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Increasing Window to Wall Ratio with Electrochromic Glazing: a Simulation-based Review of Occupant Comfort and Energy Efficiency

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Abstract

Incorporating glass in buildings presents a unique set of challenges for designers who want to maximize connection to the outdoors but also need to protect occupants from glare and heat. Buildings with standard Low-E glazing often end up with poor occupant comfort and high thermal loads, requiring larger HVAC equipment and expensive post-design window treatments that block views and reduce daylight. Often, a direct consequence of this is to reduce window area, which however is at odds with occupant preference and architects' desire to design buildings with glass. Electrochromic (EC) glazing actively adjusts window transmission to provide outdoor views and natural light while maintaining occupant comfort and energy efficiency at high Window to Wall Ratio (WWR). This study provides a simulation-based quantitative analysis of thermal & visual comfort and energy use with a commercially available EC glazing product vs conventional Low-E glazing + manual shades. A mid-rise commercial office has been modeled with a gross WWR of 40% with Low-E + shades and then the WWR incrementally increased with EC glazing till there is no energy or peak HVAC penalty. The study found that for this office building EC glass can increase WWR by 25-50% while providing better occupant comfort, more daylight, unobstructed outdoor views and lower annual energy use.

Keywords: Electrochromic, Energy efficiency, Daylighting, Glare, Thermal comfort, Dynamic façade

1 Introduction

Incorporating glass in buildings presents unique challenges for designers since windows can drive up the energy use from solar gain and conduction losses but are also needed for outdoor connection and daylight. Buildings with standard Low-E glazing often end up with poor occupant comfort and high thermal loads, requiring larger HVAC equipment and expensive post-design window treatments that block views and reduce daylight. Often a simplistic consequence of this is to reduce the WWR, which leads to an unacceptable loss of outdoor views and daylighting. In fact, addressing this issue purely from an energy optimization standpoint will simply lead to windows being as small as possible to minimize solar heat gains and conductive heat loss [1]. This is contradictory to the very purpose of windows and is also at odds with both occupant preference and architects' desire to design with glass. The problem stems from the fact that windows create “dynamic” indoor conditions that change over time based on climate, building geometry, sun position and occupant preference but a typical window by itself is “static” in terms of modulating heat and light transmission. Dynamic glazing technologies can help balance both energy use and indoor comfort without compromising the visual connection to outdoors [2]. Such glazing products manage heat and light through tunable transmittance of solar energy. This type of glazing is often also called “smart” or “intelligent” and is based on chromogenic materials [3] with electrochromic (EC) materials currently being the most widely studied and important option. EC windows allow solar transmission to be changed in a controlled and reversible manner using low voltage electric current. This paper will provide simulation-based analysis of occupant comfort and energy savings in high WWR buildings using a commercially available EC glazing product vs conventional Low-E glazing with manual shades, for a midrise commercial office located in three very distinct climate zones.

2 Electrochromic glazing product overview

View Dynamic Glass (VDG) is a commercially available EC glazing product that is manufactured as Insulated Glazing Units (IGU) in sizes up to 6ft x 10ft. In its standard confirguration, there are two panes of glass with a 6 mm clear outer lite with the EC coating on surface 2 and a 6mm clear inner lite.The IGU is filled with argon gas for insulation. A standard IGU has four 'tint' states with Visible Transmittance (Tvis) of 1% ,6%, 40% and 60%, and a corresponding Solar Heat Gain Coefficient (SHGC) of 9%, 11%, 28% & 40%. Tint state selection is fully automated and controlled by an algorithm designed to manage three functional priorities :

1. Ensure there is no direct sun penetration beyond a specified indoor distance and within specified view angles of an occupant – This controls for glare
2. When glare is not prsent ensure that transmitted solar gain is below a specified limit – This controls heat gain

3. Use real time data from a single roof mounted sensor array to select a lighter tint state during overcast and cloudy conditions – This maximizes daylight in the absence of glare and heat

3 Methodology

3.1 Prototype building description

The DOE Medium Office 90.1 2010 prototype [4] with a floor area around 5000 sqm (53,600 sft) and 3 floors, is representative of the medium commercial office building stock in the US. Hence this model was chosen as the baseline building for three distinct climate locations - Phoenix, Chicago and San Francisco. The building has a footprint of 50m (163ft) x 33m (109ft) , with the longer sides facing North-South. Floor to ceiling height is 2.74m (9ft) and floor to floor is 3.96m (13ft) . Each floor has four perimeter zones of depth 4.57m (15 ft) and one core zone.The perimter zones have stepped lighting control that can reduce the lighting power down to 30% if there is sufficient daylight to maintain an illuminance setpoint of 500 Lux . The peak lighting power density of 9.68 W/m2 (0.9 W/ft2).

