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Chapter 6.3 Innovative Glazing Materials

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Innovative Glazing Materials

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Abstract

Windows have the unique capability of being able to achieve a *net zero* energy impact by admitting solar gains in the winter to offset thermal losses and admitting daylight to offset electric lighting. If rejection or admission of solar heat gains and daylight are appropriately timed, then heating, cooling and lighting energy use at the perimeter zone can be reduced to net zero energy levels. Nano-scale switchable coatings on glass have been developed to actively modulate solar intensity and spectral transmission. We provide a brief overview of these switchable glazing materials, discuss the desired performance objectives for such materials, and present results from recently completed monitored studies of state-of-the-art switchable windows, particularly with respect to occupant response and market factors. Careful application of state-of-the-art switchable windows and new material science developments on the horizon can deliver the desired net zero energy performance while meeting critical human factors and market related requirements.

Keywords: Electrochromics; Thermochromics; Switchable windows; Smart windows; Solar control; Daylighting; Building energy efficiency; Building controls,

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1. Introduction

Over the past forty years, there has been substantial progress towards improving the energy-efficiency of windows. Low-emittance (low-e) coatings introduced in the 1980s enabled significant reductions in radiative heat transfer. Sputtered low-e coatings combined with an inert gas (i.e., air, argon, or krypton) in a dual-pane insulating glass unit (IGU) followed, with additional improvements to reduce thermal bridging through the window frame and spacers that make up the IGU. The center-of-glass U-value of windows was lowered from 6.19 to 1.65 W/m^2-ºK (1.09 to 0.29 Btu/h-ft^2-ºF). With increased stringency in building energy efficiency codes and standards and standardized labeling of manufactured window products, low-e windows have reached broad market adoption at a level of 80% in the US residential buildings sector and more than 50% in the commercial sector [1]. Research has continued to evolve with the goal of attaining a U-value that begins to approach that of an insulated wall. R&D areas include reducing heat transfer with light-weight, triple-pane IGUs, vacuum insulated glazings, aerogel transparent insulation, and continued frame improvements.

Control of solar radiation through windows occurred in parallel with the development of insulating windows. Between the 1950s to the 1980s, dark tinted and reflective glazings were developed to reduce total transmitted solar energy in residential and commercial buildings. These glazings significantly reduced daylight admission in buildings, increasing lighting energy use. To counter this negative impact, spectrally selective low-e coatings were introduced to the market in the 1990s, enabling selective admission of the visible (VIS) wavelengths of solar radiation while rejecting the near infrared (NIR). When combined with spectrally selective glazing substrates (e.g., blue or green glass) or low-iron clear glass, daylight and solar control performance could be further improved. Industry continued to develop multi-layer thin film coatings over the subsequent decades to improve spectral selectivity. The light-to-solar gain ratio (LSG), defined as the ratio of visible transmittance (Tvis) to solar heat gain coefficient ((SHGC) or g-value), has improved from 0.7 for conventional tinted glass to 2.3 for today's most advanced commercially available products. These glazing products let in three times more daylight for the same level of solar control, enabling simultaneous reductions in lighting and cooling energy use in buildings that have consistent cooling loads throughout the year (e.g., buildings in moderate to hot climates or internal-load dominated commercial buildings).

Technological advancements in energy efficient windows have been exceptional but address only a fraction of the full energy savings potential of windows. Windows have the unique capability of being able to achieve a *net zero* energy impact by admitting solar gains in the winter to offset thermal losses and admitting daylight to offset electric lighting. If rejection or admission of solar heat gains and daylight are *appropriately timed* (e.g., based on season, cloud cover, occupancy, heating or cooling mode of the HVAC system), then heating, cooling and lighting energy use at the perimeter zone can be reduced to net zero energy levels. Dynamic facades enable such control through active modulation of the inherent properties of the window's glazing (i.e., "switchable" window coatings that switch from clear to a tinted state or a clear to light-scattering state, based on a given input such as applied voltage) or adjustment of indoor or outdoor shading devices at the facade.

Windows can be attributed to about 30 percent of the total heating and cooling loads in buildings and about 4.3 EJ (4.1 quads or 4.1×10^{15} Btu) of primary energy use in the United States, 87% of which is due to conductive and solar loads, and 12% of which is due to infiltration. An additional 1.06 EJ (1 quad) of lighting energy can be offset by daylight through windows and skylights. If dynamic windows are actively controlled based on solar heat gains, an estimated technical potential of 2.6 EJ (2.47 quads) in primary energy savings could be attained. If dynamic windows are constructed with a highly-insulating window configuration (U-value of 0.85 W/m^2-ºK (0.15 Btu/h-ft^2-ºF)) and controlled to minimize lighting and HVAC energy use, an additional savings of 5.13 EJ (4.87 quads) could be attained, resulting in windows being a net energy *producer* rather than a consumer of energy [2].

In vernacular architecture, this dynamic optimization was innately understood and implemented to varying degrees with manual adjustments to shades and shutters on a daily and seasonal basis for solar control and daylighting, passive solar heating, and natural ventilation. Much of this practice was lost with the introduction of centralized heating and cooling systems in the 1950s, enabling large expanses of glass in buildings without regard to energy use. In the late-1970s however, automated solar control and other active load management strategies were implemented to demonstrate the energy-savings potential of actively managed systems during the energy crisis created by the OPEC oil embargo [3]. In the 1990s, active double-envelope facades that enabled natural ventilation, heat extraction, and heat recovery were of significant interest [4]. Today, however, dynamic facades are still the exception, not the rule. Macroscopic shading systems such as automated motorized shades have not achieved significant market penetration despite their commercial availability.

While there are many types of dynamic façade technologies, this chapter focuses narrowly on achieving building energy-efficiency objectives with switchable glazings. Nano-scale switchable coatings on glass provide the building industry with dynamic, energy-efficiency windows that are integral with the very fabric of the building envelope and as such have broad applicability to residential and commercial buildings. These switchable glazings can be designed and controlled to react or adapt to changes in the indoor and outdoor environment or user-defined criteria in order to conserve energy and improve comfort and quality of life.

This chapter provides a brief overview of switchable glazing materials that have been developed since initial prototypes first exhibited the chromogenic phenomenon in research labs in the late 1960s [5]. The desired and actual physical attributes of state-of-the-art switchable windows are discussed. Findings from recent monitored case studies in real world buildings are described, providing insights into how human factors can affect energy-efficiency potential. We then discuss future work needed to realize full technical and market potential. The chapter is written with a focus on commercial building applications and is based primarily on R&D conducted by scientists at the Lawrence Berkeley National Laboratory (LBNL), but lessons learned are likely to be extensible to other countries around the world.

