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Smart PV windows for improving building energy conservation and flexibility

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ABSTRACT

The smart PV window, integrated of solar cells and electrochromic coating, is of great significance in the pursuit of building decarbonization, as it combines power generation and radiation modulation capabilities. This study aims to unraveling the untapped potential of smart PV windows in the realm of enhancing building energy conservation and flexibility in hot climates. To achieve this objective, a co-simulation approach utilizing EnergyPlus and Radiance software is employed, along with the implementation of the EMS module to control the coloring states of the smart PV window. The findings reveal that, compared to the Low-E window, the smart PV window with solar radiation control *improves the proportion of the useful daylight illuminance by 61.8%,* yields a significant reduction in peak load by 72.3%, a decrease in monthly net energy consumption by 53.9%, and an enhancement in energy flexibility by 51.8% in Hong Kong (22.32°N，114.17°E).

Keywords: Smart PV windows, energy conservation, energy flexibility, control strategy

1. INTRODUCTION

Energy consumption of the building sector consumes 36% of total energy and emitted 39% of CO2 [1], and the energy losses/gains through windows accounts for more than 30% of building energy consumption [2]. Therefore, it is essential to develop energy-efficient windows for achieving building energy conservation.

For this purpose, numerous windows aimed at lowering the heat transfer coefficient or controlling solar radiation have emerged, such as vacuum [3], aerogel [4], dynamic windows [5,6], et al. However, these windows can only suppress excessive solar heat gain and heat flow driven by temperature difference, but cannot actively utilize solar radiation incident on the building surface. In other words, the above window technology can reduce the energy consumption of a building, but it is difficult to realize the goal of a zero-energy building. In this concern, the photovoltaic window [7] has attracted the attention of scholars because of its dual function of energy saving and power generation.

Commonly, the Photovoltaic (PV) window refers to the double-pane hollow PV window, which consists of outer PV laminated glass, air cavity, and inner Low-E glass. It is reported that when comparing with the Low-E window, the PV window can reduce the energy consumption by 49%, 44%, 42%, 83% and 60% in Chengdu, Chongqing, Guiyang, Kunming, and Lhasa [8]. Besides, Zhang et al. [9] indicated that the southwest-facing PV window can generate 24.4 kWh/m^2·yr in Hong Kong. However, the uncertainty of solar radiation results in a mismatch between building energy demand and on-site energy generation [10], and further affects the stable operation of the utility grid. Therefore, harnessing the potential of building energy flexibility to alleviate the aforementioned issue has garnered growing interests in recent research [11]. This paper proposed a smart photovoltaic window with dual functionalities of power generation and solar radiation modulation, and investigated its impact on daylight utilization, building energy conservation and flexibility in hot climate.

2. METHODLOGY

2.1 Structure of the smart PV window

The smart PV window, as shown in Fig.1, consisting of a glass cover-plate, a functional layer, a glass base, an argon cavity, and a sheet of Low-E glass. The functional layer is composed of an electrochromic (EC) film and a series of strip solar cells. The upper EC film can change its transmittance according to the outdoor environment or indoor demand, thereby modulating the solar radiation entering the room and the lower solar cells harness

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incident solar radiation to generate clean electricity for building usage. The solar cells are arranged at the lower part of the window because the Daylight Standard [12] mentions that the glass area of the façade below the work plane is referred to as invalid daylight area, which has no effects on the indoor daylight environment.

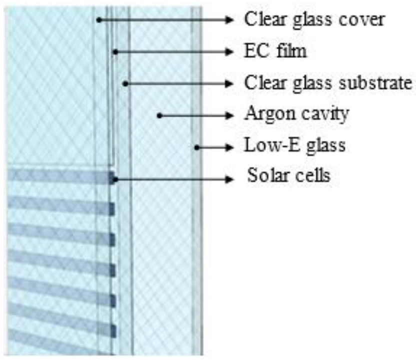

Fig. 1 The structure of the smart PV window

2.2 Simulation models

To investigate the performance of the proposed smart PV window, the opto-thermal properties were calculated in the WINDOW software based on measured spectral optical properties. Besides, the models of the commonly used Low-E and conventional PV windows were established for comparison. The results of the above window models were listed in Table 1, and exported in .xml and .idf formats for daylight and energy simulations in Radiance and EnergyPlus, respectively.

