TC material changes its nature from monoclinic (behave as semiconductors, less reflective especially in near-IR radiation) to rutile state, behaving like a semi-metal and reflecting a wide range of solar radiation. Most of heat gain in solar spectrum takes place at NIR range (800–1200 nm), therefore the more direct and intense the sunlight is on the glass the darker it will become. When the polymeric interlayer is doped with complexes of transition metals (Fe, Cu, Cr, Co etc.), a reversible change of light transmission (LT) and/ or colour occurs. Since the emissivity of the coatings are high in both monoclinic and rutile states, this technology does not work well in cooler climates currently [2]. The central part of an electrochromic device is a five layers coating applied to the glass pane: an electron accumulation layer, an ion conductor layer (usually LiAlF4), an electrode layer (usually tungsten trioxide WO3), and two outer layers made of transparent conductive oxides. When voltage is applied, Li+ ions pass from the accumulation layer to the electrode determining a change in color from transparent (SHG and LT about 0.49 and 69%) to dark (SHG and LT about 0.09 and 1%) in the electrode layer (cathodic coloration), or in the accumulation layer (anodic coloration) or in both according to the electrochromic materials employed. The process is reversible by turning off the electrical stimulus that triggers the return of ions from the electrode to the accumulation layer. Energy required to switch between the different control states is not greater than 3 Wp/m² and even less (<0.4 W/m²) is the one needed to maintain a desired tinted state (energy is required only for transition) [5]. About, EC windows require less energy for lighting than TC ones and both demand the lowest cooling energy, if compared to clear, tinted or reflective glass [13]. However, the necessity of...
wiring in EC glazing and the better ability of TC windows to maintain the visible transmission (when doped properly), besides their simple structure, make TC windows economically more competitive.

In [11, 14] energy use variations caused by the use of EC glass were calculated as differences of energy requirements for heating, cooling and annual energy needs against the reference case situation of using single glass. Considering EC lower solar factor in the clear state (0.48) and in the colored state (0.09), when compared to conventional double glazing (0.75), the higher the cooling loads, the greater are the savings caused by their use. The orientation of glass is also very important in energy evaluation, highlighting vantages in the use of EC windows in East and West facades (keeping glass always in the clear state in the heating season) but using conventional double glazing for the South facade. Further developments [13] on predictive control algorithms, to continuously meet a design illuminance level, should improve furthermore the building energy efficiency, offering reduction of about 40% electricity consumption and 38% for peak demand. The control strategy to manage when they should be in the colored or in the clear state can be based on several parameters: the unpredictable occupant’s preference (minimizing energy consumption, reducing reflections and/or glare, other), solar irradiation, external temperature, indoor temperature, indoor light level, occupation profile, time of the day and season [15, 16]. As the switching time is several minutes, a high time constant should be used to control the EC glass, in order to avoid frequent changes.

3. METHODOLOGY

The two test environments, identical in size and type of envelope, are located on the terrace of the DiCAAR Department (figure 1a) at 20 meters from each other, with gross dimensions 4.15x4.14x3.19 m. They are two wooden buildings realized with a balloon frame system, pillars and joists with reduced section, arranged at close intervals and with continuous uprights from the floor to the roof. The SE wall includes the entrance door with glazed area equal to 0.67x1.15 m; the SO wall (figura 1c) includes six windows, two with dimensions 1.42x0.94 m located in the centre, and four, of 0.60x0.95 m, on the sides. The only difference between the two buildings is precisely in these glazed elements: traditional high thermal performance window frames (7 mm external plate, 12 mm argon, 4 mm internal plate with low emission treatment) in the building further south (from here on we will call it “LE” building) and the electrochromic glass, above described, in the building further north (from here on we will call it “EC” building).
The electrochromic glazing, used in this research, consist of two glass plates separated by a 12 mm full space of argon. The outer plate is composed of a 4 mm tempered panel, a 0.9 mm ionoplastic interlayer and a 2.1 mm annealed glass sheet on which inner surface the electrochromic layers are deposited. The internal plate consists of a simple 6 mm tempered panel. The manufacturer provides the following performance characteristics, respectively for the “clear” and “fully tinted” states: solar factor $g = 48\%$ and $10\%$; light transmittance factor $TL = 62\%$ and $2\%$; thermal transmittance of the whole frame $U = 0.28 \text{ W/m}^2\text{K}$. This is not a last-generation type, which today have solar factors below $30\%$ with a selective ratio $TL/g$ greater than $2$ (high-performance selective glass).

