Challenging Glass 5 – Conference on Architectural and Structural Applications of Glass
Belis, Bos & Louter (Eds.), Ghent University, June 2016.

ISBN 978-90-825-2680-6

New Developments in Dynamic Glass: Towards a New Era in Sustainable Construction

E. Sok [a] & H. Sanders [b]
[a] *Vetrotech Saint-Gobain, France, Eloise.Sok@saint-gobain.com*
[b] *SAGE Electrochromics, Inc., U.S.A.*

Today's green building certifications such as LEED, BREEAM, and HQE all recognize that a sustainable design is not just about energy efficiency and all integrate sections related to indoor environment quality, such as provision of natural daylight and views through windows. Yet, on the other hand, with the increasing stringency of building energy efficiency targets in Europe and indeed globally, we are observing an increasing trend to reduce window area in new building energy codes, as windows are often seen as the weak link in the building envelope. Creating both energy efficient and comfortable well daylit spaces could thus be a significant design challenge. Electronically tintable glass, also known as electrochromic (EC) glass, allows the building façade to become dynamic, changing the transmission of the solar heat and light in response to the exterior environment and the needs of the building's occupants, while always remaining transparent. It thus offers a solution which avoids having to trade off daylight and views with energy performance, allowing more glass to be used without energy penalty AND without causing thermal or visual discomfort for occupants. New developments in the EC technology are reviewed here, as well as a range of new case studies of retrofit and new construction, where dynamic glass has provided increased flexibility for designers, and optimum balance between energy performance and comfort. In all cases, this technology empowered the architect to achieve sustainable design goals, without restricting their design freedom and aesthetics choices.

Keywords: Dynamic Glass, Electrochromic Glass, Green building, Daylighting, View, Solar control, Comfort, Sustainable design.

1. Introduction

1.1. The importance of the built environment for human health

From very early on man has been living outdoors and has evolved to need exposure to sunlight for our health and well-being. With the advent of architecture, man has sought means of replicating this natural light, and has developed artificial lighting to provide lighting on demand. Such invention has freed us from daylight dependence and has transformed the way we live and build. Today we spend around 90% of our time in enclosed spaces, lit with fluorescent light and in which daylight harvesting has been progressively neglected.

It is only recently that scientists have started to understand how light influences our body and mind. In addition to the cells that contribute to the formation of images, our eyes also contains cells responsible for the so-called "non-visual effects" of light (Bernson et al. 2002). Those cells are light-sensitive and key for the regulation of several of our biological functions such as sleep, mood, alertness etc. A lack of daylight exposure at the right time or too much of the wrong color light at the wrong times can thus cause several disorders both in the short term and long-term. Such risks include circadian rhythm disruptions, increased gastrointestinal disorders, increased cardiovascular disorders and cancers, risks for mental health issues (stress, depressions), brain and reproductive effects (Veitch et al. 1996; Vandewalle et al. 2010; Munch et al. 2012; Beute et al. 2014).

Recent research, in particular in "biophilic design" has also stressed out the role of connection to nature in supporting our health and well-being, which can be achieved through external views (Terrapin Bright Green, 2014; Hellinga 2013; Beute 2014). And those also play a key role in our satisfaction with the built environment, since it also depends on information not related to the task in hand, such as the hour of the day, the seasons, the weather etc.

Today, there is a vast scientific literature demonstrating both the negative impact of poorly daylit and view-less spaces on day-to-day mood, job satisfaction, and even health, and alternatively the benefits of daylight and associated views in most building use types (Elzeyadi, 2011, Walch et al. 2005; Choi et al. 2012; Heschong et al. 2002; Ulrich 1984; Farley 2001). Studies cover all building use types, such as hospitals, schools, offices and even retail spaces.

A recent report from the World Building Green Council (2014) have shown that there is "overwhelming evidence" that demonstrates the design of an office significantly impacts the health, well-being and productivity of the employees. It reveals thatun-adapted indoor temperatures could result in a reduction in performance by 4 to 6%, And thatworkers with windows sleep an average of 46 minutes more per night.

