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Electrochromic dynamic windows for office buildings

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Abstract

The next generation of advanced fenestration products includes dynamic electrochromic (EC) windows which can modulate the solar energy entering a building by application of an applied voltage. The windows can be switched from 62% visible transmittance (Tvis), 0.47 solar heat gain coefficient (SHGC) to a fully tinted state with ⩽2% Tvis, 0.09 SHGC. EC windows save energy in buildings – the total energy use for an eight story ASHRAE 90.1 2007 commercial office building with EC windows was modeled using the eQuest building simulation program and compared with the energy use of the same building with a variety of static glazings. The simulations were carried out in three US climate zones, encompassing a broad range of environmental exposure conditions from hot and dry (Arizona) to very cold (Minnesota). For all climate zones, building energy savings with EC glass were ⩾45% when compared to single pane static glazings common in existing building stock. When EC glass was compared to ASHRAE 90.1 2007 code compliant glazings, energy savings greater than 20% were calculated for the same building configuration. Optimum EC window control and performance strategies were derived from the modeling results. The EC glass and dimmable electric lights were synergistically controlled to maximize the use of natural daylighting and minimize electricity for lighting. Since EC glass can tint to ⩽2%, shades and/or blinds are not required for glare reduction, and building occupants always have a comfortable working environment and an unobstructed view and connection to the outdoors. All static glazing systems were assumed to have manual shading devices that are pulled by building occupants when glare becomes uncomfortable. For integrated building control systems, the peak load is significantly reduced when dynamic glazings are part of the building envelope. Consequently, chiller costs are lower, and the upfront capital costs for new building construction are reduced. Another key benefit of EC glass, elucidated by the simulations is reduction of CO_2 emissions. EC glass reduces peak load carbon emissions by as much as 35% in new construction and 50% in renovation projects.

Keywords: Electrochromic windows; Energy-saving windows; Dynamic window glazings; Commercial building energy savings

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1. Introduction

Electrochromic (EC) windows have significant potential to reduce energy use in buildings. EC device structures and properties are reviewed, building energy savings are computed, and other benefits of EC glazings for building occupants are noted.

Buildings account for ~40% of the world's energy use with the resulting carbon emissions substantially more than those in the transportation sector (WBC, 2009). In the US, the energy lost through today's inefficient window stock accounts for ~30% of building heating and cooling energy (Arasteh et al., 2006). We have modeled the performance of a typical commercial office building in three US climate zones, and demonstrated that innovative dynamic windows can significantly reduce building energy consumption compared to current static glazing systems. Advanced windows can be a significant factor in reducing building energy use and ultimately in achieving net zero energy buildings. Dynamic windows are key to achieving this goal while preserving the view and enhancing the comfort and productivity of knowledge workers.

Electrochromic materials, that modulate light in the visible and near infrared by application of an applied voltage, were first demonstrated in the 1950s (Brim et al., 1951) and 1960s (Deb, 1969). There have been numerous reviews of this technology over the intervening years (Lampert and Granquist, 1990; Granqvist, 1995; Lampert, 1995). A typical design for window applications consists of five thin film layers on a single glass substrate or sandwiched between two glass substrates (see Fig. 1). For inorganic metal oxide devices, the cathodic electrode is typically WO_3, and a typical anode material can be NiO. The electrodes are separated by a solid state electrolyte that is a good ion conductor, but limits electronic conduction. The mobile ionic species are small in size for optimum transport – with H^+ or Li^+ preferred. The electrodes of large area electrochromic devices for architectural applications are most often vacuum deposited (e.g. sputtering) thin films (Mathew et al., 1997). Other investigators have explored the complete fabrication of EC devices using non-vacuum sol-gel techniques (Agrawal et al., 1993). There are also organic electrochromic devices in which the chromogenic materials are polymers (Xu and Taya, 2006).

Durability of the EC device is an important property for architectural EC glazings. EC devices must withstand the full range of climatic and solar conditions for the lifetime of the window which could exceed 30 years. Consequently, the thin film materials used for EC window glazings described in this paper are all ceramic metal oxides which can withstand the full range of climate conditions. Also, Li^+ based ceramic films are much less subject to the photochemical reactions that can cause degradation in protonic as well as in EC systems with polymer films. Also, the thermal expansion coefficients of the ceramic layers closely match the glass substrate resulting in lower stresses over the full range of temperatures that windows experience.

SageGlass® electrochromic coatings are applied to a single piece of glass, which is then fabricated into an architectural insulating glass unit (IGU). The coating can be tinted or cleared electronically to control solar heat gain and glare in buildings without ever blocking the view to the outside. These EC IGUs are nearly identical in form factor to a standard IGU, except that they have a wire exiting the IGU for electrical interconnections. The glazing can be controlled in a variety of ways, including integrating it into the building energy management system. It takes less electricity to operate 1500 sq. ft. of SageGlass windows than is needed to power a single 60-W light bulb. All materials properties and performance parameters for EC glass in this paper are derived from SageGlass films and window constructions.

Fig. 1 shows what happens when electricity is applied to SageGlass glazing. The EC coating, which is made up of five layers, darkens as lithium ions and associated electrons transfer from the counter electrode (CE) to the electrochromic electrode (EC) layer. Reversing the voltage polarity causes the ions and associated electrons to return to their original layer, the CE, and the glass returns to a clear state. This solid state electrochromic reaction is controlled through a low voltage DC power supply. It takes less than 5 V to switch the glazing.

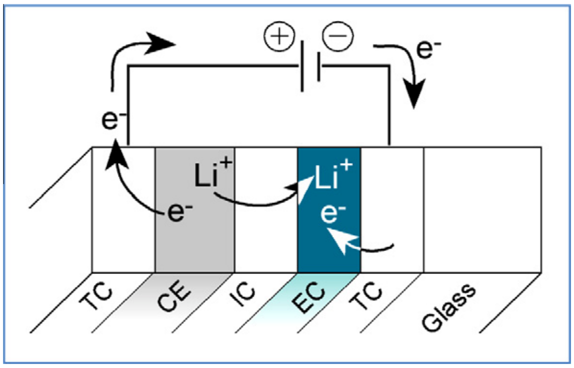

Fig. 1. SAGE thin film electrochromic stack on glass. TC-transparent conductor, CE-counter electrode, IC-ion conductor, EC-electrochromic layer.

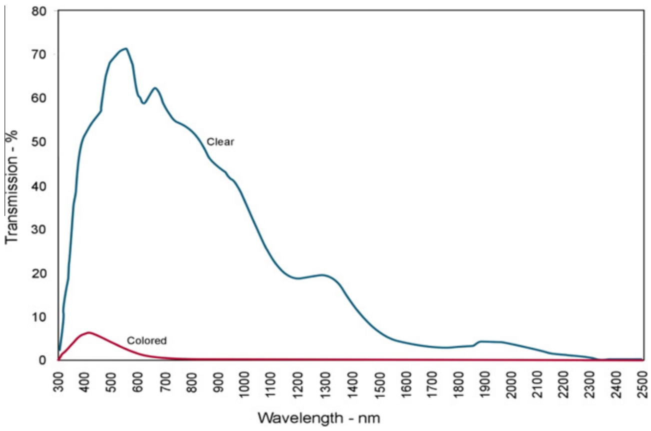

Fig. 2. SAGE transmission spectra.