The stratigraphy of the vertical opaque walls and their transmittance, calculated in accordance with UNI EN ISO 6946 [17], is reported in figure 2. The two test environments were instrumented (figure 3) for the detection of the main parameters for assessing indoor comfort, with sensors having metrological characteristics in accordance with ISO 7726 [18]. Furthermore, in order to measure surface temperatures of window elements, K-type thermocouples, suitably shielded by solar radiation, have been placed on the internal and external surfaces of the two larger windows on the SO side and of the window on the SE side. The uncertainty of measuring the surface temperature is better than $\pm 1\degree C$.

It should be noted that the two rooms are not equipped either with air conditioning systems, or controlled ventilation systems, therefore the measurements were finalized to compare the indoor conditions in the two di occupazione, ora del giorno e stagione [15,16]. In tal caso però si tenga conto che, poiché il tempo di commutazione è di alcuni minuti, è necessario utilizzare una costante di tempo elevata per controllare il vetro EC, al fine di evitare frequenti cambiamenti.

3. METODOLOGIA

I due ambienti di prova sono costituiti da due costruzioni in legno, posizionate sul terrazzo del Dipartimento DiCAAR dell’Università di Cagliari (figura 1 a), realizzate con sistema ad ossatura lignea controventata (balloon frame), con pilastri e travetti standardizzati, di sezione ridotta, disposti a intervalli ravvicinati e montati continui dal basamento alla copertura.

Le costruzioni, identiche per dimensioni e tipologia di involucro opaco, sono poste ad una distanza di 20 metri una dall’altra, con dimensioni $4.15\times4.14\times3.19 m$, con pareti opache poste sui lati NE e NO, e superfici vetrate sulle restanti pareti. La parete SE ospita il serramento di ingresso con area vetrata $1.42\times0.94 \text{ m}$ e quella SO (figura 1 c) ospita sei vetrate di cui due da $1.42\times0.94 \text{ m}$ e quattro da $0.60\times0.95 \text{ m}$. L’unica differenza tra i due ambienti di prova è proprio nei sistemi vetrati adottati: infatti tradizionali ad alta prestazione termica (7mm lastra esterna, 12 mm argon, 4 mm lastra interna) nell’edificio più a Sud (che chiameremo LE) e vetri elettrocromici, opportunamente controllati da remoto nell’edificio più a Nord (che chiameremo EC).

I vetri elettrocromici sono costituiti da due lastre di vetro separate da un’intercapedine da $12 \text{ mm}$ piena di argon. La lastra di vetro esterna è composta, a sua volta, da un pannello temprato da $4 \text{ mm}$, un film intercicale ionoplastico da $0.9 \text{ mm}$, una lastra di vetro ricotto da $2.1 \text{ mm}$ sulla cui faccia interna vengono depositati i layer elettrocromici. La lastra...
rooms, for different outdoor climatic conditions. The sampling period was equal to 15 min. The electro chroming glass are equipped with a remote-control system able to manage four different chromatic spectrums, ranging from light green on 4 variants (fully clear) to dark blue (fully tinted), according to the solar path. In order to verify the shielding effectiveness on the internal solar radiative load, the authors set a hourly programme to switch on (fully coloured) and off (fully clear) the SW windows and the SE ones, as shown in table 1.

![Stratigraphy of the vertical opaque walls.](image)