3.2 Insulated glazing unit properties

Spectral performance data for VDG was exported from LBNL Window v7.6.4 for a standard dual pane IGU configuration. The VDG IGU has four tint states (numbered henceforth as Tint 1 through 4) with Tvis varying from 1% to 60% and SHGC varying from 9% to 40% for the darkest (Tint 4) to clearest (Tint 1) state. A dual pane IGU with air fill and PPG Solarban60 Low-E coating (SHGC – 0.39 and Tvis – 70%) on surface 2 was used as the comparison static glazing. The NFRC 100-2010 center of glass U-value for both VDG and the Low-E is around 1.639 W/m2-K.

3.3 Internal shade properties and manual control model

The Low-E glazing option has been provided with 3% openness factor white fabric shades to reflect standard practice in commercial office buildings with static glass. The modeled shade is assumed to be 10 cm away from the window surface with a visible transmision of 6% and solar reflectance of 55%. Haldi et. al. [5] found shade movement immediately upon arrival of occupants to be about five times more frequent than during any other period during the day; this is likely due to the rapid change in environments between before and after they enter their offices and also because people tend to set-up their office at the beginning of the work day. The manual shades in this study are modeled as fully down in the Low-E glazing scenario whenever VDG transitions to Tint 4 or 3 for the same façade, with the assumption being that conditions which require VDG to tint would also cause occupants in the Low-E building to pull the shades down. Based on findings from Haldi et. al [5], once the manual shades come down they are modeled to stay down till 7:30 am next morning, when the occupants arrive for the day.

3.4 EC glazing simulation workflow

VDG was modeled with 4 tints using the Energy Management System feature within Energy Plus v8.9 (E+) to replicate the exact manufacturer specified multi-criteria control algorithm [6]. Annual schedules generated by E+, comprising of hourly VDG tint states for each facade are used as inputs to DIVA for Grasshopper, for evaluating daylight availibility and glare. To evaluate thermal comfort, hourly results from E+, such as interior surface temperatures , zone air temperatures, air velocity, humidity, window transmission etc. are used as inputs to the Predicted Mean Vote (PMV) comfort-recipe within Honeybee for Grasshopper.

3.5 Energy analysis

The baseline energy model with Low-E IGU + Manual Shades (henceforth called LowE_Shd) is kept at 40% gross WWR while the VDG case starts from 40% with 5% increments up to a maximum of 65%. In each case the window head height is kept fixed at 2.74m (9ft) while the sill height is lowered to accommodate a higher WWR. Annual energy use and peak HVAC capacity are plotted as a function of WWR to determine the point at which VDG performance matches the 40% baseline LowE_Shd model. This determines how much more window area VDG can provide in that climate, without any energy penalty or increased HVAC capacity for the building. The impact of increased WWR with VDG is then evaluated in terms of occupant comfort and greater access to outdoor views.

3.6 Thermal comfort analysis

The predicted mean vote (PMV) model is used for comfort evaluation. The PMV model [7] estimates the mean thermal sensation vote for a large group of occupants based on four measurable (air velocity, air temperature, mean radiant temperature and relative humidity) and two expected (clothing and metabolism rate) variables. PMV is measured on a scale from -3 (Cold) to + 3 (Hot) with 0 being the neutral sensation. ASHRAE Standard 55 defines the highest comfort range to be between -0.5 and + 0.5. Glazing can greatly affect the Mean Radiant Temperature (MRT) but surprisingly the effect of direct sun on indoor occupants had not been considered till much recently. To address this gap Arens et. al. [8] have proposed a new model (SolarCal) which computes an increase in MRT, equivalent to shortwave gains from direct, diffuse, and indoor-reflected radiation on a person. This solar adjusted MRT is used to compute PMV that accounts for the increased shortwave radiation from the window. This adjustment is now a requirement for thermal comfort compliance with ASHRAE Standard 55 [9]. The PMV comfort recipe within Honeybee for Grasshopper includes this adjustment. The occupant is assumed to be seated about 1.2m (4ft) from the windows with a metabolic rate of 1.1 met (typing). The Clothing value (Clo) ranges from 0.5 to 1, as a function of outdoor air temperature.

3.7 Visual comfort and outdoor views analysis

Useful Daylight Illuminance (UDI), was used to determine annual daylight availability. $UDI_{50\%}$ represents the percentage of floor area that receives daylight between 100lux (10fc) to 2000lux (200fc) for at least 50% of typical occupied hours. These illuminance limits are based on reports of occupant preferences and behavior in daylit offices with user-operated shading devices [10]. Glare was evaluated with Daylight Glare Probability (DGP), which is a luminance based metric developed for assessing visual discomfort from daylight [11]. DGP values over 35% are considered glare. DGP analysis was performed for an occupant facing the windows at a 45º angle. The occupant is seated 1.2 m (4ft) from the façade. Research has confirmed the benefits of a visual connection to the outdoors for the psychological and physical well-being of indoor occupants, especially when there are views of nature [12]. However, shading devices such as manual shades disrupt this vital connection and rob occupants of the views and daylight afforded by the site and building design. Reducing WWR as a design solution permanently reduces the viewing area and affects daylight distribution in the space. In this paper, outdoor views have been quantified based on WWR (extent of viewing area) and manual shade deployment status (% of time outdoor views are obstructed due to shades being down).

