Electrochromic Windows in Western Canadian Climates: Impacts on Building Energy Consumption, Thermal Comfort and Daylighting

Milad Mahmoodzadeha[1], Merriam Vahidi [2], Edlyn Garcia La Torre [3], Voytek Gretka [4], Geoffrey Yamasaki [3], Phalguni Mukhopadhyaya[1]

[1] University of Victoria, Victoria, Canada
[2] Morrison Hershfield Ltd., Vancouver, Canada
[3] Morrison Hershfield Corp., San Francisco, USA
[4] Morrison Hershfield Corp., Atlanta, USA

Abstract

In recent years, climate change and extreme heat events across Canada have led to overheating in residential buildings without air-conditioning. Overheating is a major concern for the health, productivity and comfort of occupants, especially vulnerable populations such as the elderly. This study involves a simulation-based quantitative analysis to evaluate the dynamic effect of electrochromic (EC) windows on heating and cooling, while also analysing thermal and visual comfort of occupants in residential buildings. The study includes a multi-family residential building (MURB) archetype in National Building Code (NBC) climate zones 4, 5 and 6 (i.e., Vancouver, Kamloops, and Prince George, BC). Finally, a parametric study is performed to evaluate the sensitivity of design variables on conclusions, such as window-wall ratio (WWR) and incident solar radiation setpoint on the window for activation of EC window.

Introduction

Climate change has resulted in abnormal temperatures and precipitation conditions in many parts of the world. Perhaps most concerning is the unstable and unpredictable nature of these changes. It has become increasingly clear that the next generation of buildings need to be robust and dynamic, capable of adjusting to a wide range of climatic scenarios subject to seasonal variability.

Glazing can have a significant impact on building performance in terms of energy use and occupant satisfaction. Smart glazing systems, such as EC glass, thermochromic glass and photochromic glass are desirable due to their ability to dynamically change visual properties (ie. tint states) that directly impact performance (Cannavale et al. 2020). For example, EC glass changes colour in response to an applied voltage, giving users direct control compared to other smart glazing materials. This unique ability can allow users to consider multiple variables to inform an optimal tint state, potentially striking a better balance between energy efficiency and occupant satisfaction (Cannavale et al. 2020). As with any window, major factors to consider are thermal performance and optical properties. The expected thermal performance, indicated by the heat transfer coefficient, or U-Value, remains the same regardless of the colour state of the window (Kusiak et al. 2013). Optical properties, such as solar heat gain coefficient (SHGC), visible transmittance, and solar transmittance, vary based on the voltage applied.

A broad range of studies have been conducted in recent years on the impact of EC windows on energy, thermal comfort and visual comfort in buildings. For instance, Dussault and Gosselin (2017) conducted an energy simulation using TRNSYS and Radiance/DAYSIM for a representative office building to compare EC glass to a conventional window. Building location, façade orientation, window control, window-to-wall ratio (WWR), and other variables were modified to create 7680 unique scenarios. Locations considered included Atlanta, GA, Chicago, IL, Miami, FL, New-Orleans, LA, San Francisco, CA. Washington, D.C., Calgary, AB, Montreal, QC, Toronto, ON, and Vancouver, BC. The study found that location, façade orientation, and WWR were the most influential parameters on overall energy use and cooling energy use. EC glazing was found to reduce cooling energy use, while tending to increase lighting and heating energy use. It was most effective when used on east, south, and west facing façades, producing annual savings of approximately 5.0 kWh/m^2 compared to 0.7 kWh/m^2 for north facing façades. Of the 7,680 scenarios studied, 84.5% had reduction in total energy use while the remaining 15.5% increased energy use. The authors noted that the warmer the climate is, the greater the benefit of using smart windows, with changes to overall energy use being driven by lighting energy use. A DOE-2 commercial building energy simulation study was conducted by Lee and Tavil (2007) to determine if EC glazing used in conjunction with overhangs could strike a balance between visual comfort and energy savings in south-facing offices. Various overhang depths, EC glazing control strategies, and WWR were considered. The study considered Houston, TX and Chicago, IL to represent hot and cold climates, respectively. The results demonstrated that primary annual energy use increased by 2-5% at 0.30 WWR but decreased by 5% in Houston and by 10% in

