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Daylighting and overall energy performance of a novel semi-transparent photovoltaic vacuum glazing in different climate zones

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Abstract

Amorphous silicon-based semi-transparent photovoltaic windows can produce renewable electricity and offer a certain amount of natural daylight for occupants. However, it has a deficiency as the absorbed solar energy would be partially transferred into additional cooling demand in summer. In this respect, a novel semi-transparent photovoltaic vacuum glazing is proposed to improve energy performance. The selection of appropriate glazing of an energy-efficient building should take into consideration the specific climate conditions. The daylighting behaviour of the glazing will also affect the daylighting performance as well as the lighting consumption. In this paper, the thermal performance, daylighting performance and overall energy performance of the proposed vacuum PV glazing in different climate regions have been investigated. A daylighting model was conducted by DAYSIM to evaluate the annual daylighting performance. It was found that the vacuum PV glazing can balance daylighting availability and visual comfort by providing sufficient daylight in the anterior half of the room and reducing daylight glare to the minimum level. The energy simulation by EnergyPlus demonstrated that the vacuum PV glazing has the energy-saving potential up to 43.4%, 66.0%, 48.8%, and 35.0% in Harbin, Beijing, Wuhan and Hong Kong, respectively. However, the applications of the vacuum glazing lead to additional cooling consumption in the moderate climate zone, such as Kunming. The results advanced the understanding on the applicability and limitation of the vacuum PV glazing in different climate backgrounds. Furthermore, the reversed and the reversible vacuum PV glazing were proposed to enhance the adaptability. The results suggest that the reversible vacuum PV glazing can act energy response in a more efficient way and fully utilize the energy-saving potential of the integration of the PV glazing and the vacuum glazing.

Keywords: Building integrated photovoltaic (BIPV), Semi-transparent photovoltaic window, Vacuum glazing, Daylighting performance, Overall energy performance

1. Introduction

Windows and glazing façades play a crucial role in building regarding the indoor thermal comfort, building energy consumption and visual comfort. However, conventional windows are considered as the weakest thermal barrier of building envelope due to its poor thermal performance [1]. In recent years, building-integrated photovoltaic (BIPV) glazing was introduced into the design of energy-efficient building to replace conventional building facades and generate renewable energy [2-4]. For the selection of the PV element used in the BIPV glazing, the solar cells can be crystalline silicon (c-Si), amorphous silicon (a-Si), Copper indium gallium selenide (CIGS), Cadmium telluride (CdTe), or Dye-sensitized solar cell (DSSC) [5]. Despite the relatively low energy efficiency of amorphous silicon solar cell [6], a-Si semi-transparent photovoltaic (STPV) glazing can admit a certain level of daylighting [2], which provides better visual comfort than spaced type PV glazings made by opaque crystalline silicon solar cells [7, 8]. A simulation work of the overall energy performance of a single-glazed STPV window had been conducted by Lu and Law for the application in Hong Kong [9]. Their results suggested that the application of semi-transparent PV glazed window could achieve 65% of energy conservation by reducing the cooling load compared with clear glass.

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Besides the single PV window, double PV window and PV double-skin façade (PV-DSF) had also been studied. Han et al. [10] had developed a two-dimensional numerical model for the thermal behaviour of the double PV glazing so that the accurate heat transfer variables and the PV conversion efficiency can be predicted. Peng et al. had investigated the thermal performance of PV-DSF by experimental works and simulation works [7, 8, 11, 12]. The experimental results indicated that the PV-DSF system could reduce the heat gains and heat losses through the building façade. The ventilated PV-DSF can reduce 60% of solar heat gain compared with typical double-skin façade. It also pointed out that the PV-DSFs are more suitable in tropical and subtropical climate regions due to its low solar heat gain coefficient (SHGC) and high overall heat transfer coefficient (U-value) [11]. Wang et al. [13] had compared the energy performance between PV insulating glass units (PV-IGUs) and PV-DSFs in five different climatic zones in China. It was found that the PV-IGU performed better thermal insulation than the PV-DSF. The average energy-saving potential of PV-IGUs was 2% higher than which of PV-DSFs.

The previous researches about the thermal performance of different types of STPV windows suggested that the STPV window has a superior advantage in the cooling-dominated regions because of its solar control ability [14]. However, only a small proportion of receiving solar energy is used for power generation, and the majority of absorbed solar energy by the solar cells will be additional cooling demand in the cooling season [12]. In the heating season, the heating load may increase as the incoming solar heat gain is low when adopting the PV glazing [15]. Additionally, the thermal insulation performances of the aforementioned PV glazings are unsatisfied for the heating-dominated regions.

