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Term 1 Research Paper

The trade-off between visual and thermal considerations in the design of solar control.

Can Electrochromic technology change the field of solar control by introducing a new equilibrium to this trade-off?

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ABSTRACT

The old contradiction in building design between allowing daylight, solar heating and clear views through windows versus blocking undesirable solar gain, has led to the development of various solar control strategies throughout the years. This paper aims to bring these traditional strategies of solar control together with recently introduced adaptive glazing technology, which claims to revolutionize this field by reaching a new equilibrium between visual and thermal aspects. This paper will question these claims and highlight key parameters for the implementation of adaptive technologies into the solar control design field.

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ACKNOWLEDGMENTS

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1. INTRODUCTION

Solar control strategies - fixed past vs. Adaptive future

Different methods of classification were applied to solar control strategies that highlighted different criteria and marked the technological and conceptual evolution in that field; the basic division had traditionally been between inner shading and external shading. However, as solar control glazing technology emerged (e.g. low u-value glazing and low-e coating), the classification had shifted to differentiate between inner, mid pane and outer pane strategies. Nowadays, following the introduction of high performance glazing[1] and the growing need to balance between visual and thermal comfort all year round, the criteria of dynamic solar control has become more and more relevant.

The introduction of new technologies such as switchable glazing, automated louvers or automatic inter-pane blinds already shifts the classification again, this time towards the criteria of adaptability.
Rather than the dynamic or retractable technologies, adaptive technology constantly reacts to the external conditions and thus holds the potential for optimal efficiency of solar control function. In difference to other switchable technologies (photo- and thermo-chromics) which feature environmentally driven switching, Electrochromic (EC) glazing can dynamically modulate its transmittance in response to electric stimuli and thus could be controlled and switched at will. This potential marked EC as the most promising switchable technology and much attention was brought to its development to fit the building industry (See appendix for more data regarding EC technology).

However, regardless of these new technological achievements, in many built examples, solar control strategies (if even considered), are being constantly mismatched or misused, thus result in visual and thermal discomfort in buildings; The gap between knowledge and practice in solar control design is commonly associated with the lack of awareness designers have towards solar control principals; However, we must also recognize the shortcomings of current methodology to address the confusion between different glazing standards and units, and the need to set new criteria of comparison between traditional strategies and new solar control technologies that regard the balance between visual and thermal aspects differently.

In the light of the discussion about the adaptive future of solar control, this paper will focus on four key parameters for the architectural consideration of the new dynamically adaptive technologies. These key parameters could serve as starting points for designers to fit EC and other new technologies to the existing platform of solar control design:

- *Control and adaptability*
- *Visual quality*
- *Thermal vs. visual comfort*
- *The Human (user) Factor*

Each of these parameters will be used to evaluate EC technology and compare it against traditional solar control applications; through that, new possible questions and dilemmas will be indicated for the future of adaptive solar control design toward adaptability. In conclusion, this paper will discuss the ability of EC technology to change or solve the trade-off between thermal and visual considerations in solar control design.

[1] 'High performance' is referred to here as glazing which has the property of selective transmission to radiation that, by having lower transmittance in invisible part of the spectrum, reduces solar gain to a greater extent than the visible daylight (Baker 2007)

2. CONTROL AND ADAPTABILITY

Current Solar control strategies differentiate in their ability to be controlled by the user: While interior shading devices such as venetian louvers or vertical rolling blind could be easily controllable, glazing solar control is fixed and thus uncontrollable and exterior shading could be controlled usually only by applying sophisticated and usually costly technology.

Electrochromic (EC) technology is activated solely by the user (manually or automatically), thus the user interface and the control methodology are both critical issues to the system's efficiency. The EC system could be integrated with various other building systems for automatic control. However, a problem of balancing between visual and thermal considerations could occur when the control over the EC system is aligned with only one system while neglecting other considerations; For example, if the control over the glazing transmittance will be dictated by an illuminance sensor the daylight levels might be optimized while the thermal considerations might be compromised. This could be partly solved by the development of different algorithms that will optimize different aspects during different times of year or fit different locations. Another major drawback of EC technology is its relatively long switching time which makes it less intuitive and dynamic when controlled manually (Figure 2.1). Moreover, current technology offers mostly control between bleached and tinted phases; intermediate phases which are vital for EC system efficiency are still being developed and studied (Figure 2.2).