Moreover, since employees' salaries and benefits can be responsible for 90% of an organisation's expenditure, designing "green", daylit and comfortable spaces has also become a real opportunity for owner-occupiers, developers and tenants for value creation (Brager 2013).

1.2. A real design challenge
Given the findings described previously, one understands the importance of putting humans at the core of one's design strategy.

Green building certifications such as LEED, BREEAM in the UK, HQE in France, all recognize that a sustainable design is not just about energy efficiency and all integrate sections related to indoor environment quality. Those include, for example, access to natural light, quality views through windows, protection from glare, thermal comfort. However, all those criteria could be very difficult to achieve at the same time through a conventional static building envelope that cannot adapt to the changing exterior conditions.

Today, interior shades, mostly manually controlled, are often used to protect occupants from glare; however their effectiveness in preventing overheating issues is very limited. Plus, using manual blinds can also be detrimental to the space's energy and human factors performance, since they usually remain lowered long after the initial disturbance has gone. In that case, the space can no longer benefit from passive heating nor daylight harvesting, resulting in higher heating and electrical lighting needs and the needed views and daylight exposure for occupants are also lost. Many studies have shown that people are not active blind users and blinds are moved infrequently and are often left pulled, covering the majority of the window area, especially the top of the window which is most effective for daylighting (Paule, 2015).

Automated, exterior blinds then constitute the state-of-the-art dynamic solution to protect from both excess of light and heat and because of automation can help optimize the trade-off between glare control, daylight admission and energy performance. Yet, once in the down position the potential benefits of daylighting and views are offset. In addition, those system cannot be used in certain weather conditions and require on-going maintenance.

In addition, the role of windows, and more importantly the amount of glass that should be used, has been questioned back along with the increasing stringency of building energy efficiency targets in Europe and indeed globally. Due to their lower insulation performance and higher solar heat gain compared to an opaque wall, windows are indeed often seen as the weak link in the building envelope, leading to an increasing trend to reduce window area over the last few years. And with the target set by 2010 Energy Performance of Buildings Directive (EPBD) to achieve nearly zero-energy buildings by 2020 in Europe, the pressure for energy efficiency use has never been so strong, and hence the impact on glass use.

The recent research findings regarding non-visual effects of light has risen back awareness on the importance of daylight and views for people, and pushed designers and builders back to consider daylight and views as key design parameters. Some European countries have already introduced a daylight factor and minimum glazing requirements within their national construction regulations such as UK and France. However the debate still continues, even when it comes to defining standards on daylight and lighting in buildings.

Considering all the factors described above, creating energy efficient and comfortable daylit spaces could thus be a significant design challenge, schematically represented in Figure 1.

Fig. 1 A pictorial representation of the Green Building Challenge. The challenge is how to optimize both energy efficiency and daylight and views without compromising occupant comfort.

2. An elegant response to the sustainable design challenge

An elegant solution in response to that design challenge is Electrochromic (EC) glass, which enables to control the amount of visible light and solar heat gain entering a space, over a large range that varies between 60% and 1% in visible light transmission and 0.40 to 0.05 in solar g-factor, as shown in Figure 2. The modulation of light and heat can be controlled through building automation system, or at the touch of a button, so to dynamically adapt to the external climatic conditions and occupants needs, with no moving parts. EC coatings can be integrated in double or triple glazing units, with a second low emissivity coating to meet the specific insulation requirements (see Figure 3).