4 Results and Discussion

4.1 Annual energy and peak HVAC capacity

Figures 1-3 present the annual energy use and peak HVAC capacity for each location, plotted as a function of increasing WWR with VDG, compared to a fixed 40% WWR baseline with LowE_Shd. The peak HVAC capacity (cooling + heating) has been added together as one number to balance out any increase in heating capacity with decrease in cooling capacity. The right panel in figures 1-3 shows peak cooling load components for the VDG WWR case that is closest to the 40% WWR LowE_Shd case for each location.

In all three cases there is a similar trend for the peak cooling load component breakdown. Shades increase the heat gain from interior lighting because the cooling peak happens on a clear and hot sunny day when shades are down requiring full lighting power. VDG on the other hand selectively tints to its darkest state only when needed for each façade but is otherwise clear, allowing natural light to offset interior light output. The contribution of window beam solar (direct solar) is < 4% for both the VDG and shades because VDG is in its darkest tint state and the blinds are fully down under direct sun. However, there is one major difference in how VDG is blocking the solar gain vs shades. The shades are absorbing the heat after being transmitted through the window and even when reflecting some of it back, a portion gets trapped between the window and the shade, heating up the air in that gap. This converts the transmitted solar gain from a delayed to an instantaneous load and is showing up as the increase in window conduction for all three sites. VDG blocks the direct sun from coming into the space so it does not allow this phenomenon to occur, however increasing WWR with VDG does ultimately affect window conduction gains especially with summer air temperatures in Phoenix around 45ºC. This is one key factor affecting the higher WWR VDG cases.

The other component that is affecting peak HVAC sizing with VDG is the diffuse solar component. This stems from the fact that when there is no direct sun penetration VDG goes to Tint 1, transmitting diffuse solar radiation, while the manual blinds being mostly down all day continue to block the diffuse solar radiation. Therefore, the WWR increase is the lowest in Phoenix, which has high diffuse radiation and hottest summer temperatures followed by Chicago with its relatively hot and clear sky summers. San Francisco allows the highest WWR increase due to lower temperatures and lower solar radiation levels due to higher annual cloud cover. The highest WWR for VDG with no additional HVAC capacity was found to be 50%, 55% and 60% for this prototype in Phoenix, Chicago and San Francisco respectively.

