# Electrochromic Windows in Buildings

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Electrochromic systems for smart windows make it possible to enhance energy efficiency in the construction sector. The dynamic modulation of the spectral properties of a glazing, within the visible and infrared ranges of wavelengths, allows smart adaptation of thermal and optical figures of merit of a glazing, according to the everchanging conditions of the external environment. This allows appropriate control of the daylighting penetration within the building. The consequent advantages are manifold and are still being explored in the scientific literature. The reduction in energy consumption for summer air conditioning (and artificial lighting, too) becomes significant, especially in "cooling dominated" climates, reaching high percentages of saving, compared to common transparent windows; on the other hand, the continuous adaptation of the optical properties of the glass to the changing external conditions makes it possible to set suitable management strategies for the smart window, event in cold climates, in order to reduce glare and other discomfort issues.

Keywords: Electrochromic ; smart windows ; building integration ; energy saving

## 1. Introduction

Electrochromic (EC) devices essentially modulate the energy flux of solar energy through windows. This can be obtained by either controlling absorbance or reflectance. An EC glass can be considered, given the strict electrochemical analogy, as an electric battery embodying thin films of specific materials, whose loading degree is related to the degree of optical transparency. A pivotal component in EC devices is indeed the electrolyte, which is able to conduct ions but also acts as an insulator for electrons. Electrolytes typically used in EC systems are in the liquid, gel or solid state of aggregation. Liquid electrolytes may be subject to leakage or evaporation if they contain solvents. The ions shuttling through the electrolyte, upon the application of the external bias, are predominantly hydrogen and lithium or, more rarely, sodium. EC materials used in devices are mainly transition metal oxides and organic materials.

## 2. Electrochromic Windows for Energy Saving

Mainly, commercial EC devices employ radiation-absorbing materials, as reported by Jelle[1]. It therefore becomes essential to take into account the solar paths within a given location and the arrangement of the EC film on the transparent surfaces. It is quite predictable that the increase in temperature will be significant (up to 60 °C) if the device will be integrated onto skylights roof surfaces. On the contrary, overheating effects will be less marked or even insignificant on the facades of the building, mainly depending on the orientation and location. Moreover, EC glazing affects the color of windows, influencing user's visual interaction between interior and exterior environment. For this reason, the choice of the EC material should be carefully considered, before choosing a smart window. In fact, if $WO_3$ shows a transition between a transparent state and a deep blue state, other available EC materials may show other chromatic changes typically drifting towards red, green, brown, violet, grey.

As reported by several authors[2][3], windows are responsible for a large percentage of heat loss in the envelope of buildings. For this reason, the correct positioning of the EC film within double or triple glazed units may have various implications on the thermal behavior of the hosting window. In double glazed units with cavities filled using an inert gas, the EC coating should be placed on surface 2 (recalling that, conventionally, the external surface of a glazed unit is named surface 1) to prevent secondary heat gains in summer as well as glass overheating. Moreover, the transparent and conductive ITO film, generally used in EC devices, typically shows a low-emissive behavior that is a favorable plus to control radiative heat exchanges. In this way, EC films become suitable for both static selective and dynamic solar control behavior, at the same time. In a different configuration, the EC film may be interposed within laminated glazing, using PVB as a solid electrolyte, as reported by Granqvist[4]. The laminated pane may work as an EC glazing but also enhance structural properties of the external pane, according to specific regulations.

The first quantitative estimation of energy saving in buildings due to smart windows was proposed by Azens et al.[5], who took—as a starting point—the solar energy density falling onto a window (1000 kWh/($m^2$·yr)), considering that half of such amount is visible light. The amount of controllable energy throughput was considered as high as 340 kWh/($m^2$·yr), considering a visible modulation between 7% and 75%. Further estimation about occupied/unoccupied time led to a minimum value for yearly energy savings of about 170 kWh/($m^2$yr).

In 2010, Piccolo[6] listed the performance benefits associated to integration of smart windows in buildings: reduction of cooling loads in summer by decreasing SHGC in glazing; adoption of high transmittance states in winter to maximize passive solar heat gains; reduction of artificial lighting due to better exploitation of daylight; reduction of glare and of traditional shading devices (the latter often conflicting with optimal daylight use); unobstructed view of the surrounding environment; continuous adjustments of SHGC according to changing time-weather conditions. This work reported the cooling loads reduction in a cooling dominated climate, due to an EC window at the lowest transmissive state, compared to a 4 mm thick float glass: 50% for a west orientation and 60% for a south orientation.

