Performance of Electrochromic Glazing: State of the Art Review

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Abstract. Globally, buildings are responsible for about 45% of energy consumption, 40% of atmospheric emission, 30% of water usage and 30% of waste generation, yielding negative environmental impacts which drove intensive research to achieve a sustainable built environment. Architects are primarily responsible and bear a major stake in the design of the built environment; being professionally mandated to achieve environmentally friendly, functional, structurally stable, and aesthetically pleasing designs. Adopting innovative solutions, which do not compromise these conventional, building requirements, is therefore crucial to promoting sustainability in the built environment. This investigation reviews electrochromic (EC) glazing as a sustainable design option for buildings: its types and properties are presented along with an added focus on design, energy and cost analysis aspects. The findings indicate that EC glazing can reduce electricity demand by 7-8% for moderate window size and 14-16% for large windows. Based on building type, 6 to 11% and 8 to 15% savings are possible for commercial building and residential buildings, respectively. Based on their performance and market success, alternative strategies, such as hybrid EC windows with PV cells, are presented. Further research areas are then deduced based on this review, which may provide design, energy and cost saving benefits.

1. Introduction
The growing interest towards energy efficiency of buildings as well as the productivity of the building’s occupants idealizes the demands of design and social sustainability. It is occasioned by the global concerns which have arisen due to negative environmental conditions like global warming and the resultant economic and social impacts around the world. However, it has been emphasized that a drive towards environmental knowledge can impact the economic performance of corporate entities [1]. In the US buildings consume 62% of energy produced for lighting, plug loads and equipment, while 38% goes to heating and cooling conditioning systems [2]. High amounts of energy flow into and out of buildings as a direct result of the openings and glazing; which implies that high cooling or heating loads may be needed to create a balance, and ensure a comfortable indoor environment. Towards improving design efficiency and user effectiveness, the integration of advanced glazing systems into sustainable buildings could be considered as a design strategy to reduce potential energy loss. One solution is to minimize the size of the glazing; but this has a high impact on the façade design; leading to loss of view and daylighting potentials [3]. Some researchers [4] also assert that the convergence of architectural patterns towards increased use of glass and rising demand for saving energy has created an opportunity for smart windows technology. Technological advancements in glazing systems have produced “tunable transmittance of solar energy and visible light” as a response to this requirement. This type of glazing is often called “smart” or “intelligent” [5] and is based on “chromogenic” materials [6]. Of this category, electrochromic materials are currently the most widely studied and reviewed [7, 8], with
emerging investigations based on unique electroactive characteristics [9]. These advanced/smart windows are divided into two types; active and passive smart glass. Passive systems are defined by an autonomous response to natural stimuli such as light (photochromic glass) or heat (thermochromic and thermotropic glazing). Operated without any external input, they are easy to install; however, they do not allow user control to match varying needs [10, 11]. On the other hand, active systems are based on an external electrical stimulus thus allowing for user control. The manipulation of their optical characteristics to match user demand for varying environmental or functional needs is possible [7].

In view of the significant potentials of EC glazing, this paper investigates its role as a dynamic, environmentally-responsive building element. The focus is to define the core requirements for architectural design integration as a first step towards developing design prototypes. Hence, EC physical structure, operation and derived benefits are reviewed first, then the energy saving potentials of EC glazing in comparison with its core design requirements was carried and finally a comparison with novel technologies is explored.

2. Background

Active dynamic windows such as electrochromic are a key tool in innovative advanced building envelope allowing greater freedom in architectural design, better visual and thermal comfort and improved energy efficiency, enabling a climate adaptive building shell fully adjustable to any weather condition or users preference [12]. EC materials and their associated device technologies are rapidly evolving, especially with regard to implementation in windows and glass facades—jointly known as glazing—for energy-efficient buildings with good indoor comfort [3]. EC glass is an active system which operates by means of electrical voltage technology utilization. The glass pane consists of nano-thick switchable and changeable coating which is the control mechanism to regulate the amount of light passing through the windows into the interior spaces without loss of view. EC glazing is considered as an advanced fenestration system with a significant effect on the building energy performance [13]. Electrochromic glazing system in one of four categories of chromic systems; it works in response to electrical voltage to control heat and light penetration by reducing its transparency according to the external conditions. It is also called switchable glazing, and is capable of reducing energy consumption by controlling solar heat, daylight and glare [14].