Fig. 2 is a plot of the transmission spectra of the clear and tinted states over the range of the solar spectrum. The data were taken for the EC film stack on a single piece of clear glass. There is a large dynamic range, and the device modulates both visible and near IR solar radiation. In the tinted state the photopic transmission can be <2% – sufficient to effectively block glare without the need for mechanical shading devices.

The electrochromic glazing is combined with a clear glass pane to form an industry standard IGU. Both panes are 6 mm thick and the 12 mm space between them is filled with argon. In the window configuration, the EC coatings are located on the inside surface (surface 2) of the exterior pane of glass.

Fig. 3 illustrates how EC IGUs modulate sunlight and solar heat. In the clear state, the EC glazing has a visible light transmission of 62% and passes 47% of the incident solar energy to the building interior. When a low DC voltage is applied to tint the films, the amount of incident solar energy allowed into the building is reduced by 81%. The top layer of the EC film stack is a low-e coating (emissivity ~0.15). When the films are tinted, they absorb solar irradiation, and the resulting thermal energy is re-radiated based on the emissivities of the films and the glass (glass surface 1 emissivity is 0.85). Consequently, heat absorbed is selectively ejected to the exterior where it can be convected away.

The spectral properties of the SageGlass EC IGU are determined according to the procedure in the National Fenestration Rating Council Document NFRC 302-2009. The measured emittance, solar transmittance, solar reflectance (front), and solar reflectance (back) of a single glass pane with SageGlass EC coatings are submitted to the International Glazing Data Base (IGDB) which is maintained by Lawrence Berkeley National Laboratories (LBNL) (http://windows.lbl.gov/materials/IGDB/). The spectral properties of each glazing are listed by manufacturer, and the SAGE ID Numbers are 8902-8905. Then more complex window structures such as double and triple pane IGUs are constructed using the IGBD data and the Window 6.3 software (http://windows.lbl.gov/software/window/6/index.html). Table 1 Lists key performance parameters for a dual pane electrochromic IGU. EC IGU properties for four tint levels are listed – the background data for Figs. 3 and 4.

Today's static glazings do not approach the energy savings possible with dynamic glazings. Each static glazing

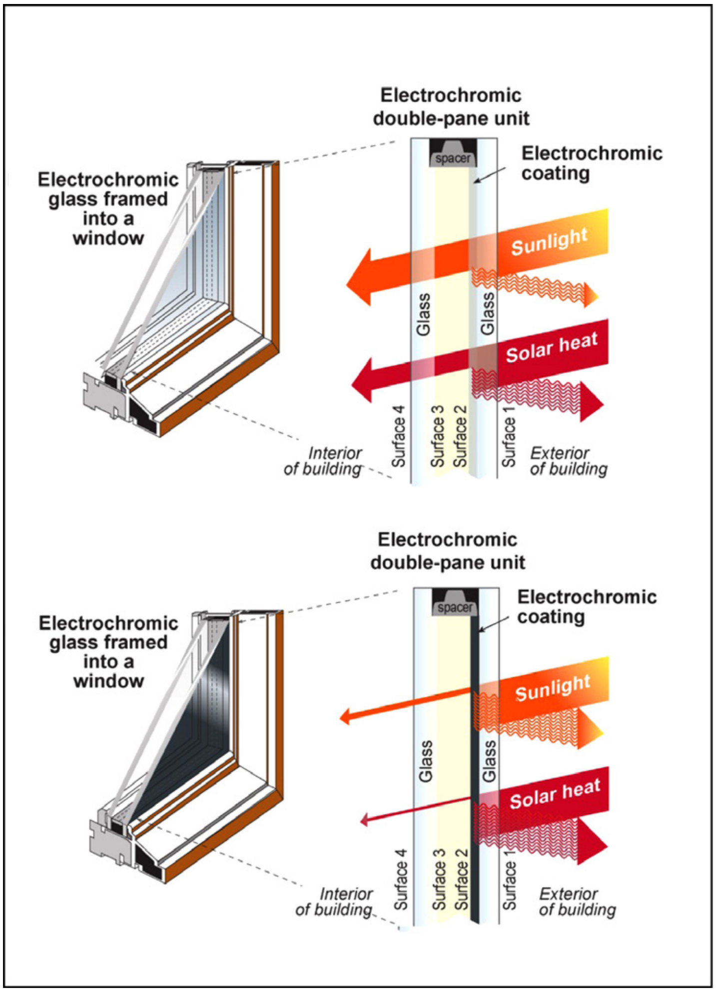

Fig. 3. EC technology in clear and tinted states.

Table 1
Key optical and thermal properties for SAGE EC IGUs.

Product		Transmittance		*U*-Factor		SHGC
Level of tint	Inner Lite	Visible (%)	Solar (%)	Winter	Summer	
Clear	6 mm	62	38	0.29	0.28	0.47
Intermed. 1	Clear	21	9	0.29	0.28	0.17
Intermed. 2		6	2	0.29	0.28	0.11
Fully tinted		2	0.7	0.29	0.28	0.09

offers the architect a single fixed light transmission with associated fixed energy transmission. At one extreme, the choice of high transparency allows daylight to enter the building at the cost of high solar heat gain and high cooling loads. Low transparency static glazings reduce solar heat gain but also restrict natural daylighting. Detailed comparisons of energy use for a building with SageGlass vs. static glazings are in Tables 5–7. Electrochromic performance is shown in Fig. 4 which compares the individual solar control coordinates of static glazings with the wide range of EC glazing – that can tint or clear according to changing environmental conditions to achieve optimum energy performance.

EC dynamic glass controls sunlight to optimize daylight, outdoor views and comfort while preventing glare, fading and overheating. By letting sunlight in on cool days and blocking it on hot days, EC windows dramatically reduce energy demand. By eliminating the need for shades, blinds and louvers, dynamic glass preserves views of the outdoors (the reason we have windows and skylights in the first place). And by negating the costs of these add-ons – e.g., purchase price, installation, cleaning and maintenance – the dynamic glass solar control solution costs less.

2. Performance assessment of EC windows in a commercial office building

The following analysis compares the energy performance of windows incorporating dynamic EC glass with other conventional and high performance static glazings. Each window type was modeled in a standard eight-story office building using eQuest (2011) computer simulations based on the ASHRAE 90.1 2007 national energy code. Analysis was conducted for three different US climates: Minneapolis which is very cold in winter; Phoenix which is hot and dry; and Washington, D.C. with a mixed hot/cold climate.

Table 2
Glazing performance per ASHRAE 90.1-2007 and actual EC characteristics.