Jonsson et al.[7] clarified that the link between energy saving due to smart windows and internal comfort is represented by an optimal control strategy of these devices. Different SHGC values should be adopted, for instance, in occupied/unoccupied hours and according to the season thermal requirements. Then, the authors defined four different strategies respectively aiming at: energy optimization, neglecting the use of artificial lighting; daylight optimization, reducing glare when the Sun is low in the sky; Office 1, assuming the Daylight optimization mode between 7:00 am and 6:00 pm; Office 2 mode, taking into account unoccupied hours in the weekend and then mixing the first two strategies. EC windows yielded the best energy saving compared to other static alternatives, especially according to the “Office 2” control strategy which yielded a reduction in energy uses of 200 kWh/($m^2$yr) normalized to window area.

In 2012, Aste et al.[8] studied a virtual test cell by using EnergyPlus, the well-known dynamic simulation engine, to compare EC glazing (SHGC = 0.468 to 0.163) with a common glass (SHGC = 0.462) and another one equipped with an external venetian blind system (SHGC = 0.759 when lifted up) in an office building ideally located in Milan (Italy). A minimum illuminance of 500 lx was set as a threshold for the work plane in the room. Apart from this, the control strategy included activation of shading systems when glare index exceeded a value of 19 and when the incident solar irradiance on the window was more than 200 W/$m^2$. The simulations carried out showed that EC glazing reduced primary energy use by 39.5% compared to common glazing and by 26.2% compared to venetian blinds.

Sbar et al.[9] assessed the energy savings due to EC glazing in buildings with a window to wall ratio (WWR) of 60% in different climate zones within the United States. By means of the eQuest building simulation program, they compared the performance of buildings with EC dimmable properties, suitably controlled to maximize the use of daylighting, with several static glazing technologies. In every climate zone, energy savings attainable were higher than 45% compared to single pane static glazing. Dramatic reductions in peak demand were demonstrated for buildings equipped with EC glazing. In turn, peak demand reductions allowed a reduced chiller size. Thus, EC technology, apart from optimizing energy use and daylight control, also allows to use smaller chillers and limits other system components, reducing capital expenses and eventually partially offsetting the increased costs of EC glazing.

Tavares et al.[10] investigated the impact of EC glazing, when used in refurbishment of old buildings in the Mediterranean area. Their simulations were carried out for different façade orientations and window surface area, within a test room, using spectral data of commercially available SAGE EC glazing. Their study reported energy saving in the range between 20 and 37 kWh/($m^2$·yr) normalized to window area. These values were quite low, if compared to other similar studies, as the authors declare, suggesting that the other studies generally employ optical properties of innovative EC prototypes, rather than commercial data and often neglect the heating season and the negative effect of smart windows in that season.

A complete review of existing and commercially available EC glazing was presented by Sibilio et al.[11], in 2016. They reported that EC layers are typically coupled with double or triple glazing, including a low-E coated glass pane, to maximize thermal performance. Minimum visible transmittance values in the clear state ranged from 0.4 to 0.5, whereas minimum SHGC observed ranged from 0.29 to 0.32, in the same optical state. Maximum $T_{vis}$ values, in the tinted state, spanned between 0.09 and 0.1, with SHGC varying from 0.1 to 0.13. All the EC windows investigated were supplied with direct current and very low voltages between 1 V and 5 V. Switching times could range from 7 to 20 minutes. Among their concluding remarks, the authors observed that EC devices can allow high energy savings (up to 39–59%, in some cases) but their benefits are indeed influenced by orientation, control strategy adopted, climatic condition and location.

Piccolo et al.[12] carried out an experimental (and numerical) simulation setting up a test cell oriented toward the south and west directions, collecting data in Messina (Italy) referring to clear sky conditions. They investigated effectiveness of EC devices in terms of overheating effects on the internal glass pane, by reporting the temperature difference between internal and external surface in bleached and colored state. As predictable, the difference was higher in the colored state. This fact was explained in terms of the EC effect, that involves mainly absorption of radiation, rather than reflection and demonstrates the ability of switchable glass to reduce heat loads in summer. The authors also analyzed the different components of heat entering indoor through the glazing, observing that the direct irradiance is reduced by 83% whereas a 46% increase was observed in thermal irradiation (although in absolute terms the reference thermal irradiation is 7.5% of the direct irradiance) and 14% in convective heat transfer, with a net decrease by 64% for south orientations (70% for west orientations). To further reduce heat transfer, the authors suggested the use of low-E reflective coatings on surface 3, already compulsory, in Italy (according to EU Directives), in almost all the climatic zones to fulfill with thermal transmittance requirements.

DeForest et al.[13][14] investigated potential energy savings in buildings, due to integration of near-infrared EC devices throughout U.S. climate regions, finding up to 50% energy saving by dynamic simulations. Unlike conventional EC glazing, near-infrared EC devices can modulate thermal radiation while remaining transparent to visible light, without affecting either daylighting or building aesthetics.