2. What's needed: Technological solutions and performance objectives

2.1. Switchable glazing materials

There are a broad range of switchable glazing materials that provide intensity, spectral, and light-redirecting control of incident solar radiation. A comprehensive review of the broad range of nanotechnologies available for improving the energy-efficiency of optical materials is given in [6]. We describe the make-up and properties of a few key devices that provide intensity and spectral control:

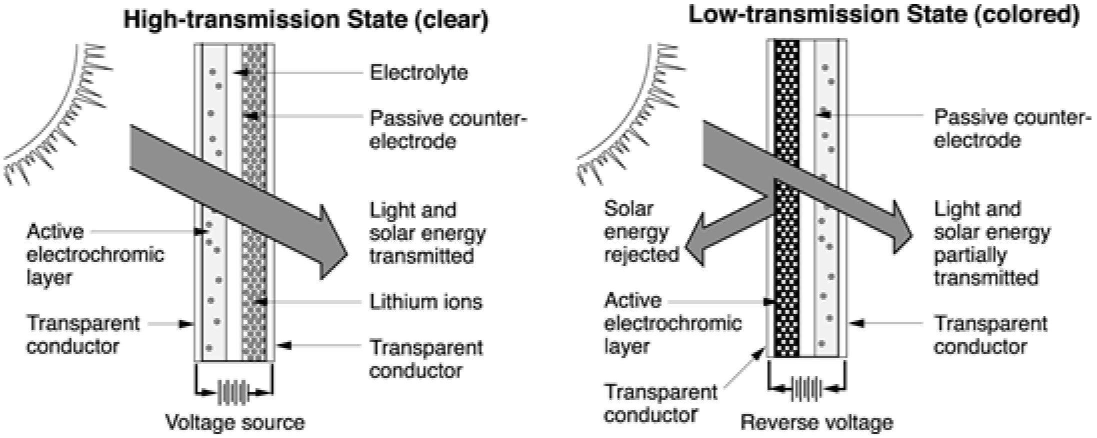

Figure 1. Diagram of an electrochromic device in its clear (left) and tinted (right) states.

Electrochromic (EC) glazings. An electrochromic device or coating is a multi-layer thin film stack deposited on a glass or plastic substrate [7-12]. The stack consists of an active electrochromic layer, an ion-conducting electrolyte layer and passive counter electrode layer all sandwiched between two outer transparent conductor layers (Figure 1). When a bipolar potential is applied to the outer transparent conductor layers, ions migrate across the ion-conducting electrolyte from the counter-electrode to electrochromic layer causing a reversible electrochemical reaction to occur. The reaction is exhibited by tinting of the glass layer. When the potential is reversed, the ions are withdrawn from the electrochromic layer, causing the glazing to return to its original clear or bleached appearance. The coating is switched using a small applied potential (around 3-5 V dc) and when unpowered, the EC typically switches to a clear state. Transparent view is maintained over the full range of switching.

The design of this multi-layer stack dictates the switching properties of the coating – spectral range of switching, how fast it switches, color when switched, power consumption levels, etc. State-of-the-art EC windows are based on tungsten oxide which exhibit a Prussian blue color when activated with a lithium ion exchange. Most sputtered switchable devices that are commercially available today fall under this category. EC devices produced on plastic or metal foils using roll-to-roll processing have also been developed and can be configured as a laminate or between-pane suspended film window.

Other metal oxide devices have been under development to reduce cost, improve color efficiency, and achieve color neutrality when switched [13]. Advances in material science have demonstrated that EC devices can switch faster without haze using nanoparticles to increase ion conductivity in the electrolyte layer. Nanoparticles have also been used to increase NIR absorption and decrease solar heat gains without reducing VIS/ daylight transmission [14].

Gasochromic glazings. This thin film is similar in principle to EC glazings in that it switches reversibly from a clear to tinted transparent state but is activated by the insertion and removal of a gas into the air cavity between the two layers of glass [15]. Exposure of the film to hydrogen gas causes the thin film to tint. Exposure to oxygen causes H_2O to form and the film to bleach. The film switches much faster than EC coatings but exhibits a lower contrast ratio (ratio of bleached to colored state) compared to EC glazings. Activation requires careful proper implementation of the gas insertion and extraction process over the broad hot-cold cycling of temperatures that windows are subjected to. To improve thermal performance, the dual-pane gasochromic must be combined with a third glass layer with a sputtered low-emittance coating, whereas with EC windows, the low-e properties can be incorporated within the dual-pane unit. There are a few commercial products currently available in the European Union. Complexity of installation may be a significant market barrier.

Reflective metal hydrides. Almost all commercial and research EC windows are absorptive devices, reducing effectiveness of solar heat gain rejection. Research conducted in the 2000s demonstrated the feasibility of glazing materials that switch from a transparent to reflective, mirrored state with either applied voltage or exposure to hydrogen gas [16-17]. This type of material would be considerably more efficient at rejecting solar radiation compared to absorptive devices [18] but it faces the same market challenges that prior static reflective glazings faced in the 1980s; e.g., zoning regulations restricted use of reflective mirrored windows in many cities.

Near-infrared plasmonic electrochromics. Organic NIR electrochromic materials have been demonstrated as feasible with properties of fast switching speed, high contrast ratio, long term stability, and low cost [19]. As an example, a spectrally-selective NIR EC demonstrated a large spectral shift in the NIR region when degenerately doped semiconductor nanocrystals were activated with an applied voltage [20-22]. Unlike absorptive broadband EC devices, these narrowband devices have the potential to minimize HVAC energy use independently from lighting energy use. Energy savings were estimated for residential and commercial building applications in the US [23] but savings were less than optimal due to the modest NIR switching range of the modeled window (40% NIR modulation for the initial prototype). Additional study is warranted.

Electrophoretic or suspended particle devices (SPD). SPDs are similar to electrochromic glazings in that they switch between a clear and tinted transparent state. The mechanism for switching is however quite different from that of an EC device. When voltage is applied, randomly oriented suspended particles are aligned, allowing light to be transmitted (the SPD has a dark tint when unpowered). The film emulsion switches within a few seconds, exhibits a contrast ratio greater than that of EC devices, but requires a higher voltage (65-220 V ac) to operate and constant power to maintain the window in the clear state (2-16 W/m^2). SPDs were introduced to the US market in the late 2000s as a film that could be cut to size then laminated between glass, but durability was determined to be limited (<1000 cycles) [13, 24].