Table 1 *The opto-thermal properties of different windows*

Windows	*U-value W/m²·K*	*SHGC*	*Tvis*
Low-E	*1.43*	*0.65*	*0.77*
PV	*1.42*	*0.44*	*0.48*
Smart PV (bleached)	*1.43*	*0.38*	*0.51*
Smart PV (low tinted)		*0.20*	*0.27*
Smart PV (medium tinted)		*0.13*	*0.12*
Smart PV (fully tinted)		*0.08*	*0.01*

The southern perimeter zone of the typical medium office building was selected as the building model, as shown in Fig.2. The dimension of the building model is 2.7 m in height, 50m in width, and 4.6 m in depth. Besides, Hong Kong (22.32°N, 114.17°E) was selected as the representative city for hot climates, and the temperature and solar radiation were depicted in Fig.3

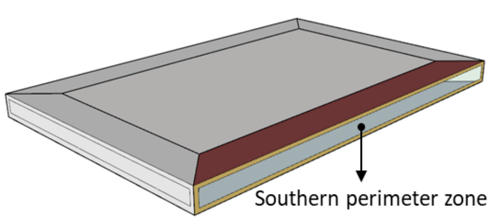

Fig. 2 Schematic of the building model

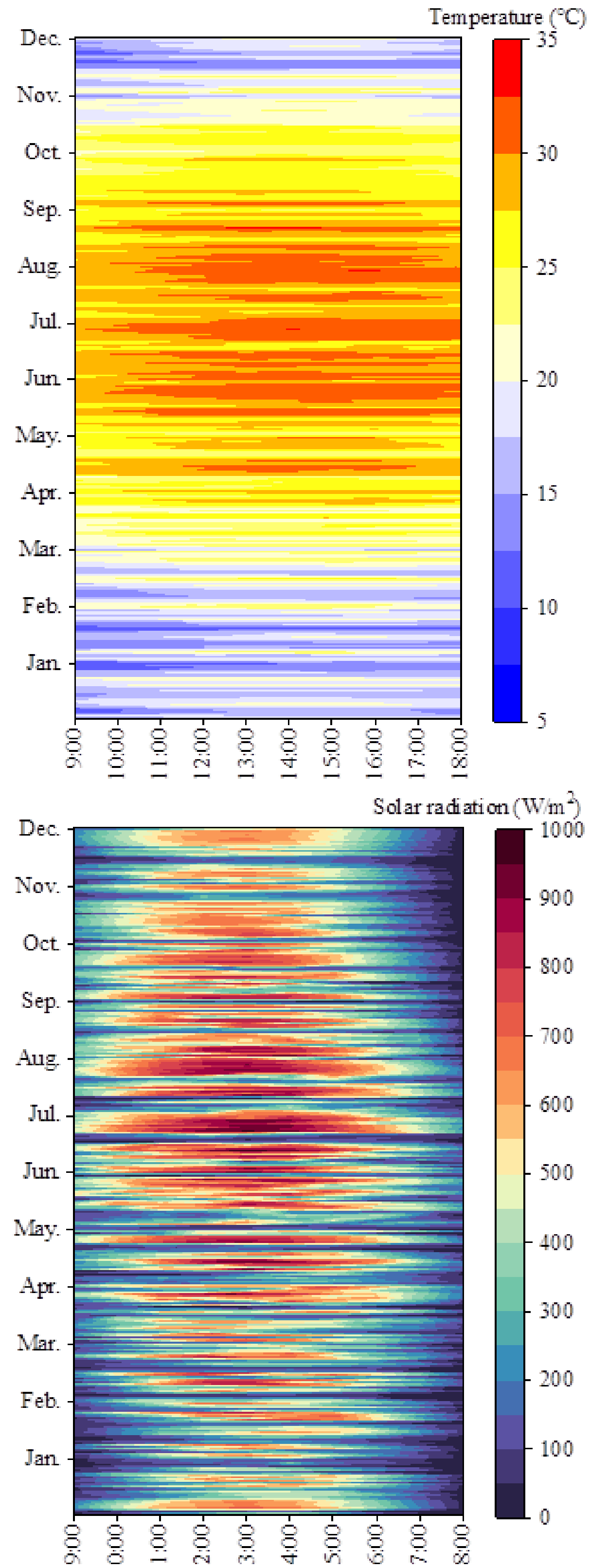

Fig. 3 Hourly temperature and radiation distribution in Hong Kong

The daylight model of the office building equipped with smart PV window was established in Radiance software, of which the accuracy has been widely validated [13]. The three-phase method, embedded in the Radiance software, was adopted for illuminance calculation, and the mathematical description is as follows:

