Characterization and energy performance of flexible photochromic window films

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Abstract. Windows are considered the weakest components in the building envelope, driven by their low thermal resistance and static transmittance to solar gains. Consequently, innovative coatings are often proposed to promote energy saving performance of windows. This article investigates several flexible photochromic window films capable of reversibly modulating solar gains based on the abundance of ultraviolet radiation. The peel-and-stick films are applied to the internal glazing surface, making them suitable for window retrofits without interrupting building occupancy. The optical properties of the photochromic films are experimentally characterized at various solar radiation intensities. The results are then used to numerically evaluate the energy-saving potential of the different films for a representative room in a high-rise office building located in Tokyo’s warm climate. The results of the experimental and numerical investigations are discussed to show the potential of photochromic films for window-retrofit applications.

1 Introduction

With the increased frequency and magnitude of climate change-associated heat waves, more attention is paid to improving building energy efficiency [1]. Windows are often considered the weakest components in the building envelope, driven by their low thermal resistance and static transmittance to solar gains, the latter contributing to higher cooling loads [2]. Hence, research on dynamic/smart/adaptive windows has been increasing rapidly in recent years and mainly focussed on electrochromic and thermochromic devices, while photochromic windows have received less attention [3].

Photochromism is a dynamic phenomenon where glass passively switches from clear to tinted states due to increased visible light absorption in response to ultraviolet (UV) solar radiation and bleaches back to its clear state in the absence of that radiation [4]. Photochromic glazing can be achieved using two approaches. On the one hand, photochromic glass can be produced by the dispersion of photosensitive particles (i.e., silver-based crystals) formed during glass manufacturing imposing limitations on the large-scale production of photochromic glass [5]. On the other hand, photochromic coatings can be fabricated by embedding organic, inorganic, and hybrid photoactive materials into transparent host matrices. The coatings can then be deposited on flexible polymeric films that are later applied on the glass surface [6].

In recent years, several photochromic window films have been introduced in the glazing market [7]. These films are produced using roll-to-roll physical techniques, making them more cost-effective while having faster bleaching rates and higher visible transmittance than photochromic glass [8]. Nevertheless, little is known about their energy-saving performance due to the lack of information regarding their thermo-optical characteristics [9]. Recently, several studies assessed the daylight and energy performance of photochromic coatings applied to exterior window surface [10] and interior surface of the outer glass pane [11], both found to have significant cooling savings and improvements in daylighting quality.

In this article, the thermo-optical properties of five commercial photochromic (PC) window films are experimentally characterized, and their energy-saving potential, relative to clear glazing, is numerically evaluated in the warm climate of Tokyo when applied to interior window surfaces as intended by the manufacturers. The PC films gradually tint and bleach within 30 seconds and 10-15 minutes under and after radiation exposure, respectively. Figure 1 shows the appearance of these films at their clearest states.

Fig. 1. Appearance of investigated PC films at clear states.

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2 Methods

2.1 Optical Measurements

The films were applied to clean 3mm clear float glass substrates (5cm x 5cm). The optical data (total transmittance, total front reflectance, and total back reflectance) at clear states were collected using a Cary 5000 UV/VIS/NIR spectrophotometer equipped with a 110mm Agilent Diffuse Reflectance Accessory (DRA-2500) in the wavelength range between 300 and 2500 nm at 5nm intervals. A customized Scientech AM 1.5 solar simulator equipped with a class (A) 300W xenon light source was then used to irradiate the applied films for 30 seconds, after which the optical properties were quickly measured in the range between 380 and 780nm at 5nm intervals. However, it was made sure that the films’ properties in the UV (300 - 380nm) and near-infrared region (780 - 2500nm) do not vary with light intensity. The power output of the lamp was measured to 100 mW/cm2 (1 Sun) using a 20mm x 20mm VLSI Standards calibrated reference monocrystalline silicon solar cell. The solar cell's current-voltage (I-V) characteristics were obtained by applying an external potential bias and measuring the maximum generated power using a Keithley digital source meter (Model 2400). The data was then interpolated to estimate the optical values at various solar intensities between 0 - 1 Sun at 111 W/m² intervals to match the simulation engine’s input limits, as discussed later. The following equations were also used to calculate:

1- UV transmittance:

\[ T_{UV} = \frac{\sum_{\lambda=300 \text{ nm}}^{\lambda=380 \text{ nm}} T(\lambda) S_{\lambda} \Delta \lambda}{\sum_{\lambda=380 \text{ nm}}^{\lambda=780 \text{ nm}} S_{\lambda} \Delta \lambda} \]  

