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Review

Smart Electrochromic Windows to Enhance Building Energy Efficiency and Visual Comfort

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Abstract: Electrochromic systems for smart windows make it possible to enhance energy efficiency in the construction sector, in both residential and tertiary buildings. The dynamic modulation of the spectral properties of a glazing, within the visible and infrared ranges of wavelengths, allows one to adapt the thermal and optical behavior of a glazing to the everchanging conditions of the environment in which the building is located. This allows appropriate control of the penetration of solar radiation within the building. The consequent advantages are manifold and are still being explored in the scientific literature. On the one hand, 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, in order to offer optimal conditions to take advantage of daylight within the confined space. This review aims at a critical review of the relevant literature concerning the benefits obtainable in terms of energy consumption and visual comfort, starting from a survey of the main architectures of the devices available today.

Keywords: building integrated electrochromic; device architectures; energy saving; control strategies; visual comfort

1. Introduction

The recent growing interest in problems within the construction sector related to energy consumption and emissions of climate-changing gases in the atmosphere, raises the need to define novel strategies to design buildings capable of minimizing energy consumption from fossil sources and, simultaneously, to reduce energy consumption. The latter is responsible for about 30–40% of primary energy consumption worldwide [1] and, according to the Global Status Report 2018, edited by the United Nations, building construction and operations accounted for nearly 40% of energy-related carbon dioxide (CO_2) emissions in 2017 [2].

If, on the one hand, it becomes fundamental to increase the rate of renewable sources use in the national energy mix, at the same time, the rationalization of energy consumption and its simultaneous reduction play, indeed, a central role. For instance, in a two-storey house, with one third of external surfaces covered by windows, 60% of energy is lost through glazing and energy losses through windows has been estimated to range from 10% to 25%, in residential buildings [3]. This point suggests a need to improve glazing properties, enhancing the spectral response to external conditions, possibly in a dynamic fashion, so as to responsively control the energy throughput through windows, according to changing seasonal demands.

The development of chromogenic materials [4] and devices has recorded a strong interest, with a sharp acceleration in studies on nanotechnology. In fact, starting from the 80s, the fundamental studies of Deb [5,6] and Granqvist [7] have attracted the attention of numerous research groups around the world, interested in the use of electrochromic (EC) materials to achieve a dynamic and interactive control of the spectral characteristics of glass used in various sectors, from automotive and aerospace industries, to the broad field of construction. The aforementioned scientists are mainly responsible for advancing research dealing with EC devices and materials. EC systems are just one of the smart systems [8,9], able to dynamically activate the transparency modulation of a glass pane, by applying an external bias. Being "smart" materials, chromogenics require the activation of their own functionality through the application of an external stimulus, in a reversible way. The physical stimulus gives its own name to the material (or device that embodies such material), based on the mechanism that triggers the activation. For example, the reaching of a critical temperature will activate the chromatic modulation of a thermochromic film [10,11], effecting the transition from a semiconductor behavior—typically in vanadium dioxide—to a metallic type behavior. On the other hand, photochromic materials [12–14] are activated upon irradiation in precise wavelength ranges. The main difference between these three categories of chromogenic material consists mainly in the nature of the stimulus that guarantees activation but, only EC devices allow control by users, interactively, according to their needs.

The wide range of chromogenics represent promising materials towards the design of transparent components in the envelope of buildings. The goal is to achieve the possibility of designing an adaptive envelope, which behaves just like a "third skin" for building users, capable of dynamically controlling the multiple energy throughput of glazing. Energy transfer through windows involves a part of the so called "thermal radiation" (10 μm–100 μm), with components close to solar radiation and infrared radiation, involving combined heat transfer mechanisms between solids and gases. This makes the design of smart windows systems particularly delicate and certainly sensitive to performance requirements as well as to the climatic characteristics of the building location, with particular reference to solar radiation and temperatures. If free solar gains can be considered as a "plus" in winter, for example, the same cannot be said with reference to the summer season: the same solar gains now become undesired cooling loads.

This review is aimed at a wide range of readers, from researchers to designers; without any claim of completeness, it will examine the benefits achievable by integrating EC glass in building facades. The benefits can be analyzed from two main points of view: the energy savings resulting from the spectral modulation of smart windows and the optimal use of natural light during daylight hours, which involves greater levels of visual comfort as well as savings on consumption for the artificial lighting. To this end, the examination of the (most recent) scientific works concerning the building integration of EC glass has been deepened, with particular reference to current research trends in this field, considering the architectures of devices and materials used to realize them, as well as the effects on energy consumption and visual comfort deriving from the different control strategies and from the climatic characteristics of the locations considered.