Chicago at 0.60 WWR. In another study, a series of experimental tests, aided by computer simulations, were conducted by Piccolo to evaluate the performance of double-glazed EC windows compared to clear float glass in a test-cell located on a roof in Messina, Italy (Piccolo 2010). Only south and west façade orientations were tested. The experiment showed that double-glazed EC windows, when fully coloured, reduced cooling load by 50% for west oriented façades, and by 60% for south oriented façades. The author notes, however, that energy for artificial lighting use was not measured and may negate the energy savings provided by reduced cooling energy (Piccolo 2010).

Sbar et al. (2012) used eQuest to compare the energy performance of dynamically controlled EC windows with static glazing in Phoenix, AZ, Washington, DC and Minneapolis, MN. Dynamic control was established using rule-based control (RBC) based on daylight, schedule, and glare. The study found that dynamic EC glazing produced at least 45% energy savings in all locations compared to single pane static glazing, and at least 20% compared to ASHRAE 90.1 2007 code compliant glazing. Tavares et al. (2014) conducted a simulation study of Mediterranean homes using ESP-r to determine changes in heating and cooling energy when either double paned windows or double paned EC windows are used to retrofit single pane glazing. The study found that retrofits with double paned EC glazing produced an energy savings of 20.28 kWh/m^2/year when used on the east façade, and an energy savings of 36.94 kWh/m^2/year when used on the west façade. Annual heating energy savings were better for standard double paned windows compared to double paned EC glazing when used on the south façade.

Other factors could lead to thermal discomfort for occupants. For instance, Lee and DiBartolomeo (2002) report that thermal discomfort can occur when occupants are struck directly by solar radiation. Furthermore, EC glazing absorbs heat, rather than reflecting it, creating the potential for thermal discomfort if occupants touch the surface of the glass. This is primarily a concern with single pane EC glazing.

The preceding literature review has highlighted the potential energy savings that can occur when incorporating EC glazing instead of traditional glazing. As with traditional windows, façade orientation has a significant impact on performance, with many studies reporting limited energy-related benefits of using EC glazing for north facing façades. EC glazing on east, south, and west façades have demonstrated significant promise; however, climate and latitude are important considerations, with some authors noting that the warmer the climate, the greater the benefit of using EC glazing.

In recent years, residential suite overheating has caused major issues for health, productivity and comfort of occupants in buildings without air conditioning systems. While the previous investigations have mainly focused on commercial buildings, this study attempted to evaluate the impact of EC windows on energy and occupant comfort in western Canadian multi-unit residential buildings (MURBs) in three climate zones.

Methodology

This paper evaluates a two-tint state EC in a MURB using EnergyPlus v9.4. The energy model is compared with a baseline model that has standard double-glazed windows. EC glazing was modeled in EnergyPlus as a shading device utilizing the "SwitchableGlazing" object. This control switches the glass construction for a window between two tint states, fully clear and fully tinted, based on the user control type "OnIfHighSolarOnWindow" where a solar radiation incidence setpoint on the exterior surface of the window can be specified (W/m^2). In this paper, to determine the optimized performance of the EC window in different cities, a parametric analysis was conducted using jEPlus where different ranges of WWR and incident solar radiation setpoint were considered. The shading control is activated whenever the incident solar radiation exceeds the setpoint value (W/m^2). It should be noted that for the energy and thermal comfort analysis, it was assumed that occupants are seldom present during the day. Hence, the variation of visual transmittance from EC window activation was not expected to add significant error on lighting energy, and consequently, its increased radiant energy in the thermal comfort analysis.

Table 1 indicates the range of variables used for the parametric analysis. In addition, thermal and visual comfort are evaluated with and without EC windows. Table 2 summarizes EC window properties simulated for each tint state. EC windows are compared with standard benchmark double glazed windows (U = 1.63 W/m^{2}K) with a low-emissivity coating to illustrate performance impacts on a relative basis. It is to be noted that the baseline model used tint state 1.