### Table 1

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness [mm]</th>
<th>R [m²·K/W]</th>
<th>λ [W/m·K]</th>
<th>ρ [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal admittance (horizontal flux)</td>
<td>0,130</td>
<td>7,690</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A - oriented wood fiber boards (OSB)</td>
<td>10,0</td>
<td>0,077</td>
<td>0,130</td>
<td>650,000</td>
</tr>
<tr>
<td>B - rock wool slab</td>
<td>150,0</td>
<td>4,167</td>
<td>0,036</td>
<td>130,000</td>
</tr>
<tr>
<td>C - oriented wood fiber boards (OSB)</td>
<td>10,0</td>
<td>0,077</td>
<td>0,130</td>
<td>650,000</td>
</tr>
<tr>
<td>D - EPS 100</td>
<td>60,0</td>
<td>1,667</td>
<td>0,036</td>
<td>33,000</td>
</tr>
<tr>
<td>E - fiberglass mesh</td>
<td>2,0</td>
<td>0,080</td>
<td>0,025</td>
<td>100,000</td>
</tr>
<tr>
<td>F - external plaster</td>
<td>3,0</td>
<td>0,003</td>
<td>0,900</td>
<td>1,800,000</td>
</tr>
<tr>
<td>External admittance (horizontal flux)</td>
<td>0,040</td>
<td>25,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2. Stratigraphy of the vertical opaque walls.**

**Figure 3. Measuring instruments for the evaluation of internal thermal comfort.**
Table 1. Scheduled switch-on times, in different months of the year, for EC windows on SE side and SW side.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE</td>
<td>Off</td>
<td>Off</td>
<td>7:30-13:30</td>
<td>7:30-13:00</td>
<td>7:00-12:30</td>
<td>7:00-12:30</td>
<td>7:00-13:00</td>
<td>8:00-13:30</td>
<td>8:00-13:30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO</td>
<td>Off</td>
<td>Off</td>
<td>10:30-18:00</td>
<td>11:00-18:30</td>
<td>11:00-19:00</td>
<td>11:00-19:30</td>
<td>11:00-19:00</td>
<td>10:30-18:00</td>
<td>10:30-17:00</td>
<td>10:30-16:30</td>
<td>Off</td>
<td></td>
</tr>
</tbody>
</table>

In order to have a more effective characterization of the two test environments, in different climatic conditions and with the variation of the main typological and performance parameters of the glasses, the same environments have been suitably modeled (figure 1.b) with Termolog IX®, able to perform dynamic energy simulation according to the new UNI EN ISO 52016 [19]. The standard specifies a calculation method for the assessment of the sensible heating and cooling load, in a thermal zone, based on hourly calculations, taking properly into account the hourly variations of the climate, the presence of the people in the simulated environments and their actions on the shading or conditioning regulation systems.

4. RESULTS

It is evident in figure 4 that the greater internal load, from solar gain, occurs in both buildings in the afternoon, due to the glazed surface on the SW wall, causing operative temperature peak higher than 16 °C (for the LE environment) and 8 °C (for the EC environment), if compared to the contemporary outdoor air temperature.

A similar analysis can be made for the surface temperatures measured on the different glazed windows. When the EC windows are switched ON, the incident solar radiation, absorbed in the first external layers (7 mm) and

![Figure 4: Operative temperature in EC and LE test environments, referred to the external air temperature and to the solar radiation on the glazed walls.](image-url)
rejected by the “active layer”, is partially reabsorbed, causing an increase in the external surface temperature up to about 52 °C, compared to external surface ones of about 45 °C for the LE windows. These data are confirmed by the results plotted in figure 5. They refer to the test in which the surface temperatures have been measured on two different EC windows, placed on the same wall (SW) but set, respectively, one in ON mode (as required by the scheduled daily program), the other always in OFF mode. As evident from figure 5, when the direct solar radiation on the windows reaches the peak conditions, their external surface temperatures reach differences up to about 12 °C. On the other hand, this effect is less evident on the respective internal surface temperatures, where it is possible to notice the greater thermal inertia of the internal sheet of the window in OFF mode, contributing to the radiative
gains in the evening hours. As regard the dynamic simulation the results in figure 6 show that the use of EC glass in winter condition could cause a partial nullification of the advantages achieved during the summer. In winter, not being able to count on solar inputs in the central hours of the day corresponds to an increase of more than 80% of the relative energy need, from 15 kWh/m$^3$ with LE glazing to about 27 kWh/m$^3$ with EC glazing. On the other hand, in the summer, the benefic effects in a Mediterranean climate are evident with a reduction in energy conditioning needs near to 90%, from about 71 kWh/m$^3$ with LE glazing to about 8 kWh/m$^3$ with EC windows.