As reported in Figure 1, EC [15–18] and thermochromic windows are the most suitable technologies in reducing the required cooling energy load.

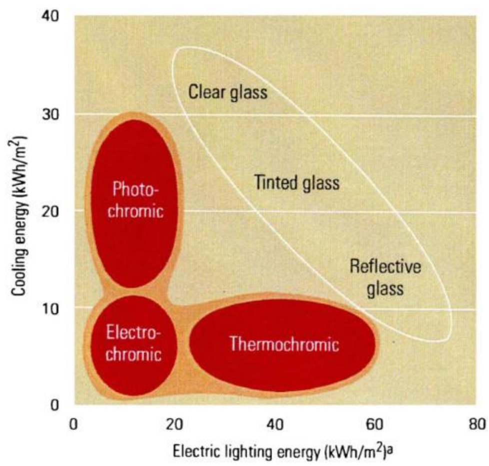


Figure 1. Comparison of electric lighting energy and cooling energy among different glazing typologies. Reprinted from "Progress in chromogenics: New results for electrochromic and thermochromic materials and devices", Solar Energy Materials & Solar Cells 93 (2009) 2032–2039, Copyright (2009), with permission from Elsevier.

A Short Glossary of the Main Parameters Used for the Characterization of EC Devices

As already stated, EC smart windows open the way to achieving dynamic control of the solar radiation that passes through windows. The quantification of these energy flows can take place by means of specific figures of merit, briefly recalled hereafter, for which a complete discussion may be found in the contribution of Jelle [19].

High transparency in building integration is required in order to maximize the variation between bleached and colored state and ensure the most flexible control of dynamic coloring, while optimizing daylight use. The relevant parameter to quantify this attitude is the *visible transmittance* (T_{vis}), also named light transmittance, provided by the following expression [17]:

$$T_{vis} = \frac{\sum_{380nm}^{780nm} T(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{380nm}^{780nm} D_\lambda V(\lambda) \Delta\lambda}, \quad (1)$$

where D_λ is the relative spectral distribution of illuminant D65, $V(\lambda)$ is the spectral luminous efficiency for photopic vision of a standard observer, $T(\lambda)$ is the spectral transmittance of the glass at the given wavelength and $\Delta\lambda$ is the wavelength interval. On the other hand, *solar transmittance* (T_{sol}), including the contribution of infra-red radiation, is given by the following expression [19]:

$$T_{sol} = \frac{\sum_{300nm}^{2500nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{300nm}^{2500nm} S_\lambda \Delta\lambda}, \quad (2)$$

where S_λ represents the relative spectral distribution of solar radiation.

Moreover, average visible transmittance (AVT) is often adopted as a measure of the mean transmittance, without any weighting, between 380 nm and 780 nm. Transparency in glazing is indeed a pivotal feature and minimum acceptable values exist for AVT. A specific study by Boyce et al. [20], found that the minimum acceptable glazing transmittance for office buildings should fall within the range between 25% and 38%. This is a fundamental parameter for EC glazing, semitransparent PVs and photo-electrochromic devices [21–23]. Moreover, a specific survey showed that effective smart glazing for building integration should be capable to switch their T_{vis} from 50–70% in the bleached state to less than 10–20% in the colored state [24]. With these premise, one can observe that most of EC and photo-electrochromic devices have reported compatible values of transmittance, with reference to both the lower and the upper thresholds [25].

A typical measure of the dynamic spectral modulation of an EC device is expressed by the contrast ratio (*CR*):

$$CR = T_b/T_c, \tag{3}$$

where T_b is the T_{vis} in the bleached form, and T_c is the transmittance in the colored state. The higher this ratio is, the greater the ability of the EC device to alter its optical figures of merit, according to the users' desired conditions. Recommended values range between 5:1 and 10:1. It is worth noting that optical modulation in EC devices is generally connected to an increase in absorption, rather than reflectance, which may have effects in terms of energy balance.

Solar heat gain coefficient (SHGC), although not strictly related to EC devices, is an essential metric for any window when dealing with thermal performance and energy balance issues. It is defined as the ratio of transmitted solar radiation (including both directly transmitted portion and that absorbed and subsequently reradiated) to incident solar radiation of an entire window assembly.