$$E=VTDs$$

Where, E is the illuminance at reference points, lx; V is the view matrix; T is the transmission matrix; D is the daylight matrix, and s is the sky vector. In this study, the daylight reference point was located on the central axis of the room, 1m away from the window with a height of 0.75m. Then, the daylight utilization and visual comfort of the smart PV window were analyzed based on the illuminance calculated in the Radiance. Then, the average real-time illuminance of the work plane was used for lighting energy consumption calculation. In this study, a dimmable luminaire was adopted to meet the illuminance requirement of office building work plane. The hourly lighting energy consumption of the dimmable luminaire can be calculated according to the following formulas:

$$E_{lights} = P \cdot A \cdot f_p \cdot t$$

$$f_p = \max[0, \frac{I_{set} - I_{ave}}{I_{set}}]$$

Where, E_{lights} is the hourly lighting energy usage, kW; P is the lighting power density of the luminaire, W/m^2; A is the area, m^2; f_p is the power proportion fraction of the luminaire; I_{set} is the required illuminance of the work plane, lx; and I_{ave} is the hourly average illuminance of the work plane, lx.

The air conditioning energy consumption of the office building was simulated through EnergyPlus software, a robust building performance simulation tool. According to the climatic conditions in Hong Kong, the cooling season is set from May to October, and a package heat pump was used to maintain the thermal comfort. The cooling setpoint is set to 26 ˚C, and the occupied period is from 9:00 to 18:00 for weekdays. The internal heat gains, including equipment heat dissipation, occupant density, zone infiltration, etc., are set in accordance with energy-saving standards.

As for PV power generation simulation, the simple model with temperature correction was adopted, and the mathematical expression is as follows:

$$E_{PV} = I_{incident} \cdot PV_{coverage} \cdot \eta$$

$$\eta = \eta_0[1 - \beta(T_{pv} - 25)]$$

Where, E_{PV} is the hourly PV power generation, W; $I_{incident}$ is the incident solar radiation on the outer surface of the smart PV window, W/m^2; $PV_{coverage}$ is the coverage ratio of the solar cells, %; η is the real-time conversion efficiency of the smart PV window, %; η_0 is the conversion efficiency under standard test conditions, %; β is the temperature coefficient of the solar cells (%/K); and T_{pv} is the hourly temperature of the smart PV window, °C.

2.3 Control strategy

As a dynamic building envelope, the performance of the smart PV window is not related to its opto-thermal properties and climate conditions, but also its control strategy. Commonly, various decision-making variables are selected for different goals to control the real-time state of the dynamic envelope, such as solar radiation, outdoor temperature, indoor illuminance, etc. Among them, solar radiation is the most commonly used decision variable [14]. Therefore, the incident solar radiation on outermost surface of the smart PV window was adopted as the decision variable in this study. The control strategy was determined by analyzing the relationship between incident solar radiation and indoor load, as depicted in Fig.4. The detailed control strategies were listed in Table 2, and implemented through the embedded EMS module in EnergyPlus software.

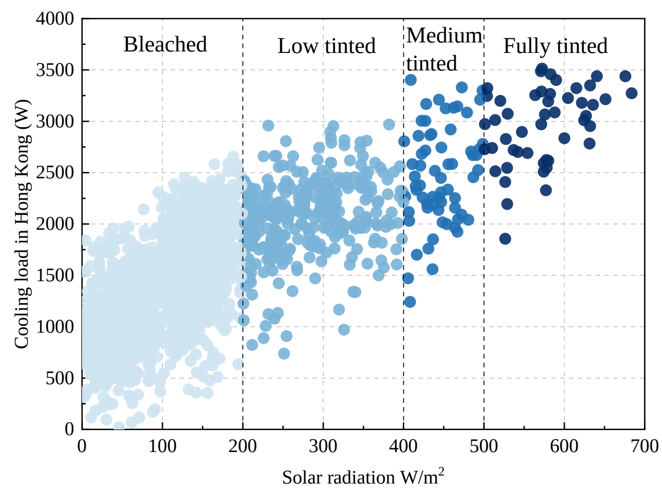

Fig. 4 Relationship between solar radiation and indoor load in Hong Kong

Table 2 Control strategy of the smart PV window

Conditions	Incident solar radiation	States
If	<200	Bleached
Else if	<400	Low tinted
Else if	<500	Medium tinted
Else	-	Fully tinted

Based on the above control strategy and models, the hourly illuminance, air conditioning energy, lighting energy, PV power generation can be calculated. Subsequently, the peak load reduction capacity, energy saving potential, and energy flexibility of the smart PV window can be analyzed.