Thermochromic (TC) glazings. Thermochromic glazings consist of a thin film polymer or inorganic coating on glass that switches passively from a clear to tinted state in response to glass surface temperature (transparent in all states). Like photochromic glazings, which switch based on amount of incident light, these passive technologies offer variable solar-optical properties without the need for power or controls. The transition or critical temperature can be tuned by the material composition; some devices switch over a very narrow range of temperatures (which can have a variegated appearance if the window is non-uniformly irradiated) while others exhibit thermochromic behavior over a broad range of temperatures. Thermochromics typically exhibit absorption in the visible range (380-780 nm) when switched. There is ongoing R&D to develop devices that selectively switch in the near-infrared (750-2500 nm) at critical transition temperatures useful for achieving building energy-efficiency goals. Recently a NIR-switching vanadium dioxide thermochromic polymer film was developed using tunable and reflective nanoparticles [25]. The technical potential for energy savings with broadband and NIR-switching devices was evaluated in a simulation and field study [26-27]. A photovoltaic-thermochromic prototype device composed of a metal halide perovskite-methylamine complex was presented recently that generates photocurrent when it reaches a critical switching temperature threshold (i.e., 35°C). The device switches from a high visible transmittance (Tvis=0.68) transparent state to an absorbing, photovoltaic colored state (Tvis<0.03) and produces efficient solar energy conversion at efficiencies as high as 11.3% [28]. A similar device was presented with a Tvis range of 0.82-0.35, a 7% peak efficiency, and transition temperature of 105°C [29]. These multi-functional materials add an exciting dimension to dynamic window applications and deserve further study.

Liquid crystal devices. Liquid crystal devices are similar to SPD devices in that when voltage is applied, the randomly oriented elements are aligned in a single direction. With liquid crystal devices, switching occurs from a light-scattering translucent state to a clear transparent state (on-off, no modulation between the two states). When power is removed, the “off” state is the light-scattering state. Polymer dispersed liquid crystal (PDLC) and encapsulated liquid crystal (NCAP) devices have been offered commercially. In the past, PDLC glazing was used for indoor privacy applications due to poor durability when exposed outdoors to ultraviolet (UV) radiation. Power requirements to maintain the window in a transparent state has also been significant (e.g., initially about1000 W/m^2, now 4-16 W/m^2). Most commercial devices have a minimal contrast ratio/ dynamic switching range (change in Tvis and Tsol of 0.02) but a few have exhibited a significant dynamic range [13].

A new transparent LCD device was recently introduced to the market [30-31]. The device switches continuously between a clear and dark tinted transparent state (without scattering) in less than 1 s at 0-80ºC and 10-30 s at -20ºC (for a 1.6 by 3.5 m area) and can be produced with a neutral color or other specified colors. The solar-optical range is not as broad as that of EC windows, producing greater modulation in Tvis than the SHGC range. The insulating glass thickness is at minimum 38 mm but can be produced in a variety of shapes (trapezoid, triangles, etc.). Another recent innovation includes an LCD window that can be subdivided into an array of individually-controlled sub-elements, where each sub-element can be switched to modulate transmitted solar intensity, offering the capability to control small sub-areas of the window for daylight and glare [32].

2.2. Properties of switchable windows for building energy-efficiency applications

We put aside for the moment the prodigious advances in material science that have occurred over the past few decades and review the *energy-efficiency* performance objectives that have shaped the direction of these technological advances. Initial design objectives were developed based on knowledge of fundamental building physics [33] and market studies then later refined based on feedback from detailed building energy simulation studies, field studies, and real-world experience in buildings (discussed in Section 3). Today, most objectives have been met to varying degrees with commercial products but lessons learned from early commercialization activities continue to be fed back to R&D activities to further improve performance. For reference, Table 1 summarizes the properties of switchable glazing materials discussed in Section 2.1.

Table 1
Properties of switchable glazing materials.

Device	Switching range				Ke range (Tvis/SHGC)		Switching speed	Color when switched	State unpow./ powered	No. of states	Operat-ing voltage	Power in transition; when static
	SHGC		Tvis									
Electrochromic: broadband	0.41	0.09	0.60	0.01	1.46	0.11	15-20 min for 90% of dynamic range	Blue	Clear/ tinted	Cont.[a]	3-5 V DC	3 W/m^2; 1 W/m^2
Electrochromic: broadband (laser-etched TCO)[b]	0.46	0.05	0.66	0.03	1.43	0.60	< 3 min for >25°C; 5 min at 10°C	Gray	Clear/ tinted	Cont.	48 V DC	14 W; 1 W
Gasochromics: broadband (3-pane IGU)	*0.01*[c]	*0.77*[c]	0.76	0.18	NI	NI	< 1 min	Blue	Clear/ tinted	Cont.	NA	NA
Reflective metal hydride	NI	NI	NI	NI	NI	NI	Instant	Mirrored	Clear/ mirror	2 states (on-off)	NI	NI
Electrochromic: NIR plasmonic[d]	0.67	0.3	0.78	0.69	1.16	2.30	NI	NI	NI	NI	NI	NI
Suspended particle device	NI	NI	NI	NI	NI	NI	1-2 s	NI	Tinted/ clear	2 states (on-off)	65-220 V AC	2-16 W/m^2; 2-16 W/m^2
Thermochromic: broadband	0.37	0.16	0.54	0.08	1.46	0.50	Gradual with temp (24-75°C)	Blue-gray	Clear/ tinted	Cont.	NA; passive device	NA
Thermochromic: NIR-reflective[d]	0.47	0.12	0.53	0.27	1.13	2.25	NI	NI	NA	NA	NA	NA
PDLC or LCD: broadband: privacy (indoor only)	Minimal change		0.85	0.75	NI	NI	< 1 s	White	Translucent/ clear	2 states (on-off)	65-110 V AC	NI
LCD: broadband (38 mm, 2-pane IGU)	0.36	0.22	0.58	0.27	1.61	1.23	<1 s at 0-80°C; 10-30 s at -20°C for 1.6x3.5 m area	Neutral or other colors	Tinted/ clear	Cont.	24/48 V DC	1 W/m^2; 1 W/m^2

[a] Continuous modulation; offered with 4 discrete states

b See Section 2.2.4 for a discussion of this device

c Asol values are given (SHGC not available)

d Hypothetical SHGC and Tvis based on [23,27]

NI: no information; NA: not applicable

2.2.1. Solar-optical performance of switchable glazing materials

Switching range. Generally, an ideal switchable glazing would have a Tvis range of 0-1 and a SHGC (or g-value) range of 0-1. For solar control, the ideal device would admit or reject solar radiation to offset heating or cooling requirements when needed. For daylighting, the device would admit daylight under overcast sky conditions but reduce daylight intensity during sunny periods to satisfy human visual performance and comfort requirements. Note that unlike operable window shades that can modulate day- and nighttime thermal and/or radiative performance through the raising and lowering of the shade, switchable glazing materials typically produce no change in U-value.