The color rendering index (CRI) of the glass is also relevant for architectural applications. CRI is the ability of transmitted daylight (through the glazing) to render colors compared to those seen under daylight without the glazing. It must be greater than 80 to ensure acceptable color reproduction.

The modulation kinetics of chromogenic materials and devices can be reported in terms of *response time*, that is the time required to activate the transition between two different color states, such as the colored and the bleached condition. In some cases, it expresses the time to activate a given fraction of the complete modulation. Response time is generally measured at a specific wavelength. For building applications, they can range from 10 sec to 5 min.

Another relevant parameter, frequently used in order to analyze performance of chromogenics is the coloration efficiency (*CE*), i.e. the change in optical density per unit of charge inserted. The change in optical density (ΔOD), depending on the *CR*, is first expressed, at each wavelength, by:

$$\Delta OD = ln[T_b\ (\lambda)/T_c\ (\lambda)]. \tag{4}$$

Then *CE* is generally related to the wavelength of maximum absorbance as a function of charge density (Q/A), and can be expressed as follows:

$$CE = \Delta OD/(Q/A) = ln[T_b\ (\lambda)/T_c\ (\lambda)]/(Q/A). \tag{5}$$

A high value of *CE* is an index of a large *CR* activated using a small amount of charge extraction and insertion. This parameter is generally adopted in EC devices in which the charge density is provided by an external circuit.

Open circuit memory (or optical memory) represents the time in which the device keeps its coloration unvaried, without requiring any bias to restore the desired coloration stage. For this reason, this is an asset for chromogenics, because in devices with large open circuit memory, electrical power must be drawn only to effect changes in the optical properties. Devices showing small drifts of optical state after several hours will be by far preferred. Furthermore, a good level of open circuit memory allows to reduce the energy consumption of EC devices. Values between 2 h and 12 h are recommended.

The minimum duration of EC devices is guaranteed in terms of the number of cycles. They must be sufficient to cover 3–5 complete switchings per day, for a period of 20 or 30 years. That is why some commercial glasses are guaranteed for 100,000 cycles, within a temperature range between −30 °C and 60 °C. Moreover, low switching voltage is ideal for architectural applications, generally lower than 5 V DC. DC current values must also be rather low, in order to reduce the consumption of electric energy needed to power the smart window.

2. Device Architectures

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. Recently, it has been demonstrated that transparent conducting oxides, in the form of nanoparticles, can also exhibit plasmon absorption in the near-infrared wavelength range, by altering the plasmon absorption: Llordes et al. [25] managed to tune infrared and visible light independently, in a "dual band" device.

Organic ECs, on the other hand, are molecules that undergo color changing due to redox processes. They are generally based, for instance, on bipyrilidilium systems, conducting polymers, quinones, cyanobiphenyls, phthalocyanines [4]. Jensen et al. [26] reported an innovative fabrication process for a flexible solid state ECD, based on photo crosslinking of acrylate-based electrolytes, in a small "curing chamber", soon after slot die coating. The photo-curable PEG-based electrolyte was based on a homopolymer named ECP-magenta. It was a relevant demonstration of compatibility between fabrication of EC devices and continuous roll-to-roll processing.

Among inorganic ECs, tungsten trioxide (WO_3) is the most widely investigated inorganic transition metal oxide, used as an EC material [5,27,28] (Figure 2). When it is charged with electrons, it tends to attract small cations inside the network of available channels within its structure. Following this intercalation, the semi-conductive structure of EC materials undergoes a reversible modification of the optical properties, which gives rise to a color switch to dark blue, for WO_3. This phenomenon corresponds to a redox reaction. Coloring due to ion intercalation as described, takes place in cathodic EC materials. On the other hand, several other materials (such as nickel oxide), undergo coloration upon de-intercalation.

The latter EC materials are named "anodic", due to their complementary coloring features compared to cathodic ones and, for this reason, they are used as EC materials on the opposite electrode. It is worth noting that EC materials are subject to a double conduction of ions and electrons and consequently they have been defined mixed conductors. The activation of reversible chromatic transitions of coloring and bleaching can be activated by means of a slight voltage (in general, a few volts DC). EC devices already on the market require a few minutes to completely switch the coloration of a one square meter window. Such kinetics do not conflict, inherently, with use of smart windows in the residential or tertiary sector, being compatible with the adaptation times of the human eye [7].