		SHGC	U-Value	VLT
Phoenix, AZ		0.25	0.75	40%
Washington, DC		0.4	0.55	40%
Minneapolis, MN		0.4	0.55	40%
SageGlass Double Pane (Argon)	Clear	0.47	0.29	62%
	Tinted	0.09	0.29	2.0%
SageGlass Triple Pane (Argon)	Clear	0.38	0.14	52%
	Tinted	0.05	0.14	1.9%

Several key assumptions were made during performance modeling:

(1) ASHRAE 90.1-2007 was used to define the performance of a standard code compliant building. Minimum insulation levels, occupant load, equipment efficiencies and schedules were all established by this standard. The only modifications made between modeling runs were revisions of glazing parameters enabling the comparison of electrochromic glazings to static window options. ASHRAE standard glazings were used as the base case in each climate zone.
(2) Each window system must be capable of blocking uncomfortable glare that negatively impacts occupant comfort and performance. The EC glazing system can be electronically tinted to block glare when it is present and requires no shades or blinds. Commercial static glazing systems must include shading devices to reduce glare to comfortable levels.

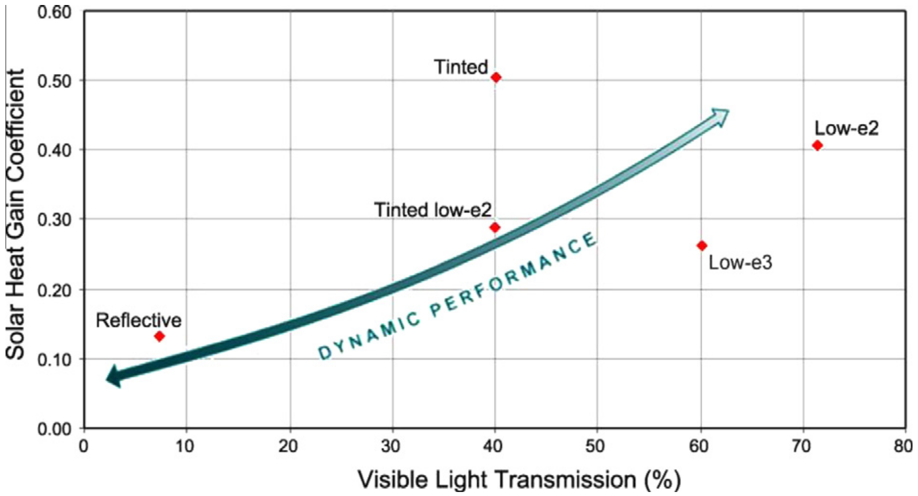

Fig. 4. EC–SHGC to VLT relationship: EC glazing can be tinted from a highly transmitting state to a very dark state to adapt to a wide range of sunlight conditions. Today's static glazings (the individual points on the chart) are specific to one condition and cannot be changed.

Table 3
Calculated impact of glare control for EC glass.

Climate	Zones	No: of hours with glare control		Increase in energy use (%)	Increase in energy cost (%)
		Summer	Winter		
Washington, DC	East/West	25	20	1	0.60
	South	59	191		
Minnesota	East/West	40	230	2.0	2.3
	South	122	450		
Phoenix	East/West	48	324	−0.4	−0.6
	South	138	323		

(3) Dynamic EC operation was modeled using integrated controls connected to building management systems for optimum energy performance and glare management. All static glazing systems were assumed to have manual shading devices that are pulled by building occupants when glare becomes uncomfortable.

(4) Daylight controls and electronic dimming were included in all results (SageGlass and static options) except for comparisons to single pane clear glazings which represent older, less energy-efficient building stock.

3. Energy analysis parameters

3.1. Model configuration

The energy model developed for this study assumed a standard rectangular office building configuration – with floor dimension 70 × 285 ft. – that can be found throughout the United States. The building model assumes a 15 ft. perimeter open office space surrounding a 40 ft. deep core. The resulting section of 70 ft. allows for the maximum amount of workers to be located within the daylit zone of the building, while elevators, restrooms, stairways, equipment rooms, and conference areas are located within the non-daylit core of the building. The building consists of 20,000 sq. ft. floor plates, contains eight total floors, and has 160,000 total sq. ft. The orientation of the building was set such that the long side of the building faced East/West and a window to wall ratio (WWR) of 60% was used. While a traditional building is optimally orientated with a North/South orientation, the ability of EC glass to be tintable and maintain views make the ideal application of the product on a building facing East/West. While this may result in higher cooling energy savings in warmer climates due to the blocking of solar gain, this has the opposite effect in colder climates that have a negative impact in heating savings as less solar gain is admitted to the space.

Table 4
Performance modeling simulations runs.

Modeling run	Application of ASHRAE standard	Glazing characteristics
Run 1: Single pane clear	Based on climate specific ASHRAE requirements for an office occupancy except glazing	COG U-val = 1.03, SHGC = 0.82, Tvis = 0.89
Run 2: Double pane clear	Same as Run 1	COG U-val = 0.48, SHGC = 0.76, Tvis = 0.81
Run 3: ASHRAE	Based on climate specific ASHRAE requirements for an office occupancy except glazing	Washington DC: COG U-val = 0.55, SHGC = 0.40, Tvis = 0.4 Minneapolis: COG U-val = 0.55, SHGC = 0.40, Tvis = 0.4 Phoenix: COG U-val = 0.75, SHGC = 0.25, Tvis = 0.4
Run 4: ASHRAE + DL + manual blinds	Same as Run 3 with daylight controls and manual blinds for glare control	Washington DC: COG U-val = 0.55, SHGC = 0.40, Tvis = 0.4 Minneapolis: COG U-val = 0.55, SHGC = 0.40, Tvis = 0.4 Phoenix: COG U-val = 0.75, SHGC = 0.25, Tvis = 0.4
Run 5: Commercial Static Double (Air) + DL + manual blinds	Same as Run 1 with daylight controls and manual blinds for glare control	Washington DC: COG U-val = 0.29, SHGC = 0.38, Tvis = 0.71 Minneapolis: COG U-val = 0.29, SHGC = 0.38, Tvis = 0.71 Phoenix: COG U-val = 0.29, SHGC = 0.28, Tvis = 0.62
Run 6: SAGE double w. Argon + DL + manual blinds	SageGlass-Double pane, with daylight + glare controlling the glass during the summer, and only glare controlling the glass during the winter	Clear State: COG U-val = 0.29, SHGC = 0.47, Tvis = 0.62 Tint State: COG U-val = 0.29,SHGC = 0.09, Tvis = 0.02
Run 7: Commercial Static Triple Argon + DL + manual blinds	Same as Run 1 with daylight controls and manual blinds for glare control	COG U-val = 0.12, SHGC = 0.33, Tvis = 0.55
Run 5: SAGE Triple w.Argon + DL + glare control	SageGlass-Triple pane, with daylight+glare controlling the glass during the summer, and only glare controlling the glass during the winter	Clear State: COG U-val = 0.136, SHGC = 0.382, Tvis = 0.523 Tint State: COG U-val = 0.136,SHGC = 0.053, Tvis = 0.019

Table 5
Washington, DC; Energy analysis: energy, cost and emissions data.