In 2018, Cannavale et al.[15] investigated the effect of innovative solid-state EC devices (**Figure 1**) in commercial buildings, by using experimental data to feed numerical simulations carried out with the EnergyPlus software. The EC technology was compared to commercial EC glazing, a selective glass and a clear glass, in three locations: London, Rome and Aswan. The innovative adaptive system was controlled by an illuminance-based strategy and was also considered compatible with retractable rolling shutters, so to maximize heat gains in winter, compared to commercial EC and selective glazing. The lowest global energy uses were reported for the innovative EC device, capable of reducing energy uses per floor area from 28.7 kWh/($m^2$yr) to 20.7 kWh/($m^2$yr), in the best case scenario, observed for Rome.

**Figure 1**. (a) Scanning electron microscopy image of the cross-section of a solid-state EC device. (b,c) Pictures reporting the device fabricated on polyethylene naphtalate flexible substrates, in bleached and colored conditions. (d) Transmittance spectra in several modulation conditions, according to the external bias applied. Reprinted from Room temperature processing for solid-state electrochromic devices on single substrate: From glass to flexible plastic, Solar Energy Materials & Solar Cells 155 (2016) 411–420, Copyright (2016), with permission from Elsevier.

Recently, Tallberg et al.[16] compared performance of different building-integrated adaptive chromogenic technologies (already on the market) in numerical simulations. EC windows were compared to photochromic and thermochromic glazing. From this study, it appeared that EC glazing controlled by different parameters showed the lowest energy consumption. The three control strategies adopted were: operative temperature, irradiance impinging the external surface, illuminance level on a work plane. The first control strategy offered the best results, in this work. The authors observed that the energy saving potential of EC windows was lower respect to other works, probably due to the WWR adopted, the analysis limited to a single test room with all walls modelled as external surfaces instead of a complete building model and the different control strategies adopted. **Table 1** summarizes the main figures of merit previously discussed.

**Table 1.** Summary of the main technologies and relevant figures of merit of EC glazing.

| Reference. | Technology | Control strategy | Energy savings |
| --- | --- | --- | --- |
| Azens et al.[5] | Solid-state device with hybrid EC (WO3 and NiO technology) | N/A | 170 kWh/m2yr with reference to one square meter of glazed area. |

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|---|---|---|---|
| Piccolo[6] | [illegible] | [illegible] | [illegible] |
| Jonsson et al.[7] | N/A | [illegible] | [illegible] |
| Aste et al.[8] | [illegible] | Minimum illuminance level of 500 lx on the work plane. | [illegible] |
| Sbar et al.[9] | SAGE EC glass. ID Nr. 8902-8905. | Daylight and glare control in summer; [illegible] | [illegible] |
| Tavares et al.[10] | SAGE EC glass. | Solar irradiance, outdoor air temperature; [illegible] | [illegible] |

| | | | |
|---|---|---|---|
| Piccolo et al.[12] | [illegible] | Illuminance-based control | [illegible] |
| DeForest et al.[13] | [illegible] | [illegible] | [illegible] |
| Cannavale et al.[15] | [illegible] | [illegible] minimum illuminance of 500 lx and 300 lx [illegible] | [illegible] |
| Tallberg et al.[16] | SAGE EC glass. | [illegible] | [illegible] |

EC smart windows have not yet had the expected spread on the market, although they can offer different types of advantages, that have been discussed in this work, albeit in a non-exhaustive way. This is mainly due to their still high cost, but also to the typical inertia of the construction sector with respect to new technologies, mainly due to precautional attitude and the impact of new technologies on construction process and costs. Moreover, builders, designers and users are not in conditions to evaluate the long-term benefits that these systems could offer, against a higher purchase cost. Despite the higher first and maintenance cost, compared to other traditional shading methods, it has been observed that EC windows can be fully paid for by the reduced cooling energy consumption[17], apart from indisputable comfort benefits for users. This work may help designers and building constructors make a critical and conscious choice, when suggesting the use of EC windows, considering several parameters, like latitude, façade orientation, climate, obstructions and so on. Anyway, further research activities are in progress aiming at reducing process costs, simplified device architectures; another relevant challenge is to replace expensive materials used in the fabrication process. Some of them are undergoing cost increase due to progressive shortage, like indium, generally used in indium tin oxide ($In_2O_3$:$SnO_2$) transparent conducting oxides[18]; many other options already exist, showing high electrical conductivity and good optical properties. The sheet resistance of existing conducting oxides still acts as limiting factor for the transverse dimension of smart windows. An increase in size of smart windows pushes to increase the thickness of conductive films; this leads to increases in the cost and opacity of the device. In terms of cost of EC windows, as reported by Baetens et al.[19], a

median of 500 $/m$^2$ would represent a maximal cost for every construction project. The spread of these new technologies could certainly be favored by the adoption of tax relief measures by national governments, which could reduce the impact of the higher initial investment cost of users, in view of
long-term benefits, either on energy consumption or on indoor visual comfort. Furthermore, use of IoT and smart sensing tools, although not yet investigated in this specific context, might pave the way to a more widespread use of EC windows in buildings and to an even smarter use of energy.

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