Typical EC devices can be considered as a mere sequence of thin films deposited on the glass substrate by physical vapor deposition. The electrolyte is positioned between the two substrates, which house the respective materials; it can be solid, as in the case of tantalum oxide [29–31], liquid or gel [32]. Some typical electrolytes made of $LiBO_2$, $LiNbO_3$, SiO_2, $LiAlF_4$, MgF_2; polyethylene oxide (PEO), polyaniline (PANI), polymethyl methacrylate (PMMA), raise their ion conductivity by adding specific salts, like $LiClO_4$, LiTF, LiI, Li_2SO_4 [3]. If the substrate is made of polyethylene terephthalate (PET), the weight of the device can be minimized by opening new chances for integration in glazing with different approaches, including lamination (Figure 3).

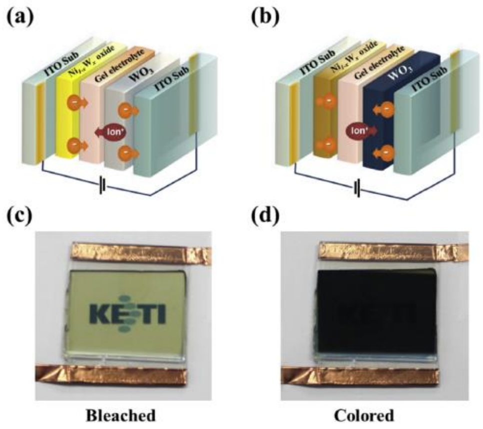


Figure 2. Schematic and optical images of an EC device embodying a gel electrolyte and two complementary inorganic anodic/cathodic materials. The bleached and colored states are reported. Device scheme in bleached (**a**) and colored (**b**) conditions. Device pictures reporting bleached (**c**) and colored (**d**) conditions. Reprinted from "Investigation of all-solid-state electrochromic devices with durability enhanced tungsten-doped nickel oxide as a counter electrode", Journal of Alloys and Compounds 815 (2020) 152399, Copyright (2020), with permission from Elsevier.

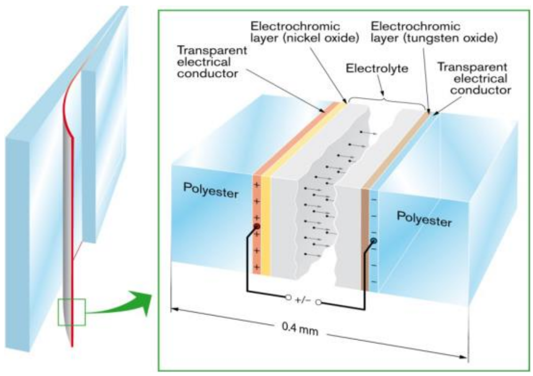


Figure 3. Principle design of an EC device fabricated in the form of a foil to be used for glass lamination, as indicated in the left-hand part. Reprinted from "Electrochromics on a roll: Web-coating and lamination for smart windows", Surface & Coatings Technology 336 (2018) 133–138, Copyright (2018), with permission from Elsevier.

Dyer et al. [33] demonstrated the potential of a solar-powered EC device. Two airbrush sprayed polymer EC materials were used: PProDOT-$(CH_2OEtH_x)_2$, also named ECP-Magenta, and PProDOP-N-$C_{18}H_{37}$, referred to as MCCP. Two PV cells (connected in parallel or series) work as a tandem cell. The combined device produces net positive energy, because it generates electricity but may also modulate the energy throughput of windows. This device was obtained using organic solutions and it was compatible with printing or roll-to-roll techniques. Fair transmittance modulations were observed, between 400 nm and 630 nm.

Piccolo et al. [34] reported measurements of an EC switchable window (Figure 4), embodying a device based on the complementary behavior of WO_3 and NiOH:Li, acting as an active layer and as ion storage materials, respectively. The electrolyte adopted was a lithium conducting polymer including PEO-PEGMA:Li. The device was scaled up to size of 12 cm by 12 cm, reporting switching times of 5–6 min with T_{vis} varying from 70% to 30%.