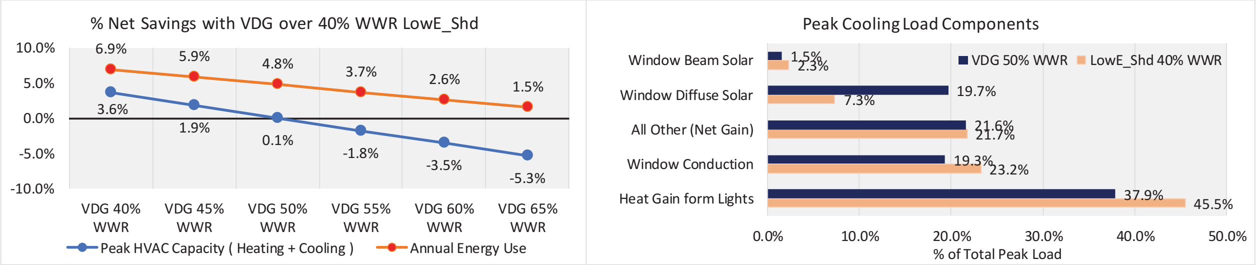

Figure 1. Annual Energy and HVAC Sizing Results - Phoenix, AZ

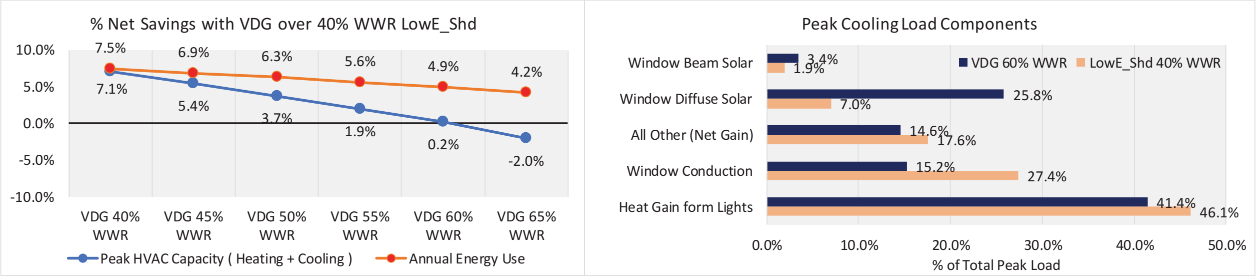

Figure 2. Annual Energy and HVAC Sizing Results - San Francisco, CA

For both Phoenix (Figure 1) and San Francisco (Figure 2) the annual energy savings goes down but stays positive all the way upto 65% WWR, despite the slight increase in HVAC capacity. This is primarily because as the WWR goes up the artificial lighting usage comes down with greater daylight availability. This reduces the cooling load from lighting driven heat gain. VDG is also very effective in reducing the direct solar gains even at high WWR, leading to HVAC operational savings.

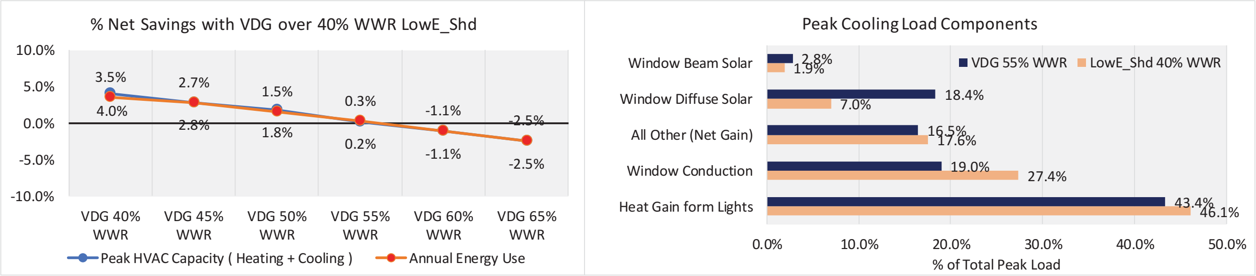

Figure 3. Annual Energy and HVAC Sizing Results - Chicago, IL

For Chicago (Figure 3) however the dominant energy use was found to be annual heating , which is greatly affected by conduction losses from increased WWR, so the energy savings potential is much lower. It should be noted that the manual shades were found to increase the heating energy use in all cases by blocking solar gain that could otherwise be used for passive heating whenever glare was not a concern. Figure 4 shows the additional energy savings potential with VDG over the LowE_Shd cases for the same WWR.

Site EUI	**Phoenix**			**Chicago**			**San Francisco**		
	50% WWR			**55% WWR**			**60% WWR**		
	LowE_Shd	VDG	% Savings	LowE_Shd	VDG	% Savings	LowE_Shd	VDG	% Savings
kWh/m2	128.6	114.5	**11%**	132.7	122.1	**8%**	103.1	87.5	**15%**

Figure 4. Energy Use Intensity (EUI) savings with VDG over LowE_Shd at increased WWR

4.2 Thermal comfort

For the summer comfort analysis, the west façade of the building in Phoenix was analyzed between 8 am to 6 pm daily, during the hottest week defined in the Energy Plus Weather (EPW) file. This week (Aug 3-9) represents the effect of very high incident solar gain on the west (~ 800 W/m^2) combined with the highest average Outdoor Air Temperature (OAT > 40 ºC) of all three sites. Figure 5 shows that the PMV is typically below +0.5 for both the LowE_Shd and VDG scenarios whenever VDG is tinted (Panel 1) or manual shades are fully down (Panel 3), confirming that all direct shortwave radiation is blocked from reaching the occupant. One critical difference between the two glazing scenarios however is that to provide comfort the shades block all outdoor views for 45% of total hours of that week (Panel 2) while VDG uses a mix of tint states (Panel 4) to modulate light/heat while always preserving outdoor views. In this case the modeled internal shades are light colored and reflective, but it should be noted that darker and more absorptive blackout shades can get excessively hot.

Panel 3 confirms that VDG transitions to Tint 4 each day from 2 to 5 pm, closely following the west façade incident radiation profile (Panel 5). Since the priority for VDG is to control glare, unless there is direct sun penetration reaching the occupant, VDG will not use Tint 4. Therefore, VDG is in Tint 1 on the west façade from 8 am to 2 pm. In general, this allows greater daylight for the west offices but for days 1, 4 and 5 (Panel 5) there is relatively high morning diffuse radiation causing the PMV with VDG in Tint 1 to go above 0.5 for those hours. The same is true for the LowE_Shd cases since the shades are also modeled as being up in the morning, in the absence of direct sun on the west. Clearly, VDG can eliminate the slight discomfort from the increased diffuse radiation levels in the morning by using a darker tint state, as demonstrated by the fact that PMV is below +0.5 in the late afternoon under much more intense incident radiation and hotter OAT. So VDG can technically provide full comfort under all summer conditions, however this is where the opposing needs of thermal comfort and daylight autonomy come into play, requiring project specific assessment of occupant preferences, acceptable comfort ranges and energy use targets.