Adaptation of current solar control strategies is commonly limited to retractable elements which mostly act on on/off switching (e.g. blinds that operate up and down). Venetian blinds introduce more adaptive opportunities by allowing intermediate phases of adjustments to varying conditions by the user. However, their light and mobile structure limits their use to the interior and usually interferes with window opening and ventilation (Baker, 2002).

EC is a highly-adaptive technology. As different from the thermo or photochromic technologies which respond to only one fixed condition (temperature and light levels respectively), EC is responsive to electrical stimuli. That property enables it to disconnect from any fixed factor of adaptability, to be coupled with different sensors (hardware) or algorithms (software), and by that respond in real time to limitless conditions. However, EC technology will be highly adaptable only if considered in very early design phases and with very high level of collaboration between architects and engineers. Moreover, once the system is implemented it cannot be modified or retracted. These pose a great challenge for EC technology to adapt to the currently "fragmented building industry" (LBNL 2006), and combined with the risk and cost issues which serve as market barriers to EC marketability, tag EC as a high end technology for "intelligent" buildings only.

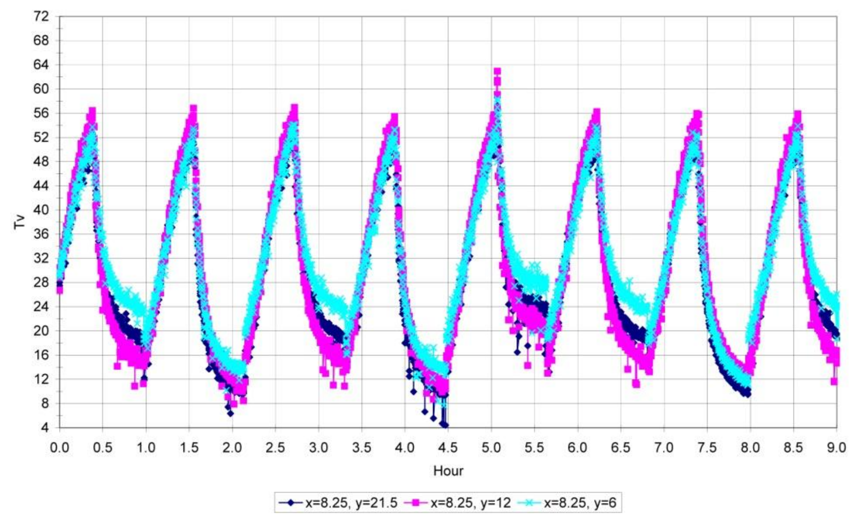

Figure 2.1 Graph illustrating the switching time cycles of EC technology. Switching between colored (Tv = 0.13) and bleached phase (Tv = 0.56) could take up to 37 minutes. (Source: LBNL)

Figure 2.2 Solardigm vision of intermediate EC user control through personal tablet; Current interfaces account for colored/bleached phases only. (Source: Solardigm)

3. VISUAL QUALITY

The term 'Visual quality' was addressed here in its broader context and included the following criteria: (1) glare prevention, (2) preservation of the view to the outside, (3) indoor and outdoor appearance.

Glare - The use of common solar control applications separately to prevent glare, currently involves a trade off with other important considerations of solar control; for example, using internal vertical roller blind which is one of the most commonly used application against glare will block the visual connection to the outside, and is less effective thermally. This results in solar control strategies being coupled together (e.g. an exterior overhang with an internal retractable louvered blind) which could result in rather costly and sometimes complicated daylight systems.

EC technology manufacturers claim to prevent glare as part of the "all in one" solution by modulating the glazing transmittance to diffuse unwanted direct solar radiation. However, LBNL field tests had shown that when using EC technology, disability glare which is caused by the direct exposure to the orb of the sun, could not be avoided and opaque venetian blinds must also be installed to achieve comfort. Moreover, in order to reduce glare, EC glazing shifts to its maximum colored state which substantially reduces the visual connection to the outside.

View - Most of the current internally used solar control applications to some extents obstruct or interfere with a clear view to outside; though vertical roller blinds could be half transparent and venetian blinds could be modulated, the view is almost always compromised (Figure 3.1).

EC technology offers the advantage of being able to provide views outside for higher percentage of the day (LBNL), (Figure 3.2). When considering the importance of the visual contact between indoors and outdoors and its correlation to productivity and visual comfort, this advantage could become a key motivator to apply EC technology in the future.