Run no	Runs	Annual site energy		Annual operating cost ($)[2]	Peak demand		Chiller cost ($)[a]	Annual CO_2 emissions (kG) [b]	Annual site		Lighting	Misc equip.	HVAC		
		Total (Mbtu)	EUI (kBtu/sf/yr)		Elec (kW)	Cooling (tons)			Elect (kWh)	Nat Gas (Therms)	Electric (kWh)	Electric (kWh)	Electric (kWh)	Nat Gas (Therms)	Total (Mbtu)
1	Single-pane clear	8949	55.9	$384,095	873	465	$302,250	1016151.4	1,597,522	34,981	394,679	383,439	819,400	32,768	6,073
2	Double-pane clear	6645	41.5	$333,954	821	429	$278,850	855411.0	1,484,604	15,795	394,679	383,439	706,481	13,592	3,770
3	ASHRAE	6532	40.8	$298,840	725	366	$237,900	774638.2	1,263,476	22,209	394,679	383,439	485,353	19,996	3,656
4	ASHRAE + DL + Manual Blinds	6363	39.8	$284,622	689	359	$233,025	740322.7	1,188,484	23,083	332,297	383,439	472,745	20,870	3,701
5	Commercial static double glazing (SHGC=0.38) + DL + Manual Blinds	5460	34.1	$269,162	681	354	$229,775	686755.3	1,172,244	14,600	331,247	383,439	457,554	12,396	2,802
6	SageGlass double pane – 12 mm Argon (Summer-switching controlled by daylight lvl; Winter - switching OFF)+DL + Glare Control	4932	30.8	$222,526	564	297	$192,977	573667.7	928,486	17,150	268,064	383,439	276,983	14,930	2,438
7	Commercial static triple glazing (SHGC=0.33) + DL + Manual Blinds	5055	31.6	$259,555	666	343	$222,950	657234.2	1,148,663	11,354	331,510	383,439	433,711	9,153	2,396
8	SageGlass triple pane – 12mm Argon (Summer – switching controlled by daylight lvl; Winter - switching OFF)+ DL + Glare control	4231	26.4	$205,857	527	274	$177,982	522477.4	886,238	11,654	269,077	383,439	233,721	9,441	1,742

Source: Industry information from http://www.archiexpo.com/architecture-design-manufacturer/chiller-1046.html.

[a] Includes chiller, cooling tower with pump, piping and installation cost.

[b] Calculated using Portfolio Manger's Emissions calculation methodology.

Table 6
Minneapolis, MN, Energy analysis: energy, cost and emissions data.

Run No	Runs	Annual site energy		Annual operating cost ($)[2]	Peak demand		Chiller cost ($)[a]	Annual CO2 emissions (kG)[b]	Annual site		Lighting	Misc equip.	HVAC		
		Total (Mbtu)	EUI (kBtu/sf/yr)		Elec (kW)	Cooling (tons)			Elect (kWh)	Nat Gas (Therms)	Electric (kWh)	Electric (kWh)	Electric (kWh)	Nat Gas (Therms)	Total (Mbtu)
1	Single-pane clear	12936	80.8	$232,878	917	482	$313,300	1780577.1	1,682,081	71,965	394,679	383,439	903,956	69,541	10,039
2	Double-pane clear	8810	55.1	$160,936	847	448	$291,200	1452882.1	1,515,430	36,398	394,679	383,439	737,308	33,985	5,915
3	ASHRAE	9076	56.7	$169,246	734	385	$250,250	1323216.0	1,293,978	46,614	394,679	383,439	515,854	44,191	6,180
4	ASHRAE + DL + Manual Blinds	8959	56.0	$ 167,246	701	373	$ 242,125	1271314.2	1,223,655	47,842	331,487	383,439	508,725	45,419	6,279
5	Commercial static double glazing (SHGC=0.38) + DL + Manual Blinds	7355	46.0	$ 137,864	689	385	$250,250	1153714.9	1,173,992	33,494	330,947	383,439	459,602	31,078	4,677
6	SageGlass double pane – 12mm Argon (Summer-switching controlled by daylight lvl; Winter – switching OFF)+DL + Glare Control	7069	44.2	$ 132,613	550	265	$171,976	970924.3	927,290	37,668	267,324	383,439	276,525	35,236	4,467
7	Commercial static triple glazing (SHGC=0.33) + DL + Manual Blinds	6591	41.2	$ 124,565	677	387	$ 251,225	1087831.1	1,135,116	27,182	331,070	383,439	420,604	24,770	3,913
8	SageGlass triple pane – 12mm Argon (Summer – switching controlled by daylight lvl; Winter – switching OFF) + DL + Glare control	5627	35.2	$ 106,925	501	237	$ 154,320	841008.0	843,110	26,396	267,823	383,439	191,848	23,971	3,052

Source: Industry information from http://www.archiexpo.com/architecture-design-manufacturer/chiller-1046.html.

[a] Includes chiller, cooling tower with pump, piping and installation cost.

[b] Calculated using Portfolio Manger's Emissions calculation methodology.

Table 7
Phoenix, AZ, Energy analysis: energy, cost and emissions data.

Run no	Runs	Annual site energy		Annual operating Cost ($)[3]	Peak demand		Chiller Cost ($)[a]	Annual CO2 emissions (kG) [b]	Annual site		Lighting	Misc Equip.	HVAC		
		Total (Mbtu)	EUI (kBtu/sf/yr)		Elec (kW)	Cooling (tons)			Elect (kWh)	Nat Gas (Therms)	Electric (kWh)	Electric (kWh)	Electric (kWh)	Nat Gas (Therms)	Total (Mbtu)
1	Single-pane clear	7495	46.8	$ 213,013	968	534	$ 347,100	1304687.1	2,049,945	5,004	394,679	383,439	1,271,826	3,169	4,658
2	Double-pane clear	6830	42.7	$198,840	871	465	$302,250	1166733.2	1,931,933	2,381	394,679	383,439	1,153,810	554	3,993
3	ASHRAE	5375	33.6	$ 157,511	719	336	$218,400	873771.8	1,413,616	5,513	394,679	383,439	635,494	3,676	2,536
4	ASHRAE + DL + Manual Blinds	5131	32.1	$ 149,570	686	334	$216,775	889527.9	1,331,492	5,880	330,097	383,439	617,954	4,042	2,513
5	Commercial static double glazing (SHGC=0.28) + DL + Manual Blinds	5019	31.4	$151,083	674	327	$ 212,550	898828.9	1,391,521	2,708	329,840	383,439	678,240	882	2,403
6	SageGlass double pane -12mm Argon (Summer-switching controlled by daylight lvl; Winter - switching OFF) + DL + Glare Control	4018	25.1	$ 125,728	592	304	$197,595	702625.4	1,110,298	2,459	265,060	383,439	461,797	628	1,639
7	Commercial static triple glazing (SHGC=0.25) + DL + Manual Blinds	4841	30.3	$ 146,707	642	299	$ 194,350	817910.6	1,347,578	2,428	329,908	383,439	634,156	604	2,225
8	SageGlass triple pane-12mm Argon (Summer - switching controlled by daylight lvl; Winter – switching OFF)+ DL + Glare control	3780	23.6	$118,500	548	281	$ 182,967	661261.1	1,049,738	2,135	265,306	383,439	400,992	306	1,399

Source: Industry information from http://www.archiexpo.com/architecture-design-manufacturer/chiller-1046.html.