2- Solar Skin Protection Factor:

\[ SSPF = 1 - \frac{\sum_{\lambda=300 \text{ nm}}^{\lambda=380 \text{ nm}} T(\lambda) E_{\lambda} S_{\lambda} \Delta \lambda}{\sum_{\lambda=380 \text{ nm}}^{\lambda=780 \text{ nm}} E_{\lambda} S_{\lambda} \Delta \lambda} \]  

3- Solar Material Protection Factor:

\[ SMFP = 1 - \frac{\sum_{\lambda=300 \text{ nm}}^{\lambda=380 \text{ nm}} T(\lambda) C_{\lambda} S_{\lambda} \Delta \lambda}{\sum_{\lambda=380 \text{ nm}}^{\lambda=780 \text{ nm}} C_{\lambda} S_{\lambda} \Delta \lambda} \]  

Where:

- \( T(\lambda) \) is the spectral transmittance of glass.
- \( \lambda \) is the wavelength in nm.
- \( \Delta \lambda \) is the wavelength interval in nm.
- \( S_{\lambda} \) is the relative spectral distribution of solar radiation (ISO 9050-2003).
- \( E_{\lambda} \) is the CIE erythemal effectiveness spectrum (ISO 9050-2003).
- \( C_{\lambda} = e^{-0.12\lambda} \) (ISO 9050-2003).

2.2 Numerical Simulations

The simulation methodology involved using several tools, including Notepad, Optics 6.0, Window 7.8, and EnergyPlus 9.4 through its DesignBuilder 7 interface. The thermo-optical data of 51 samples (one 3mm clear glass and five [x10 states] PC films applied to 3mm clear glass samples), including transmittance, front/back reflectance, front/back emissivity (provided by the manufacturer), was firstly organized according to the International Glazing Database (IGDB) format using Notepad. Optics software was then utilized to calculate the spectral properties of the individual glass samples in accordance with the National Fenestration Rating Council (NFRC) standard 300-2003. Window software was then used to calculate the thermal and optical properties of the double-glazed Insulating Glazing Units (IGU) comprised of external 3mm clear glass/ 13mm argon-filled gap / interior 3mm clear or PC glass. The properties include thermal transmittance (U-value) in W/m².K, Solar Heat Gain Coefficient (SHGC), overall solar transmittance (\( T_{SOL} \)), and overall visible transmittance (\( T_{VIS} \)) in accordance with NFRC 100-2010. Finally, EnergyPlus and DesignBuilder were used for simulating a thermal zone with different window and shading configurations and for various orientations and window-wall ratios (WWR).

A medium 6m x 6m x 3m representative room of a high-rise office building in Tokyo, Japan (WMO 476620) was modelled. Firstly, the assessment involved comparing a base-case scenario of an IGU (3mm clear/13mm argon/3mm clear) against the same IGU with the interior clear pane upgraded with the photochromic films at a WWR% of 80%, representing curtain wall construction, and for all cardinal exposures (S, W, N, E). Then, the best-performing glazing configuration at the exposure with the highest energy-saving potential was investigated at various WWR% between 10% - 100% at 10% intervals. Window frames and dividers were ignored in the model. Similarly, the windows were considered without shading systems since their impact on energy consumption would vary across different seasons and for different exposures.

The building model was selected to match a relatively new and real office building in Japan [12]. The ceiling, floor, and partitions were assumed to be adiabatic, while the exterior wall was constructed of 80mm brick tile, 20mm cement mortar, 150mm medium-density concrete block, 25mm polyurethane foam, and 13.7mm gypsum plastering, with a surface-to-surface U-value of 0.74 W/m².K. An occupant density of 0.2 people/m², metabolic emission rate of 123 W/person, 7 L/person mechanical ventilation rate, equipment power density of 25 W/m², lighting power density of 2 W/m²-100 Lux (0.72 radiant/0.18 visible/0.1 convective fractions), a target illuminance of 400 Lux with linear control (minimum output fraction of 0.1) for a sensor located at a working plane height of 0.75m at the centre of the room, and an air infiltration rate of 0.7 ACH were fixed. Natural gas heating (SEER 0.85) and electric cooling (COP of 3) systems were auto-sized to maintain indoor air temperatures at 20°C and 26°C in winter and summer, respectively, during occupancy hours (8 AM – 7 PM) without daylight savings based on a 5-day weekly working schedule. The tinting of the photochromic glass panes was achieved using the window shading module in DesignBuilder. The SageGlass Electrochromic template allowed varying the internal glass pane based on the
incident vertical solar irradiance (W/m²). The template allows up to 10 states (including the clearest state) to be adopted; hence, the optical data was interpolated at various solar intensities between 0 and 1 Sun at 111 W/m² intervals. The shading control was set to Daylight Only, where stepped tinting based on the sensor operation is defined only by the operation schedule (On 24/7), and using the Individual Sensors option, where each window is treated as if it has its built-in sensor. Finally, the Time-Frequency Shadow Calculation Method was used to ensure that the transparency of the glazing was updated correctly during simulation, and the time-step was set to 10 minutes to account for the bleaching rate of the PC films.