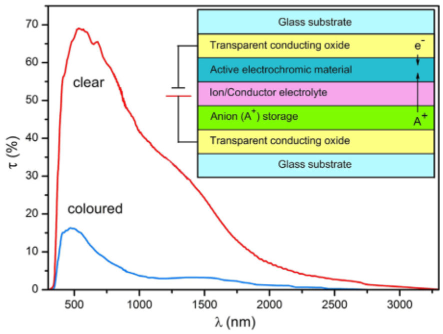
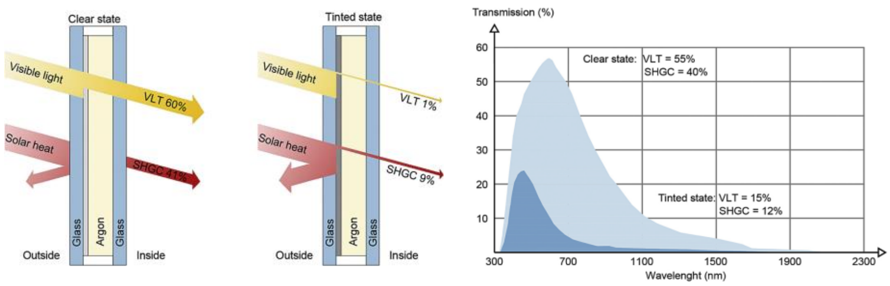


Figure 4. Transmittance modulation of an EC device, between the colored and bleached conditions. The insert reports the cross-section of the multi-layered device measured. Reprinted from "Energy performance of an electrochromic switchable glazing: Experimental and computational assessments", Energy & Buildings 165 (2018) 390–398, Copyright (2018), with permission from Elsevier.

A complete review of active dynamic windows already available on the market containing a full description of main active chromogenic technologies, including commercial EC smart windows was prepared by Casini [35]. Among the different technologies presented in the paper, the five-layer architecture selected as an example, embodies two substrates and as many transparent conductive films, an active WO_3 (or niobium pentoxide Nb_2O_5) layer and counter-electrode made of $Li_xV_2O_5$ (or nickel oxide hydroxide NiOOH, or iridium oxide IrO_2) separated by $LiAlF_4$, acting as an electrolyte. Such device may switch the SHGC from 0.41 (in the bleached state) to 0.09 in the colored state, with T_{vis} passing from 60% to 1%, requiring a minimal amount of electric power (2.5 W/m^2) (Figure 5). Commercial products of this kind offer 10 years warranty, with a theoretical 30 year service life, after passing accelerated aging test, according to ASTM E2141-14.



(**a**) (**b**)

Figure 5. (**a**) Electrochromic glazing control states. (**b**) Spectral transmission of Electrochromic glass in different tint states (EControl-Glas). Reprinted from "Active dynamic windows for buildings: A review", Renewable Energy 119 (2018) 923-934, Copyright (2018), with permission from Elsevier.

In 2016, Cossari et al. [36] presented a solid-state EC device fabricated on a single substrate, using a low-cost, room temperature process. A Nafion film was used as a solid electrolyte and WO_3 was the only EC material involved in this simple architecture (Figure 6). Nafion is an ion conductive polymer ionomer with a structure consisting in a tetrafluoroethylene (PTFE) backbone, with perfluoro-ether side chains, end-capped with HSO_3^- (sulphonic acid groups), that explain the high conductivity value. A transparent In_2O_3:SnO_2 (ITO) counter electrode was then RF-sputtered on top of the electrolyte, so as to complete the device without requiring a secondary substrate. Such device was fabricated both on glass and on highly flexible polyethylene naphtalate conductive substrate. This device reported optical modulation of 49% at 650 nm and a switching time of 30 s.

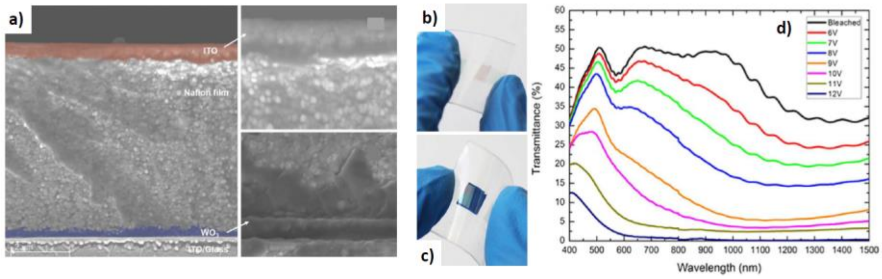


Figure 6. (**a**) Scanning electron microscopy image of the cross-section of a solid-state EC device. (**b**,**c**) Pictures reporting the device fabricated on polyethylene naphtalate flexible substrates, in bleached and colored conditions. (**d**) Transmittance spectra in several modulation conditions, 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.