[a] Includes chiller, cooling tower with pump, piping and installation cost.

[b] Calculated using Portfolio Manger's Emissions calculation methodology.

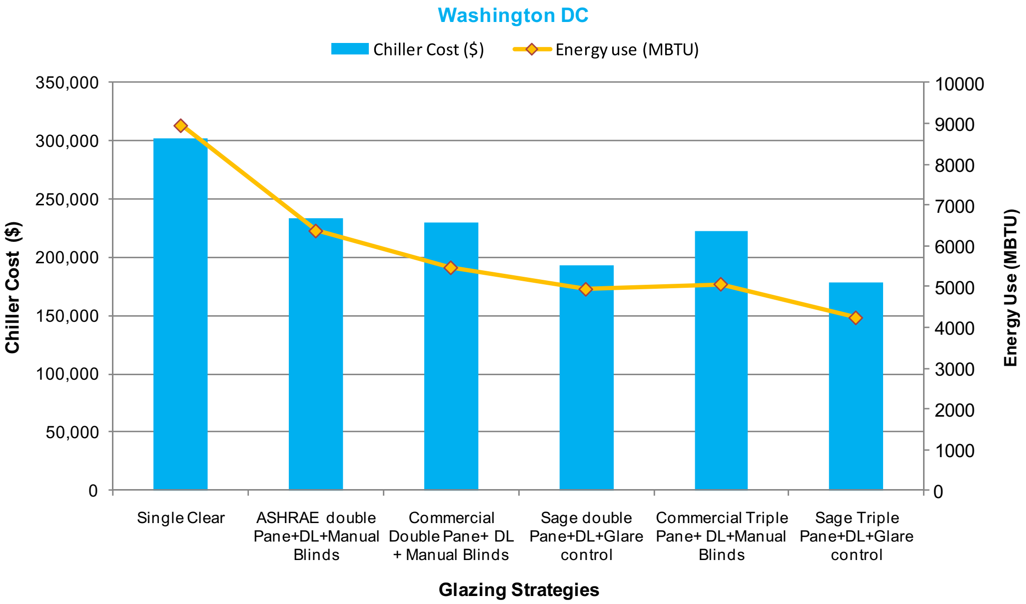

Fig. 5. Washington, DC – Energy use and Chiller cost for different glass types.

See climate zone modeling impact below for additional information.

Appendix A shows that even with a high WWR of 0.6, primary energy consumption in a building can be minimized by using appropriate daylighting controls and shading strategies.

Total plug loads for an office building were assumed to be 0.75 W per sq. ft. representing typical office loads of computers, task lamps, copiers and other standard office equipment.

The national energy code, ASHRAE 90.1-2007, was used to define the minimum code compliant baseline, as this system is the most widely adopted version of the energy code and is the standard that will be enforced during most code reviews. The standard provides minimum insulation levels for the envelope, mechanical efficiency requirements, and maximum lighting power densities. Thus, the building modeled represents the minimum code compliant building that can be constructed today (refer to Appendix B for all modeling inputs). It should be noted that this energy code represents a leap forward in energy performance compared to the typical building stock today. A study conducted by the Energy Systems Laboratory of Texas A&M University System in October 2011 (Mukhopadhyay et al., 2011) indicated that the ASHRAE 90.1-2007 is roughly 28.1–33.9% more efficient than buildings constructed 20 years ago using ASHRAE 90.1-1989.

3.2. Climate zone modeling impact

The maximum energy impact of EC glass is determined by the climate zone in which the building is located. To understand the relative range in performance, three climate zones were simulated to show the extreme conditions found within the US to demonstrate the range of performance offered by the use of SageGlass and associated daylighting controls. Phoenix, AZ, was simulated to represent a hot, dry climate in which daylight is prevalent and a cooling load is dominant throughout the year. Minneapolis, MN, was simulated to represent a cold climate that is dominated by a heating load. Washington, DC, was used to represent a composite climate that has both extreme heating and cooling seasons.

3.3. Glazing performance

ASHRAE 90.1-2007 offers various minimum performance values for glass for each climate zone located within the US. These performance values are determined by the needs of the climate and are established as the optimal static level. Among the several parameters associated with glass performance are thermal transmittance or *U*-value, solar transmittance, visible transmittance, and *g*-value, also called solar heat gain coefficient (SHGC). The *U*-value represents the resistance offered by the glass to conduction of heat flow from the inside to the outside or vice versa. The SHGC generally ranges between 0 and 1, where 1 is low shading and zero is high shading. The lower the number, the less heat gain there is through the window system.

In a Minneapolis climate, a lower *U*-value is desired to offset major heat loss through direct conduction due to extreme cold temperatures, though a high SHGC is allowed as solar gain is desired to help passively heat the building. In Phoenix, a low SHGC is required to attenuate the intense sun and limit solar gain, though a higher *U*-value is allowed as the temperature difference between the inside and outside is less than for cold climates. For Washington, DC, the code offers the best static condition between both solar gain and conduction, though neither is suited ideally for the extremes of the climate.

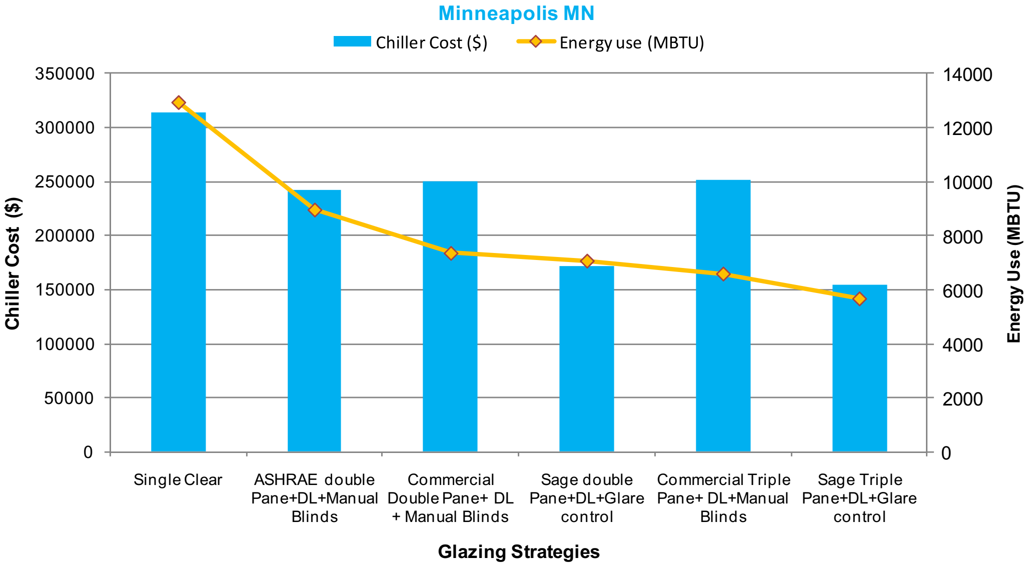

Fig. 6. Minnesota, MN – Energy use and Chiller cost for different glass types.