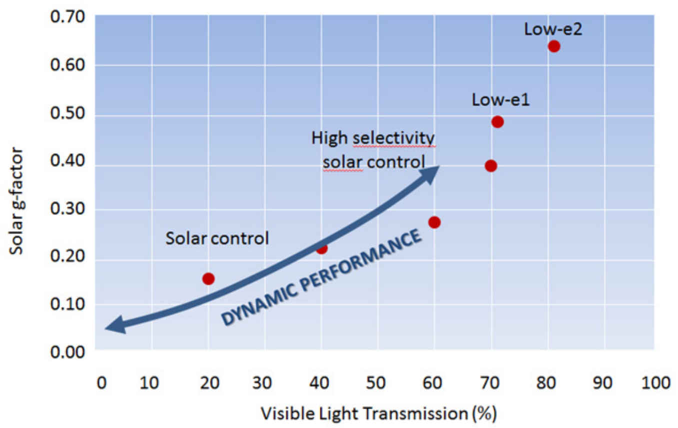


Fig. 2 Graph of visible light transmission versus solar g factor which demonstrates the heat gain and light transmission range of EC glass compared with examples of standard static glass.

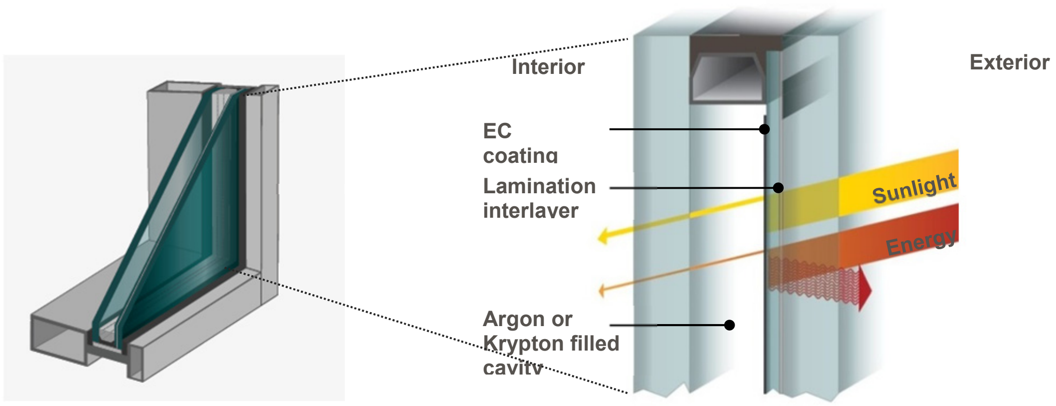


Fig. 3 All ceramic thin film electrochromic insulating glass unit.

With such specificities, EC glass can have a significant impact on reducing the energy bill. During the heating season, EC glass reduces the need of heating by providing passive solar gains when clear. During the cooling season, it minimizes the cooling loads when tinted. It also allows optimum use of the daylighting during all year long, limiting the use of electrical lighting. Past studies done for European climates have shown that EC glass could save up to 34% in cooling loads and 29% in electrical lighting use (Jestico 2015). Note that automatically continuously dimming lighting controls should be used in combination to EC glass to achieve maximum savings.

In terms of occupant comfort, EC glass is also able to manage efficiently glare issues without using blinds. Indeed, past studies have shown that 1% visible light transmission is required to be able to control extreme glare situations effectively (LBNL 2006; Kelly et al. 2013). However, the view and connection with the outside world is preserved, providing the occupant an enhanced indoor comfort.

As previously mentioned, the quality of light is also part of the equation of our satisfaction with the visual environment, which implies a good color rendering. That aspect is also key to defining the atmosphere of a space. Although EC glass tends to appear blue-gray colored when tinted, studies (Mardaljevic 2014) have confirmed the empirical observation that the light in spaces equipped with EC glass is essentially the same as in spaces glazed with clear glass, as long as a small proportion of the glass is kept in the highest transmittance state. Figure 4 shows the spectral power density of the light coming through EC glass in the fully clear and fully tinted states. As can be seen, the flat nature of the spectrum of light coming through the clear state demonstrates that the spectrum of daylight is not significantly altered. However, light transmitted through the fully tinted state takes on a blue hue, as shown by the peak at around 450 nm.

