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Influence of control strategy and split-band spectral modulation on the energy performance of electrochromic smart windows

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ABSTRACT

Electrochromic smart windows represent advanced adjustable envelope technology, where the solar radiation transmittance can be dynamically adjusted in response to changes in the applied voltage, thus demonstrating superior energy-saving potential. In this paper, a cell room office located in a multi-story office building was constructed in DesignBuilder to explore the effects of window-to-wall ratio, outdoor temperature-based control strategy, and spectral modulation characteristics on the energy performance of electrochromic smart windows. The conclusions show that for Helsinki, Beijing, and Miami, electrochromic windows with visible modulation spectral characteristics are more energy efficient compared to near-infrared modulation spectra, and this phenomenon is more pronounced with larger window-to-wall ratios. Selecting a suitable control strategy can make the electrochromic window adapt to change the transmission state with the change of weather conditions and achieve the best energy saving effect. The energy-saving effect of triggering the electrochromic window state change at 15℃ is better than that at 27℃. It is hoped that this paper will enable electrochromic windows to contribute in a small way to the field of effective solar energy utilization and solar thermal management and to promote the development of smart window technology.

Keywords: electrochromic windows, adjustable envelope, solar energy utilization, solar thermal management, control strategy, solar modulation

NONMENCLATURE

Abbreviations

WWR	Window-wall ratio
NIR	Near-infrared
VIS	Visible
Tvis	Visible light transmittance
Tsol	Solar radiation transmittance
To	Outdoor temperature
Tt	Trigger temperatures

1. INTRODUCTION

Improving envelope performance is a major focus for energy efficiency in buildings [1]. Windows are the weak link of heat preservation and insulation, and the impact of windows on indoor environment and building energy consumption becomes more and more significant under the large window-to-wall ratio. As a new technology of adjustable envelope, smart windows provide a new solution for building energy efficiency [2]. The transmittance characteristics of electrochromic smart windows change when voltage is applied [3]. The higher the voltage, the lower the transmittance of electrochromic windows and the stronger the shielding against solar radiation, so it shows great energy-saving potential as an active adjustable envelope technology.

The control strategies have a significant impact on the application performance of electrochromic windows as they determine the conditions that trigger changes in the optical properties of the windows. The effect of control strategies of electrochromic windows on their application performance has been widely evaluated [4-6], and the control parameters can usually be outdoor

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temperature, outdoor illuminance, and facade radiation. However, the optimal control thresholds may vary with building type and window-to-wall ratio. Spectral modulation characteristics determine the solar radiation transmittance before and after discoloration, and split-band spectral modulation is the way forward for smart windows [7-9].Split-wavelength modulation of visible and near-infrared light allows smart windows to have more flexible solar energy management capabilities and shows a wider range of energy-saving potential in different climate zones.

In this work, we built a cell room office in DesignBuilder, defined hypothetical NIR-modulated and VIS-modulated split-band spectra, and implemented an outdoor temperature-based control strategy through EnergyPlus. The purpose of this paper is to investigate the effects of the split-band spectral modulation characteristics and control strategies on the energy performance of electrochromic windows when applied to different climate zones. We also want to clarify the following questions through this study:

(1) For each city, how does the total energy consumption and sub-energy consumption change with the window-wall ratio and control strategy?

(2) For specific climates, what is the difference between NIR modulation and VIS modulation in the spectral modulation characteristics of electrochromic Windows?

(3) Does the effect of spectral modulation characteristics on energy performance change as the window-to-wall ratio varies?

2. METHODS

2.1 Building model

In this paper, we built a cell room office in DesignBuilder that has only its south-facing facade exposed to the outdoors and has a certain area of windows. The other-oriented envelopes are adiabatic to represent a single south-facing office most commonly located on the middle floor of a multi-story office building.