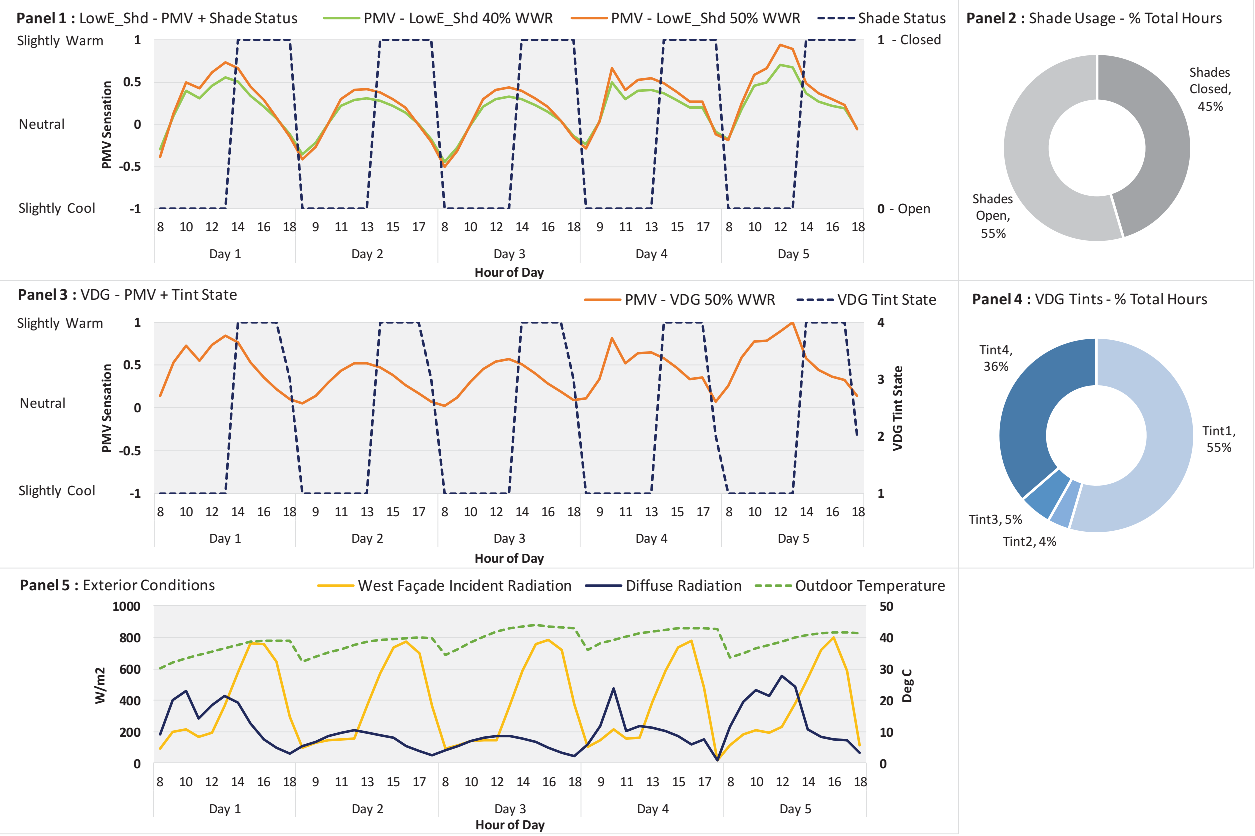

Figure 5. Thermal Comfort Chart for West Façade – Phoenix, AZ (Extreme Hot Week selected from weather file)

For the winter comfort analysis Chicago was selected with the occupant facing the south façade from 8 am to 6 pm daily, during the extreme cold week which is Jan 27 to Feb 2 as per the EPW file. This week represents the effect of intense solar gain on the south along with the lowest average outdoor air temperature (OAT < -10 ºC) of all three sites. Due to the low sun altitude (< 30º) in winter whenever there is a clear sunny day the occupants on the south side will experience severe discomfort from glare and overheating even though the OAT is well below 0º C. This condition exists for days 1 & 4 with high incident radiation throughout the day (Fig 6: Panel 5). As a result, VDG stays at Tint 4 and the shades are also fully down. However, on days 3 & 5 there are only a couple of hours requiring the darkest VDG tint state and as the incident radiation levels go down VDG selects lighter tint states (Fig 6: Panel 3). A lighter tint state with higher Tvis and SHGC allows more daylight as well as passive heating potential. On the other hand, once the manual blinds come down at any point in the day they are modeled to stay down (Panel 1) regardless of improved outside conditions. So, given the fact that the south facade gets the most direct sun hours in winter, the shades are found to be down for 85% of the hours in that week.