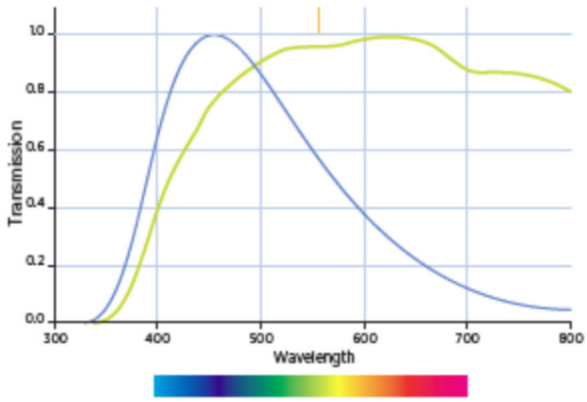
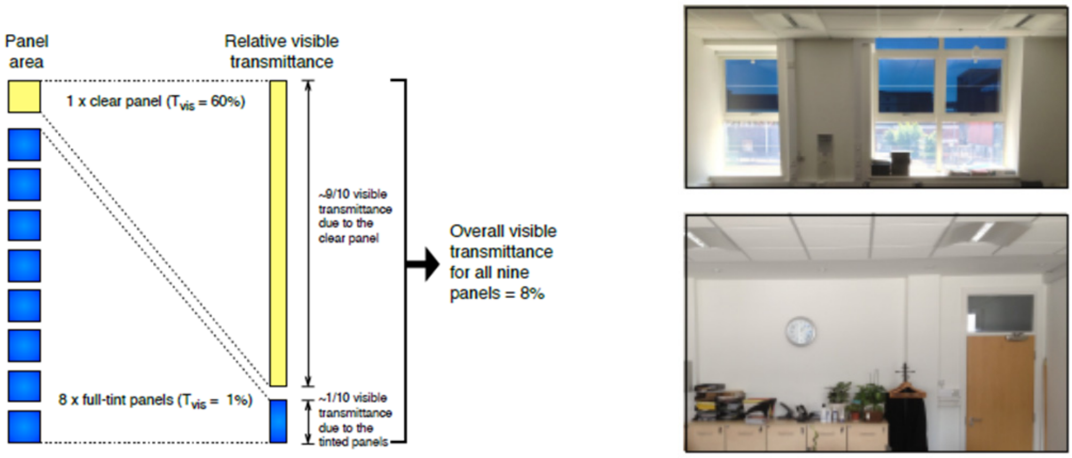


Fig. 4 Transmission spectra of light coming through EC glass in the fully clear (green line) and fully tinted (blue line) states.



a) b)

Fig. 5a) Combination of one EC glass pane set to clear and eight set to full tint. The majority of the visible transmittance is that due to clear glass, resulting in dominantly neutral light in the space (Mardaljevic, 2014). b) Photos of the room facing the EC windows and the wall opposite the windows, showing that the color of the light is essentially neutral at al positions of the room. The color rendering index (CRI) measured was 93, which is generally accepted good color rendering (Mardaljevic, 2014).

The conservation of color neutrality when the EC glass is appropriately zoned can be explained by the fact that the EC glass area in the clear state is responsible for the majority of the light coming in the space since it transmits 60% of the light, while the tinted state only transmits 1%. Since light passing through the clear state remains essentially neutral, and assuming good light mixing, the overall illumination of the space appears essentially neutral. Figure 5a) shows the resultant spectral power densities of light coming through combination of differently tinted EC zones. Figure 5b) shows pictures of the office room where the study was conducted and the resulting light color.

In contrast to static facades with mechanical alternatives, by using EC glass the benefits of daylighting are not outweighed by the problems of overheating and glare. This thus allows designers to use more glass to reach the daylight harvesting potential, maintain exterior views, and meet their aesthetics and design desires, without energy or comfort penalty.