The size of the cell room office is 8 m×8 m×3.5m. The information of the building model was set as follows: the staff density was set at 10 m²/person, and the working hours are from 8 a.m. to 6 p.m. from Monday to Friday. The indoor design temperature is 20 to 24℃ to maintain a comfortable temperature for normal work. The equipment has a power density of 15 W/m2 and the desired work surface illumination is 300 lux. If at some point the natural lighting does not meet this target value, the luminaires will be automatically switched on to supplement the required lighting. The effects of varying window-wall ratios (WWR) (0.1 to 0.9) on building energy consumption were simulated (see Fig.1). The heat transfer coefficients of the envelope are satisfactory for the climate zones. Heat pumps with COP of 2.5 were used to provide heating and cooling for the HVAC system.

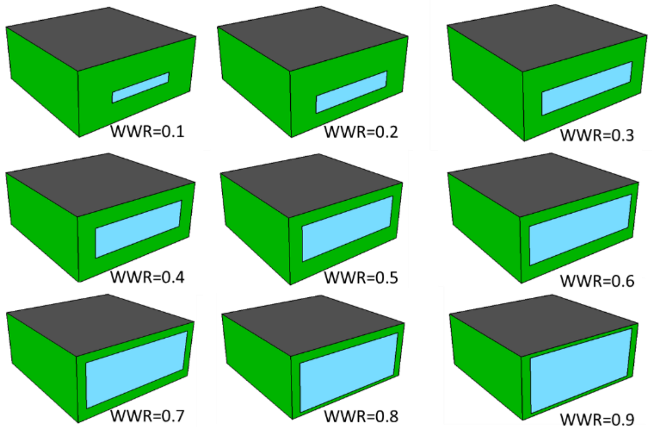
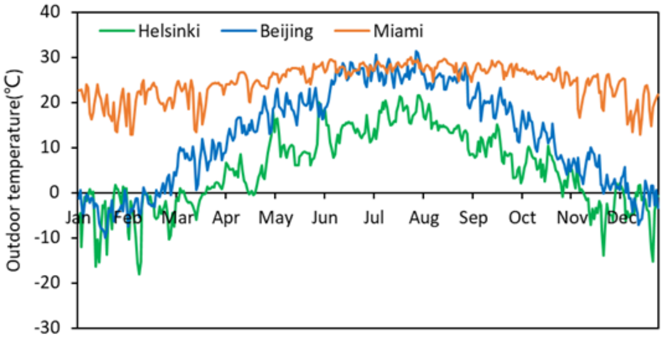


Fig. 1 Cell room office.

2.2 Climate zones

Three climate zones were selected. They are Helsinki with heating demand, Beijing with mixed climate, and Miami, which is dominated by hot climate conditions. The climatic conditions of these three cities are shown in Fig. 2.



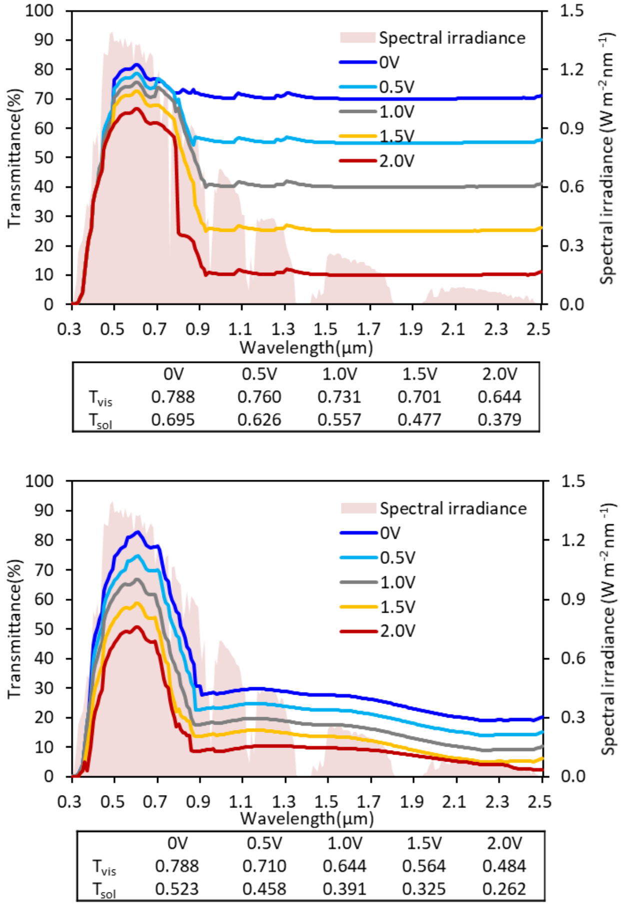
City	Helsinki	Beijing	Miami
ASHRAE climate zone	6A	4A	1A
Min temperature(℃)	-22.1	-11℃	8.7
Max temperature(℃)	26.9	35	33.2