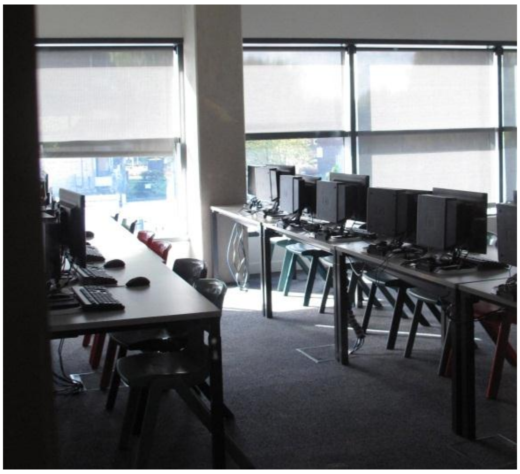

Figure 3.1 Photograph of a classroom in London showing how roller blinds which were lowered to reduce glare block the view to outside.

Figure 3.2 Image illustrating EC windows preserving view to outside while modulating solar transmittance. However, direct sun patches can be clearly seen even in the colored phase. (Source: Solardigm).

Appearance & Aesthetics – Though we would expect the traditional solar control applications which are rooted deep into our building tradition to be harmonized with the overall expression of our buildings, the debate on the relationship between the environmental performance and the architectural expression of buildings has yet to be fully understood (Yannas 2012); In some cases, the exterior solar control application is regarded by the architect as an add-on which interferes with the overall look of the building and thus avoided, internal shading which than usually retrofitted after occupation could conflict with the rather clean look the architect had envisioned (Figure 3.3). However, more and more built examples account for better integration of solar control strategies and environmental features into the architectural expression of buildings (Figure 3.4);

Figure 3.3 Internal venetian blinds poorly retrofitted into a new building in London.

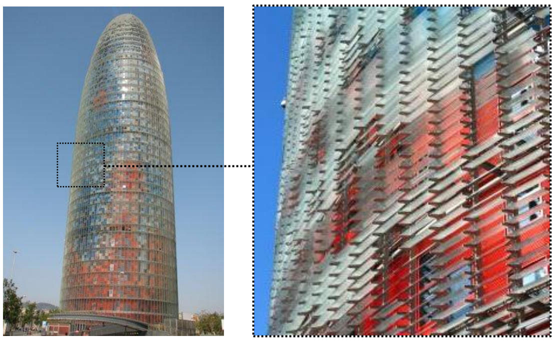

Figure 3.4 Torre Agbar, Barcelona demonstrates solar control application as a major feature in the design of the tower (Jean Novel Architects)

EC technology is aiming to supply the desirable all-glazed appearance of buildings without any additional exterior attributes or add-ons. However, this feature does not come without a penalty; although it is argued that "…EC offers a potential dynamic envelope to a building, thus adding significant advantages to the building's architectural style and aesthetic appeal" (S. Papaefthimiou 2010), EC's dark blue tint dynamic aesthetics introduces a critical question whether that specific feature would fit the architect's vision of the building (Figure 3.5).

Moreover, when EC widows will be installed side by side, it is likely that tint colors between windows would not match and the façade can have a slight to noticeable checkerboard appearance (LBNL 2006), (Figure 3.6). Adding to that the bluish color effect of EC glazing on the interior and the non-uniform coloration which is noted in the process of switching, the overall categorization as EC technology as "aesthetic" should not be taken for granted.

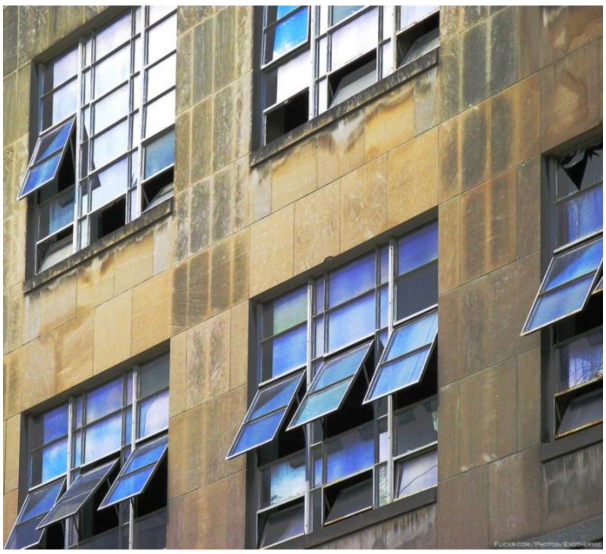

Figure 3.5 Photograph showing the EC dark blue tint effect on the overall appearance of an exterior façade. (Source: NREL)