NIR and VIS switching range. In the early 1990s during the early stages of development, simulation studies were used to characterize the solar-optical range of switchable materials engineered to achieve intensity control within a specific range of the solar spectrum [34]. The analysis compared the Tvis and SHGC range of EC devices designed to provide broadband switching over the entire solar spectrum versus narrowband switching in just the VIS or NIR range. Narrowband switching in the NIR range, for example, maintained a relatively high switching range in Tvis while producing modulation in the lower SHGC range (analogous to static spectrally-selective low-e windows). Narrowband switching was set as a performance objective for commercial buildings because such materials enable daylighting and good solar control. With today's advanced materials demonstrating the ability to switch independently in the VIS and NIR range, further study is needed to develop revised performance objective guidelines.

Tvis of 0.01 and contrast ratio. Subsequent analysis in the mid-1990s addressing visual performance, comfort, and privacy shifted guidelines for material science R&D activities towards a significantly lower minimum Tvis. Switchable materials have physical limits in the contrast ratio that can be achieved between the bleached and colored states. The larger the ratio, the broader the dynamic range. Simulation studies indicated that if discomfort glare were to be controlled using switchable windows without the addition of an indoor shade, a Tvis of 0.01 or less would be required to maintain visual comfort when performing critical tasks involving computer displays if occupants had a direct view of the orb of the sun [35]. With an upper Tvis of 0.60 to maintain daylight, a contrast ratio of 60:1 is needed to satisfy both objectives. State-of-the art EC devices have been able to achieve a contrast ratio of 30:1 with a Tvis range of 0.60-0.02.

Blocking and admitting sunlight. A transparent state is assumed to be a fundamental property of all switchable glazings, since transparent views to the outdoors is the uniquely desirable property of windows. Discomfort glare could be managed using light scattering elements to block sunlight and/or admit diffuse daylight in lieu of switching to a very dark tint. If light-scattering materials such as liquid crystal devices are used to maintain comfort, then the materials should provide sufficient intensity control of incoming sunlight to minimize glare. The challenge with diffusing materials like the PDLC is that the materials can be too bright when backlit by direct sun. Combining a variable tint device and variable light-scattering device into a single window (independent controls for each function) could address this issue.

2.2.2. Solar-optical performance of switchable windows

The make-up of the insulating glass unit not just the switchable coating dictates whole window performance. The details of automated control also influence overall performance. This section lists some of the additional design options that can be used to achieve energy efficiency objectives.

Low-e and IGU makeup. State-of-the-art EC devices achieve optical control through absorption so placing the EC coating on the #2 surface[1] with a low-e coating on the #2 or #3 surface of a dual-pane unit is critical to achieving adequate modulation of solar loads for commercial building applications. The overall solar-optical switching range of the IGU can also be fine-tuned through the selection of the substrate glazing layers.

SHGC versus Tvis range in the IGU makeup. The relative importance of solar control (i.e., SHGC switching range) versus daylighting (i.e., Tvis range) is determined by the application: climate, building type, the relative efficiencies of the HVAC versus the lighting system, size and orientation of the window, variable energy and demand cost, and other factors that influence magnitude of the energy and demand end uses. If the targeted market is commercial buildings that have limited peak cooling capacity and minimal heating requirements (e.g., due to increased internal loads from high-density occupancy and plug loads), then specifying a switchable window with more stringent solar control capabilities when fully tinted may be more beneficial overall than specifying the window with a high maximum Tvis. If the targeted market is commercial buildings with adequate solar control (e.g., overhangs) but poor daylight transmission, then specifying windows with a high maximum Tvis to enhance daylight may yield greater energy savings.

SHGC vs Tvis range per application. Designing the window and controls to optimize for *temporal* shifts in priority of minimizing HVAC and/or lighting demands can also improve energy-efficiency performance. A library with east facing windows in a cold climate might prioritize passive solar heating in the morning rather than controlling for glare, assuming occupants have the flexibility to move to another location. A deep open plan office might prioritize daylighting over solar control to reduce lighting energy use, enhance indoor environmental quality (IEQ), and enhance human health during the winter (even though offices tend to be in a cooling mode even during the winter). Solar-optical range is important but when and how the device is controlled is equally important in reaching zero net energy objectives. Parametric optimization studies can help determine the best combination of switchable window and controls for an envisioned application.

SHGC and Tvis range with within-pane zoning or with multiple windows. Subdividing the window wall into independently controlled zones provides another degree of freedom when controlling for overall energy-efficiency objectives. In an early field test, EC zones were controlled separately for daylight versus solar control objectives, improving overall performance compared to a single control zone [36-37]. The manufacturer subsequently developed within-pane switching capability by introducing bus bars in the transparent region of the window. Multiple EC windows designed with independent switching ranges could also be installed to improve overall performance: e.g., an upper clerestory window with a high Tvis switching range and a separate lower view window with a low SHGC switching range.

2.2.3. Appearance, color, uniformity of coloration, haze

For aesthetic reasons, switchable glazings should have a uniform tinted appearance across its entire surface when switching and after having completed switching. The tint should have a neutral color and the transparent glass should have no haze or optical distortion. Commercial EC devices switch from a clear to Prussian blue color but when combined with tinted substrates and other coatings, the color can be shifted to a more neutral hue. Recent material science developments have resulted in alternate device compositions that exhibit a neutral color when switched. When switching, EC windows exhibit a slight iris effect, darkening at the edges closest to the bus bars first with the center darkening last. The iris effect tends to be more noticeable at the beginning of the switch from clear to tinted then becomes less noticeable as the pane is switched to darker states. When switching has been

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[1] Window glazing surfaces are numbered from the outdoors to the indoors. The #1 surface is the outdoor glass surface.

completed, commercial EC windows exhibit a tint that is uniform across the pane with full transparency and no haze.

Light-scattering liquid crystal devices switch uniformly between a transparent state to a translucent white state. There was perceptible haze with early devices but recent devices exhibit little to no haze when in its transparent state.