The primary cause of winter discomfort near the windows is inside glass surface temperature, which is dependent on the fenestration U-Value (~ 2.2 W/m2-K in this case) and the OAT. Hence, given the extreme low OAT for the chosen period the PMV is almost always below -0.5 for both glazing scenarios. It should be noted that the PMV model itself is known to have limitations due to having been derived under steady-state laboratory conditions that don't always match with dynamic indoor conditions in regular buildings. Also, the clothing insulation and metabolic rate of occupants is very difficult to predict accurately and can lead the PMV model to under or over-estimate thermal sensation [7]. The winter comfort due to U-value can be further improved for VDG with an additional Low-E coating or selecting a triple IGU configuration. But even with the default dual pane configuration VDG still offers comparable winter comfort with substantially more daylight, unobstructed views and greater scope for passive heating. Any improvement in U-value from shading devices is minimal unless a relatively air-tight seal is made between the shade and window frame (e.g., with a track). Hence despite the manual shades being down for 85% of the time the PMV is mostly below -0.5.

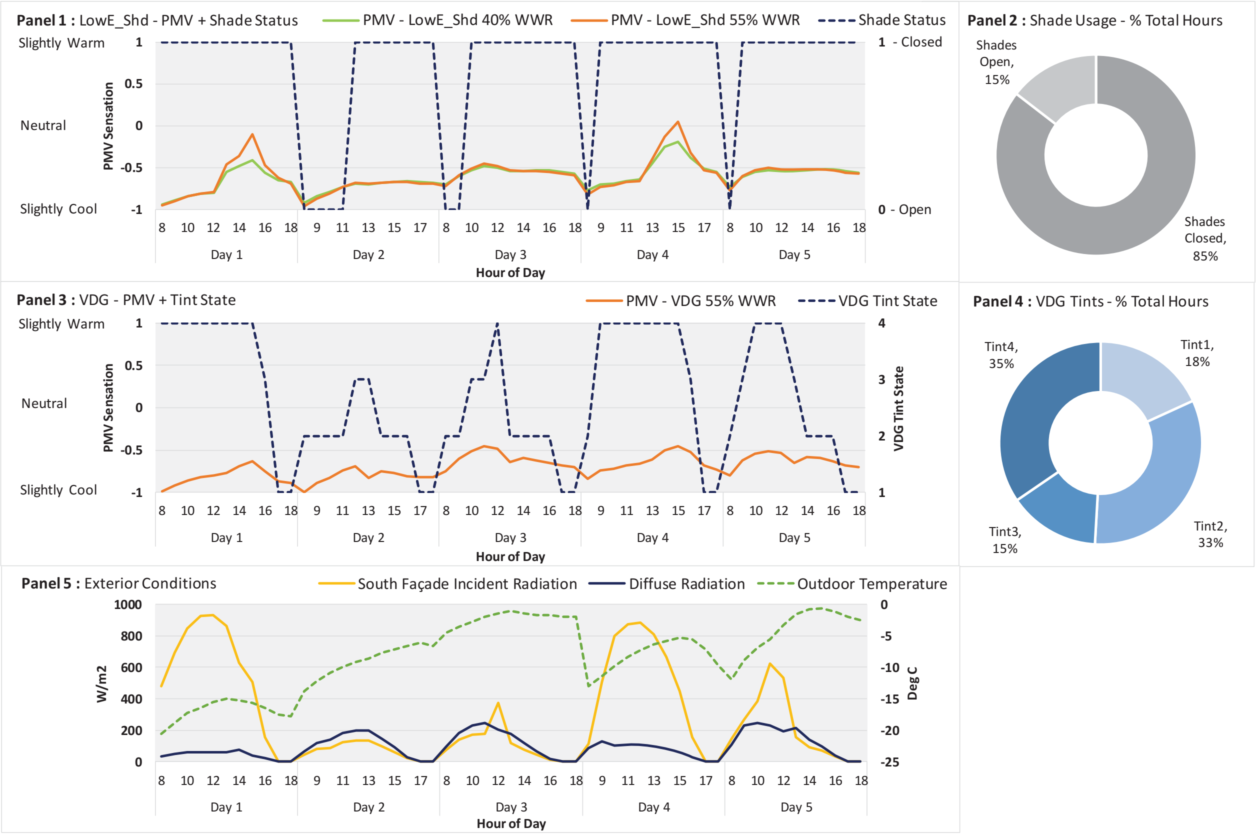

Figure 6. Thermal Comfort Data for South Façade – Chicago, IL (Extreme Cold Week selected from weather file)

4.3 Visual comfort

The higher WWR allowed by VDG vs the baseline 40% WWR LowE_Shd case allows occupants to have 25-50% more viewing area. Larger windows also provide greater access to outside views for occupants further from the façade and bring in more daylight.