Figure 3.6 Photograph showing multiple EC windows installed side by side, resulting in checkerboard pattern. (Source: LNBL)

4. THERMAL VERSUS VISUAL PERFORMANCES

Glazing technology has evolved immensely since clear single glazing performance, and nowadays through applying different manipulations and technologies, the designer is offered a variety of products that aim to improve the thermal performance while allowing as much visible transmittance through the glazing. While double glazed low-e coated systems has become the most commonly used amongst these products; fritted, tinted reflected and lately high performance glazing products introduce more sophisticated approach toward the glazing energy balance, the latter being the most promising with the ability to modulate between the visible and invisible spectrums (figure 4.1).

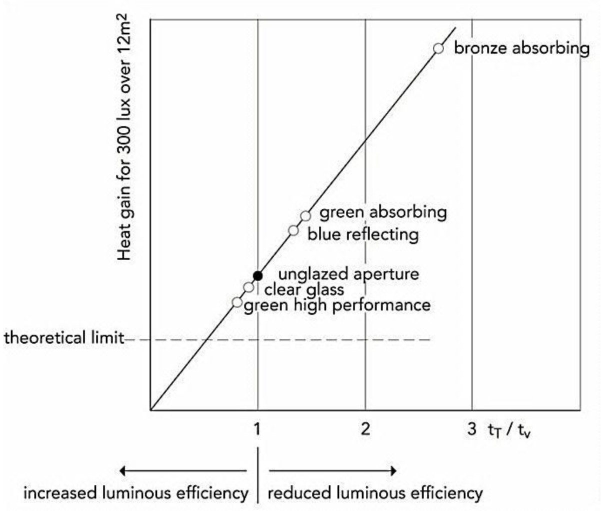

Figure 4.1 Graph showing solar heat gain plotted against the ratio of total transmittance to visible transmittance, for a given average illuminance of 300 lux, illustrates the efficiency of high performance glazing compared to other glazing products (Source: Baker 2007).

However, as these glazing control products' properties are fixed, their ability to respond to different climatic conditions is restricted; Moreover, as they aim to block excess high gains due to solar radiation, these selective transmittance materials would fit mostly hot climates with mild winters in which useful solar heat gains are not accounted for. (Baker 2007)

As response to the increasing demand for year round high thermal and visual performance, more integrated solar control approaches had been introduced such as the one introduced by N. Baker as "High Performance Daylighting". This approach strives to reach optimal performance by harmonizing both selective and dynamic solar control methods; this is done by taking all the functions which are required from the glazing system into considerations and adding the important feature of daylight distribution across the room.

By using the principal of absorbance of solar radiation, EC at its tinted phase reduces both visible and invisible transmittance, while at its clear phase allows both of them in. This might have been considered as a thermal performance problem in both phases – overheating at its tinted phase by the high temperature of the heat absorbed glass, and additional overheating at its clear phase when invisible transmittance is allowed inside; However, by installing the tinted EC coating at the second surface of the outer glass of double glazing system (Figure 4.2), and achieving relatively low g-value in its clear state (Figure 4.3), these two challenges are faced respectively.

Figure 4.2 Diagram of a typical EC insulating glass unit (Source: Sage Electrochromics)

	bleached					coloured				
Manu-facturer	T_{vis}	$R_{vis,\ out}$	SHGC (g value, TSET)	U value $Wm^{-2}K^{-1}$	Inter-mediate states possible	T_{vis}	$R_{vis,\ out}$	SHGC (g value, TSET)	U value $Wm^{-2}K^{-1}$	Standard
Asahi	0.70	0.11			yes	0.20	0.06			ISO9050
FLABEG	0.50		0.36	1.3	yes	0.15		0.12	1.3	DIN 52619
Gentex device 1	0.81	0.09			yes	0.05	0.05			ISO9050
Gentex device 2	0.82	0.09			yes	0.25	0.06			ISO9050
Inter-pane	0.58	0.25	0.49	1.0	not yet	0.13	0.07	0.13	1.0	ISO9050 /ISO150 99
SAGE	0.70		0.51	1.9	yes	0.04		0.09	1.9	NFRC
Saint-Gobain	0.47	0.14	0.28	1.4	yes	0.10	0.08	0.11	1.4	ISO9050 /ISO150 99