The EC glazing system contains multiple layers and changes its transparency and absorbance to manipulate its optical properties reversibly [15]. 3.5% of incoming visible light in the low dark end, and 36% in the high clear end can be blocked by EC glazing [16, 17]. The technology works by applying low electrical voltage, pass through the thin coating layer of the glass surface. The color of the glass changes through three stages from clear to bright then dark, causing a change in transparency of the windows [14, 18-23]. Metal oxide-based EC glazing has a few drawbacks; for instance, the low switching time which implies that it takes a long time to respond, and has poor coloration properties. These technologies are however in competition with conducting polymer materials because of its low-cost and fast preparation process [24-27].

2.1 Electrochromic Glazing System Benefits

This is based on the properties that allow EC glazing to be tuned, persistently and reversibly, through the application of electrical current or voltage [28, 29]. EC devices use electrical power only during switching; with such technology based on low voltage to switch approximately 1 to 5 V. In addition, it possesses a long-term memory to preserve constant dimming from 12 – 48 hours; it reduces the energy consumption to almost zero in constant conditions and improves the daylighting for residential and offices building. These result in cost savings and improve occupant productivity. The coloration attribute which is infinite has the ability to prevent direct and diffuse solar radiation emission [30]. EC Glazing prevents 99.4% of UV radiation transmission directed at the interior and thus, reduced the damage of furniture and curtain fabrics [31]. However, these benefits are yet to be fully maximized undertaken,
due to the significant drawbacks such as cost, durability and functional problems. Table 1 shows a summary of smart glazing technologies such as EC glazing and its benefits.

Table 1. Active Glazing [32, 33]

| TYPES                              | BENEFITS                                                                 |
|------------------------------------|--------------------------------------------------------------------------|
| Electrochromic                     | - Solar modulation<br> - Glare control<br> - Enhanced building aesthetics<br> - Daylighting and View potentials of glazing<br> - User control on demand |
| Spectrally tunable EC              | - Independently modulation of NIR and visible spectra<br> - SHGC may be controlled without affecting visible transmittance<br> - Useful for various climates<br> - Glare control<br> - User control on demand |
| Building integrated Photovoltaics (BIPV) facades | - Daylighting and view as well as energy generation<br> - Potential application as opaque or semi-transparent/translucent glazing<br> - Hybrid design with thermal insulators (e.g. PCM)<br> - Sun shading device |
| Photovoltaic Electrochromic (PV EC) | - Solar shading and modulation<br> - Glare control<br> - Self-powered<br> - Daylighting<br> - Enhanced building aesthetics |
| Gasochromic                        | - Solar modulation<br> - Glare control<br> - Faster response time relative to EC<br> - Simpler layer structure than EC |
| Suspended particle (SP) windows    | - Solar modulation<br> - Glare control<br> - Fast response time<br> - Vast transparency levels |
| Liquid crystal (LC)                | - Glare control<br> - Becomes translucent (for privacy applications) |

2.2 EC Device Structure
Electrochromic devices consist of two panes of coated glass as a clear conductive coating on the internal surface of the glass with several sandwiched layers in between. Two embedded electrodes are assembled alongside a sandwich cell and sealed with a hot-melt film; between the two electrodes, 1mm thick electrolyte layer (ion conductor) is injected. This is positioned between the electrochromic layer and the counter electrode layer (ion storage layer) with a syringe to fabricate the glass of EC device. The device is then sealed with vacuum glue around the electrodes and electrolyte [34, 35]. The central part of an electrochromic device has a five-layers coating applied to the glass pane as shown in Figure 1 below. These include an electron accumulation layer (counter-electrode, LixV2O5), an ion conductor layer (or electrolyte, usually LiAlF4) and, an electrode layer. Tungsten trioxide WO3 or niobium pentoxide
Nb2O5 are commonly used for this third layer; finally, there are two outer layers made of transparent conductive oxides (TCO) [7].