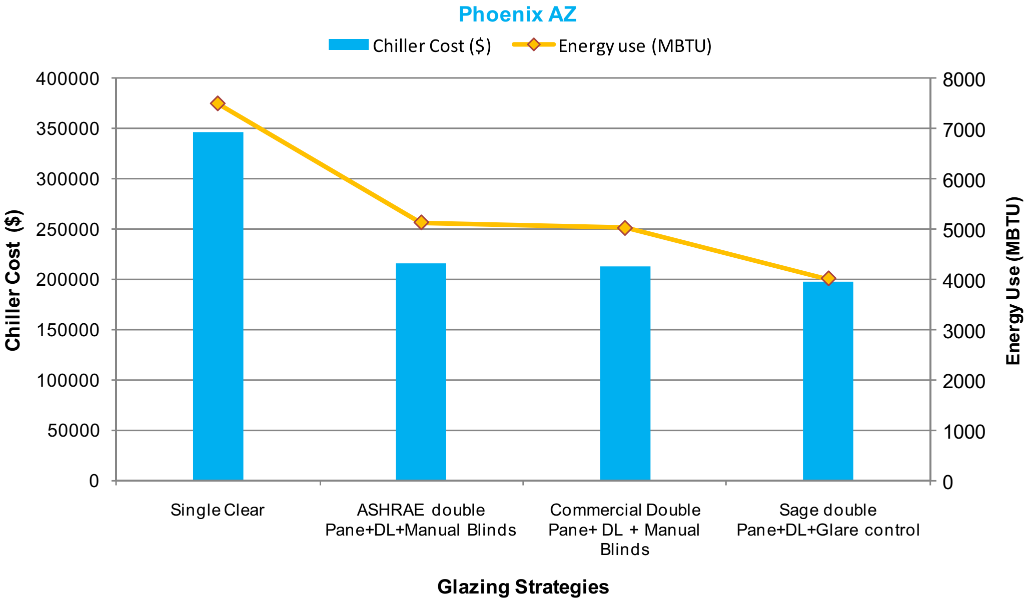

Fig. 7. Phoenix, AZ – Energy use and Chiller cost for different glass types.

Visual Light Transmission (VLT) is a performance target desired by architects and engineers. The higher the VLT percentage, the greater amount of natural daylight allowed entering the space and the clearer the views to the outside. High VLT values exhibited by clear glass are optimal to daylight a building. Low VLT values are the result of tinting, reflectance, or low-e coatings that have been applied to the glass to limit solar heat gain or decrease the *U*-value of the glass.

Thus, code performance targets assigned in ASHRAE 90.1-2007 for both SHGC and *U*-value impact the specification of clear glass desired to daylight a building. Oftentimes, the specification of clear glass occurs to maximize views to the outside and an energy penalty is accepted in either SHGC or *U*-value that must be offset by other systems in the building. VLT values for each of the climates modeled in this study represent values that can be achieved in static glass while hitting the SHGC and *U*-values dictated by ASHRAE 90.1-2007.

Table 2 shows the performance levels for ASHRAE 90.1-2007 code specified static glass per climate zone and EC IGU performance for both tinted and clear states.

4. EC glass control strategies

As electrochromic glass is electronically controlled, there are various means for determining when windows should be in either a darkened, clear or intermediate tinted state. The most logical means to control the level of tint of the glass is to directly link it to the amount of daylight that is needed within the space. Work at Lawrence Berkeley National Laboratory (LBNL) has shown that control algorithms based on daylight illuminance result in the best overall annual energy performance (Sullivan et al., 1995). For purposes of this modeling exercise, a 30 footcandle (IESNA, 2000) level delivered at the work surface (30 in. above the finish floor) was determined to be ideal for an office environment where computer screens are in use.

4.1. Daylight control

Daylighting is the synergistic control of dimmable electric lighting and natural light from windows for maximum natural daylight and optimum energy management. Depending on the condition of the sky (cloudy vs. clear), the position of the sun and the orientation of the glass, a daylight sensor within the space can be used to control the level of tint desired to achieve the design footcandle level. If the sky is dark or overcast, the glass may be clear and electric lights on in order to achieve the 30 footcandle level. If the sky is clear, the daylight sensors can control the EC windows to be in a darkened or partially tinted state to limit the amount of daylight needed to obtain the same 30 footcandle target, but limit solar gain so as not to exceed the 30 footcandle level.

4.2. Schedule control

EC glass can also be controlled based on the time of year and desired amount of solar energy that is allowed to pass into the space. During the summer, blocking solar gain may be desirable to reduce the load on building air conditioning systems. Conversely, allowing needed solar gain during the winter will reduce energy needed to heat the building. Thus, seasonal variation in combination with daylighting controls can secure an optimal energy performance of the glass façade with EC windows.

4.3. Glare control

SageGlass, which tints to less than 2% visible transmittance, can directly control glare in a space. Glare is produced when a direct beam of sun lands on the horizontal plane of a work surface or the vertical surface of a computer screen. It is necessary to tint the glass fully (to 2% VLT or less) to achieve occupant comfort in direct sunlight or when exposed to intense reflected light. By allowing the user to control EC glass through a timed override, the offending window zone can be tinted while allowing other panes to permit daylighting in the space and/or heat the building during the winter. Since EC glass has the benefit of electronic control, the glass can be reset when conditions change, unlike manual blinds that are rarely optimally controlled by users. For this reason, manual blinds cannot be adequately deployed for energy efficiency, while electronically controlled systems, such as SageGlass, can be optimally set by building management systems.

For purposes of this study, the EC windows were optimally controlled in each of the climate models for maximum energy performance using a combination of daylight control and seasonal schedule. When glare control is added to the control sequence, there are times of year in which glare overrides optimal tinting of the glass. This mainly occurs during the times of the year when the glass should be clear or partially tinted to optimize daylighting, but sometimes needs to be completely tinted to control glare. In full glare mode, electricity use can increase due to electric lighting. Per simulation results, the energy impact of adding glare control ranges from +2% to −0.4% based on climate. However, this is much less than the impact of manual shades on static glazings. In this case, energy use increases in the range of 5–6% due to loss of potential daylight savings that is described in more detail below.

4.4. Energy impact from glare control

To determine the energy impact of glare on a space when using EC glass, the number of hours that glare control is required was determined based on the hours that direct sun was incident on the work surface. Table 3 indicates the total number of winter and summer hours that require glare control with SageGlass per zone of the building for different climates. The corresponding energy impact from glare control as reported by energy modeling runs using eQuest is also listed.

Table 8
Energy performance results.

	% Annual energy savings			% Peak demand reduction (kW)		
EC Double Pane Compared to	MN	DC	AZ	MN	DC	AZ
Single-Pane Clear	45%	45%	46%	40%	35%	39%
ASHRAE 2007 Double	21%	22%	22%	24%	18%	14%
Commercial Static Double	4%	10%	20%	20%	17%	12%
EC Triple Pane Compared to						
Single-Pane Clear	57%	53%	NA	45%	41%	NA
ASHRAE 2007 Double	37%	34%	NA	29%	23%	NA
Commercial Static Triple	14%	16%	NA	26%	21%	NA

4.5. Energy impact from manual blinds

Similarly, the energy impact of using manual blinds was determined based on the findings from the study *Manual vs. Optimal Control of Interior and Exterior Blinds* carried out by the Department of Architectural Engineering, SungKyunKwan University of South Korea authored by Kim and Park (2009).