Figure 4.3 Different technical properties of chromogenic glazing products showing relatively low g-value in bleached phase (Source: IEA Task 27)

EC manufacturers claim to reach the balance between thermal and visual considerations single handedly, year round and across the day by modulating transmittance from clear to tinted phases:

"...It is a beautiful and cost-effective way to control sunlight without shades or blinds, so you can manage glare and heat while maintaining a connection to the outdoors." (Sage Electrochromics)

However, studies had shown that when the EC window acting as both the shade and the daylight provider, there is no optimal balance between daylighting for energy efficiency and direct sun control, because satisfying one criterion would be to determine the other (S. Papaefthimiou 2010 after Lee and DiBartolomeo, 2002), (Figure 4.4). Thus to supply both thermal and visual considerations which are bound together in one element, it would probably be required to couple EC windows with both opaque shading system for its clear phase and artificial lighting for its colored phase to achieve adequate overall thermal and daylight performance (and also visual quality as shown in the previous chapter).

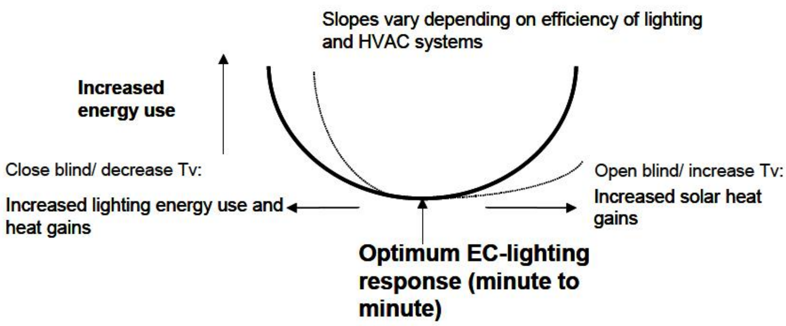

Figure 4.4 Real-time trade-offs between cooling and lighting energy use. (Source: LBNL)

5. THE HUMAN (USER) FACTOR

When evaluating the performance of available active solar control applications, we must take into account the critical influence of the occupants' behavior on their efficiency; Even though it is expected that occupants of buildings equipped with sophisticated manually controlled solar control systems would modulate these system accordingly to achieve optimal comfort conditions, in most cases it proves otherwise; Interior blinds or louvers are usually being left down even when glare control is not anymore needed, thus views are blocked and lighting energy increases. The fact that these applications are usually shared between few occupants and lack fixed 'owners', in addition to other operational disadvantages like noise, distance from the window pane or too complicated user controls lead them to be misused in many cases (CIBSE 1999).

As the acceptability of EC technology by the occupants had been recognized by the manufacturers and researchers as a critical element to its adoption and marketability, a considerable effort had been made in recent years to study the occupants' attitude towards EC through various observations and surveys. Some of these studies involved real human subjects who performed office tasks in a working environment in which EC and standard windows with solar controls systems where installed and compared. Although the overall results of these studies indicated that the occupants' response to EC windows was largely positive, occupants responded negatively to some user oriented aspects of EC performance that require attention: the rendering coloration of EC, lack of control over individual EC window panes, long switching time and the shortcomings of the transmittance range of EC to solve glare issues where mentioned by the occupants; Moreover, some occupants even preferred EC windows to be darker in their colored phase to satisfy privacy issues (Lee and DiBartolomeo, 2002).

The overall positive occupants' reaction toward EC is encouraging on the one hand, however the negative feedbacks of occupants mentioned above could easily become the market barriers which would prevent this technology form being widely implemented, and thus should be further studied accordingly. The lack of intuitive use of EC technology by the users in comparison to the well know traditional solar control applications such as louvers or blinds should also be taken into account when considering the human factor influence on the system's efficiency.

6. CONCLUSIONS

Electrochromic technology has introduced considerable advantage and innovation to the solar control field by being able to dynamically modulate direct solar gain while maintaining the view to outside.
Nevertheless, these advantages do not come without a price, and as this paper showed, multiple questions rise regarding EC technology application, control, functionality and its ability to fit or replace current solar control methodology. These 'warning points' for EC technology could be highlighted through the main criteria which had been used in this paper, and serve as a starting point for a wider debate regarding the new challenges for solar control technology;

Control and adaptability – Linking new technologies with building management system opens a new world of possibilities for improved efficiency and performance. However, while functional adaptability of new solar control applications is extremely needed, these applications must also demonstrate flexibility in their implementation, cost and interface in order to fit the existing building industry and currently used systems.