3. RESULTS AND DISCUSSIONS

3.1 Peak load analysis

The hourly load of the building model with different windows in a week of consecutive sunny days was depicted in Fig.5. It is seen that the average peak load during this week of the Low-E, PV, and smart PV windows are 5162 W, 3179 W and 1426 W, respectively. It is seen that the daily load curves of the PV window are relatively flatter than that of the Low-E window. This is because the opaque solar cells encapsulated in the PV laminate can block part of the excessive solar radiation. Therefore, PV window can reduce the peak load by approximately 38.5%. As for the smart PV window, its solar modulation capability results in a higher peak load reduction ratio of 72.3%.

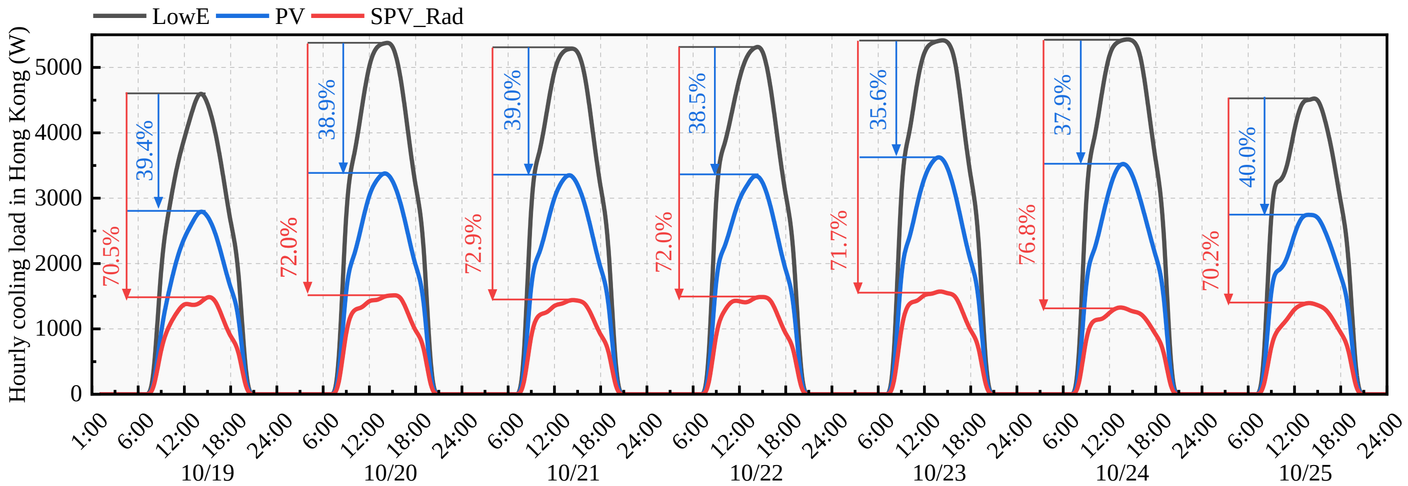

Fig. 5 The hourly load of building model equipped with smart PV window

Fig. 6 depicts the hourly load statistics corresponding to different windows. It is seen that 50% of hourly load of Low-E, PV, and smart PV windows is concentrated in 1921-3105W, 1346-2193 W and 1128-1760W, respectively. The corresponding average hourly load are 2566 W, 1767 W, and 1431 W. Compared to the Low-E and PV windows, the smart PV window can reduce the average cooling load by 41.7% and 19.0%, respectively.