2.2.4. Switching speed of switchable devices

For optimal energy efficiency and comfort, the ideal device would be capable of providing the appropriate level of tint control within a few seconds, because variable sky conditions can cause sunlight levels to change by a factor of 10:1 within a few seconds. Most commercial automation systems initiate adjustment of motorized shades to block direct sunlight immediately when discomfort occurs (control is usually achieved in less than 1 minute) but refrain from raising the shades immediately to avoid the noise and visual distraction that can often disturb occupants. Devices that meet this near-instant switching speed criteria include liquid crystal devices and SPDs, both of which can switch from clear to opaque or tinted within a second or two. It is not yet clear whether such speeds are distracting for devices that produce no modulation between the on-off states (i.e., SPDs, PDLCs) – the near instant change in outdoor view and obscuring of the sun may be welcome for comfort and privacy but a more gradual change in indoor light levels across the room cavity and on work surfaces may be less distracting to occupants.

Commercially available EC devices can take 5-10 min to switch from fully bleached to fully tinted, longer if the surface temperature of the window is cool and the area of the window is large (30 min or more). Decreasing distance between bus bars can increase switching speed (i.e., use of narrower windows). A new innovation was recently introduced to the market, enabling fast switching and tint uniformity (minimal iris effect) while switching. Laser etching of the transparent conducting oxide (TCO) layers is used to change the typical non-uniform sheet resistance of the TCOs produced by bus bars at the edges of the window to a uniform voltage differential across the TCO surface [38-39]. The EC glazing can be switched at the same rate independent of size, taking 3 min to fully switch for temperatures above 25°C, 5 min at -10°C and up to 30 min at -40°C.

2.2.5. Open circuit memory, operating voltage, operating temperature range

Power requirements for switching should be minimal and once switched should ideally require no power to maintain the window at the selected tint state (open circuit memory). Today's EC windows use a small amount of power to switch and maintain tint state. A polymer based EC window that was tested in the 1990s had excellent open circuit memory, requiring no power to maintain its tint state once switched, but subsequent commercial offerings have required small amounts of power to maintain tint state.

To reduce the cost of installation, low-voltage dc systems using the existing networking/ communication infrastructure (e.g., power over Ethernet (PoE)) could be a viable option. Others have explored use of photovoltaics with battery backup to reduce installation cost for retrofit applications. Systems requiring high-voltage ac power to switch (e.g., SPDs) require a licensed electrician, which can raise installation costs.

2.2.6. Durability

Durability is a critical concern, due to the prohibitively high cost of replacing windows should the glazing fail to switch. A life of 30-60 years is desirable since it is not unusual to have conventional windows in buildings last for more than 60 years. For EC materials, durability is tied to the number of bleach to tint cycles, depth of switching, and conditions of exposure to solar radiation and extreme temperatures, similar to a rechargeable battery. The failure mode for the EC windows involves a decline in optical performance – i.e., a reduction in switching range (contrast ratio) at the upper or lower ends of the switching range over part or all of the window surface [40-41]. EC windows that have passed the testing requirements for durability defined by the ASTM E-2141-06 standard are projected to have a life of 20 years. Most EC commercial products are warrantied for 10 years.

3. How switchable glazings fulfill energy-efficiency needs

Given the stated energy-efficiency performance objectives above and state-of-the-art devices available today, how well do switchable glazings actually perform in building applications? Building energy simulation studies and field testing on emerging market products provided early insights into performance. We also describe outcomes from subsequent monitored studies in real world buildings.

3.1. Building energy simulations

There are many studies based on building energy simulations in the literature quantifying the energy savings potential of switchable windows [42-51]. For conventional commercial office building applications in moderate to hot climates, for example, EC windows are projected to save 10-20% total primary (source) annual energy use in south-, east-, and west-facing perimeter zones, particularly if the windows are large and have considerable exposure to sunlight. Peak electric demand is projected to be reduced by 20-30% [52]. The study showed that EC windows were able to reduce perimeter zone energy use to levels that were lower than an opaque wall, meeting the aspirational goal of being a net energy producer. In these studies, the EC window was assumed to have broadband switching capabilities, achieving solar rejection through absorption at the exterior glazing layer in combination with a low-e glazing layer. The EC windows were also switched to just meet the daylight illuminance setpoint so that maximum reductions in lighting energy and heat gain from the lights could be attained with commensurate cooling load reductions from the window.

3.2. Monitored studies in outdoor instrumented testbeds

When developers began producing early-market prototype windows, additional insights into actual performance were gathered through bench-scale and field tests in full-scale outdoor testbeds [53-56, 36, 57-60]. The initial monitored evaluations supported the energy savings potential projected by the simulation studies when controlled to minimize energy use but also raised questions regarding the quality of the resultant indoor environment and occupant comfort. For example, if the window wall was subdivided into zones to improve daylighting, comfort, and indoor environmental quality, would independent switching of the daylight and solar control zones degrade or increase total energy savings? Would occupants be willing to tolerate some discomfort for the time it takes EC windows to switch in order to have access to an unobstructed view and if not, how would energy savings be affected if indoor shades were added to reduce discomfort? Early field tests with short-term exposure of occupants to the technology provided only initial answers to these questions (Figure 2). Long-term monitored studies in real buildings were needed to obtain more definitive answers.

Figure 2. Occupants switched individual EC window panes to suit their preferences for view, glare control, and privacy. *Image from [56]*.

3.3. Monitored building demonstrations

Monitored building demonstrations provide industry stakeholders with a unique opportunity to gauge occupant response to switchable window technologies under long-term occupied conditions and evaluate the impact of their response on building energy efficiency [61-65]. We focus our discussion on the outcomes of one recent study conducted in Portland, Oregon (45.60°N latitude with a predominantly overcast climate) whose outcomes reflect the typical rich, diverse set of market and technical challenges that most applications involving dynamic windows must resolve [66]. Some of these challenges could be addressed with technological advancements. Other challenges will require changes in design practice and shifts in market related, ingrained expectations or assumptions about building facades.

Figure 3. Photograph of the west wing of the south façade, April 9. The EC windows on Floors 6–7 were set to Tint 4 (Tvis=0.02). The EC windows on Floor 5 were operating in the automatic mode (Tints 1–3). Floors 3-4 (EC windows not yet installed) and Floor 8 show the appearance of the original ("o") existing reference low-e windows.

3.3.1. Influence of indoor environmental quality on energy –efficiency outcomes

One key lesson learned from the monitored demonstration in Portland was that indoor environmental quality must be considered when designing and controlling EC windows for building applications. In this monitored study, EC windows were installed on the south façade of five floors of an existing eleven-story building; the façade was 107 m

(350 ft) long with 0.96 by 1.87 m (3.14 by 6.14 ft) windows. The window-to-exterior-wall ratio (WWR) was 0.46. The type of EC replacement windows were selected in part based on the *aesthetic* appearance of the exterior facade: the owner wanted the EC windows to match the existing windows since only a portion of the façade was being retrofit (Figure 3). The existing dark tinted windows had an estimated Tvis=0.15 and SHGC=0.20 and the owner requested that the EC windows match the color and tint level of the existing windows when in its bleached state.