Visual quality – the 'all in one' promise of one product to supply optimal comfort in some case might prove wrong; it might still be needed to look at solar control as a systems to achieve overall comfort, certainly when taking into account the response to extreme conditions such as disability glare. The visual effect of new technology should be carefully considered in order not to dictate certain look that might conflict with the architect's vision of the building.

Thermal vs. visual comfort – when visual and thermal considerations are bound together such as in EC, satisfying one criterion will come on the expense of the other. The assumption that when reduction in solar gain is needed, also less visibility is acceptable (and the other way around) might limit the users to achieve comfort in only specific conditions.

End user experience – The human factor is crucial to the marketability of new technologies; thus major development should be conducted regarding user interfaces, intuitivity of use and intermediate controls to achieve best efficiency and acceptability by the users.

EC technology modulates both ends of the tradeoff between thermal and visual comfort, thus balancing between these aspects with EC will always be associated with compromising one or the other. The need to couple EC with other solar control application undermines one of the fundamental advantages it brings. Studies and research have proved EC technology to have energy savings potential to reduce heating, cooling and ventilation loads, specifically in hot climates; thus it is expected to gain increasing recognition and marketability during years to come, assuming that it will overcome great current market barriers such as its increased cost, immature product phase and wide users' acceptance.

Bringing EC technology together with current solar control strategies, in the light of the increasing need for adaptive opportunities in buildings, raises fundamental questions for further research regarding how solar control strategies should be assessed, designed and implemented to fit the adaptive future of solar control for better comfort and efficiency.

APPENDIX

Electrochromic glazing technology - short introduction.

Electrochromic (EC) glazing technology is part of a broader category of switchable glazing technologies. These can dynamically change their transmittance in response to different conditions (thermal, electrical or visual). While photo- and thermo-chromic technologies feature environmentally driven switching, EC glazing can be controlled and switched at will, thus much more attention was brought to its development to fit the building industry.

EC coating is a thin (nano-meter thick) film coating consists of five layers of ceramic material that changes appearance from clear to dark blue tint when applied a low voltage of electricity. This voltage drives lithium ions and electrons from one EC layer to another and causes the window to switch from clear (bleached) mode to dark (tinted mode) (Figures 7.1-3). The EC coating is applied on the interior surface of the exterior pane of a double glazing system. By shifting between clear and dark modes selectively, EC windows can control the amount of daylight and solar gain penetrations through the glazed area, and thus have the potential to maintain the view outside while controlling transmitted light, glare and solar heat gains. Typical visible transmittance of EC glazing will range between 10 and 70 % between bleached and colored modes respectively, while the g-value will typically range between 0.1 and 0.5 for the same modes respectively. Switching speed between bleached and colored phases will vary mostly as a function of glazing size and temperature – switching time will be reduced in colder temperatures and higher glazing areas (large area windows on a mild climate measured 20-40 minutes of switching time).

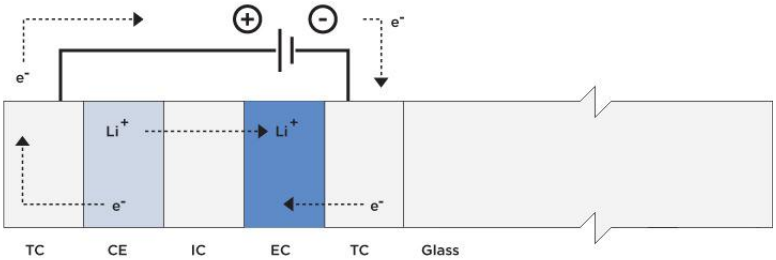

Figure 7.1 Diagram of a typical electrochromic coating layers (Source: Sage Electrochromics)

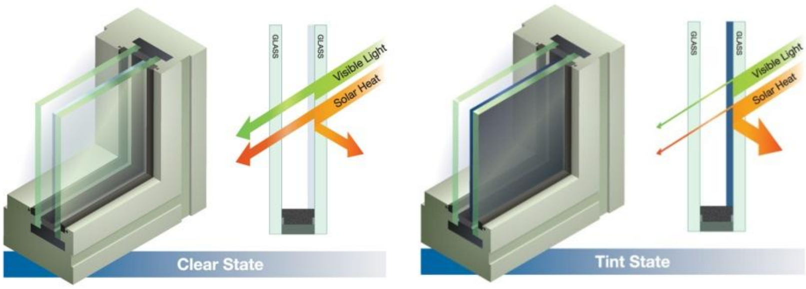

Figure 7.1 Electrochromic windows in a fully bleached state (left) and fully colored state (right). (Source: Solardigm)