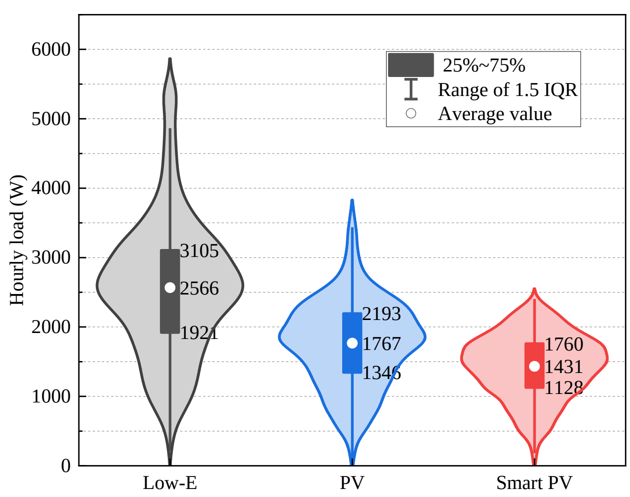

Fig. 6 Hourly load statistics of different Windows

3.2 Daylight utilization analysis

Daylight utilization of different windows are analyzed in this section. Usually, the illuminance is categorized into three levels: illuminance below 300 lx falls under insufficient illuminance ($UDI_{<300lx}$), illuminance ranging from 300-3000 lx is referred to as useful daylight illuminance ($UDI_{300-3000lx}$), and illuminance exceeding 3000 lx is considered excessive illuminance, which posing a higher risk of glare ($UDI_{>3000lx}$). Fig.7 depicted hourly illuminance distribution of different windows. It is seen that a large proportion of illuminance of Low-E window during 10:00-16:00 exceeds the upper limit of useful daylight illuminance, and the corresponding average illuminance was 3669 lx, 3603 lx, 3790 lx, 3783 lx, 3759 lx, 3663 lx and 3441 lx, respectively. The average illuminance of the PV window corresponding to the above time is 2268 lx, 2230 lx, 2347 lx, 2343 lx, 2328 lx, 2266 lx and 2126 lx. Compared with the Low-E window, the PV window can effectively reduce the risk of glare. However, 30% of the illuminance of the PV window still exceeds the UDI's upper limit at 12:00-14:00. For smart PV windows, the corresponding average illuminance during 9:00-18:00 is 1442lx, 1687lx, 1427lx, 1239lx, 1121lx, 1114lx, 1132lx, 1190lx, 931 lx and 378 lx, respectively. All of them belong to the range of effective solar illumination

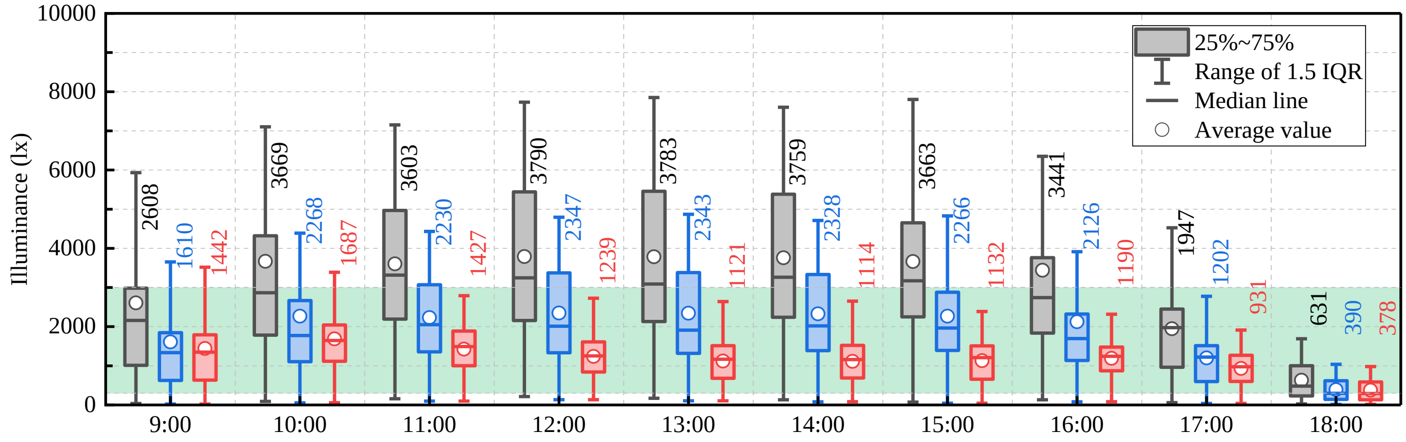

Fig. 7 Illuminance distribution of different windows

The annual illuminance statistics of Low-E, PV, and smart PV windows are depicted in Fig.8. It is seen that the smart PV window can effectively improve the proportion of useful daylight illuminance while decreasing the proportion of excess daylight. Specifically, the proportions of the useful daylight illuminance of Low-E, PV, and smart PV windows are 55%, 73%, and 89%, and the corresponding proportions of excess daylight are 40%, 19%, and 2%. Compared to Low-E and PV windows, the smart PV window can improve the proportion of the useful daylight illuminance by 61.8% and 21.9%, and decrease the proportion of excess daylight by 95.0% and 89.5%.