Unlike the PV glazing, which is considered as solar control glass, the vacuum glazing is known for the best thermal insulation. It consists of a vacuum gap and two glass panels separated by an array of small support pillars [16]. The 0.1 mm evacuated gap can eliminate the heat conduction and heat convection through the glazing. The combination of low-e coatings and vacuum glazing can achieve excellent thermal insulation performance [17]. The first reported fabrication method of vacuum glazing was succeeded by using solder glass for edge sealing in 1989 [18]. However, the soldering temperature is around 500 ℃ which will restrict the use of soft low-e coatings. In the 2000s, Fang et al. had developed the low-temperature soldering method (less than 200 ℃) by using indium alloy edge sealing, which provides the opportunity to manufacture the vacuum PV glazing with high performance low-e coatings and tempered glasses [19]. The best commercial vacuum glazing was reported with U-value of 0.86 W/m^2K [20]. Compared with double-pane glass, vacuum glazing could reduce 53% heat loss and present almost identical heat gain [21].

In respect of the above discussion, a novel semi-transparent photovoltaic vacuum glazing is proposed to improve the thermal performance of conventional PV window [22]. The thermal and electrical characteristics of the a-Si vacuum PV glazing had been evaluated by laboratory experiments and field tests [23]. The overall energy performance of the vacuum PV glazing in Hong Kong was investigated [24]. It was suggested that the vacuum PV glazing could enhance the thermal performance and overcome the deficiency of the PV glazing.

Besides the energy performance of windows, the daylighting performance should be regarded as another critical aspect of the modern building design [25]. PV glazings have the potential to achieve a comfortable natural light environment. Liu et al. [26] evaluated the daylight performance of the CdTe PV glazing with four different transparencies. Compared with ordinary double glazing, the PV glazing performed a better daylight performance due to the improvement of daylight distribution and the control of glaring risk. Peng et al. [27] utilized photometers and shielded thermistors for the daylighting tests to investigate the daylighting performance of a c-Si based semi-transparent solar photovoltaic window. The lighting system of the test room deployed dimming control based on the daylight illuminance measurement. The results indicated that when applying the BIPV window, the visual comfort level was improved compared with the clear glass, while more lighting energy was required. In respect of the application of the vacuum PV glazing, Qiu and Yi [28] conducted a validated daylighting model to represent the daylighting behaviour of a vacuum cadmium telluride-based photovoltaic glazing with three-layer structure. An artificial neuron network (ANN) daylighting model was developed for the annual daylighting prediction. The coupling between the ANN-based daylighting model and EnergyPlus was also conducted to calculate the lighting consumption. It was found that the visible transmittance of the glazing not only affects the visual comfort for occupants but also has an impact on for the artificial lighting consumption in the building when the energy-saving lighting control strategy adopted. The stepped control strategy and continuous dimming control strategy can save the electricity consumption by utilizing the daylighting as a supplement for the artificial lighting system when the daylighting can provide sufficient interior illuminance for occupants.

Although the previous study on the vacuum PV glazing provided an understanding of the thermal performance and the daylighting behaviour of the vacuum PV glazing, the climate conditions must be taken into account to fully understand the applicability and limitation of the vacuum PV glazing. Moreover, the annual daylighting performance of the vacuum PV glazing needs to be investigated since the daylighting performance and the overall energy performance of window systems can be recognized as two individual evaluation indicators [29]. The thermal behaviour, daylighting behaviour and power generation ability of the proposed vacuum PV glazing have complex interactions, which depend on the specific thermal and optical properties of the glazing system. Therefore, the objective of this paper is to conduct a comprehensive investigation on the thermal performance, the daylighting performance and the overall energy performance of the vacuum PV glazing in different climate regions. Section 2 introduced the structure and the measured physical characteristics of the proposed vacuum PV glazing. In Section 3 and Section 4, the development of the energy simulation models by EnergyPlus and the daylighting simulation models by DAYSIM were demonstrated. In Section 5, the simulation results were presented to detailed discuss the thermal performance, the daylighting performance and the overall energy performance of the vacuum PV glazing. Based on the analysis, the reversed and reversible vacuum PV glazing were proposed to achieve the full potential of this novel BIPV window system. Section 6 summarized the key findings of this study. On account of different climate backgrounds, the advantage and limitation of the vacuum PV glazing were determined and provide the opportunity to optimize the design in future research.