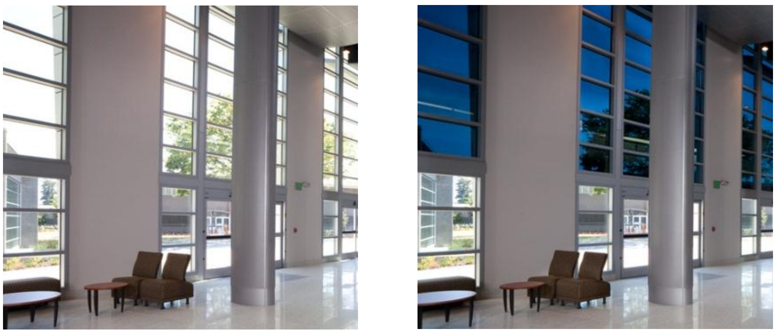

Figure 7.2 Electrochromic windows in a fully bleached state (left) and fully colored state (right). (Source: Sage Electrochromics)

A series of experiments, reports and studies were conducted regarding EC over the past 20 years, mainly by collaborations between manufacturers and research institutes. The most notable among them were the SWIFT (Switchable Façade Technologies) project in 2000 supported by the EU, and the LBNL (Lawrence Berkeley National Laboratory) study that followed by a detailed report in 2006. LBNL studies showed that compared to effective Low-e system, EC window could achieve 19-26% annual peak cooling load reduction and 48-67% of lighting energy use savings when control for visual comfort was applied (LBNL 2006). The complete energy balance for an EC window with expected life time of 25 years was studied (Figure 7.3), and it was concluded that cost savings could range up to 569€/m^2 for that period (Papaefthimiou 2010).
Lately, the potential of EC for reducing both cooling and lighting energy had been recognized and referred to in the annual 2007 UNEP report where the trade-off between cooling and lighting energy consumption was studied for different glazing types (Figure 7.4).

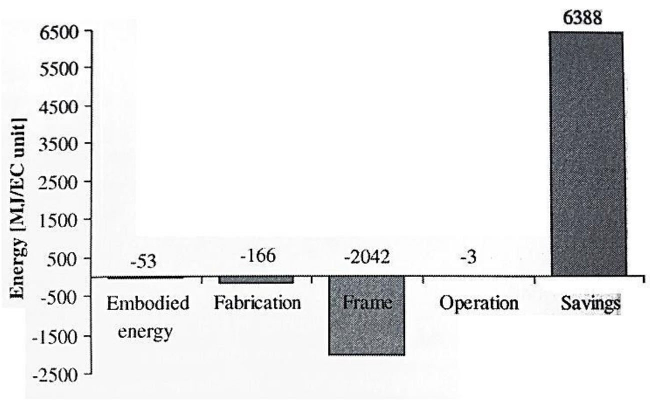

Figure 7.3 Energy analysis of EC prototype window (Source: Papaefthimiou et al, 2007)

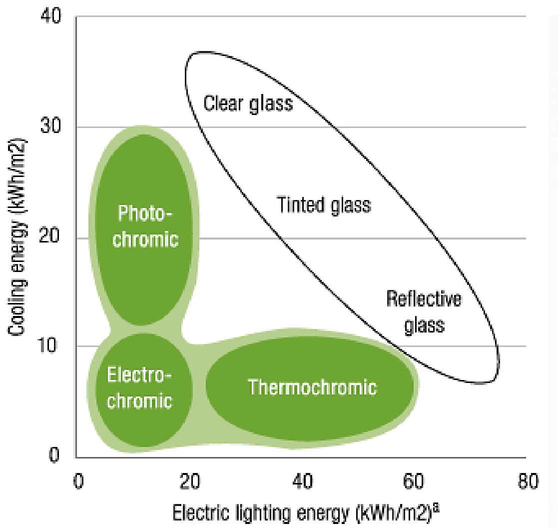

Figure 7.4 Lighting energy versus cooling energy for different glazing types (Source: UNEP 2007)

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