Table 1: List of simulation scenarios

Variables	Values
WWR	25%, 30%, 40%, 50% and 60%
Incident solar radiation setpoint (W/m^2)	50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550 and 600

Table 2: EC window properties simulated

Tint state	Visible Transmittance (VT)	Solar Heat Gain Coefficient (SHGC)	U-value (W/m^2 K)
Tint 1	0.58	0.41	1.63
Tint 2	0.01	0.09	1.63

Building Model

An archetype energy model was developed for a six-storey mass timber building. The archetype consists only of residential suites, which are accessed by way of exterior stairwells and/or elevators from the common courtyard. The building is shown in Figure 1, and totals 6,673 m^2 of floor area. The thermal transmittance (U-value) of exterior opaque wall and windows in all climates are 0.24 W/m^2 K and 1.63 W/m^2, respectively. Mass timber wall assemblies were selected that met the NECB 2015 minimum prescriptive requirements in all climate zones, while window performance was suggested based on current industry practice.

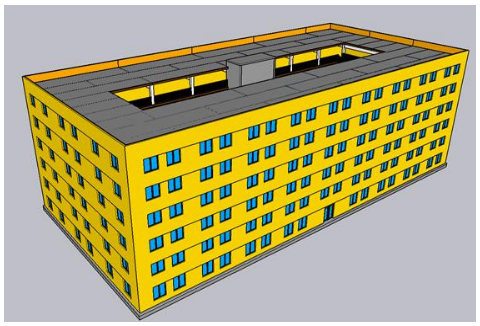

Figure 1: Schematic of building geometry

The HVAC system consists of decentralized heat recovery ventilator systems (HRVs), with fan coils connected to electrical heating and cooling coils that cycle to serve heating and cooling loads served by packaged terminal heat pumps (PTHPs). The service hot water was provided by an electrical boiler and the interior lighting was assumed 5 W/m^2. To assess the impact of the EC windows as a potential design element to improving the thermal comfort in MURBs without an air conditioning system, a cooling system was not modelled but considered natural ventilation instead (ie. user-operable windows) by utilizing the “AirFlowNetwork” objects in EnergyPlus.

Climates

The simulations were performed in National Building Code (NBC) climate zones 4, 5, and 6. EnergyPlus weather data files (.epw files) were used for the simulations. The climatic information for the three selected cities is summarized in Table 3.

Table 3: Summary of climate data for the three selected cities

City	Climate zone	Heating Degree Days (HDD)	Cooling Degree Days (CDD)
Vancouver, BC	4	2797	42
Kamloops, BC	5	3417	312
Prince George, BC	6	4906	31

Thermal Comfort

Overheating in buildings can be analysed by measuring indoor air temperature outside the ASHRAE 55 operative range (comfort zone). Also known as a thermal comfort analysis, it helps inform the severity of occupant discomfort in the summer months, thus enabling mitigating efforts by design teams. In this study, the thermal comfort analysis was undertaken to analyse the synergy of natural ventilation and EC windows. Solar heat gain and warm outdoor air are two major components contributing to overheating during the summer season in buildings without mechanical cooling (air conditioning). In the thermal comfort model, natural ventilation is provided by operable windows in the suites. Additionally, it assumes that at least 25% of the total window area in each suite is operable. It is assumed that occupants open the windows anytime the interior temperature is above 23°C. This action allows cooler outdoor air to influx and mix with the warm indoor air and bring down the interior temperature to comfortable levels. It is assumed the operable windows are open fully (i.e., no limiters) when the interior temperature is above 23°C and all ventilation is 100% outdoor air, delivered directly to the suites.

The B.C. Energy Step Code requires that occupied residential suites demonstrate less than 200 annual overheated hours in reference to the 80% Acceptability Limits defined in ASHRAE 55 if a mechanical cooling system is not designed (ASHRAE 55-2020). For buildings designed for vulnerable populations and in any BC Housing projects, this limit is reduced to 20 hours. Therefore, the design of windows, shading devices, and the HRV system are collectively critical to meeting the requirements; in this study, the impact of EC windows is evaluated at various incident solar radiation setpoints to complement traditional design strategies. For brevity, thermal comfort analysis is performed on a critical zone (highest number of overheated hours). The critical zone was selected based on the highest overheating hours in the baseline model, and the changes in the thermal comfort level were examined while other variables changed.