In operation, voltage is applied to cause the Li + ions pass from the accumulation layer to the electrode. This determines the change in the color of the electrode layer transforming from a transparent to darkened state (cathodic coloration), or in the accumulation layer (anodic coloration). This change may also occur in both layers based on the type of EC materials used in the device. Transparency is restored by switching off current; this triggers the return of ions from the electrode to the accumulation layer. Alternating different control states requires a minimal amount of electricity (2.5 Wp/m2); and less is needed to maintain a desired tinted state (less than 0.4 W/m2) [7]. Figure 1 below shows the EC system before and after the current is allowed to pass through the embedded layers.

![Figure 1. Electrochromic devices structure before and after switching [36]](image)

3. Energy Savings Potential

External shading devices have been used in countless architectural epochs as a means of reducing internal heat gain. They variably reduce overheating in summer seasons - particularly in hot climate regions, and associated cooling loads [16]. As an active shading device, EC windows can provide annual cooling load reduction also by controlling solar heat gains for all orientations of the windows [27, 35, 37, 38]. This can ultimately lead to energy savings for the benefit of the building owner. Using a full-scale office experimental study, [33] conducted an investigation on the performance of EC window prototypes and recorded savings 59% in comparison with classic windows. In 2009, Rudolph et al carried out an EC glazing system study with the California Energy Commission [4]. The study reported a 44% savings in lighting energy compared to a reference case with no daylighting controls. Window cooling loads also recorded a peak demand reduction of 19% to 26% on clear sunny days. Another study [39] on experimental simulations was carried out in three US climate zones of varying environmental exposure conditions from hot and dry. The study recorded savings greater than 45% when EC glass was compared to conventional single pane static glazing. In another study [40], a simulation was conducted in order to evaluate the lighting energy saving potential of an EC window. By simulating the performance on the south facing office with two independent EC windows, about 48% of energy saving was recorded when compared with clear glass.

In order to investigate the energy saving potential of EC glazing, there are several parameters that need to be considered of which the EC type, window design and the prevailing climate are the primary ones.
3.1. EC Glazing Device Types

Investigations into EC technologies have focused on their substantial materials characteristics and appropriateness of application potential on buildings [30]. This has helped to establish newer EC technology with different dynamic, optical and switching properties. This also enhances the understanding of these novel glazing systems in terms of energy performance to target materials characteristics of electrochromic glazing devices. There are various types of EC glazing systems which has been improved and developed over decades; such as the conventional electrochromic (CEC) glazing, near-infrared electrochromic (NEC) glazing and dual-band electrochromic (DBEC) glazing. Table 2 illustrates the differences in energy savings and thermal comfort between the three types of ECs glazing systems.

3.1.1 Conventional electrochromic (CEC) glazing

Basically, EC glazings consist of tungsten oxide coating which has been developed over decades. The currently available coating is designed to reduce transmission by absorption and is effective at blocking solar heating induced by near-infrared radiation (NIR). This occurs in bright and dark states, and moderate glare that lead to a noticeable darkening. Photovoltaic electrochromic glazing structure shows the transition performance of NIR, VL and UV through three states of glass transmission. The observed performance of CEC, in the case of transition from cool (state 2) to dark (state 3) as it decreases transmission of NIR and visible light [41]. Conventional electrochromic glazing systems performed as a highly efficient component in decreasing peak cooling loads and moderating the daylight in order to capture savings of electric lighting and reduce glare. The energy savings results show 10% to 20% saving in the surrounding zones by using U.S simulation of commercial building stock. As for the Mediterranean zones, the simulations measured annual energy savings are as high as 54%. [41]. Comparing CECs glazing systems as a dynamic window and applied to the split-pane window and static window with controlled blinds, CECs windows boost of saving up to 37% - 48% of lighting savings [40].