Fig. 2 Climatic conditions in Helsinki, Beijing, and Miami.

3. ELECTROCHROMIC WINDOWS AND SPECTRAL MODULATION

3.1 Spectral characteristics

When the voltage is applied, the electrochromic layer undergoes a reversible redox reaction, which is reflected in the change of color and transmittance of the electrochromic glass. The voltage usually does not exceed 2.5V. In order to investigate the effect of sub-band spectral modulation characteristics on the performance of electrochromic windows, two hypothetical spectra were defined: near-infrared (NIR) modulation and visible (VIS) modulation. The spectral performance indicators of smart windows are usually visible light transmittance (Tvis) of 380-760nm and solar radiation transmittance (Tsol) (300-2500nm) [8].



	0V	0.5V	1.0V	1.5V	2.0V
T_{vis}	0.788	0.760	0.731	0.701	0.644
T_{sol}	0.695	0.626	0.557	0.477	0.379

(a)

	0V	0.5V	1.0V	1.5V	2.0V
T_{vis}	0.788	0.710	0.644	0.564	0.484
T_{sol}	0.523	0.458	0.391	0.325	0.262

(b)

Fig. 3 Spectral modulation characteristics of electrochromic glasses: (a) NIR modulation spectra, (b) VIS modulation spectra.

As shown in Fig. 3(a) and (b), the NIR modulation spectra ensure that the Tvis of the electrochromic window is always above 0.6, and the main modulation of the color change process is in the NIR band. The VIS modulation spectra allow the Tvis of the smart window to vary between 0.484 and 0.788, while the NIR transmittance is always below the smaller value of 0.3.

3.2 Control strategy

In this paper, the electrochromic process was realized through the EMS function of EnergyPlus, which provides a user-friendly programming interface to define sensors and actuators to dynamically control the state of the external window in real time.

The electrochromic window consists of the outermost electrochromic glass, the middle air layer and the clear glass facing the room. For the hot city of Miami, the thickness of the glass layer is 3mm and the thickness of the air layer is 6mm; For Beijing, the glass thickness of 12mm and the air layer of 13mm were selected. For Helsinki, a three-glass, two-cavity window was used, where the thickness of the glass layer is 12 mm and the thickness of the air layer is 13 mm.

In order to realize the simulation of electrochromic windows, for NIR modulation or VIS modulation spectra, it is necessary to first define five electrochromic glass, and secondly to construct five types of electrochromic windows according to the number of window layers, which represent the states of electrochromic windows at five voltages (0 V, 0.5 V, 1.0 V, 1.5 V, and 2.0 V). The