Daylighting and Glare Control

Daylighting is regarded as a synergistic control of dimmable electric lighting in response to available natural light from windows, to maximize the natural daylight and reduce lighting energy consumption. The daylight sensor can control the tint level based on the condition of the sky and the orientation of windows. For instance, if the sky is dark and overcast, the glass might be on clear tint and the electric lights would be on to achieve visual comfort for the occupants. In other words, EC windows can play a key role in minimizing glare and improving visual comfort for occupants. The dark tint state that minimizes window visible transmittance (VT) can be activated to achieve occupant comfort in direct sunlight, on the horizontal plane of a work surface, or vertical surface of a computer screen.

To this end, this paper analyses the impact of EC windows on visual comfort based on two tint states using Radiance.

After obtaining results from the energy model, the tint activation schedule and setpoints were applied to the daylight analysis and results. The baseline model was used for the daylight analysis, where the windows had a baseline VT of 0.60. This baseline condition is comparable to Tint 1. Annual daylight simulations were applied to the baseline model with tint states 1 and 2 and an automated shading schedule where the tint state 2 would be activated when daylight grid sensors reached 50 W/m^2. Based on the energy model results, window schedule results were compared to understand when the tint state 2 would be activated.

The following metrics were used for the daylight and glare study: sDA – Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Useful Daylight Illuminance (UDI). The model and simulation were set up based on IES LM-83-12. sDA describes how much of a space receives sufficient daylight. Specifically, it indicates the percentage of floor area that reaches at least 300 lux for at least 50% of occupied hours (8am-6pm). The UDI metric quantifies the percentage of time the space would be within an adjusted range of 200-2000lux. ASE is used to understand the % of occupied area with sunlight levels above 1000 lux for at least 250 hours. The adjusted lux range for the UDI metric is based on CIBSE-recommended illuminance levels of 200lux for residential spaces such as living rooms and kitchens.

These metrics help to understand if the space has sufficient natural daylight during the day, even when Tint 2 is activated, focusing on how this could reduce lighting loads and needs. In addition, glare metrics help understand if Tint 2 needs to be activated to improve visual comfort.

Results and Discussion

Energy

In addition to the total energy use intensity (EUI), thermal energy demand intensity (TEDI) and cooling energy demand intensity (CEDI) were considered to evaluate the effect of WWR and the EC window control system (incident solar radiation setpoint). TEDI refers to annual heating energy requirement from all types of space and ventilation heating equipment, per unit of modeled floor area. Likewise, CEDI refers to annual cooling energy requirement from all types of space, per unit of modeled floor area. It is to be noted that this study did not account for how much energy the EC system actually uses. However, according to the manufacturer it is small and on the order of 1kW for a MURB.

The results in Figure 2 revealed that when EC windows were implemented in the model, the CEDI decreased in all cities, varying between 70% and 85% in the best case scenario (60% WWR & 50 W/m^2 setpoint), depending on the climate. Expectedly, EC windows at a higher solar incidence setpoint (i.e., 600 W/m^2) yield lower relative cooling energy demand savings. The CEDI reduction with EC windows is smaller in Kamloops than others because of extreme summer weather, where conduction heat transfer through the building envelope is more dominant than the other climates studied. Nonetheless, it can be deduced that the setpoint value plays a key role in controlling CEDI.

By contrast, Figure 3 shows EC windows had an adverse effect on TEDI, increasing in all climates relative to the baseline by 60% in the worst case scenario (50 W/m^2 setpoint and 60% WWR). It is to be noted that the maximum reduction in CEDI occurs at 50 W/m^2, unlike TEDI, which is at its maximum. In other words, the larger the solar incidence setpoint, the smaller the TEDI is in all cities. This is attributed to the fact that by activating the EC window at a higher setpoint, the window will receive a larger fraction of solar energy (heat gain is higher), and as a result, the heating demand is lower.