This study shows that user-controlled manual blinds have a substantial impact on daylight energy savings.[3] As blinds are typically controlled manually, they are deployed based on extreme conditions, such as to close them when glare is present, and are rarely re-opened at the optimized time when glare control is no longer needed. The study indicates that manual blinds can negatively impact the energy savings associated with daylighting strategies from 0% (blinds completely raised) to 100% (blinds down & closed), depending on the number of blinds in the open or closed position, and the angle of the blinds. In other words, maximum energy savings from daylighting strategies is achieved when the manual blinds are completely raised, and zero energy savings (from daylighting strategies) are achieved when the manual blinds are completely lowered and closed.

To determine blind impacts, a control strategy was assumed in energy modeling runs that there were an equal percentage of down and closed blinds, raised blinds, and those that are down but with the vanes open at various angles. Using this control assumption, energy simulation results indicated a 50% reduction in daylighting energy savings (lighting and cooling energy savings associated with reduced artificial light use) and a slight increase in heating energy savings, for a total of 5–6% more annual energy consumption in comparison to a case with static glass, dimmable lights and no manual blinds. There will be little to no change in the cooling energy use in the space due to manual blinds (unlike exterior shades or integrated blind systems)[4] as the heat gain is already in the space.

5. Energy modeling protocol

ASHRAE 90.1-2007 Appendix G represents the most prevalent standard for determining energy performance of a building. The code requires that two models are run to compare a minimum code compliant building (a baseline model) against a proposed building (design case) ANSI, 2007. The protocol requires that occupancy, plug loads and annual operating hours remain constant in the two models. All results indicated in this report were simulated using eQuest v3.63 that is a DOE-2 compliant modeling program allowed by Appendix G. This software was selected over other simulation energy simulation programs as it contained the ability to model dynamic glass and in which the level of tint could be variable depending on solar gain, desire for glare control, and seasonal/daily schedules.

Various parametric modeling simulation runs were completed to demonstrate performance levels of different control strategies of SAGE EC windows. Table 4 below describes the variances between the modeling runs as allowed by Appendix G. Daylighting and glare controls are integrated into all SageGlass results. Data for static glazings should include these options where appropriate. For runs 1 and 2, it is assumed that single and double pane clear glass are only used in older buildings without daylighting controls, ASHRAE 90.1 glazings in runs 3 and 4 were analyzed with and without daylighting controls and manual blinds. Higher performance static glazings in modeling runs 5 and 7 also included daylighting controls and interior manual shading device.

6. Energy results

Detailed energy analyses from eQuest modeling including cost and emissions data are listed in Tables 5–7. This data is used to plot total annual energy use and chiller costs for key glazing strategies in Washington, D.C., Minneapolis, MN, and Phoenix, AZ (Figs. 5–7).

Referring to the energy analysis tables, the annual site energy use is given in million Btu (MBtu), and the EUI is the Energy Use Index in kBtu/sq.ft./year for the 160,000 sq.ft. building. The annual operating cost is the sum of the annual use cost and the electricity demand charges. The total cost is calculated from actual rate schedules for each of the three cities studied.

Based on the ASHRAE 2007 defined HVAC system, the simulation computes cooling system size in tons. The cooling system is sized to meet peak demand conditions. The peak load is significantly reduced when dynamic glazings are part of the building envelope. Consequently, chiller costs are lower, and the upfront capital cost of the building is reduced. For example, when we compare the prototype building with ASHRAE 2007 base case glazing to the same building with EC glass, the upfront chiller savings are \$233,025–192,977 = \$40,048.

Annual CO_2 emissions are calculated using the Portfolio Manager's emissions calculation methodology (http://www.energystar.gov/ia/business/evaluate_performance/Emissions_Supporting_Doc.pdf?1e58-ae89). This approach determines total CO_2 emissions associated with the building's energy use. This includes CO_2 from both fossil fuels consumed on-site (direct emissions), as well as CO_2 emissions generated off-site at power plants that deliver electricity to the building (indirect emissions).

The total annual site energy use consists of electricity and natural gas. The electricity is consumed by lighting, miscellaneous equipment in the building, and the HVAC

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[3] Daylight energy savings: when daylight strategies are employed, the lighting energy savings achieved from the reduced use of artificial lighting and the associated reduction in cooling energy.

[4] In case of interior blinds, solar radiation passing through the window is distributed on internal surfaces (wall, floor, ceiling, slats, furniture), and the effect of blocking solar radiation is not significant compared to the exterior blinds.

system. Natural gas is primarily used to heat the building and provide domestic hot water.

In Figs. 5–7, both the energy use and chiller costs are plotted for the key glazing types in the climate zones simulated in the eQuest analyses.

As shown in Table 8, EC windows generate substantial energy savings in all three climate zones. % Energy savings for dynamic EC double pane glazings compared to static options are listed in the top rows of the table. Similar data for EC triples are listed in the bottom rows. For retrofit applications in which EC glazings replace single pane glass, the annual energy savings is ⩾45% in every case. Currently, the ASHRAE 90.1 2007 standard is used in building codes across most of the US When EC glazings are compared with ASHRAE 2007 glass, very significant energy savings are achieved for both EC doubles and triples. Even when compared with high performance commercial double and triple glazings, there are important energy benefits for EC glass. It is interesting to note that in cold climates, e.g. Minneapolis, EC energy savings compared to the commercial double are less because there is a larger heating component, and high transmittance static glass favors efficient passive solar heating especially with the low-e coating on surface 3.

Table 8 also shows dramatic reductions in peak demand for the EC glazings. Peak demand reductions can be correlated with reduced chiller size. If EC glazings enable smaller chillers, upfront capital expenses can be reduced, partially offsetting the increased costs of EC dynamic glazing systems.

EC glazings provide glare control that improves occupant comfort without a significant energy penalty. EC glass tints to ⩽2% Tvis, blocking glare while still permitting a view to the outdoors. Mechanical shading systems for static glass block the view and absorb incoming solar radiation which is subsequently reradiated to the interior as long wavelength IR heat. Also, smart controls only tint windows when and where necessary, Mechanical shades are often pulled when glare is present and then left in position all day.

With respect to CO_2, utility companies run their most efficient power plants to meet base load demand and slowly bring on lesser efficient, more CO_2-emitting plants as demand increases. Since EC glazings reduce the load on a building during peak utility times, their use exponentially reduces power plant emissions. EC glass reduces peak load carbon emissions by as much as 35% in new construction and 50% in renovation projects.