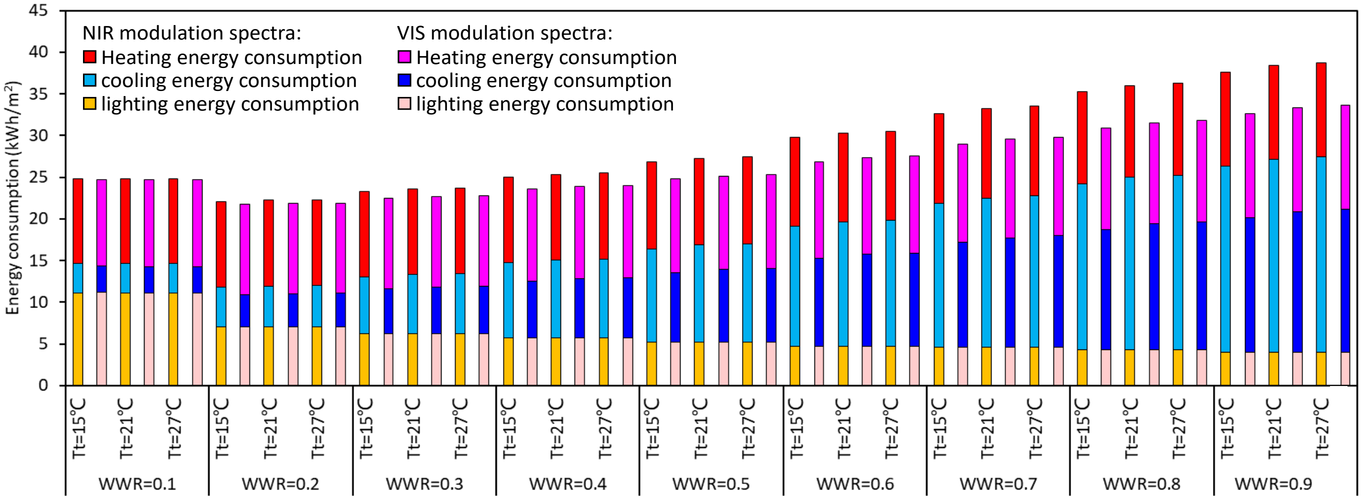


Fig. 4 Energy consumption in Helsinki

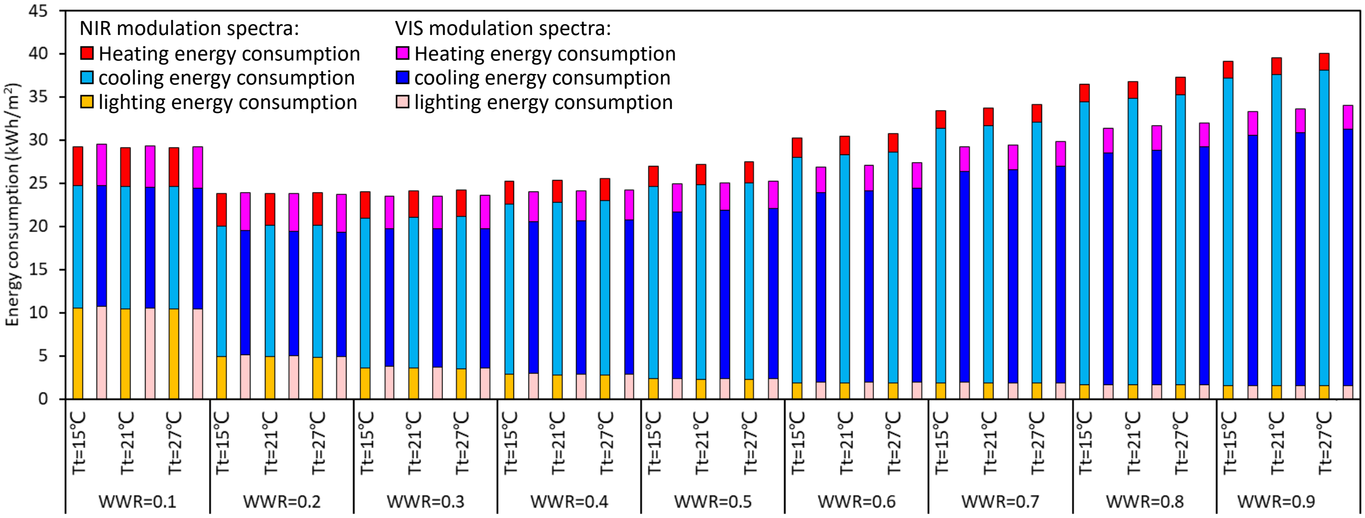


Fig. 5 Energy consumption in Beijing

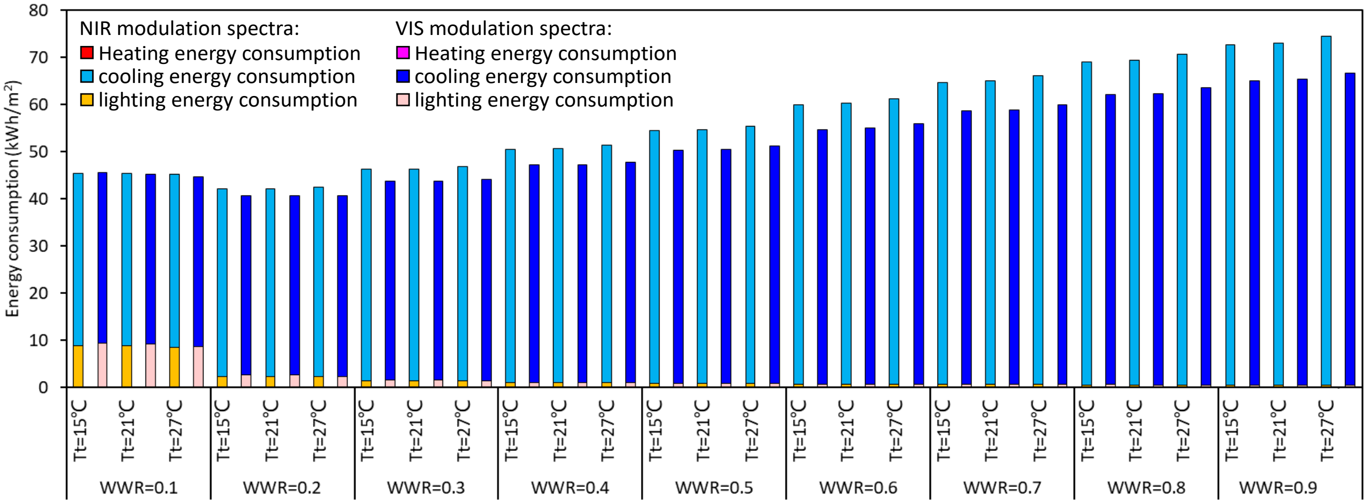


Fig. 6 Energy consumption in Miami

actuator switches the window state according to the change of the corresponding parameters of the sensor, so as to realize the simulation of the adaptive electrochromic window.

The control strategy of electrochromic windows in this paper is based on the outdoor temperature (To). Three control strategies were defined with trigger temperatures (Tt) of 15°C, 21°C, and 27°C, respectively. The difference between the trigger temperature and the outdoor temperature corresponding to the full coloring of the window is 9°C. Tt=15°C means that if the To reaches 15°C, the actuator will control the window state with a voltage of 0.5V, when the To reaches 18 °C, the window will be applied with a voltage of 1.0V, and when the To rises to 21 ° C, the window will have a voltage of 1.5V. When the To is greater than 24 ° C, the voltage of the window is 2.0V and the darkest tinted state is reached to shield the solar radiation.

4. RESULTS

4.1 Helsinki

Helsinki is located in Northern Europe, where heating must be ensured during the long winter months. As can be seen in the Fig. 4, the total energy consumption for heating, cooling and lighting is minimized at a window-to-wall ratio of 0.2 for both NIR-modulated and VIS-modulated spectra.

In Helsinki, when the electrochromic window exhibits the NIR modulation spectra, the share of heating energy consumption in total energy consumption decreases from 41% to 29% as WWR increases from 0.1 to 0.9. If the electrochromic window modulates mainly visible light before and after the color change, the share of heating energy consumption decreases from 42% to

37% as the WWR increases. However, the absolute value of heating energy consumption does not change greatly, and the change in its proportion is mainly due to the increase of cooling energy consumption when the window wall ratio increases, resulting in an increase in total energy consumption, so the proportion of heating energy consumption decreases.