3. Electrochromic Windows for Energy Saving in Buildings

EC devices essentially modulate the energy flux of solar energy through windows. This can be obtained by either controlling absorbance or reflectance. Mainly, commercial EC devices employ radiation-absorbing materials, as reported by Jelle [19]. 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 [3,37], 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 (Figure 7), 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 [1]. The laminated pane may work as an EC glazing but also enhance structural properties of the external pane, according to specific regulations.

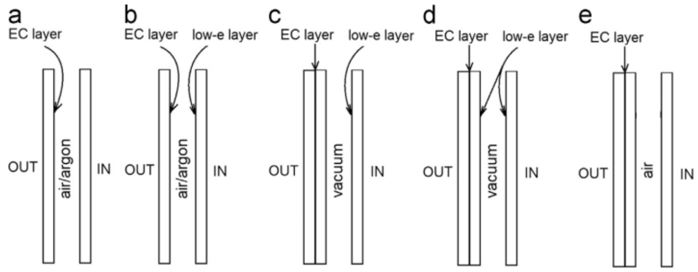


Figure 7. Layouts of different configuration of glazed panes hosting EC devices and low-e layers. (**a**) EC layer on Face 2 of a double glazed unit; (**b**) EC layer on Face 2 and low-e layer on Face 3 in a of a double glazed unit; (**c**) double glazed unit embodying an external laminated glazing containing EC layer and a low-e layer on Face 3; (**d**) laminated glazing containing EC layer and low-e layer on both faces of the vacuum interspace; (**e**) double glazed unit with EC layer in a laminated glazing. Reprinted from: Performance requirements for electrochromic smart window, Journal of Building engineering, 3, 94-103, with permission from Elsevier; copyright (2015). Reprinted from "Performance requirements for electrochromic smart window", Journal of Building Engineering 3 (2015) 94–103, Copyright (2015), with permission from Elsevier.

The first quantitative estimation of energy saving in buildings due to smart windows was proposed by Azens et al. [38], who took—as a starting point—the solar energy density falling onto a window (1000 kWh/(m^2·year)), considering that half of such amount is visible light. The amount of controllable energy throughput was considered as high as 340 kWh/(m^2·year), 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·year).

In 2010, Piccolo [39] 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. [40] 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·year) normalized to window area.

In 2012, Aste et al. [41] 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. [42] 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. [43] 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·year) 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. [44], 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 min. 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. [45] 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. [46,47] 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. [48] investigated the effect of innovative solid-state EC devices 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·year) to 20.7 kWh/(m^2·yr), in the best case scenario, observed for Rome.

Recently, Tallberg et al. [49] 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 discussed in this Section.

Table 1. Summary of the main technologies and relevant figures of merit discussed in Section 3.

Reference.	Technology	Control Strategy	Energy Savings
Azens et al. [38]	Solid EL device with cathodic (WO3) and anodic (NiO_xH_y) EC materials for laminated glazing.	N/A	170 kWh/m^2·year with reference to one square meter of glazed area.
Piccolo [39]	Fully solid state EC device based on the complementary electrochromism of WO_3 and NiOH:Li.	Static and dynamic strategies. Full coloring in unoccupied hours. high solar transmittances at near-normal incidence directions; low solar transmittances at off-normal incidence directions.	Load reductions of 50% compared to the performance of a clear float glass.
Jonsson et al. [40]	N/A	Four control strategies: "Energy optimization, with windows always kept in the best state with regards of heating and cooling; "Daylight optimization", with windows in an optimized state from daylight perspectives; "Office 1" and "Office 2" modes correspond to intermediate modes, during daytime.	EC windows always yield a lower need for cooling than static alternatives. 100 kWh/m^2·year in daylight optimization mode and 200 kWh/m^2·year in daylight optimization mode (per square meter of glazed area).
Aste et al. [41]	EC glazing properties from the International glazing database (IGDB)	Minimum illuminance level of 500 lx on the workplane.	Virtual test cell compared to automated external venetian blinds properly used (−7.3% for yearly cooling loads and base case clear glass (−40% for yearly cooling loads).
Sbar et al. [42]	SAGE EC glass. ID Nr. 8902-8905.	Daylight and glare controlling in summer; only glare controlling in winter.	Global energy saving of 57% compared to static single pane glazing and 37% compared to ASHRAE compliant glazing in the USA climate (Minneapolis).
Tavares et al. [43]	SAGE EC glass.	Solar irradiance; outdoor air temperature; indoor air temperature.	From 20 kWh/m^2·year to 37 kWh/m^2·year (per square meter of glazed area).
Piccolo et al. [45]	Solid-state EC device with WO_3 and NiOH:Li complementary EC materials and PEO-PEGMA:Li conducting polymer electrolyte.	Illuminance-based control	In cooling dominated climate (Messina, Italy) from −20% to −40% in cooling energy use, compared to a common double glazed unit.