As illustrated in Figures 2 and 3, WWR has a significant impact on the heating and cooling demand in all cities, whereby increasing the WWR, both heating and cooling demands in baseline model increased. This is justifiable since windows in the model have a larger U-value compared to the opaque wall (1.63 W/m^{2}K vs. 0.25 W/m^{2}K). In addition, the building is subject to more solar radiation in the summer which leads to an increased cooling demand. It can also be seen that at higher WWR, the increase in TEDI with EC windows is smaller (relative to baseline model), which is due to higher solar gain at higher WWR. Likewise, CEDI reduction with EC windows is greater at high WWR. Ultimately, designs with higher WWR have higher potential total energy savings with EC windows.

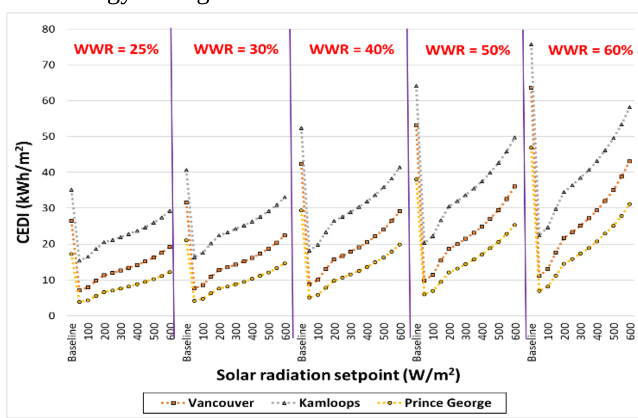

Figure 2: Variations of CEDI with WWR and incident solar radiation setpoints in different cities

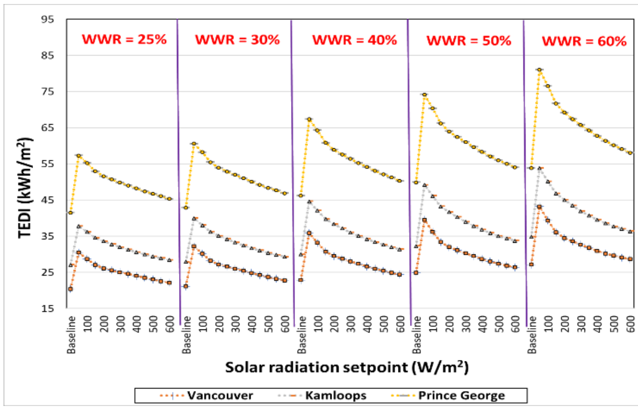

Figure 3: Variations of TEDI with WWR and incident solar radiation setpoints in different cities

Figure 4 shows the impact of WWR and solar irradiance setpoint on EUI. It is seen that EUI in Vancouver increased relative to the baseline model with EC windows, ranging from 6% to 11% depending on WWR and solar setpoint. Since Vancouver is in a relatively milder climate (higher HDD and low CDD), implementing EC windows has a larger impact on the increase of heating load than the reduction of cooling load. Interestingly, similar trends are evident for Prince George for WWR between 25% and 30%. However, at higher WWR and solar irradiance setpoint >300 W/m^2, there was a reduction in EUI compared to the baseline model by almost 2%. By contrast, hot Kamloops summers result a deeper reduction in CEDI than an increase in TEDI, ultimately resulting in an EUI reduced by almost 8% at 60% WWR. It can be concluded that particular attention should be devoted to designing a building with EC windows to ensure that the design can actually improve overall energy performance.