4.2 Beijing

Beijing is hot in summer and cold and dry in winter, so it is necessary to take into account both summer cooling and winter heating. However, in offices where there are people and equipment to dissipate heat, there will be more need for cooling than heating.

As shown in Fig. 5, In Beijing, we still find that for a south-facing cell room office, a WWR of 0.2 seems to be more appropriate. As the WWR increases further, the lighting situation becomes better therefore the lighting energy consumption tends to decrease. As the WWR goes from 0.1 to 0.9, the cooling energy consumption increases from 14kWh/m^2 to 36kWh/m^2 for the NIR modulation spectra and from 13kWh/m^2 to 29kWh/m^2 for the VIS modulation spectra. This is due to the fact that the NIR modulation spectra allow more NIR to enter the room during the modulation process. When electrochromic windows have VIS modulation spectra, the heating energy consumption is greater than that when NIR modulation spectra are applied. In terms of total energy consumption, the total energy consumption increases from 29kWh/m^2 to 40kWh/m^2 when the NIR modulation spectra are used, and from 29kWh/m^2 to 34kWh/m^2 when the VIS modulation spectra are used. As the WWR increases, the difference between the two spectra becomes more and more obvious, and the VIS modulation spectra show better energy-saving effect.

4.3 Miami

For Miami, where cooling demand is dominant, the internal heat generated in a single office is sufficient to maintain a comfortable room temperature in winter, so the total energy consumption is mainly composed of cooling energy and lighting energy. As shown in Fig. 6, when the electrochromic glass is NIR-modulated, the total energy consumption increases from 45kWh/m^2 to 74kWh/m^2 as the WWR increases. If the electrochromic glass is VIS modulated, the total energy consumption increases from 45kWh/m^2 to 67kWh/m^2 as the WWR increases. Thus it can be seen that for hot regions it is desirable to further modulate the visible transmittance while keeping the NIR transmittance of the window low, which provides the potential for a reduction in cooling energy consumption without affecting daylighting.

4.4 Brief discussion

Fig.7 shows the difference in energy consumption between NIR modulation and VIS modulation spectra for electrochromic windows. It can be seen that the difference in energy consumption corresponding to the different spectra is more obvious as the WWR increases. Since the energy-saving effect of electrochromic windows is mainly reflected in the reduction of cooling energy consumption, and hot cities are the main demand for cooling, the difference between the two spectra on energy consumption is more significant in hot cities.

Further discussion of the effect of control strategies on energy consumption reveals that the larger the WWR, the more pronounced the difference between control strategies with different trigger temperatures. In particular, the higher the trigger temperature, the greater the energy consumption. This is because it is difficult to stimulate the state change of electrochromic windows when the trigger temperature is too high, and electrochromic windows do not give full play to energy saving. This can also reflect the energy-saving potential of electrochromic windows, especially at large WWR. For hotter cities, the control strategy has a greater impact on energy consumption.

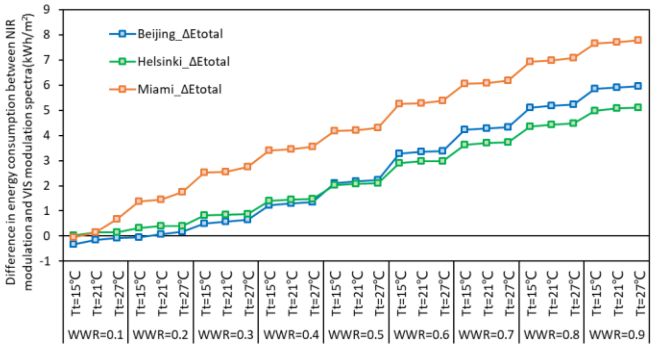


Fig. 7 Difference in energy consumption between NIR-modulated and VIS-modulated spectra.