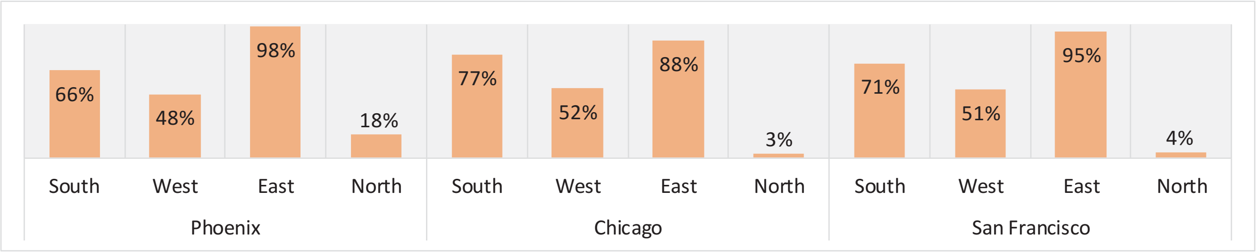

Figure 7. % Hours (8 am to 6 pm) Outdoor Views blocked by Shades down

The other parameter used for evaluating access to outdoor views is the duration that shades are down, causing visual obstruction. The east façade has manual shades down for 88-98% (Figure 7) of the time because typically those get pulled down first thing in the morning (even if there is direct sun penetration for only 10 mins) and are modeled to stay down for the rest of the day. Shade usage on the south is relatively higher in winter due to the low sun altitude, in contrast to the summer months when the sun is usually high enough (especially in Phoenix) to not require shades for direct glare. The west façade was assumed to have shades open each morning and then come down only in the afternoon if needed, so there are fewer hours with shades down compared to east and south. Finally, the north façade has the least shade usage, except for the longest days in summer when the sun rises and sets due north.

The higher WWR with VDG increases UDI between 1.5 to 2 times (Figure 8) because larger windows allow more floor area to have daylight access. However increasing WWR for the LowE_Shd cases has little to no impact on the UDI because the manual shade usage stays the same and once shades are down they stay down blocking daylight (Figure 7). VDG uses the darkest tint state only when necessary for glare control and otherwise selects lighter tint states to allow greater daylight illuminance throughout the day. The variation in UDI with VDG is due to the difference in weather conditions across the three sites. Phoenix has the highest UDI because it has more sunny days throughout the year with high ambient outdoor illuminance (more light transmitted indoor) while San Francisco has more annual cloudy days with lower outdoor illuminance.

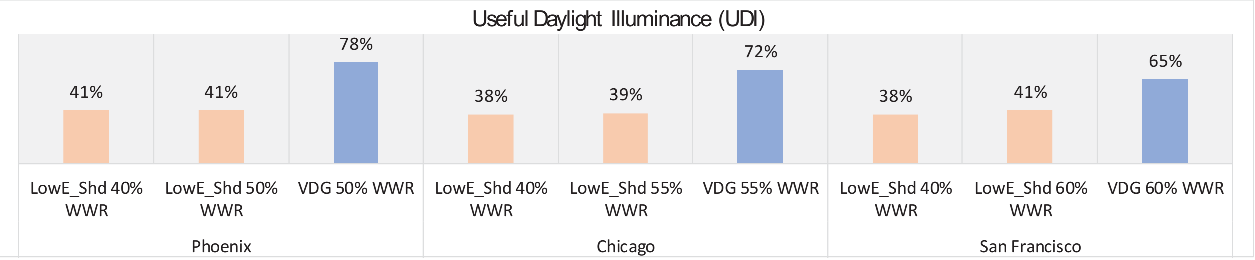

Figure 8. $UDI_{50\%}$ Comparison Between LowE_Shd with VDG

Figure 9 shows that, for the chosen occupant position, VDG eliminates glare for 99% of operating hours (8 am to 6 pm) across all three sites. Manual shades when fully down also eliminate most of the glare but there are still 80-90 annual hours, especially on the east and west façade when the shades with a Tvis of 6% (3% openness) cannot block the low altitude sun as well as VDG in its darkest tint with a Tvis of 1%. In fact there are a few hours (< 40) where even VDG at 1% Tvis cannot keep DGP < 35%, mainly on the east and west façades in the summer months in Phoenix. To account for those hours VDG can actually be programmed to tint down to a Tvis of 0.5%. This effectively brings down the DGP well below 35% and eliminates glare, as shown in Figure 10, for a week in June when this problem was observed around 4 pm each day. With this setting VDG was found to eliminate any remaining hours of direct glare for the year. However, a Tvis of 0.5% will also marginally reduce the UDI.