3 Results

3.1 Optical Characteristics

Figure 2 reports the measured total (diffuse + direct) transmittance of the PC films applied on 3mm clear glass irradiated at different solar intensities (reflectance data was omitted for brevity). Firstly, all applied PC films have lower transmittance in the whole solar spectrum when compared to 3mm clear glass sample. In particular, the films completely cut off the transmittance of UV radiation in the range of 300-380nm; hence have values of less than 0.1% for T_UV compared to 68.2% for clear glass.

In addition, two factors were calculated to investigate if the PC films can be employed to provide the desired protection of materials and human skin inside buildings under direct solar radiation. On the one hand, the calculation of the Solar SSPF extends over 300-400nm, including UV and visible radiation that contribute to solar radiation damage to the human skin. The SSPF improves to above 99% for all PC films compared to 79.7% for clear glass, which already provides some protection since it absorbs some of the incident UV and visible radiation. On the other hand, the SMPF extends over 300-600nm, including UV and a significant portion of visible radiation that contribute to material degradation. The SMPF also improves from 15.7% for clear glass to 46.3%-60.4% for PC-1, 46.4%-55.9% for PC-2, 58.1%-64.2% for PC-3, 71.2%-76.1% for PC-4, and 77.2%-81.1% for PC-5 at the clearest (0 Sun) and most tinted (1 Sun) states, respectively. These values imply that PC films significantly improve the protection of human skin and materials compared to clear glass.

Secondly, as reported in Figures 2 and 3, all applied PC films samples cause a reduction in the visible transmittance compared to clear glass, and the reduction rate increases going from PC-1 to PC-5. For PC-1, PC-4, and PC-5, this is attributed to the simultaneous increase in the visible light front/back reflectance and absorptance. On the other hand, increased absorptance mainly contributes to visible light transmittance reduction for PC-2 and PC-3 with no change in the front and back reflectance.

Fig. 2. Transmittance of PC films applied to 3mm clear glass.
Furthermore, visible transmittance is further reduced as the samples are irradiated. $\Delta T_{\text{VIS}}$ reduces going from PC-1 (22.3%), PC-2 (14.7%), PC-3 (9.3%), PC-4 (7.0%), to PC-5 (5.4%). The reduction is strictly attributed to increased light absorptance of all PC films under irradiation. Notably, both the front and back reflectance also decrease. For PC-1, PC-4, and PC-5, the front reflectance decreases by 4.8%, 4.3%, and 6.3%, while a less significant reduction in the back reflectance (film side) of 1.9%, 0.4%, and 0.3%, respectively, can be seen. On the other hand, for PC-2 and PC-3, the front reflectance reduction is only 0.6% and 1.5%, while the back reflectance decreases by 1.3% and 0.7%, respectively.

Finally, all PC films significantly reduce the transmittance of near-infrared solar radiation (780-2500nm) compared to clear glass. The reduction is attributed to increased front and back reflectance and is less significant for PC-1, making it more effective when solar heat gains are beneficial in winter. On the other hand, the near-infrared transmittance is similar for all other PC films. Conversely to the visible properties, irradiating the samples does not cause any changes in the near-infrared region.

Based on these results, $\Delta T_{\text{SOL}}$ in the whole spectrum decreases for all the films, with PC-1 exhibiting the highest solar modulation by 7.2%, followed by PC-2 (4.6%), PC-3 (3.0%), PC-4 (2.3%), and PC-5 (1.8%), implying that PC-1 could yield higher cooling energy savings. For all PC films, the front and back emissivity are constant at 0.85 (provided by the manufacturers) compared to 0.84 for clear glass.