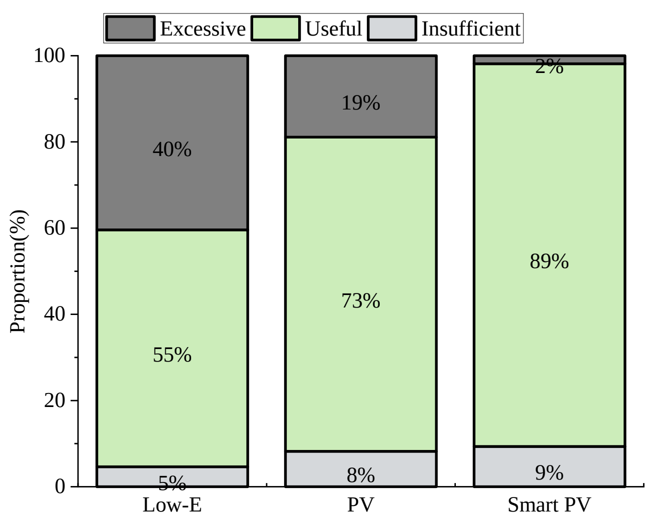

Fig. 8 Illuminance statistics of different windows

3.3 Energy consumption analysis

As a representative city of hot climate, the air conditioning energy consumption occupies the majority of building energy consumption in Hong Kong. Therefore, the monthly (from May to October) air conditioning energy consumption corresponding to different windows were compared, as shown in Fig.9. It is seen that the air conditioning energy consumption of the Low-E window is the highest, followed by the PV window, and the smart PV window results in the lowest monthly air conditioning energy consumption. The monthly energy consumption with the Low-E window is 624 kWh, 673 kWh, 761 kWh, 775 kWh, 844 kWh, and 1079 kWh. The corresponding energy consumption of the PV window is 433 kWh, 483 kWh, 555 kWh, 560 kWh, 572 kWh, and 672 kWh. Compared to the Low-E window, the monthly reductions are 30.5%, 28.1%, 27.1%, 27.8%, 32.3%, and 37.7%, respectively. It is seen that the monthly air conditioning energy consumption of the smart PV window is lower than that of PV window, and the corresponding energy consumption from May to October is 389 kWh, 453 kWh, 518 kWh, 466 kWh, 433 kWh, and 395 kWh, respectively. Compared to the Low-E and PV window, the average monthly reductions of the smart PV window are 42.4% and 17.6%. From the above analysis, it is seen that the smart PV window can reduce the air conditioning energy consumption demand.

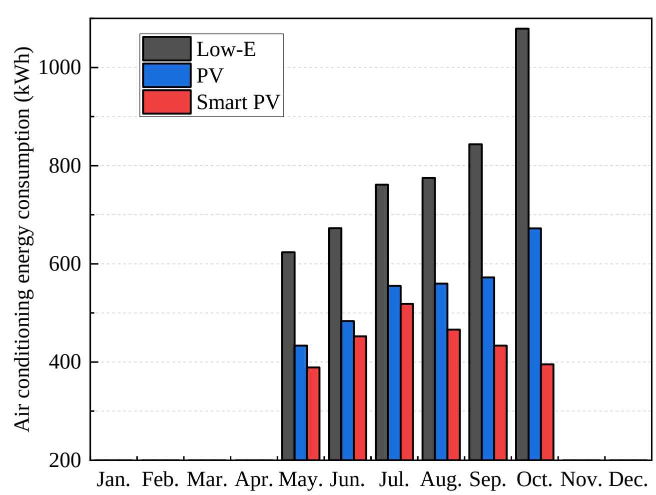

Fig. 9 Monthly air conditioning energy consumption

The net energy consumption, considering lighting energy, air conditioning energy, and PV power generation, was depicted in Fig.10. It is seen that the PV and smart PV windows can achieve monthly net energy during non-air conditioning seasons, and the corresponding average monthly residual electricity is 480 kWh and 91 kWh. As for the monthly energy consumption during air conditioning seasons, it is seen that the monthly energy consumption of the PV window is the lowest, followed by the smart PV window, and the Low-E window consumes most energy. The average monthly energy consumption of the above windows is 811 kWh, 193 kWh, and 374 kWh. Compared to the Low-E window, the PV and smart PV windows reduce the average monthly energy consumption by 76.2% and 53.9%, respectively.