5. CONCLUSIONS

With the national decree of 11th of January in 2017 the new Minimum Environmental Criteria for public buildings have been published. They provide, throughout the national territory, for renovation and/or energy requalification projects concerning the building envelope, for compliance with the minimum values of thermal transmittance. In this regard, for redevelopment of public buildings (with degree days from 900 to 1400), involving the replacement of window frames with orientation from East to West, the value of the total solar transmission factor must be not greater than 35%. The technology to overcome the impasse in the use of shielding on historic buildings is available today, albeit at a still high cost, with the use of windows able to switch between different shielding capabilities, as widely demonstrated in this paper for electrochromic technologies. Significant progress has been made in recent years, above all on the activation times of the active layer. Surely, the window of the future should firstly remain “a window”, ensuring visibility outside and visual comfort inside, but it should be able to convey heat and light separately, through a dynamic switch between the visible and infrared spectra, possibly including shielding elements for privacy. It should remain a durable and reliable element but should become multi-functional: source of natural light (in OFF mode) or artificial (in ON mode) through built-in micro accumulation systems; a decorative element or a projection surface. The next step is therefore its transformation from a simple transparent element of the envelope, into an active element, equipped with sensors for the detection of the main internal comfort parameters, varying the transparency range (or duration) according to the seasons or weather conditions. It will probably be the moment when it will finally stop to be “transparent”.

4. RESULTS

In figure 4 are reported the values of the irradiation solar incident on the surfaces and the values calculated of the temperature operative during the internal part of the two ambienti of prova, a partirire dalle misure di temperatura dell’aria effettuate nella seconda settimana del mese di giugno. Come risultato evidente il maggiore carico interno, da apporto solare, si verifica in entrambi gli edifici nella fascia pomeridiana, per effetto del maggiore rapporto della superficie vetrata sulla parete SO, causando valori di picco di temperature superiore all'interno di locali mediamente superiori di 16°C (per l'ambiente LE) e di 8°C (per l'ambiente EC) rispetto alla temperatura contemporanea dell'aria esterna. Un discorso analogo vale anche per le temperature superficiali raggianti dai vetri esposti all’irraggiamento solare. L’accensione delle vetrate EC comporta un parziale riassorbimento della radiazione solare assorbita nei primi strati esterni (7 mm) e rispetta del “layer attivo”, comportando un innalzamento della temperatura esterna del vetro fino a valori mediamente prossimi ai 52°C, a fronte di valori superficiali esterni di circa 45°C per le vetrate LE. Ciò è confermato dalla misura delle temperature superficiali effettuate contemporaneamente su due vetrate EC, l’una accesa come da programma giornaliero, l’altra mantenuta sempre OFF, per tutta la giornata di prova (figura 5). Al raggiungimento delle condizioni di irraggiamento di picco sulle superfici vetrate, le temperature superficiali esterne dei due vetri raggiongono differenze di picco di circa 12°C. Tale effetto è meno evidente, per contro, sulle temperature superficiali interne dei due vetri. In merito alla simulazione dinamica oraria, i risultati riportati in figura 6 evidenziano come l’utilizzo di vetrate EC in regime invernale porti ad una varificazione dei suoi effetti generali di comfort, tendendo ad annullare i principali vantaggi connessi agli apporti termici gratuiti solari. In regime invernale il non poter contare sugli apporti solari nelle ore centrali della giornata corrisponde ad un incremento anche superiore al 90% del relativo fabbisogno, passando da valori di circa 15 kWh/m$^3$ con vetrate LE a circa 27 kWh/m$^3$ con vetrate EC. Per contro, in regime estivo, gli effetti benefici in un clima mediterraneo si evidenziano con una diminuzione del fabbisogno per il condizionamento estivo prossimi al 90%, passando da valori di circa 71 kWh/m$^3$ con vetrate LE a circa 8 kWh/m$^3$ con vetrate EC.

5. CONCLUSIONI

Con il decreto 11 gennaio 2017 pubblicato in G.U. 23 del 28/01/2017 sono state rese note le nuove indicazioni in merito ai Criteri Ambientali Minimi per gli edifici pubblici che prevedono, su tutto il territorio nazionale, per progetti di ristrutturazione importante di secondo livello e di riqualificazione energetico, riguardanti l’involvere edilizio il rispetto dei valori minimi di trasmittanza termica contenuti nel decreto “Richiami Minimi” relativamente all’anno 2021.
6. REFERENCES


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