Table 1. *Cont.*

Reference.	Technology	Control Strategy	Energy Savings
DeForest et al. [46]	Near-Infrared EC device showing optical properties of PPG Solarban 72 glass in the blocking state and of PPGSungate 400 in the "clear" state.	Simple control mechanism switching the EC device when the indoor temperature reaches 0.5 °C below the cooling setpoint temperature.	The best results were obtained in heating-dominated climates, in USA. Energy saving per unit window area ranged from 50 to 200 kWh/m^2
Cannavale et al. [48]	Single-substrate, solid-state device with substrate/ITO/WO_3/Nafion/ITO architecture.	minimum illuminance of 500 lx and 300 lx on the work surface	Overall yearly energy savings as high as 40 kWh/m^2 year (per square meter of glazed area)
Tallberg et al. [49]	SAGE EC glass.	Sun-control strategy (radiation exceeds 450/m^2); Operative-temperature strategy (when the measured operative temperature exceeds 24 °C); Daylight control strategy (with a threshold of 500 lx on a work desk).	Lowest energy demand in Madrid with total delivered energy of 69% compared to the reference case.

4. Effects of Electrochromic Glazing on Visual Comfort

As reported by Boubekri [50], daylight affects our body by impinging our retina and, consequently, modifying our endocrine system; on the other hand, it interacts with our derma, activating the photosynthesis that produces vitamin D. Moreover, daylight acts as an effective signal, activating the suprachiasmatic nucleus, a sort of "body clock" within the hypothalamus. This control center is responsible for the regulation of sleep and activity rhythms. Furthermore, daylight catalyzes the secretion of hormones in the pineal gland (melatonin and serotonin), influencing the circadian rhythms.

A paradigm generally used to assess the amount of daylight available in buildings is called Useful Daylight Illuminance, a widespread metric based on yearly time-series of values for illuminance, predicted using realistic sky conditions, modelled starting from standard climatic datasets for a given location. UDI overcomes the well-known limits of Daylight Factor (the ratio of internal illuminance at one point to the horizontal unobstructed illuminance under a CIE overcast sky), consisting in the absence of consideration for non-overcast skies and different building orientations. The UDI paradigm, introduced by Nabil and Mardaljevic [51], occurs when all the illuminances fall within the range 100–2000 lux, although one of the same authors proposed to narrow the interval from 300 to 2000 lux [52].

Wienhold et al. [53,54] developed a specific metric to assess Daylighting Glare Probability (DGP), using a combination of existing discomfort glare algorithms and a novel empirical approach. The DGP formula is the effect of a combination of vertical eye illuminance and the glare source term of the existing CIE glare index. Sometimes, and particularly in dynamic simulation tools like EnergyPlus [55], an easier to calculate metric named Daylight Glare Index (DGI) is used. Unlike DGP ouit is a logarithmic ratio of source and background luminances.

In terms of effects of EC glazing on visual performance, Cannavale et al. [56] used experimental data from the fabrication and characterization of a solid-state EC device in simulation activities carried out in the EnergyPlus software platform. Various control strategies were adopted and compared with each other: illuminance on the work plane (with setpoint at 300 lx); glare (Daylight glare index DGI < 22); irradiance on the external surface of EC glazing (with more setpoints at: 200 W/m^2, 250 W/m^2 and 300 W/m^2). The best results in terms of overall yearly energy savings—as high as 13% compared to a double pane glazing (6 mm—clear glass / 20 mm—air gap / 6 mm—clear glass with WWR = 0.42) were obtained adopting the illuminance-based strategy. The overall energy consumption was calculated taking into account lighting, heating and cooling.