The original 1953-vintage building had also been designed with the air handling unit (AHU) serving both the north and south zones. As a result, there was significant thermal discomfort in the north zone due to the loads imbalance between the north and south zones with the existing windows (i.e., overcooling on the north zone). The EC windows were designed with a lower SHGC switching range to minimize solar heat gains in the south zone to better balance the loads with the north. A dark tinted glass substrate was used with the EC coating, resulting in a limited switching range of Tvis=0.36-0.02 and SHGC=0.43-0.09. Controls played an equal role in the resultant indoor environment. The manufacturer designed the window to switch automatically to one of four discrete tint states – four equal incremental steps between fully bleached to fully tinted. All EC windows in each office were zoned to tint to the same state automatically in response to incident vertical irradiance. Occupants in the private offices were provided with a manual switch to override the automatic system.

Within a few weeks after the installation, it became apparent that automated switching to the darkest tint state ("Tint 4", Tvis=0.02) produced a gloomy daylit environment that was unsatisfactory to the majority of the occupants. The general sense of gloom was due to the overall lack of interior brightness and potentially to over-tinting under variable sky conditions by the controls. The cool color of the daylight produced by the deep blue tint of the glass also contributed to a sense of gloom. In response to these complaints, the automated controls were adjusted to tint to only the three lighter tint states, but with all four tint states available to occupants through manual override (Figure 4).

The requirement for more daylight influenced the energy-efficiency outcome of the study – HVAC load management goals were not satisfied. However, modifications to the controls could have made up in part for this deficiency. For example, the controls could have been adjusted to be a little smarter; i.e., switching to the dark state for a portion instead of the entire window wall in each private office, allowing daylight to brighten the space; or informing the occupant through a green-red light indicator on the manual switch plate or an email-alert that the EC windows were being automatically switched to the darker state to reduce peak cooling and thermal discomfort only on critical hot, sunny days. In a prior study [67], receptivity to automated control increased when occupants understood the basis for real-time control actions. The number of tint states could also have been increased. Manufacturers offer four discrete tint states but in an earlier testbed study [36], continuous modulation enabled greater fine tuning of daylight and cooling load trade-offs.

This example also illustrates the downstream IEQ and energy-efficiency impacts of decisions based on real estate valuation criteria (i.e., aesthetics of the façade). A façade with a uniform, uncluttered appearance from the exterior can have a higher market valuation in some regions, particularly for mid- and high-rise buildings with a curtainwall facade. EC windows may continue to be paired with tinted substrates to mute variations in exterior appearance despite the negative impacts on daylight.

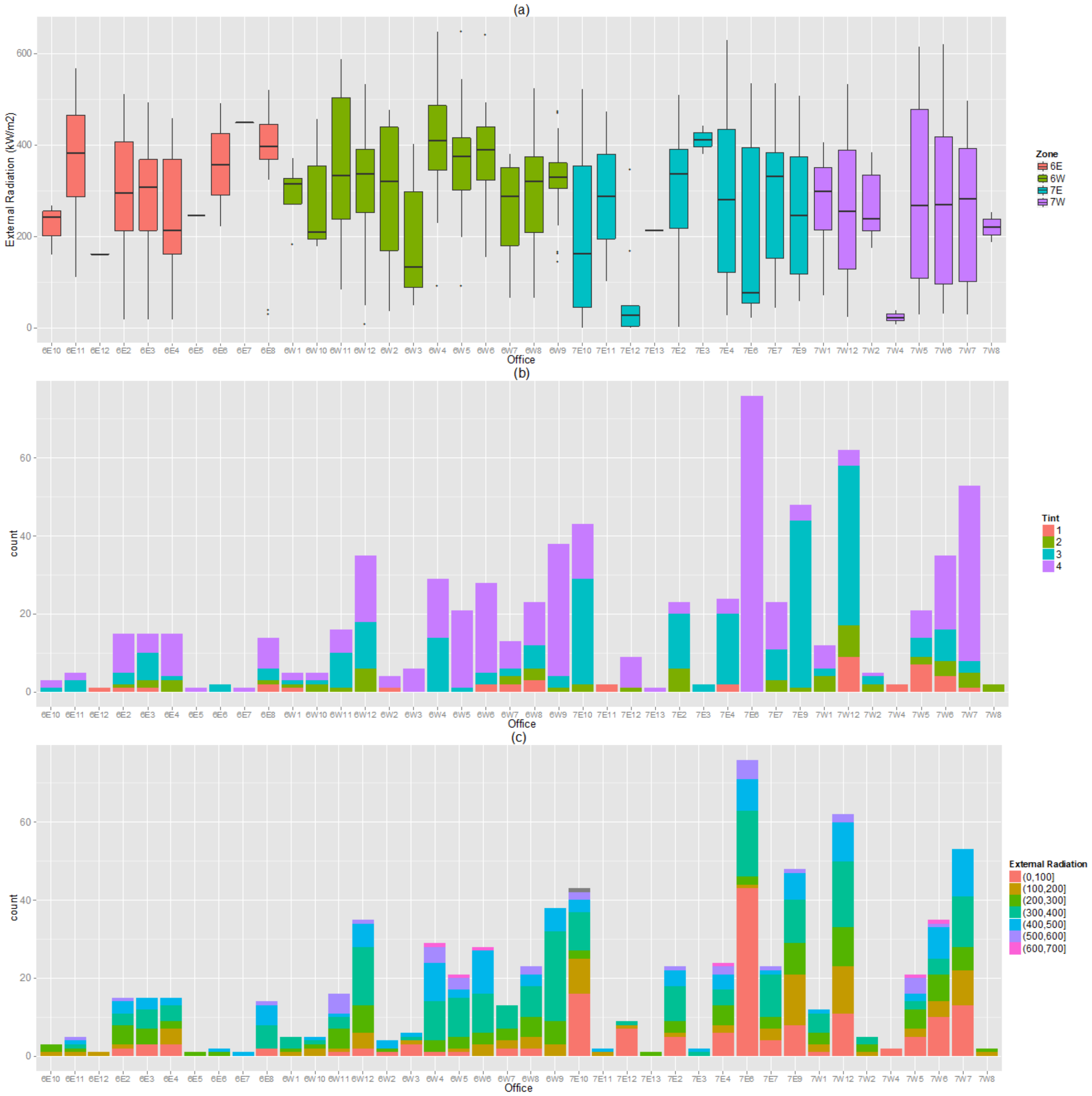

Figure 4. Summer. Number of manual overrides (total count/three-month period) for each of the 40 offices (x-axis) on the sixth and seventh floors between May 25 and August 23: (a) box plots* of the vendor's measured exterior vertical irradiance (W/m^2) when the manual override occurred, where the different colors represent different areas of the floors; (b) frequency of tint level selected with manual override per office; and (c) frequency of the vendor's measured exterior vertical irradiance (presented as intervals) when the manual override occurred. (* Note: box plots show the minimum and maximum as whiskers, and the first quartile, median, and third quartile as the lower, mid, and top edges of the box.) *Image from [66]*.