Appendix A. Window to wall ratio

In this paper we have defined window-to-wall ratio (WWR) of a building as the percentage of its facade taken up by light-transmitting glazing surfaces, including windows and translucent surfaces such as glass bricks. It does not include glass surfaces used ornamentally or as cladding, which do not provide transparency to the interior. Only facade surfaces are counted in the ratio, and not roof surfaces. The WWR of the prototype building used in this simulation is 60% at all levels and four elevations. Architects, building owners and occupants love large expanses of glass for daylighting, views, and building appearance. There are many modern buildings with WWRs of 0.6 or larger. Fig. A1 was extracted from LBNL (Lee et al., 2004) data, and shows the total annual primary energy as a function of WWR for a South facing perimeter zone in a Chicago office building with spectrally selective low-e glazings.

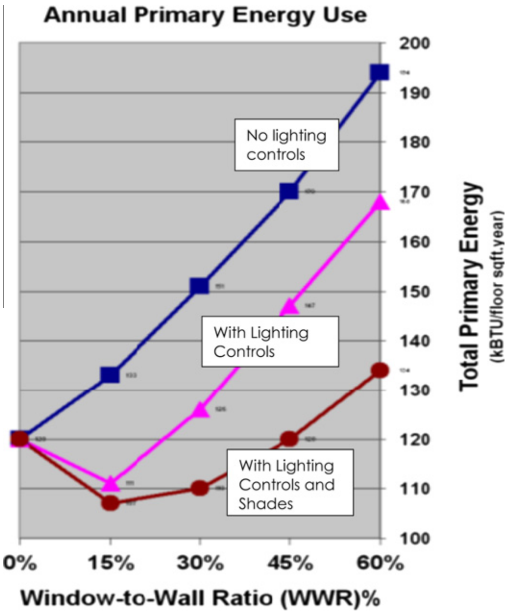

Fig. A1.

The plot shows that it is possible to achieve better energy efficiency with WWRs above 30% if daylight is harvested and artificial lighting is controlled. A building with 60% WWR, lighting controls and a shading system has better energy performance than the 30% WWR building without lighting controls or shading devices. Electrochromic glazings provide a similar shading function while maintaining the view. We conclude that even for WWRs as high as 60%, total primary energy use can be minimized with appropriate daylighting controls and shading systems.

Appendix B. Detailed simulation input values: office building.

Category	Description	Reference in ASHRAE Standard 90.1-2007
Building envelope		
# Of floors	8	–
Floor dimension	70′ by 285′	–
Building gross floor area	159,600 sq. ft.	–

(*continued on next page*)

Appendix B (*continued*)

Floor-to-floor height	12′	–
Floor-to-ceiling height	9′	–
Window height	5.4′ (vision glazing) 1.8′ (daylight glazing)	–
Window sill height	1.6′	–
Window-exterior wall-ratio	60%, at all levels and four elevations	–
Roof *U*-value	0.048 For DC (Zone 4A) Phoenix (Zone 2B) and Minneapolis (Zone 6A), insulation entirely above deck	Table 5.5 and Table G3.1 (5)
Exterior wall *U*-value	0.064 For DC (Zone 4A) 0.124 for Phoenix (Zone 2B), and 0.064 for Minneapolis (Zone 6A), steel-framed exterior walls	
Floor *U*-value	0.038 For DC (Zone 4A) and 0.052 for Phoenix (Zone 2B), 0.038 for Minneapolis (Zone 6A), steel-joist floors	
Slab-on-grade floor F-factor	0.73, 6″ concrete with no insulation for DC (Zone 4A) and Phoenix (Zone 2B), 0.54, 6″ concrete with no insulation for Minneapolis (Zone 6A)	
Window assembly *U*-value	0.55 for both DC (Zone 4A) and Minneapolis (Zone 6A), and 0.75 for Phoenix (Zone 2B)	
Window assembly SHGC	0.40 for both DC (Zone 4A) and Minneapolis (Zone 6A), and 0.25 for Phoenix (Zone 2B)	
Shading devices	None	

Category	Description	Reference in ASHRAE Standard 90.1-2007
HVAC systems		
System Type	#7 – VAV with reheat	Table G3.1.1
Fan control	VAV	
Cooling type	Chilled water	
Heating type	Hot water gas boiler	
Economizers	Included for and Phoenix (Zone 2B), 0.038 for Minneapolis (Zone 6A), not included for DC (Zone 4A)	G3.1.2.6
Economizer high-limit shut-off	75 F (Zone 2B) and 70 F (Zone 6A)	
Supply air temperature	55F/95F, reset based on minimum cooling conditions; Delta 5F	G3.1.2.8 and G3.1.3.12
Fan system operation	Continuous whenever spaces are occupied; Cycled on to meet heating and cooling loads during unoccupied hours	G3.1.2.4
Supply fan volume	Calculated by eQuest	–
Fan power	Calculated based on supply/return air volume	G3.1.2.9
VAV minimum flow set point	0.4 cfm/sq. ft.	G3.1.3.13
VAV fan part-load performance	Using part-load fan power equation	Table G3.1.3.15
Number and type of chillers	2 Screw chillers	Table G3.1.3.7
Chiller capacity	Sized by eQuest	–
Chiller efficiency	4.9 COP	Table 6.8.1C for screw chillers of 150 ton to 300 ton capacity each

Category	Description	Reference in ASHRAE Standard 90.1-2007
Chilled water supply/return temperature	44 F/56 F, supply temperature reset based on outdoor dry-bulb temperature	G3.1.3.8 & G3.1.3.9
Chilled water pumps	Primary/secondary system, two primary pumps and one secondary loop pump VSD on the secondary loop pump Pump power = 22 W/gpm	G3.1.3.10
Number and type of Boilers	2 Gas boilers	G3.1.3.2
Boiler capacity	Sized by eQuest	-
Boiler efficiency	80% For capacity more than 2500 kBtu/h	Table 6.8.1F
Hot water supply/return temperature	180 F/130 F, supply temperature reset based on outdoor dry-bulb temperature	G3.1.3.3 & G3.1.3.4
Hot water pumps	Primary-only system 2 primary pumps with VSD Pump power = 19 W/gpm	G3.1.3.5
Heat rejection	One axial fan cooling tower, 2-speed fans	G3.1.3.11
Condenser water loop	Tower water entering temperature: 85F leaving temperature: 70 F	
Condenser water pump	One single-speed pump for each chiller Pump power = 19W/gpm	
Occupant density	ASHRAE 62.1-2004 default occupant densities	–
Outdoor air rate	20 cfm/person	–
Heating set point	70 F, and 64 F during unoccupied hours	Assumed
Cooling set point	76 F, and 82 F during unoccupied hours	Assumed
Lighting and receptacle loads		
LPD	1.1 W/sq. ft	Space-by-space method in Table 9.6.1

	1.5 W/sq. ft. for mechanical/electric rooms 0.9 W/sq. ft. for rest rooms 1.3 W/sq. ft. for lobbies	
Receptacle loads	0.75 W/sq. ft.	Table G-B of ASHRAE 90.1-2004 User's Manual
Domestic hot water system		
Water heating equipment	Four 100-gal gas storage water heaters, one for two floors	Assumed
Heating capacity/Tank volume	Sized by eQuest based on the water use assumption of 1 gal/person/day	–
Thermal efficiency	80%	Table 7.8
Tank standby loss	1.27 kBtu/h	Table 7.8 for heater capacity more than 75,000 Btu/h

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