3. New developments in dynamic glass

Since its first commercialization in the U.S. market in the early 2000s, electrochromic glass has undergone significant developments, especially in the last couple of years. These developments have allowed architects higher design flexibility, while providing the optimum balance between energy performance and comfort. Among the key improvements are:

- Increased size availability (up to 1,50m x 3, 05m)
- Availability of a range of exterior colors (neutral, green, blue, gray, bronze) for architects to choose from to match their project color aesthetic (see Figure 6)
- Improved reflected color characteristics
- Visible light transmittance down to 1% in the fully tint state, for effective glare control
- New geometric shapes (e.g. triangles, see Figure 10), giving architects additional design freedom
- Ability to control independently up to three different areas of a single EC glass pane as different segments (see Figure 7)

Fig. 6 Examples of different exterior color aesthetics in EC glazing (from top left to bottom right: Classic, Green, Blue, Gray).

Fig. 7 Example of one of the new developments in EC glazing: in-pane zoning. This shows EC glass installed in a refurbished building in Switzerland with the top of each pane in a tinted state and the bottom in a clear state. ©Vetrotech Saint-Gobain.

The latest so-called in-pane zoning characteristic is essential in the case of façades using single large panes to span most or all of the floor to ceiling height in order to effectively co-optimize glare control, daylight admission, light color quality and energy performance. Indeed, effective glare protection requires the glass to tint at 1%T, however this could be counterproductive in terms of daylight admission and light color quality, if the whole façade is fully tinted. With the ability to tint several zones within a pane to different transmission states, glare can be managed through fully tinting one fraction of the EC glass, while allowing sufficient daylight admission and managing color quality by leaving the remaining parts in intermediate and clear states. With this new in-pane zoning characteristic of EC glass, optimized performance across multiple parameters can thus be achieved, without the need of adding mullions in the framing system.

4. Case studies

4.1. EC glass in retrofits: Solving thermal and visual comfort and energy efficiency problems while preserving historic appearance

EC glass can be used in retrofit applications to solve overheating and glare control issues, while preserving the historic building appearance. Figure 8a) and b) illustrate the case of the iconic Modissa upscale retailer located in one of the most fashionable shopping street in Zurich, Switzerland, before and after renovation with EC glass. The façade was originally made of bronze-tinted double glazing with associated internal blinds. EC glass was used as a response to the thermal and visual discomfort caused by the intensity of the heat and light transmitted by the large windows. EC coated glass was used in combination with a bronze tinted glass to match the color appearance of the original façade, and the interior blinds were totally eliminated. This solution provides the customers with a totally new experience with access to natural light and unobstructed views, as shown in Figure 9. From the exterior, the walkers can enjoy the elegant and refined façade of the fashion store without the visual obstruction of the exterior blind system.

EC glass also ensures excellent protection against fading and sun damage to the interior clothing and furniture of the store. Indeed, fabrics are highly sensitive not only to UV light, but also to visible light and direct heat. EC glass blocks 99% of the light including UV and visible wavelengths responsible for fading in the fully tint state and 87% in its fully clear state.

Fig. 8a) and b) The exterior façade of Modissa fashion store, before and after retrofit with EC glass. ©Vetrotech Saint-Gobain

Fig. 9 The interior of Modissa fashion store. EC glass is used to provide customers a pleasant indoor feeling and an unobstructed view of the Bahnofstrasse in Zurich. ©Vetrotech Saint-Gobain.

4.2. Allowing more creative and better learning environment

The Frost School of Music at the University of Miami, a LEED Platinum modern music academy designed by HOK, uses EC glass to offer a more comfortable and creative environment for music making, while also meeting aggressive energy-efficiency goals.

In South Florida, the light and the sun is particularly strong due to the steep angle of the sun. But natural lighting and outdoors views are also of high importance to stimulate the creativity and learning of the students. Thus, EC glass is a good fit to maintain the views and keep people comfortable inside, while meeting the sustainable design goals searched by the architect.

Besides, arrays of triangular EC glass were used for the first time to give the façade a distinctive visual statement and the exterior shading that would have otherwise been necessary to make the interior comfortable and minimize energy impacts would have detracted from the triangular design. Figure 10 shows outdoor and indoor views of the school.