5. CONCLUSIONS

This paper discusses the effects of split-band spectral modulation characteristics and control strategies on the energy-saving effect of electrochromic smart windows. The main conclusions are as follows:

(1) Impact of spectral modulation characteristics on energy saving:

When electrochromic glass exhibits NIR modulation spectra, its coloring process mainly regulates the NIR transmittance to change the solar radiation transmittance, while the visible light transmittance is always above 0.6. Therefore, it can shield the excess heat under the premise of ensuring light. The contribution to energy saving is mainly the reduction of cooling energy consumption. The VIS modulation spectra allow the electrochromic glass to further modulate visible light on the basis of a lower near-infrared transmittance, and this spectral modulation characteristic has a more obvious energy-saving effect in hot regions, while in cold regions there is a risk of increased heating energy consumption, especially when the trigger temperature is too low, electrochromic windows are tinted most of the time, which may lead to insufficient passive heating in winter.

For Helsinki, Beijing, and Miami, electrochromic windows applying VIS-modulated spectra were more energy efficient than NIR-modulated spectra, and the larger the WWR, the more significant the difference in energy savings between these spectra. At a WWR of 0.9, the difference in energy consumption for buildings deploying electrochromic windows with NIR spectra compared to VIS spectra is 5.11 kWh/m^2 (Helsinki), 5.96 kWh/m^2 (Beijing), and 7.79 kWh/m^2 (Miami).

(2) Impact of control strategy on energy saving:

When deploying electrochromic smart windows in buildings, it is important to choose the appropriate control strategy so that the smart windows can maximize the ability to adaptively change the transmittance state with changing weather conditions and achieve optimal energy savings. Taking the control strategy based on outdoor temperature as an example, the energy-saving effect of triggering the electrochromic window state change at 15℃ is better than that at 27℃.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Cuce, & Riffat, S. B. (2015). A state-of-the-art review on innovative glazing technologies. Renewable & Sustainable Energy Reviews, 41, 695–714. https://doi.org/10.1016/j.rser.2014.08.084

[2] Hee, Alghoul, M. A., Bakhtyar, B., Elayeb, O., Shameri, M. A., Alrubaih, M. S., & Sopian, K. (2015). The role of window glazing on daylighting and energy saving in buildings. Renewable & Sustainable Energy Reviews, 42, 323–343. https://doi.org/10.1016/j.rser.2014.09.020

[3] PICCOLO A. Thermal performance of an electrochromic smart window tested in an environmental test cell[J/OL]. Energy and buildings, 2010, 42(9): 1409-1417. DOI:10.1016/j.enbuild.2010.03.010.

[4] Jonsson, & Roos, A. (2010). Evaluation of control strategies for different smart window combinations using computer simulations. Solar Energy, 84(1), 1–9. https://doi.org/10.1016/j.solener.2009.10.021

[5] Hoon Lee, Jeong, J., & Tae Chae, Y. (2020). Optimal control parameter for electrochromic glazing operation in commercial buildings under different climatic conditions. Applied Energy, 260, 114338. https://doi.org/10.1016/j.apenergy.2019.114338

[6] Oh, Park, J., Roh, S., & Lee, C. (2018). Deducing the Optimal Control Method for Electrochromic Triple Glazing through an Integrated Evaluation of Building Energy and Daylight Performance. Energies (Basel), 11(9), 2205. https://doi.org/10.3390/en11092205

[7] DeForest, Shehabi, A., Selkowitz, S., & Milliron, D. J. (2017). A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings. Applied Energy, 192(C), 95–109. https://doi.org/10.1016/j.apenergy.2017.02.007

[8] Wu, Sun, H., Duan, M., Mao, H., Wu, Y., Zhao, H., & Lin, B. (2023). Applications of thermochromic and electrochromic smart windows: Materials to buildings. Cell Reports Physical Science, 4(5), 101370. https://doi.org/10.1016/j.xcrp.2023.101370

[9] DeForest, Shehabi, A., Garcia, G., Greenblatt, J., Masanet, E., Lee, E. S., Selkowitz, S., & Milliron, D. J. (2013). Regional performance targets for transparent near-infrared switching electrochromic window glazings. Building and Environment, 61, 160–168. https://doi.org/10.1016/j.buildenv.2012.12.004