### 3.2 Energy Performance Analyses

Figure 4 reports the double-glazed unit properties at various solar intensities between 0 and 1 Sun. The clear baseline IGU has constant SHGC (0.76), $T_{\text{SOL}}$ (0.70), and $T_{\text{VIS}}$ (0.81). Applying the PC films on the interior glass surface significantly reduces these properties. Conversely, the U-value has a negligible increase from 2.55 to 2.56 W/m².K due to increased front/back emissivity of the PC interior panes. Moreover, as the glazing units are irradiated, their visible and solar (to a lesser extent) transmittances significantly decrease with increased solar intensity. However, SHGC is only slightly reduced for PC-1, PC-2, and PC-3 and eventually increases for PC-4 and PC-5 at higher solar intensities.

Nevertheless, as reported in Figure 5, for a south-facing façade with 80% WWR, energy savings can be achieved by applying any of the PC films to the interior side of the glazing unit. The energy savings are attributed to a reduction in cooling energy consumption with a less significant increase in heating and lighting energy use. This is because the PC films absorb substantial portions of the incident visible radiation preventing it from directly transmitting indoors. Consequently, more heating and lighting energy are required to maintain the indoor air temperature at a comfort level in the winter and the target work plane illuminance all year round, respectively.

PC-1 has the highest energy-saving potential, followed by PC-5, PC-4, PC-3, and PC-2. Compared to the clear baseline, PC-1 improves the cooling performance by 20%, while the heating and lighting performances are negatively affected by 68% and 2%. PC-4 and PC-5 cause more significant increases in heating and lighting by up to 130% and 18%, respectively. However, they perform better in the cooling season, with cooling reductions of up to 30%, compared to clear glass. PC-2 and PC-3 slightly reduce the cooling energy by up to 16% while heating and lighting increase by up to 65% and 6%, respectively.

For the west and east-facing facades, only PC-1 and PC-2 imply cooling savings higher than the increase in heating and lighting energy use. However, the improvement in cooling load is negligible (1%). Furthermore, PC-3, PC-4, and PC-5 cause an annual increase in total energy use compared to clear glass. Similarly, for the northern façade, all the PC films lack the potential for energy savings.

### Figure 4

Window properties at various solar intensities.

### Figure 5

Energy consumption for different exposures.
Figure 6 further evaluates the performance of the PC-1 IGU compared to the baseline for various WWR%. Firstly, for 10% WWR, lighting and heating energy use account for nearly 50% and 30% of the total annual energy use, respectively, causing higher yearly energy consumption than all other WWR%. Here the clear IGU has better energy performance than the PC glazing since the latter results in even higher heating and lighting use with negligible reductions in cooling. Furthermore, for the clear IGU, as the WWR% increases, the heating and lighting energy uses decrease at higher rates than the increase in cooling use up to 40% WWR, which is the optimal layout from an energy-saving perspective.

Similar trends can be seen for PC glazing. However, the PC film, although it increases the heating and lighting loads slightly compared to baseline, it significantly reduces the cooling loads and the rate of increase in cooling loads at higher WWR%; hence, the optimum WWR% shifts to 50% (instead of 40% for clear glazing). As the WWR% increases to values more than 50%, the trend of lesser heating and lighting continues; however, the cooling also increases at higher rates. With the PC film, the rate of increase in cooling energy use is minimized. Hence, the highest cooling energy savings of the PC glazing compared to the clear unit occurs at 100% WWR. Here, PC glazing reduces the cooling energy use by 333 kWh (22%), significantly overcoming the increase of heating energy by 60 kWh (75%) and lighting energy by 8 kWh (<2%).

Figure 7 summarizes these findings for different WWR%. Based on this, PC glazing (PC-1) has the potential to improve the south-facing window’s annual Energy Use Intensity (EUI) by 2 - 7.5 kWh/m² (1% - 12.5%) for WWR% between 60% and 100% in Tokyo’s climate. While at 50% WWR, the clear and PC glazing consumes an equal amount of total energy, clear glazing outperforms PC glazing at WWR% below 50%.

To further investigate the reasoning behind these savings, Figure 8 reports the average annual PC glazing solar gains and heat losses compared to clear glazing at various WWR%. With increasing WWR% for both glazing configurations, the magnitude of heat losses and solar gains increase linearly. Clear glazing transmits more solar gains and heat losses around the year for all WWR% compared to PC glazing, while the differences increase at higher WWR%.