Fig. 10 Exterior and interior of the LEED Platinum-Frost School of Music at the University of Miami. EC glass enhances the indoor environment by providing natural light and outdoor views to the beautiful lakefront campus throughout the day. Photographer: Moris Moreno.

4.3. Creating expansive views of nature without compromising thermal and visual comfort

Ashford Castle, a luxury hotel located in the western part of Ireland, has used EC glass mounted in curtain wall for its spa and fitness room to enhance the customers experience looking for rest reshaping and relaxation. Some pictures are shown in Figure 11.

In the space dedicated to the spa, high performance thermal insulation was required to maintain a comfortable indoor thermal environment, even under very low external temperatures which is quite frequent in this part of Ireland. In the fitness room, limiting the unwanted solar energy was the main objective due to high internal heat gains generated by the people while exercising. On the other hand, preserving the transparency of the glass was also a key objective since people staying at the hotel come to enjoy the surrounding beautiful and peaceful environment, and as we know, views of nature reduce stress and can help people relax.

Given the large area of glass, it would have been a real challenge to achieve such a level of performance and comfort with conventional solutions. Now, EC glass enables to eliminate glare and keep thermal comfort during all seasons, while simultaneously offering splendid and expansive views to the gardens and to Loch Corrib, second largest lake in Ireland.

The combination of EC glass and clear fritted glass in the clerestory windows enable to achieve an excellent color rendering, which was also an important requirement here.

4.4. Enhanced comfort in work places with EC glass

Daylight and views are highly preferred by office workers over window-less places with electric lights, and are likely to enhance work and well-being in several ways including job satisfaction, perceptions of self-productivity and physical working conditions.

BCS, one of the most renowned façade engineering offices in Switzerland, perceived EC glass as an innovative and adapted solution to bring all those benefits and respond to many of its customers' needs. Thus, BCS recently retrofitted their meeting room with EC glass to be able to experience it themselves. Now, the staff members can continuously benefit from daylight and views without heat and glare issues while working, which is a real and unprecedented transformation in their working conditions.

Fig. 11 The exterior and interior of Ashford Castle Hotel & Spa. EC Glass offers a unique experience to the customers looking for reshaping and relaxation. ©Vetrotech Saint-Gobain.

The use of EC glass also reflects some core values of the company as transparency and quality, which their customers and collaborators can immediately feel when visiting their offices. Figure 12 shows some pictures of those offices. Note how the color rendering in the space looks neutral because of the use of in-pane zoning which enables the combination of zones in the clear state and zones in the tinted state in a same glass pane.

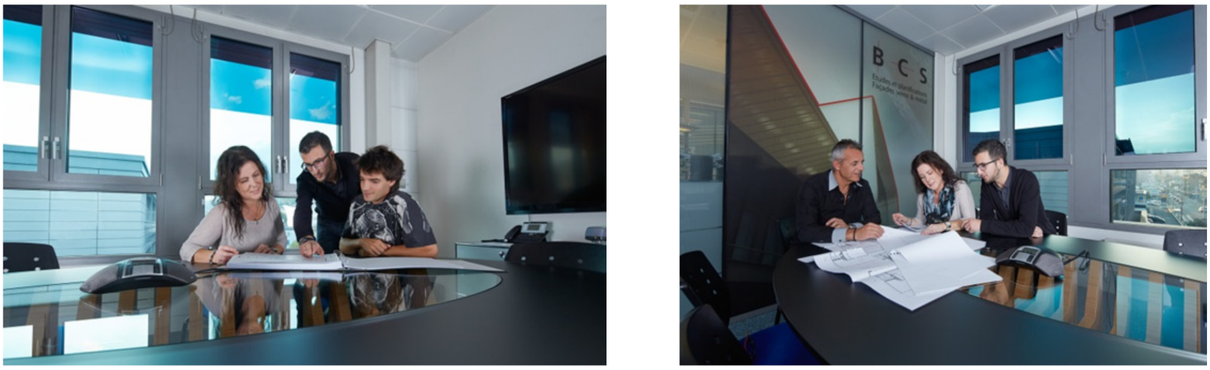


Fig. 12 Offices in Neuchatel equipped with EC glass and in-pane zoning. The upper zone is in the fully tinted state to black glare while the lower zone is in the clear state to admit sufficient daylight. Views to outdoors are maintained all the time. ©Vetrotech Saint-Gobain.