2. Amorphous silicon-based vacuum PV glazing

2.1 Structure of vacuum PV glazing

As an innovative fenestration product, the initial concept of the proposed vacuum PV glazing is to combine the excellent thermal insulation performance of the vacuum glazing and solar control ability of the PV glazing. Compared with other common window products, such as a double-pane window, a conventional PV glazing has a relatively low SHGC and almost the same U-value. When the semi-transparent PV glazing is applied in the building envelope, part of visible light can penetrate the indoor room since it has a certain degree of transparency. The solar cells will absorb the vast majority of the solar irradiation and convert part of solar energy into electricity by the photovoltaic effect. The remaining solar energy will increase the temperature of the whole glazing system. In the cooling season, this part of unwanted heat could increase the cooling demand due to the poor thermal insulation performance of the back glass sheet of the conventional PV glazing. In the heating season, the conventional PV glazing would increase the heating demand due to the reduction of solar heat gain. Since the vacuum glazing is regarded as an advanced thermal insulation glass, it can drastically reduce the heat gain and the heat loss of the window. As the internal layer of the vacuum PV glazing, the vacuum glazing will block the waste heat which comes from the absorbed solar energy in summer. Moreover, it can minimize the heat loss from indoor to outdoor in winter.

The cross-section of the construction of the vacuum PV glazing is illustrated in Fig. 1. An amorphous silicon-based PV glazing as the external layer and a vacuum PV glazing as the internal layer were bonded into an integrated glass unit by a layer of polyvinyl butyral (PVB). The vacuum glazing comprises a narrow vacuum gap with only 0.1 mm width between two glass sheets. The support pillars between two glass panes are small glass spheres with 0.05 mm radius and evenly spaced 50 mm apart. Therefore, the occupants' view will not be interfered. The vacuum gap can eliminate the heat conduction and heat convection through the glazing area. The low-e coating with the emissivity of 0.042, which is deployed on the interior surface of the vacuum glazing towards outside, reduces the radiative heat transfer to an extremely low level. Consequently, the thermal insulation performance of the vacuum PV glazing can be enhanced.

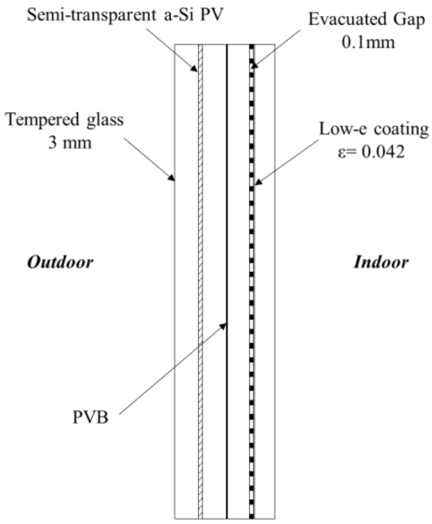


Fig. 1 The cross-section of the vacuum PV glazing

The sample of the vacuum PV glazing was fabricated by gluing the external PV laminated glazing and the internal vacuum glazing together with a layer of polyvinyl butyral (PVB) as shown in Fig. 2. The vacuum PV glazing has a thickness of 20.8 mm, which is thinner than common double-pane windows with an air gap. Therefore, the vacuum PV glazing can not only be a novel BIPV system employing in a new building but also have the feasibility to replace conventional windows of the existing building to improve the thermal performance.

(a) Front view (b) Side view

Fig. 2 Pictures of the vacuum PV glazing

2.2 Physical characteristics measurement

The physical characteristics of the vacuum PV glazing must be firstly determined before the simulation study. The reliability of the developed simulation model of the vacuum PV glazing depends on the measured optical parameters and the electrical characteristics. A spectrophotometric test was conducted to determine the optical characteristics of the vacuum PV glazing, including the spectral transmittance, reflectance, and absorption. A Hitachi UV-VIS-NIR spectrophotometer was used in this test to simulate the solar spectrum with a range of 300 nm to 2500 nm. The size of the vacuum PV glazing sample was manufactured as 300 mm × 300 mm to fit in the equipment. From Fig. 3, it can be seen that the average solar transmittance (T), reflectance (R) and absorption (A) for vacuum PV glazing were 8.9%, 14.3%, and 76.8%, respectively. The visible transmittance was around 12%. In the near-infrared (NIR) range, it was observed high reflection and low transmission as a result of the presence of the low-e coating of the vacuum glazing.