Figure 9 also reports the monthly average heating, cooling, and lighting energy use shares for clear and PC glazing at an 80% WWR. Firstly, heating is not needed in Tokyo between May and November, while some heating is required in April and December due to the high WWR. In contrast, the heating load is significant and comprises between 30% (baseline) and 50% (PC) of total monthly consumption between January and March, with February having the highest heating load influenced by the lowest outdoor air temperatures. On the other hand, cooling is required all year round, impacted by high solar gains and high WWR%. In August, the cooling load reaches its maximum comprising 90% of total energy consumption when clear IGU is used; however, it significantly decreases by more than 60% for PC glazing. From a lighting energy use perspective, clear and PC glazing behave similarly all year round (highest in December and lowest in July), with a slight increase for PC glazing.

This is elaborated on in Figure 10, which shows the hourly power consumption breakdown during typical summer (August 21st) and winter (February 21st) days in Tokyo for PC and clear glazing (80% WWR). Firstly, the lighting loads are less significant than the heating and cooling. In the summer, daylighting through both glazing configurations covers most of the lighting demand to achieve target illuminance except after 6 PM,
when the lighting load increases significantly. In the winter, artificial lighting is needed early in the morning (before occupancy) and later in the afternoon, starting at 3 PM. In all cases, PC-glazing consumes slightly more power for lighting, driven by its lower visible transmittance at clear states. On the other hand, heating is not required during the summer, while PC glazing increases the heating power consumption in the winter throughout the day but mainly in the afternoon. Nevertheless, PC glazing also reduces the cooling power required to maintain thermal comfort throughout the whole summer day. Although the reduction is not significant, the decline in the cumulative daily cooling power consumption in the summer, along with Tokyo’s cooling-dominating climate, overcome the increase in heating power demand.

Figure 11 further investigates the monthly glazing solar gains and heat losses. Firstly, both baseline and PC units (80% WWR) significantly reduce transmitted solar gains compared to the vertical solar incident radiation levels. Solar incident radiation is at its most significant in the winter (January) and lowest in summer (June) due to the variation of the sun's position around the year. However, there was an increase in the abundance of solar radiation in August due to less significant cloud cover, which drives the highest cooling loads in this period, as discussed earlier. Here, PC glazing significantly reduces solar gains and heat losses all year round.

Fig. 11. Average monthly solar gains and heat losses.

This is investigated more thoroughly in Figure 12, where the interior surface of the PC glazing has higher temperatures by 1 - 3°C than the baseline unit all year round. Although this drives the indoor air temperature to be cooler by 1 - 2°C, the temperature difference between the indoor air and interior glazing temperature is significantly lower in the winter months. In the summer months, the indoor air temperature tends to be higher than the interior surface temperature, and the temperature difference for PC glazing is higher. Nevertheless, the decrease in solar transmittance overcomes the increase in heat gains, resulting in the PC glazing performing better than clear glazing in the summer and overall, although its winter performance is depreciated. The exterior surface of both glazing configurations behaves similarly year-round with a slight increase in the outer surface temperature of the PC glazing, which is driven by the increased interior surface temperature as well as the slightly higher emissivity of the PC glass pane.

Fig. 12. Average monthly indoor air and surface temps.

Although small, the reduction in indoor air temperature with the use of PC glazing is critical not
only from an energy perspective but also from an occupant’s thermal comfort perspective. Figure 13 reports the Fanger’s average monthly Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD). PMV is an index that predicts the mean value of votes of occupants on a seven-point thermal sensation scale based on thermal equilibrium achieved when an occupant’s internal heat production rate equals its heat loss (calculated according to ISO 7730). A PMV value closer to zero implies that the space is more thermally comfortable, where zero is neutral, +3 is too hot, and -3 is too cold.

The average monthly PMV of clear glazing is only closer to neutral in the winter between January and April. Otherwise, for most of the year, PC glazing performs better from May to December including August, when extreme outdoor air temperatures combined with moderate solar gains occur. Based on the PMV, the PPD, an index that determines a quantifiable prediction of the percentage of thermally dissatisfied occupants, can be determined. The PPD results further support the results with a higher and lower PPD in the winter and summer months, respectively. While PC glazing improves the PPD the most in October (although the highest PPD occurs in August) by 5% compared to clear glazing; however, it negatively affects the PPD only in April by 6%.

The previous results showed that applying the PC-1 film to a south-facing clear IGU enhances the cooling and overall annual energy performance for a WWR above 50% in a cooling-dominated climate like Tokyo. However, climatic conditions, as well as the heating, cooling, and lighting systems and their efficiencies, could significantly affect the energy-saving aspects. It may be even that PC-1, although has the highest solar modulation ability, not be the most beneficial in other climates. Hence, identical simulations were conducted for the cold climate of Toronto, ON (WMO 712650).