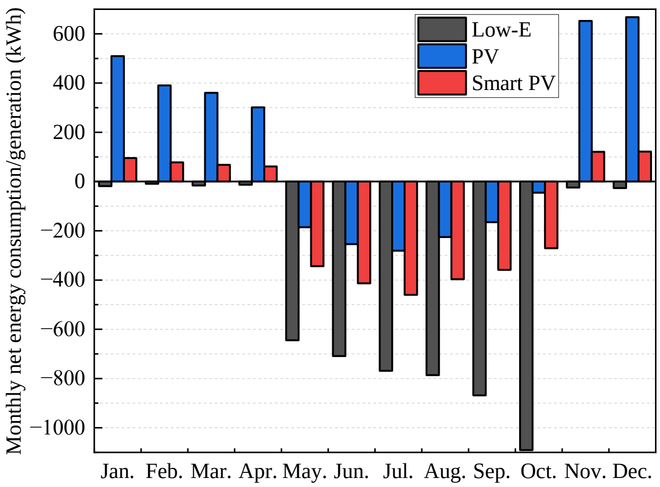

Fig. 10 Monthly net energy consumption

3.4 Energy consumption analysis

The energy flexibility of the smart PV window is evaluated by the flexibility ratio (ΔP%) [15], of which the formula is described below:

$$\Delta P\% = \frac{P_{ref} - P_{flex}}{P_{ref}} \times 100\%$$

Where, P_{ref} is the building electrical load under reference scenario (kW), and P_{flex} is the electrical load with smart PV window (kW).

The flexibility ratios of the smart PV window during the air conditioning seasons are depicted in Fig. 11. It is seen that the smart PV window can significantly improve the building energy flexibility when comparing to the Low-E window. The monthly average flexibility ratios from May to October are 50.0%, 41.8%, 40.8%, 47.7%, 58.9% and 71.8%, respectively.

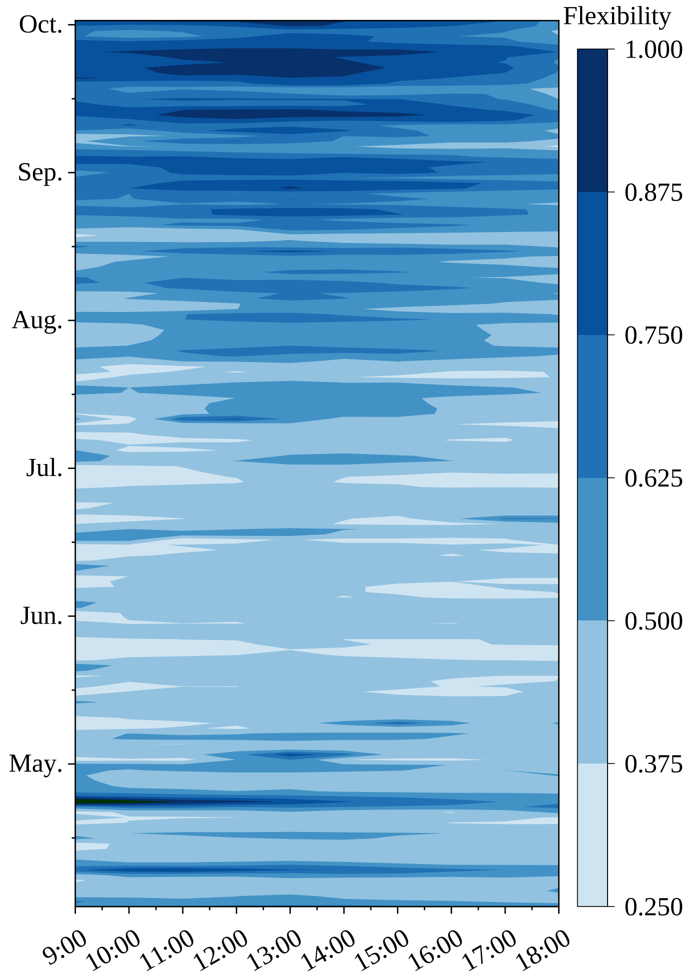

Fig. 11 Flexibility ratio of the smart PV window

The average daily net energy consumption curves of Low-E, PV, and smart PV windows are shown in Fig.12. It is obvious from the figure that the average daily net energy consumption curve of the smart PV window is the smoothest among the three. The corresponding daily peak-to-valley difference is 226 kWh, while the daily peak-to-valley differences for Low-E and PV windows are 859 kWh and 932 kWh, respectively.