A comparison between glare control performance of frit glass—an opaque ceramic material deposited on glass during heat treatment process—and EC windows was proposed in 2017 by

Ardakan et al. [57] for two case studies: one with a skylight and one with vertical glass. They found out that neither clear low-E glass nor frit glass were enough to adequately control sunlight glare in both cases. On the contrary, EC glazing provided suitable glare control and daylight admission, at the same time, maintaining a clear view of the outside at all times.

5. The Role of Control Strategies

All the works mentioned so far clearly show that dynamic behavior of glazing generally represents a preferable strategy compared to glazing (or other technologies/materials) with static spectral properties.

EC devices can allow an energy savings of up to 59% [44], but the actual benefits are often unrelated to the technology itself. Orientation, climatic conditions, latitude location and control strategy dramatically affect the performance of a smart window. What clearly emerges from the analysis of the works appeared so far is that beyond the performance of EC glasses, a fundamental aspect—still under investigation—is the definition of a suitable control strategy that requires consideration of many parameters at the same time, possibly involving behavioral factors into the decisional process [58].

The first attempts to investigate the role of control strategies were carried out in the nineties at the Lawrence Berkeley National Laboratory and the illuminance-based control algorithms resulted in the best overall annual energy performance [42]. A synergistic control of dimmable electric lighting and natural light entering indoor of course affects energy consumption. EC devices may play a pivotal role as an effective filter of visible and infrared radiation, depending on sky condition and other parameters that should drive its operation.

It is the case to remind that one of the earliest works concerning control strategies of EC glazing, considering both energy issues and visual comfort objectives was proposed by Gugliermetti and Bisegna [59] in 2003. They analyzed energy, thermal and visual aspects related to building integration of EC windows, with reference to non-residential buildings in the Mediterranean area. They considered on/off and linear controls for EC devices, finding that the comfort-based approach causes a slight increase in energy requirements compared to an energetic optimization. In accordance with these results, Cannavale et al. [56] found that glare-controlled EC devices performed better in terms of UDI and glare index compared to all the other control strategies but all this was achieved at the expenses of energy saving. A good compromise between energy saving, visual comfort and use of artificial lighting was found adopting an illuminance control strategy, with setpoints at 300 lx or 500 lx on the workplane.

A tradeoff between energy performance and visual comfort might derive from the application of machine learning methods and standard optimization algorithms to take into account multiple parameters and effectively exploit EC glazing. In 2007, Assimakopoulos et al. [60] proposed the use of a fuzzy controller for EC devices which was developed according to the principles of adaptive neuro-fuzzy inference systems.

More recently, Dussault et al. [61] proposed a comparison between different control strategies: heuristic controllers, based on predefined instructions, a genetic algorithm to elaborate an optimization strategy aiming at the optimal state of the window at each hour, and a model predictive control. Some of these innovative tools might allow to broaden the assessment of performance considering complex objective functions, taking into account more parameters and interactions with other zones or services, simultaneously, in a holistic fashion. In perspective, these aspects seem destined to play a fundamental role in the perspective of the commercial diffusion of EC smart windows, perhaps more than further advances in materials and performance of this technology.

Oh et al. [62] used an integrated evaluation of energy and daylight based on the results of a carefully controlled EnergyPlus simulation assuming two different control strategies. One was based on outdoor temperature (with 10 °C as a threshold), and one was based on solar radiation assuming different thresholds (50 W/m^2, 300 W/m^2, 500 W/m^2, and 700 W/m^2). Results were assessed as a function of heating and cooling load variation, change in lighting energy and visual comfort expressed in terms of DGI. The optimal control strategy proved to be the one using the 300 W/m^2 limit which balanced an excellent energy performance with an acceptable (although not the best) performance

6. Conclusions and Perspectives

Our analysis of the existing literature on the use of smart EC glazing in the building sector provides a first comprehensive collection of the many existing technologies and the way they are used to obtain smart windows. The comparison among different applications demonstrates that while the specific performance of EC devices is certainly important, in order to get the best possible results from the technology, it is the control strategy that needs to be adapted to the device features, building use, climate and location. Significant savings in terms of cooling energy may be achieved by means of EC windows, ensuring a nearly "real time" adaptation which could hardly be obtained with more conventional shading systems. By means of EC windows a proper balance between energy saving and visual comfort may be found, and even more human-related factors are worth being taken into account in order to obtain further improvements in energy use without affecting occupants' conditions.

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 [63], 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 [64]; 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. [24], 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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