- NIR-switching electrochromic glazing:

This type of glazing system is developed by moderating the solar radiation transmission without affecting the visible light transmission. The new characteristic gives the NEC glazing an aesthetic benefit in addition to the reduced cost of the new coating as compared with the CEC which use an expensive vacuum-based coating [41]. The availability of NEC glazing in markets raises the competitiveness of the EC glazing as it leads to the lower lifecycle energy cost of about 15% to 21% compared with CEC. The orientation of the building plays a role in energy saving with NEC glazing; with south facing façade, a recorded energy savings of 6% to 10% in the commercial buildings and 8% to 15% in residential buildings [41].

- Dual-band electrochromic glazing:

This is a composite glazing that combines the properties and switching ranges of previously discussed CEC and NEC glazings. As a newer and dynamic switching window, DBEC glazing is commercially available, driven by the novel advances in material science. Dual-band ECs are capable of transitioning between each of the above states. As with NEC, it can be manufactured in a potentially lower capital cost process, with a less energy intensive application and annealing process [42].

3.2. Windows Orientation and Size

Authors of ref [16] studied the energy consumption of the electrochromic glazing system with moderate and large size windows. The research found that the electric demand decreased 7-8% for the moderate size of windows and 14-16% for large windows in both climates [17, 32]. Another study compared the effectiveness and benefits of electrochromic windows and BIPV façade in terms of energy consumption. Focusing on vertical elevations, the results found that energy savings of EC glazing system for the south, east, west and north orientation about -2.86%, 1.35%, 0.89% and 7.41% respectively.
### Table 2. Comparison of EC glazing systems [41, 43]

| EC GLAZING TYPES | Conventional electrochromic (CEC) | NIR-switching electrochromic (NEC) | Dual-band electrochromic (DBEC) |
|------------------|-----------------------------------|-----------------------------------|---------------------------------|
| Films material   | Tungsten oxide films              | Antimony-doped tin oxide (ATO) Nanocrystal | Indium tin oxide Nanocrystal (ITO). |
|                  | Antimony-doped tin oxide (ATO) Nanocrystal | Transparent conducting oxides (TCOs) | Niobium oxide (NbOx) glass |
|                  | Transparent conducting oxides (TCOs) | Bulk tin-doped indium oxide (ITO) | |
|                  | Bulk tin-doped indium oxide (ITO) | Aluminum-doped zinc oxide (AZO) | |
|                  | Aluminum-doped zinc oxide (AZO) | | |

| Thermal performance | Conventional electrochromic (CEC) | NIR-switching electrochromic (NEC) | Dual-band electrochromic (DBEC) |
|---------------------|-----------------------------------|-----------------------------------|---------------------------------|
| Films material      | Highly effective in cooling loads reduction | Transmitted more insolation than optimal during portions of the year | Glare induced in winter from mid to late afternoon for south facing windows. |
|                      | Reducing glare while modulating daylight to capture electric light savings. | less significant in savings in hot, cooling-dominated regions | Insolation values will peak in midmorning hours based on the position of the sun. |
|                      | | | Glare control increases occupants comfort. |

| Energy saving | Mediterranean climates: 54% | 6 to 11% commercial buildings | Most apparent in cold region. |
|---------------|----------------------------|-------------------------------|-------------------------------|
| Perimeter zones: 10%-20% | 8 to 15% for residential buildings | In regions with less cooling loads is lower but still optimal. | Savings intensity is strongest in southern regions. |

| Lifecycle cost | Manufacturing cost durability, and other properties continue to improve incrementally. | 15–21% lower than comparable CEC glazing. | |

Katanbafnasab and Abu-Hijleh [14] tested seven EC glass configurations in terms of the tinting level: 15%, 30%, 45%, 60%, 75% and dynamic tinting. The model simulated 4 days in the year to cover the four seasons, 21 March, 21 June, 21 Sept. and 23 Dec with all four orientations considered. The results show that EC windows are able to reduce the annual energy consumption by 11.2% for the south dynamic tinting configuration façade and 75% for north EC windows. There was however an increase in annual energy consumption by 5.4% because of the artificial lighting demand as less natural light passes into interior spaces due to the high tinting level. The east and west facades only produced an annual energy savings of 1.4%.