3.3.2. EC windows, indoor shades, and comfort

A second question that was addressed in the Portland demonstration was whether a very low visible transmittance and/or indoor shade was necessary to ensure visual and thermal comfort. Outcomes were a result of both the response time of the EC windows and how the windows were controlled. Responses from the occupant survey indicated that the fully colored tint level (Tvis=0.02) was sufficient to control glare for most occupants in this predominantly overcast climate without the additional requirement for indoor shades, although occupants indicated dissatisfaction with the slow switching speed. Indoor shades were required by 23% of the occupants.

The Portland study was designed to isolate performance to the EC window alone. The existing venetian blinds were left in place but raised and tied so that occupants could not use them. If necessary, the single occupant in each of the 40 private offices could request that the blinds be made available for use. For control, the large-area windows were controlled to tint without delay when discomfort was detected, but controlled to untint after a pre-defined time delay. The system automatically tinted to at most Tint 3 (Tvis=0.13) and then could be manually switched to the darkest Tint 4 state (Tvis=0.02).

When surveyed, occupants responded that there was less glare with the EC windows compared to prior existing conditions under the reference window (which had manually-operated venetian blinds). They indicated that bright light made it more difficult to read or see with the reference windows but not with the EC windows (Figure 5). Both of these findings were statistically significant (SS) with a total of 28 survey respondents. When glare was present, the level of glare from the EC windows, however, was slightly less acceptable than the reference windows (not SS), and reported glare levels were just slightly uncomfortable for both cases.

With respect to thermal comfort, occupants were more comfortable with the EC windows (not SS) despite potential direct irradiance on occupants in the EC offices without shades. Occupants also perceived less heat from the EC windows, despite the darkest tint level being used only during times of manual override (not SS; the second to darkest tint level, Tint 3, was estimated to have the same SHGC (=0.16) as the reference windows).

How was comfort attained? In some cases, occupants used the manual override and/or un-tied the blinds to control the EC windows for discomfort. During the summer, 83% of the EC windows were unshaded (blinds fully raised) and during the winter at the conclusion of the study, 77% remained unshaded (low winter sun angles might have precipitated greater blind usage but sky conditions were cloudy and overcast during the winter). For the reference case, 50% and 15% of the windows were unshaded (blinds fully raised) during the summer and winter, respectively. For the manual overrides, the automatic controls were manually overridden and switched to Tint 3 or 4 (corresponding to Tvis=0.13 or 0.02) during the summer (Figure 4) or to Tint 1 or 4 (Tvis=0.36 and 0.02) during the winter. The number of overrides was low and the duration of the overrides was also low. Over the six month solstice-to-solstice period, there were eleven overrides per weekday during the summer and three overrides per weekday during the winter between 40 private offices. The average duration of the manual override ranged from 10 min to about an hour per day.

In discussions with the facility managers, occupants indicated that they would have used the EC windows to control glare instead of the blinds in order to have an unobstructed view to the outdoors except that the EC windows took too long to switch.

A parallel study in the sunny climate of Sacramento, California (Figure 6) was confounded by initial durability issues with the EC window itself [65]. The blinds were tied up initially, but occupants were permitted to lower the blinds because the EC windows were not providing sufficient glare control. In the second phase of the study, the majority of the occupants used the blinds with the EC windows but the reason for their use was likely habitual after their uncomfortable experience during the first phase of the study.

Figure 5. Average occupant response on Floors 6-7 regarding indoor environment with reference or electrochromic windows. *Image from [66]*.

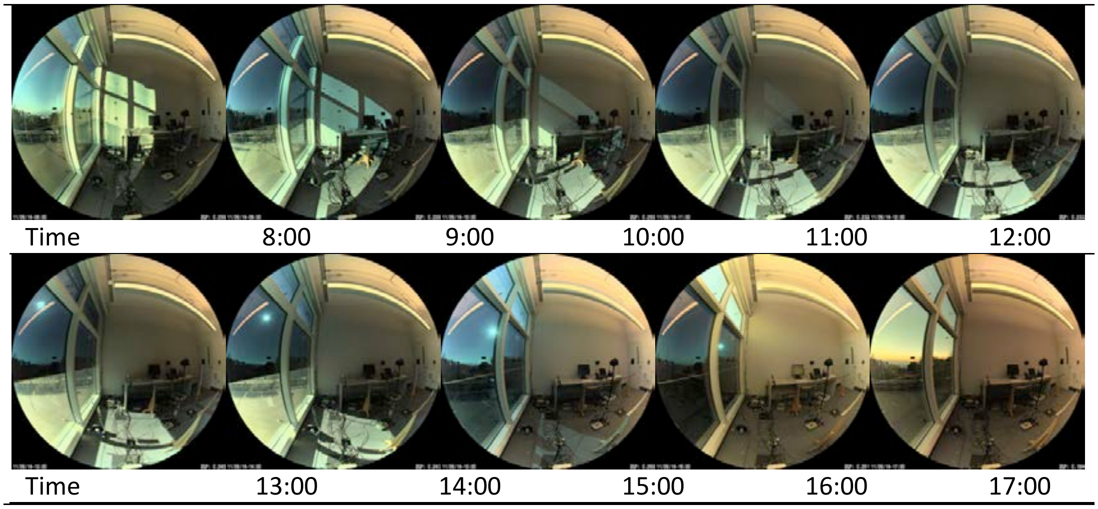

Figure 6. In the Sacramento field study, the EC window wall was subdivided into three separate horizontal control zones to meet daylight and glare control objectives. *Image from [65]*.

Given the results from the Portland and Sacramento studies, we concluded that shades or blinds will be needed to reduce the visual discomfort from today's state-of-the-art EC windows. Zoning and controlling the window separately for daylight versus solar heat gain/ glare control would help to reduce the luminance contrast between the window and room cavity and improve visual comfort. Adjusting furniture and tasks so that the occupant's field of view is parallel instead of facing the window would lessen the need for shades. The trouble with installing shades with EC windows in the first place is that occupants are likely to resort to conventional use of the shades, leaving them lowered for long periods of time out of habit and reducing daylight that would otherwise improve IEQ and energy efficiency. Automating an indoor shade would add expense and complexity and together as a system would not reach broad market adoption. Adding a PDLC switchable layer to the EC window would be an elegant solution but cost poses a significant market barrier to adoption.