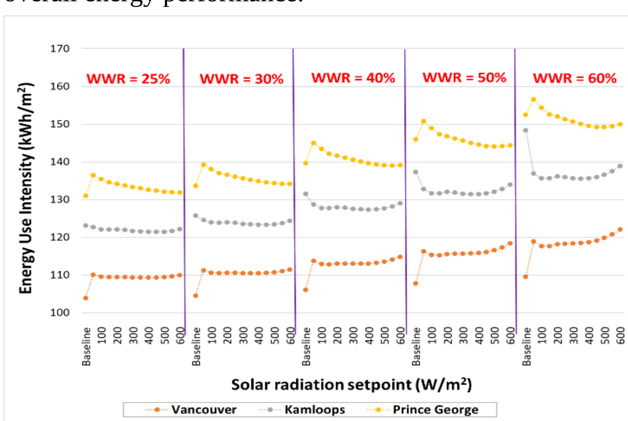

Figure 4: EUI as a function of WWR and incident solar radiation setpoints

Thermal Comfort

Operable EC windows were considered to evaluate the overheated hours in the building during the cooling seasons. The result shows that the EC windows significantly reduce overheated hours compared to the standard windows. Figure 5 shows the amount of reduction in overheated hours for the critical zone based on 40% WWR. The reduction in overheated hours varies between 6% to 60% at a solar irradiance setpoint of 600 and 50 W/m^2, respectively. When Tint 2 is triggered at a lower solar irradiance setpoint, overall solar heat gain is reduced, consequently reducing overheated hours by a greater percentage.

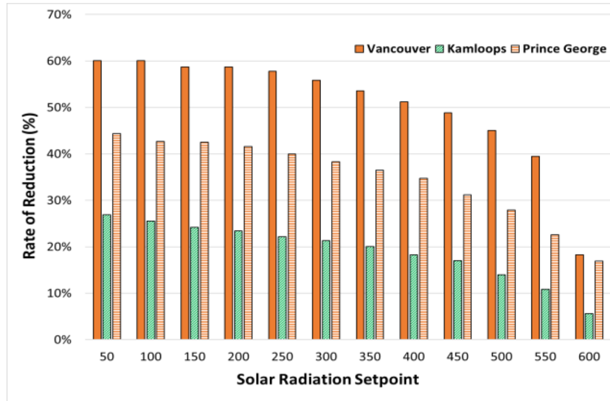

Figure 5: Percentage reduction in annual overheated hours for 40% WWR

Figure 6 shows the importance of selecting a solar radiation setpoint to balance thermal comfort with the benefit of daylighting; not compromising daylighting as much. There is a significant reduction in overheated hours at 50 W/m^2 compared to the baseline scenario. However, overheated hours vary in different climate zones. For example, overheated hours are reduced by over 60% in Vancouver but only by 27% in Kamloops. Similar to findings of the energy model, this phenomenon is likely due to the impact of conductive heat transfer in a hot summer climate presiding over any mitigation in solar heat gains through windows. As shown in Figure 6, changing the setpoint from 50 W/m^2 to 300 W/m^2 shows a nominal penalty in Vancouver (~3 hours), Prince George (~10 hours) and Kamloops (~27 hours).

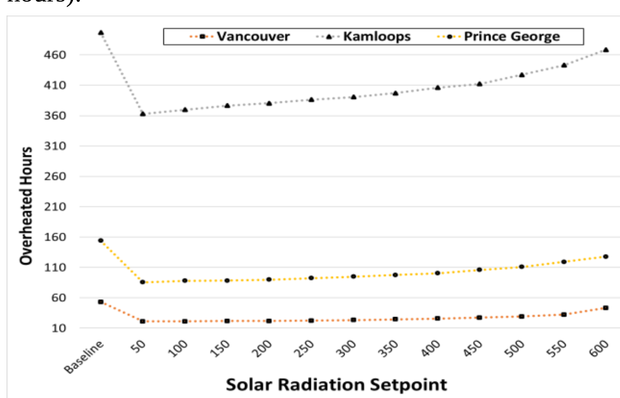

Figure 6: Overheated hours in the critical zone with standard and EC windows

These results are representative of other WWRs studied as shown in Figure 7. However, as WWR increases the impact of EC windows on thermal comfort is nominally more beneficial.