4.5. Green healthcare

Improved daylight admission and views to nature have been shown to increase recovery rates of patients in hospitals and reduce the use of pain medication (see, for example, the foundational study by Ulrich in 1984 (Ulrich 1984) and a summary of the literature developed by Velikov and Janiski commissioned by Guardian Industries (Velikov and Janiski 2012)). Also, when infection control is so important, the elimination of blinds which can harbor dirt, dust and bacteria is another key benefit for EC in healthcare applications - allowing comfortable daylighting and views with improved infection control.

Figure 13 shows some images of a healthcare application at Butler County Medical Center in Nebraska where EC glass has been used to provide an open air feel and an expansive view for the occupants of the new wellness center of the park and golf course it overlooks. The dynamic curtain wall tints automatically to tame the sun's glare while still flooding the center with natural light.

The wellness center features a unique, curved south-facing glass curtain wall that offers beautiful views of a park and golf course. Due to the complex curvature of the curtainwall and non-rectangular shapes, mechanical shades would have been problematic not just because of infection control.

Using EC glass helped the wellness center achieve its design goals of creating openness and a strong connection with the community, an important objective for this high-profile showcase project.

Fig. 13 Butler County Medical Center, Nebraska, US. EC helps a glass-enclosed wellness center tame the sun's glare and provide a comfortable healing environment. ©Daubman Photography.

5. Conclusions

EC glass has the potential to provide a step change in the way architects design buildings. While sustainable design codes and certifications increasingly highlight the importance of providing daylight and views, yet doing so often requires a trade-off between energy performance and occupant thermal and visual comfort.

Dynamic glass provides the ability to adapt the incoming heat and light to the occupant's needs, simultaneously maintaining access to views and a connection to the outside world, freeing the architects from the constraints enforced by conventional building envelopes when balancing architectural design with occupant comfort and energy efficiency. They allow designing well-daylit spaces, by achieving energy efficiency goals without continuing down the path of reducing window area.

The new developments in dynamic glass aesthetics and functionality described here, such as the capability of providing higher volumes of glass for larger building applications, improved exterior color aesthetics, and in-pane zoning, as well as the case studies presented, demonstrate that EC glass can provide a really elegant façade solution to meet the "green building challenge", i.e. achieving high energy performance, daylight harvesting and views, without compromising occupant comfort or the aesthetics of the façade design.

With the increasing stringency in energy efficiency targets and the progressive integration of "human" centric aspects in the sustainable construction standards, the interest and adoption of EC glazing technology is growing rapidly, and is on a path to becoming a standard sun management solution in the market.

References

Berson, D. M., Dynn, M. F., Takao A., Phototransduction by retinal ganglion cells that set the circadian clock, Science, 295: 1070–1073 (2002)

Beute, F.: Powered by Nature, the psychological benefits of natural views and daylight. Eindhover : Technische Universiteit Eindhoven. doi: 10.6100/IR780722 (2014)

Beute, F. and A.W. De Kort, Y., Salutogenic Effects of the environment: Review of health protective effects of nature and daylight, Appl. Psychol. Health Well Being, 6(1): 67-95 (2014)

Brager, G.S.: Benefits of improving occupant comfort and well-being in buildings. Proceedings of the 4th international Hocim Foundation (2013)

Choi, J-H., Beltran L. O., Kim H-S., Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility, Building and Environment, 50: 65-75 (2012)

Elzeyadi, I.: Daylighting-bias and biophilia: quantifying the impact of daylighting on occupants health. Available at: http://www.usgbc.org/sites/default/files/OR10_Daylighting%20Bias%20and%20Biophilia.pdf. Last accessed 19 September 2014.