The top chart in Figure 14 shows that the PC films increase the total annual energy consumption for all exposures except for PC-1 and PC-2 when applied to an 80% WWR east-facing glazing, while the predicted reductions are negligible (<1%). Here, a heat recovery system with an efficiency of 70% and a heating system SEER of 0.85 were assumed. Improving heat recovery, heating system efficiencies, and increasing WWR% would improve savings. The bottom chart in Figure 14 shows the same parameters but with a heating SEER of 3, where savings can be seen.

4 Discussion

The characterized PC films were first evaluated for their degree of protection of materials and human skin inside buildings under direct solar radiation. Two factors, including SSPF and SMPF, were calculated, and PC films proved to provide the desired protection levels. Conversely, clear glass failed.

Annual energy savings from retrofitting the clear IGUs with PC-1 were observed in the range of 1% to 12.5% for a south-facing facade with a 60% - 100% WWR in Tokyo. PC-1 had the highest energy-saving potential due to its high $\Delta T_{SOL}$, $\Delta T_{VIS}$, and its relatively higher transmittance in the near-infrared region compared to the other PC films, making it more effective when solar heat gains are beneficial in winter.

PC-1 showed substantial cooling energy reductions in the summer and higher heating demand in the winter compared to clear glass, which transmitted more solar gains and heat around the year for all WWR%. At a 100% WWR, the solar gains were double and triple (1.5 ratio) the heat losses for clear and PC glazing, respectively. The ratio increased to values above 2 for WWR% less than 50%, indicating that lower ratios are required to achieve annual energy savings in Tokyo.

Hence, with a few exceptions, all the PC films showed negative energy impacts for east/west/north orientations and at low (<50%) WWR, where they should be avoided. Nevertheless, PC-1 shifted the optimum WWR to 50% compared to 40% for clear glass. This is important as building codes typically prescribe a maximum 40% WWR. Hence, PC films allow designers to specify higher WWR% while still meeting energy targets.

PC glazing was shown to improve the thermal comfort performance of the studied office for most of the year. The film also proved beneficial for reducing the solar gains and heat losses all year round due to a
reduction in directly transmitted solar gains and increased interior surface absorptance, respectively. Although its overall winter performance was depreciated, driven solely by reduced solar gains, the temperature difference between the indoor air and interior glazing temperature was significantly lower in the winter months, causing lower heat losses. In summer, the indoor air temperature was higher than the interior surface temperature, and the temperature difference for PC glazing was higher, which increased the heat gains and negatively affected the PC glazing summer performance. However, the benefits from modulating the transmitted solar gains overcame the negative effects of increased heat gains.

For a typical winter day, PC glazing increased the heating consumption, mainly in the afternoon, attributed to the photochromic effect. Nevertheless, the photochromic effect also reduced the cooling power required to maintain thermal comfort throughout the whole summer day. In all cases, PC-glazing consumed slightly more power for lighting, driven by its lower visible transmittance at clear states. Most importantly, the photochromic effect did not worsen the situation.

Similar trends but with more significant energy savings were found in previous studies [10,11]. This is attributed to the studied PC coatings’ more significant solar modulation ability and their preferred location on the exterior glass pane. Here, the film’s location on the glazing unit's interior side, accompanied by increased absorptance of visible radiation (which is further exaggerated for PC-4 and PC-5), was shown not to be optimal since the absorbed solar radiation is later emitted towards the indoors. This was supported by insignificant reductions or even increments (PC-4 and PC-5) in SHGC for the PC units.

Finally, the annual energy performance of the PC glazing showed strong dependence on the building’s location. While savings were observed in Tokyo’s cooling-dominated climate, savings in Toronto’s cold climate were rare. However, improving the efficiencies of the heating and ventilation heat recovery systems reduced the heating energy penalties, and PC glazing exhibited more significant savings.

5 Conclusions

In this article, several commercial photochromic films were experimentally characterized, and their potential for energy savings was investigated in Tokyo and Toronto. The PC glazing performance was compared to clear IGUs for different exposures and WWR%. The results demonstrated that the PC films result in annual energy use reduction due to savings in cooling energy. Furthermore, the PC films sowed improved thermal comfort conditions, making them suitable for window retrofits without interrupting building occupancy. Future work should investigate their energy-saving potential in different climates and building types while exploring their daylighting potential in reducing glare and improving the availability of useful daylight.

References

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