It remains to be seen whether fast switching speeds will eliminate the need for shades. Not having to wait ten or more minutes for the EC to tint to its darkest state would certainly improve comfort outcomes but if inadequate control of brightness from the sun is the primary cause of discomfort, then fast switching and a very low Tvis will be needed. Industry's experience with fabric roller shades indicates that occupants are willing to tolerate infrequent glare from the orb of the sun in order to have increased view and daylight through open weave fabrics. Perhaps a similar level of accommodation will occur with fast-switching EC glazings. A suggested direction for future material science R&D as a result of these analyses is given in Figure 7.

When occupants were asked whether they preferred their existing windows or the EC windows, the response was overwhelmingly in favor of the EC windows. Windows provide the unique benefit of view to the outdoors and the transparency of EC windows enables this benefit to be maintained for a larger percentage of the year.

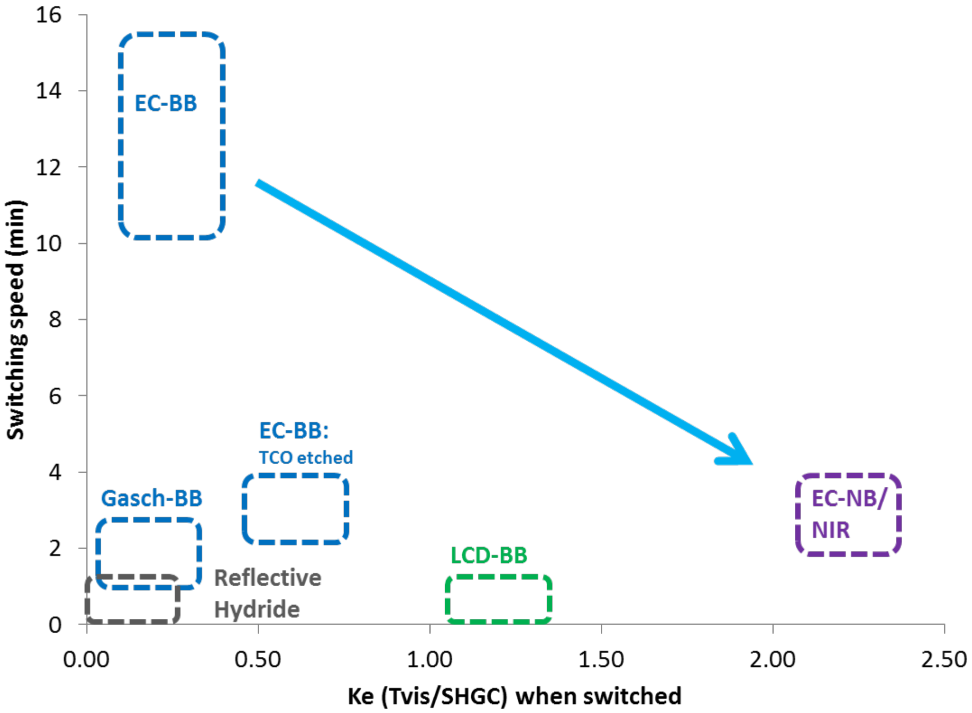

Figure 7. Suggested direction of material science R&D for dynamic glazing materials. An ideal switchable chromogenic glazing would have fast switching, narrowband near-infrared properties with Tvis>0.50 when clear/ bleached. Note: EC=electrochromic, Gasch=gasochromic, BB=broadband, NB=narrowband.

4. Future needs

When we examine our initial premise for dynamic facades, it is abundantly clear that there has been substantial progress towards transforming windows from a net energy consumer to net energy producer through active load management of solar heat gains and daylight. Advances in material science have produced fast-switching materials with a broad solar-optical range and neutral color. Various products are now commercially available and the innovation pipeline has promising new materials under development.

For state-of-the-art EC switchable windows that reduce solar radiation in both the VIS and NIR range of the solar spectrum, the most significant challenge to realizing full energy savings potential is how to maximize control of solar radiation (and glare) without adversely affecting daylight. A few suggestions were offered for the near-term EC window market: subdividing the window wall into zones of control, use of fast switching devices, smarter control logic to more optimally balance competing demands, etc. PDLCs (clear/translucent) combined with EC windows appear to be the ultimate catch-all, multi-functional solution for controlling daylight, solar heat gains, and direct source glare. NIR EC materials that provide independent switching in the VIS and NIR portions of the solar spectrum also show considerable promise in the long term.

The motivation for solving this challenge with continued industry investments in technology R&D hinges on basic bottom line economics which fuel market demand and market share. With parallel increases in energy efficiency in HVAC and lighting component end uses – the value proposition of advanced dynamic windows based solely on energy cost savings can be challenging. Reductions in capital costs can improve the return on investment; e.g., dynamic windows could be used to reduce cooling energy demand in retrofit applications where replacement of CFC-based refrigerants limit peak cooling capacity. For retrofit applications, turn-key packaged dynamic façade systems can reduce installation cost and complexity.

For activities focused on achieving net zero energy use goals, applications of dynamic windows include integration with very low energy cooling and passive solar heating strategies and demand side integration with supply side renewable energy resources [68]. Arguments regarding resiliency, energy security, demand response, and grid modernization provide additional incentives for investment in technologies that can provide peak demand reductions and active demand side management capabilities.

Human factors have not been discussed in much depth in this chapter, but the most compelling arguments for market adoption of dynamic windows may hinge on human factors. Human health, comfort, and occupant satisfaction and productivity in the workplace have become increasingly more important to employees and employers trying to attract and retain talent. The perimeter zone near windows is valued as the most expensive real estate in the entire building, particularly if there is access to views and “natural” daylight. Long before Jeffrey C. Hall, Michael Rosbash and Michael W. Young won the 2017 Nobel Prize in Medicine for their discoveries of a gene that controls circadian rhythm (which regulates behavior, hormone levels, sleep, body temperature and metabolism), building science researchers have been investigating the impacts of daylight and transparent views on human health and performance [69-72]. Can increased availability of blue daylight from EC windows during mid-day hours result in improved mood, cognitive function, performance, and creativity of occupants?

When the concept of dynamic facades was first introduced in the early 1970s, images of a chameleon-like skin that reacted to changes in context and climate captured the imagination of architects, engineers, and scientists. With powerful embedded controllers and ubiquitous sensing now available at low cost, this vision of integrated, intelligent, and responsive buildings is in the not too distant future.

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