3.3. Climate Zones

EC glazing provides a responsive control based on the exterior climatic/environmental conditions by using control variables such as daylight illuminance, space thermal load and incident or transmitted solar radiation [17, 32, 44]. Technically speaking, the higher temperature of the glazing surface –as a direct result of the prevailing climatic conditions, the lower the electrical power needed to switch [45]. Authors of ref. [39] investigated the energy performance of ECs windows in the cold climates where this technology can reduce the cooling loads by offering a low solar gain coefficient. In addition, the study notes lighting loads reductions by preserving an adequate high visible transmittance (VT) of 62% while allowing 47% of incident solar radiation. This required meeting the appropriate daylighting properties by providing needed glare control [46, 47]. Another research [16] studied the energy consumption of
the electrochromic glazing system with moderate windows size; tested in hot (Houston) and cold (Chicago) climates. The research found that the electric demand decreased by 7-8% [17, 32]. Granqvist [42] reported that the total annual energy saving for EC glazing is low in hot climates when using near-infrared electrochromic (NEC) windows. However, in the cold northern regions, the energy savings was more significant by 9% for some buildings type.

4. Further Research
Based on the current status of EC performance based on typology, climate and Further work is required to develop a unique matrix EC device which both manufacturers and designers can adopt to facilitate the development of case-specific prototypes. This is one of several other pathways for future research to harness the innovative potentials for EC glazing. Some of these include:

4.1 Polymer-based EC devices
Electrochromic coatings are generally considered as a low-cost alternative in themselves which are suitable for window retrofits [27]. However other cost effective options such as polymer-based materials are also being investigated as material alternatives [9]. The next generation of materials must provide not only cost savings but lower environmental impact; as such [48] has called for proper life cycle investigations in this regard.

4.2 Near-Infrared Electrochromic (NEC) Devices
The global warming potential (GWP) of the NEC technology is 50 kg CO2 and the cumulative energy demand (CED) is 1050MJ-eq/m2. Its energy savings in primary energy demand is 38% more and GWP is 42% less compared to CEC devices. A shift from CEC to NEC technology would open more opportunity to investigated increased energy saving and less CO2 emissions [48].

4.3 Self-tinting windows
Self-tinting windows work automatically in direct correlation to energy from the sun without using wires or any kind of controls. They do not require special skills to install, electrical contractors or drilling holes into siding and framing, as well as no accessories needed [49]. Such qualities have significant potentials in time saving construction strategies; investigation on aspects such as user control and cost comparisons will be crucial to justify its marketability.

4.4 Electrochromic windows powered by photovoltaic (PV)
This novel concept to design PV-EC devices consists of the electrochromic solution with electrical disposal between the layers of transparent non-conductive and semitransparent substrate (Figure 2, 3) [50]. By their design, the transparency and color contrast of such novel technology are improved. The electrical power is produced and generated by the PVEC which can be controlled by an additional output switch [51]. Future research will focus on the energy saving and life cycle of such novel EC glazing technology.
4.5 Customized EC glazing

The idea of customized innovative building components was expressed in a previous job as a driver for adoption in the case of Building integrated photovoltaics (BIPV) [29]. As a result, innovations like EC glazing require investigation to determine key customization requirements and strategies for multiple client preferences; specifics relating to aesthetics, shading or privacy as “soft” aspects should be matched with other issues such as EC type, cost, or size.

5. Conclusion

This review points out the state of the art of electrochromic advanced fenestration systems by investigating the technology in terms of its design and energy-saving potential. The paper shows several types of electrochromic systems, presents the key performance issues in terms of energy efficiency which is achieved to meet those performance requirements.

Generally speaking, energy savings reduction from the daylighting show that the total annual energy saving is low in hot climates when using near-infrared electrochromic (NEC) windows. However, in the cold northern regions, the energy savings were more significant by 9% for some buildings type. Some regions experience the decrease in energy saving by 2% or less. However, in other cases using DBEC glazing, the energy savings increase by 10%. Clearly, the identified energy saving parameters in this study have a significant impact on the percentage savings of the EC device. This study has paved the way for further research into the case-specific designs which can meet individual client preferences while maintaining measurable savings for economic benefits.

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