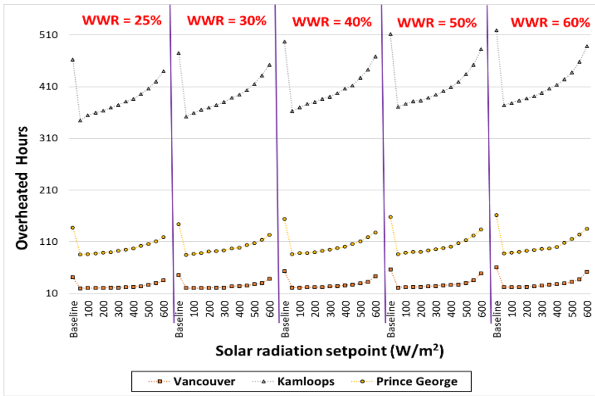

Figure 7: Annual overheated hours as a function of WWR and incident solar radiation setpoints in different cities

Daylighting and Glare

Since the baseline model had a floorplan depth about three times the height of the windows, it is understood that natural daylight was already limited to about 50% of the floor depth. In addition, the archetype model does not have interior walls dividing the zone. Therefore, the study understands that an additional reduction of daylight levels can occur, depending on the interior space layout, finishes, geometry, and location of windows.

The baseline model for Vancouver with EC windows in Tint 1 resulted in an sDA of 35% and ASE of 14%, while the UDI resulted in 66%. Based on the ASE metric, anything above 10% is recommended to use glare control devices, thus justifying implementing Tint 2 to reduce potential visual discomfort. When Tint 2 is activated at 50 W/m^2, the sDA is reduced to 22% and the UDI to 58% (shown in Figures 8 and 9).

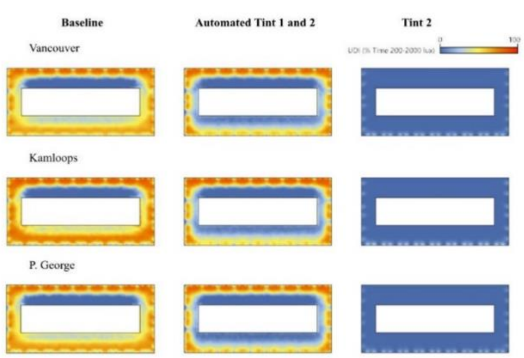

Figure 8: UDI-Useful Daylight Illuminance

For climate zones 5 and 6, these results are slightly higher. This may be due to a reduction in overcast sky in combination with longer daylight hours in the summer and lower angles of the sun during the winter, penetrating deeper into the zone. Each climate zone for the baseline model and the tint states are summarized in the Figure 9. The activation of Tint 2 occurs more on East/West orientations due to lower sun angles as indicated by % of tint inactivity.

		% of Area		% of Time	EC tint 2
		$sDA_{300/50\%}$	$ASE_{1000,250}$	UDI $_{200\text{-}2000}$	% Inactive
Vancouver	baseline	35.8	14.4	44	
	EC 02	0		1.13	
	Automated Shade	21.5		33.6	83% - South 72% - East/West 100% North
Kamloops	baseline	41.8	20.9	49.53	
	EC 02	0		1.4	
	Automated Shade	20.2		32.16	78% - South 55% - East/West 100% North
P George	baseline	38.1	16.3	45.5	
	EC 02	0		1	
	Automated Shade	20.2		32.16	83% - South 61% - East/West 100% North

Figure 7: Daylighting Metrics (sDA, ASE and UDI)

All three climates have a UDI within 44-50%, when illuminance reaches 200 lux for half of the total sunlight hours. UDI is reduced to 1% once Tint 2 is activated, requiring artificial lighting.

The daylight model schedule differs from the energy model tint schedule, being based on preventing solar heat gain; this resulted in tint activation during the majority of the daylight hours, and reducing useful daylight values within the space. This results in the need for artificial lighting during the day since the EC tint 2 is active to reduce solar gains, impacting useful daylight illuminance levels.

It is worth pointing out that energy for artificial lighting use was not measured when the EC window was implemented. This is important since it may impact the energy savings as well as overheated hours for the thermal comfort model. In other words, incorporating all aspects of energy, thermal comfort, and daylighting is vital to evaluate the impact of EC windows on building performance.

Conclusions

This paper attempted to examine the dynamic effect of Electrochromic (EC) windows on heating and cooling energy, while also analyzing thermal and visual comfort for occupants in a representative residential building. The parameters considered in the analysis were the location, window wall ratio, and rule-based control that depends on incident solar radiation. Results for every scenario were compared to the baseline case with standard double glazed windows.

The main findings of this study are highlighted as follows:

- The cooling energy demand decreased by implementing EC windows, while having an adverse effect on heating energy demand.