	Phoenix			**Chicago**			**San Francisco**		
Façade	40% WWR LowE_Shd	50% WWR LowE_Shd	50% WWR VDG	40% WWR LowE_Shd	55% WWR LowE_Shd	55% WWR VDG	40% WWR LowE_Shd	60% WWR LowE_Shd	60% WWR VDG
South	1%	1%	1%	0%	1%	1%	0%	0%	1%
West	2%	3%	1%	1%	2%	1%	1%	2%	1%
East	2%	2%	1%	0%	0%	1%	1%	1%	1%
North	0%	1%	0%	0%	3%	1%	1%	1%	1%

Figure 9. % of Annual Operating Hours (daily 8 am to 6 pm) with Daylight Glare Probability (DGP) >35%

One interesting observation is that a few hours had DGP > 35% in all three sites despite no direct sun penetration reaching the occupant. These are noon hours when the outside global horizontal illuminance was found to be very high (~ 30,000 Lux) and with VDG in clear state and the shades up, the transmitted light was also high. It should be noted that the DGP metric has known limitations with handling such high ambient light conditions (vertical illuminance at the eye > 4100 lux) and reports glare even if there is no direct glare source or high contrast ratio [13]. Hence glare predictions for such conditions need to be experimentaly verified [13].

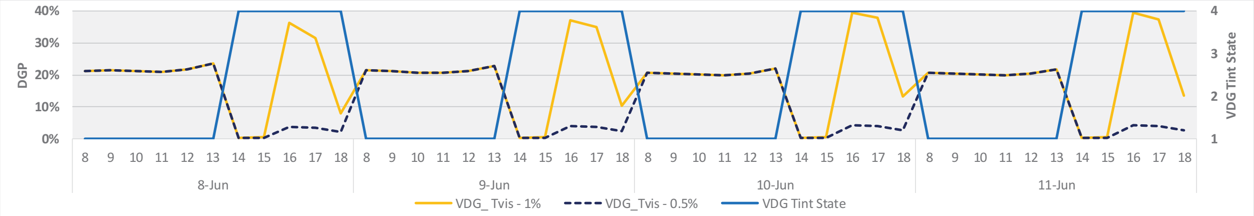

Figure 10. Using VDG with a Tvis of 0.5% to eliminate glare (West Facade June 8-11 - Phoenix)

5 Conclusion

This study found that the WWR for the selected mid-rise office could be increased by 25 - 50% with VDG, without any HVAC or energy penalty. This translated to significantly higher daylight, greater viewing area and full glare control with year-round outdoor views vs static LowE and manual shades at 40% WWR. Compared to LowE at the higher WWR cases VDG offers all the above benefits as well as annual energy savings up to 15%. The only time VDG was found to be marginally less effective than shades was under very low outdoor air temperatures that caused cold discomfort near the windows. This can be rectified with a better U-value. The final summary of benefits is presented in Figure 11.

	WWR Increase	Annual Energy Savings	Outdoor Views		Useful Daylight Illuminance	Annual Discomfort Glare Hours	Thermal Comfort	
			Increased Viewing Area	% Hours Views Blocked by Shades			Summer Time	Winter Time
LowE + Manual Shades				50 - 98% depending on orientation	38 - 41% (No benefit of WWR increase)	Upto 3% even with shades fully down	Comfortable but no views and daylight	Some discomfort for low outdoor temperature & no passive heating
View Dynamic Glass	25 - 50% (without HVAC or energy penalty)	0 - 4% vs 40 % WWR 8 - 15 % at same WWR	25 - 50% more window area vs 40% WWR	Views are never blocked	65 - 78% (1.5 to 2 times more)	1% (Can be 0 with Tvis of 0.5%)	Comfortable with 100% views	Marginally more cold discomfort (Can be improved with lower U-Value)

Figure 11. Summary of VDG Performance vs Low-E (SHGC – 0.39) with 3% Openness Factor Manual Shades

6 Limitations and Future Research

The manual shade operation assumed in this study has a direct impact on the relative benefits with VDG and modeling shades partially down instead of all the way or changing the frequency of operation from every morning to once a week or monthly will give a different set of results. Automated shades are likely to eliminate most of the shortcomings of manual shades but will still obstruct outdoor views. Compared to the standard Low-E baseline (SHGC - 0.39) used in this study a higher performance Low-E with SHGC < 0.25 will perform better in a hot and sunny climate like Phoenix but might also increase heating energy use in a colder climate like Chicago. For this study the ability to see outside without obstruction is considered a desirable outcome regardless of the “quality” of the view in terms of greenery, water features or another building. Lastly, to better evaluate the benefits of EC across a wider variety of building types this study could be extended to buildings that are different from the typical commercial office, in terms of internal and ventilation loads (hospitals & labs) and occupancy patterns (multifamily high rise).

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