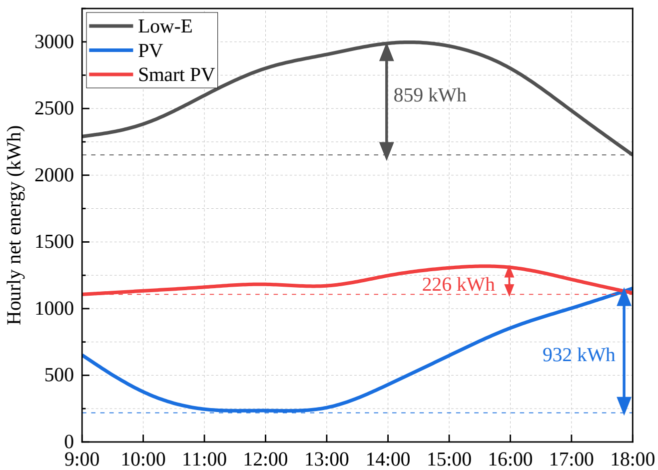

Fig. 12 Average daily net energy consumption

4. CONCLUSIONS

This paper investigated the energy conservation and flexibility performance of a proposed smart photovoltaic (PV) window in hot climates. The heat transfer coefficient of the smart window is 1.43 $W/m^2 \cdot K$, and the solar radiation transmittance ranges from 0.38 (bleached state) to 0.08 (fully tinted state). The joint-simulation of EnergyPlus and Radiance software was employed, along with the adoption of the EMS module to control the coloring states of the smart PV window based on incident solar radiation. The results indicated that when comparing to the Low-E window, the smart PV window can improve useful daylight illuminance by *61.8%,* reduce peak cooling load by 72.3%, decrease monthly net energy consumption by 53.9%, and improve energy flexibility by 51.8% in Hong Kong.

In the next study, the impact of smart PV windows on the indoor daylight and thermal environment will be explored. Additionally, a model predictive control strategy aimed at harmonizing indoor comfort, energy efficiency, and power generation will be proposed to pave the way for net-zero energy buildings.

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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] IEA. Data and statistics. (2020).

[2] Peng J, Curcija D, Thanachareonkit A, Lee E, Goudey H, Selkowitz SE. Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window. Applied Energy,2019; 242:854–72.

[3] Ghosh A, Norton B, Duffy A. Measured thermal and daylight performance of an evacuated glazing using an outdoor test cell. Applied Energy, 2016; 177: 196–203.

[4] Liu Y, Lu L, Chen Y, Lu B. Investigation on the optical and energy performances of different kinds of monolithic aerogel glazing systems. Applied Energy, 2020; 261: 114487.

[5] Ke Y, Tan Y, Feng C, Chen C, Lu Q, Xu Q, Wang T, Liu H, Liu X, Peng J, Long Y. Tetra-Fish-Inspired aesthetic thermo-chromic windows toward energy-saving buildings. Applied Energy, 2022; 315: 119053.

[6] Lee J, Jeong J, Chae Y. Optical control parameter for electrochromic glazing operation in commercial buildings under different climatic conditions. Applied Energy, 2020; 260: 114338.

[7] Wang M, Peng J, Li N, Lu L, Ma T, Yang H. Assessment of energy performance of semi-transparent PV insulting glass units using a validated simulation model. Energy, 2016; 112: 538-548.

[8] Chen M, Zhang W, Xie L, et al. Experimental and numerical evaluation of the crystalline silicon PV window under the climatic conditions in southwest China. Energy, 2019, 183: 584–598.

[9] Zhang W, Lu L, Peng J, et al. Comparison of the overall energy performance of semi-transparent photovoltaic windows and common energy-efficient windows in Hong Kong. Energy & Buildings, 2016, 128: 511–518.

[10] Salom J, Marszal A, Widen J, Lindberg K. Analysis of load match and grid integration indicators in net zero energy buildings with simulated and monitored data. Applied Energy, 2014, 136: 119-131.

[11] Luo Z, Peng J, Cao J, Yin R, Zou B, Tan Y, Yan J. Demand flexibility of residential buildings: definitions, flexible loads, and quantification methods. Engineering. 2022, 16: 123-140.

[12] Ministry of Housing and Urban-Rural Development of China. Standard for Daylighting Design of Buildings. GB 50033-2013. (In Chinese)

[13] Qiu, C, Yi Y, Wang M, Yang H. Coupling an artificial neuron network daylighting model and building energy simulation for vacuum photovoltaic glazing. Applied Energy. 2020, 263: 114624.
[14] Tan Y, Peng J, Wang M, Luo Y, Song A, Li N. Comfort assessment and energy performance analysis of a novel adjustable semi-transparent photovoltaic window under different rule-based controls. Building Simulation. 2023.
[15] Chen Y, Chen Z, Xu P, Li W, Sha H, Yang Z, Li G, Hu C. Quantification of electricity flexibility in demand response: office building case study. Energy. 2019, 116054.