- It was found that at higher WWR, the increase of TEDI with EC windows was smaller than the reduction of CEDI.
- EC windows offer greater potential total energy savings with increasing WWR.
- Implementing EC windows could decrease the EUI in cities with hot summers. Otherwise, EUI can increased in other climates (Vancouver and Prince George) if an alternative tint state control methodology is not utilized.
- EC windows improved occupant thermal comfort for all three climate zones.
- The solar radiation setpoint should be set based on the climate zone to get the most benefit. Ultimately, the setpoint should consider the energy, glare, and daylighting benefits dynamically. This scope of work will form part of a future investigation.
- The biggest improvement in overheated hours was for Vancouver in climate zone 4, Prince George with Climate Zone 6, and Kamloops with Climate Zone 5, respectively.
- As WWR increased, the impact of EC windows on thermal comfort was more noticeable.
- EC windows help prevent visual discomfort in all three climate zones.
- Useful daylight is unavailable when Tint 2 is activated, requiring interior lighting energy to effectively illuminate spaces.
- Increasing WWR and considering other tint states with a higher visibility can improve availability of hours with useful daylight illuminance. Alternatively, a careful design considering different EC window solar irradiance setpoints for different regions of the same window is one potential solution that is currently used in industry to reduce glare while allowing sufficient natural daylighting.

Overall, the performance of buildings with EC windows depends on the climatic conditions, EC activation control system and architectural design parameters such as WWR. One may assume that the alternative to EC windows could be exterior shading devices. However, this comes with additional considerations for thermal bridging, envelope detailing, and aesthetic changes. Future studies should focus on optimizing EC window performance based on other criteria such as occupant schedule and outdoor air temperature to get benefits from visual, thermal, and energy aspects. In addition, to have both the benefits of reduced solar gain while harvesting enough natural daylight, window systems should be designed with different areas with different tint states or radiation incidence setpoints. This requires further studies, which forms a future investigation. It is to be noted that conclusions drawn in this paper are based on numerical studies conducted at three cities/climate zones in Western Canada. Future studies would consider more diverse locations and climate zones in North America. Finally, field validations of the observations made from numerical studies remain a task yet to be initiated.

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Thermal Environmental Conditions for Human Occupancy; ANSI/ASHRAE Standard: Peachtree Corners, GA, USA, 2012; pp. 55–2020.

Cannavale, A., Ayr, U., Fiorito, F., & Martellotta, F. (2020). Smart electrochromic windows to enhance building energy efficiency and visual comfort. Energies, 13(6), 1449.

Dussault, J. M., & Gosselin, L. (2017). Office buildings with electrochromic windows: A sensitivity analysis of design parameters on energy performance, and thermal and visual comfort. *Energy and Buildings*, *153*, 50-62.

Kusiak, A., Zhang, Z., & Verma, A. (2013). Prediction, operations, and condition monitoring in wind energy. energy, 60, 1-12.

Lee, E. S., & Tavil, A. (2007). Energy and visual comfort performance of electrochromic windows with overhangs. Building and Environment, 42(6), 2439-2449.

Lee, E. S., & DiBartolomeo, D. L. (2002). Application issues for large-area electrochromic windows in commercial buildings. Solar Energy Materials and Solar Cells, 71(4), 465-491.

National Research Council. (2015). National Energy Code of Canada for Buildings 2015. Ottawa, ON.

Piccolo, A. (2010). Thermal performance of an electrochromic smart window tested in an environmental test cell. Energy and Buildings, 42(9), 1409-1417.

Sbar, N. L., Podbelski, L., Yang, H. M., & Pease, B. (2012). Electrochromic dynamic windows for office buildings. International Journal of sustainable built environment, 1(1), 125-139.

Tavares, P. F., Gaspar, A. R., Martins, A. G., & Frontini, F. (2014). Evaluation of electrochromic windows impact in the energy performance of buildings in Mediterranean climates. Energy Policy, 67, 68-81.

Acknowledgement

Authors would like to acknowledge the support of View Inc, University of Victoria and Morrison Hershfield Ltd. for providing financial and technical support for this research initiative.