Farley, K. M. J., Veitch, J. A.: A room with a view: a review of the effects of windows on work and well-being, IRC Research Report RR-136, Canada (2001)

Hellinga H.: Daylight and View – Iinfluence of view in the quality of indoor spaces (2013)

Heschong, L., Wright, R. L., and Okura, S., Daylight impacts on human performance in school, Journal of the Illuminating Engineering Society, 31: 101-114 (2002)

Heschong-Mahone Group, Daylighting in Schools: An Investigation into the Relationship between Daylighting and Human Performance, Fair Oaks, CA: Heschong-Mahone Group (1999)

Heschong-Mahone Group, Windows and Offices: A Study of Office Worker Performance and the Indoor Environment, Sacramento, CA: California Energy Commission (2003)

Jestico D.: Performance assessment of SageGlass electronically tintable glazing. Presented at 14th International Conference on Sustainble Energy Technologies, Notthingham (2015)

Kelly, R., Mardaljevic., J., Painter, B.: Preliminary Findings of a Case Study into The Application of Electrochromic Glazing in a UK Office. LUX Europa (2013)

LBNL Windows and Daylighting Group: Advancement of Electrochromic Windows PIER Final Project Report, CEC-500-2006-052 (2006).

Mardaljevic, J., Kelly Waskett, R., Painter, B.: Electrochromic Glazing: Avoiding the Blues, CIBSE ASHRAE Technical Symposium, Dublin, Ireland (2014)

Mardaljevic, J. : How to maintain a neutral daylight illumination with SageGlass EC Glazing. Available at: http://sageglass.com/wpcontent/uploads/2011/08/How_to_maintain_neutral_daylight_illumination_wtih_SageGlass_EC_Glazing.pdf

Münch, M., Linhart, F., Borisuit, A., Jaeggi, SM., Scartezzini, JL., Effects of prior light exposure on early evening performance, subjective sleepiness, and hormonal secretion. Behavioral neuroscience, 126(1): 196-203 (2012)

Paule, B., Boutillier J., Pantet, S., Global lighting performance, Annual report 2013-2014. Project 81 0083: Swiss Federal Office for Energy, Lausanne, 2014.

Terrapin Bright Green, LLC: 14 Patterns of biophilic design – Improving health & well-bing in the built environment. Available at: http://www.terrapinbrightgreen.com/report/14-patterns/ Last accessed 5 September 2014 (2014)

Ulrich, R., View through a window may influence recovery from surgery. Science, 224:420-421 (1984)

Vandewalle, G., Schwartz, S., Grandjean, D., Wuillaume, C., Balteau, E., Degueldre, C., Schabus, M., Phillips, C., Luxen, A., Dijk, D.J., Maquet, P. The spectral quality of light modulates emotional brain responses in humans. Proceedings National Academy of Sciences, USA, 107(45): 19549-19554 (2010)

Veitch, J. A. and Gifford, R., Assessing beliefs about lighting effects on health, performance, mood and social behavior, Environment and Behavior, 28 (4): 446-470 (1996)

Velikov, K., Janiski, J., The Benefits of Glass, A literature Review on the Qualitative benefits of Glass on Building Occupants. The University of Michigan Taubman College of Architecture and Urban Planning. Commissioned by Guardian Industries (2012)

Walch, J.M., Rabin, B.S., Day, R., Williams, J.N., Choi, K. and Kang, J.D., The effect of sunlight on postoperative analgesic medication usage: A prospective study of spinal surgery patients. Psychosomatic Medicine, 67(1): 156-163 (2005)

World Green Building Council: Health, Wellbeing & Productivity in Offices – The next chapter for green building (2014)