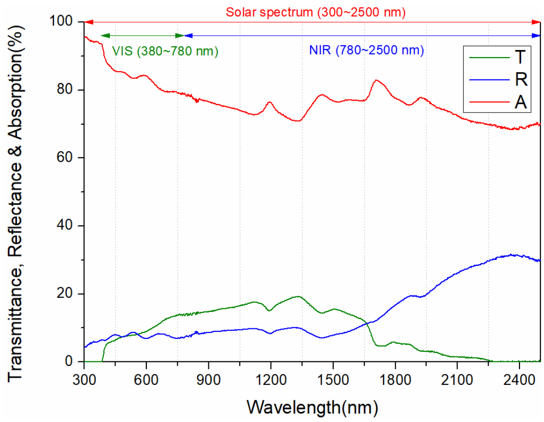


Fig. 3 The optical characteristics of the vacuum PV glazing

The electrical aspects of the vacuum PV glazing are essential in simulating the power generation by the PV modules. The key parameters have been measured by field experiments in the previous study [23]. Accordingly, the key electrical parameters under standard test condition (1.5 of air mass, 25 ℃ of cell temperature, and 1000W/m^2 of solar irradiation) are determined as shown in Table 1.

Table 1 Key electrical parameters of the vacuum PV glazing

Parameters	Value
Maximum power output (W)	74
Voltage at the maximum power point (V)	94
Current at the maximum power point (A)	0.78
Open circuit voltage (V)	120
Short circuit current (A)	0.98
Fill factor	0.62
Module efficiency	5.2%

3. Energy simulation modelling and conditions

3.1 Development of the energy simulation model

To investigate the overall energy performance of the vacuum PV glazing, EnergyPlus [30] was used in this study to develop a whole building energy model of a typical office mounted this innovative BIPV window. The process of the energy simulation consists of three stages: (1) preparation of glazing properties, (2) development of the energy simulation model, (3) simulations of different glazing systems under different climate backgrounds.

In the first stage, the optical and thermal characteristics of varies glazing systems were determined by Berkley Lab WINDOW [31]. The vacuum glazing and the PV glazing were identified in the Berkley Lab WINDOW to construct the model of the vacuum PV glazing layer by layer. The measured optical properties of the vacuum PV glazing were used for the calculation of U-value and solar heat gain coefficient (SHGC). The report of the thermal properties of the vacuum PV glazing was generated accordingly as an input file, which can be imported into EnergyPlus for the next stage. The Berkley Lab WINDOW also provides an integrated glazing system library to assist users in building up the other complex windows to meet the requirements of energy-efficient building design criteria in different climate zones.

In the second stage, a 3D model which represents a typical small office was developed with the dimension of 2.3 m wide, 3 m deep and 2.5 m high, as shown in Fig. 4. The only external wall is mounted with a window and the window to wall ratio (WWR) is 65%. The ceiling, the floor, and the other walls are considered as interior surfaces. For the cooling and heating simulation, the coefficient of performance (COP) of the air conditioning system for cooling was fixed at 2.78 [32] and the burner efficiency of the gas boiler for heating was set as 0.8. The thermostat set points were 25 ℃ for cooling and 22 ℃ for heating. Air Heat Balance Module, HVAC Module, and Surface Heat Balance Module were applied to determine the cooling and heating consumption. Continuous dimming control strategy was selected to conserve lighting consumption when daylighting was available. The set point of the indoor illuminance level at reference point was set at 500 lux. The reference point refers to the location of the lighting control sensor, which is at the centre of the working plane (0.8 m above the floor). The electricity consumption from artificial lighting was calculated based on the integration of Daylighting Module, Sky Model Module, and Window Glass Module. The equivalent one-diode model was adopted to predict the PV power generation performance with the consideration of the temperature effect of the solar cells. The hourly electric output can be obtained based on the solar irradiation and module operating temperature.

In the third stage, varies glazing systems were selected as the competitors of the vacuum PV glazing. To fully understand the feasibility and limitation of the vacuum PV glazing, five different climate conditions were applied to compare the thermal performance and the overall energy performance of different glazing systems. China can be divided into five different climate zones, namely, severe cold, cold, hot summer and cold winter, hot summer and warm winter, and moderate. Harbin, Beijing, Wuhan, Hong Kong, and Kunming were selected as the representative cites of five different climate regions of China accordingly. The weather data for the building energy simulations were obtained from Chinese Standard Weather Data (CSWD). Table 2 shows the locations and weather conditions of the representative cities in different climate zones. All simulations in various cities were carried out in five orientations, namely, east, southeast, south, southwest, and west.

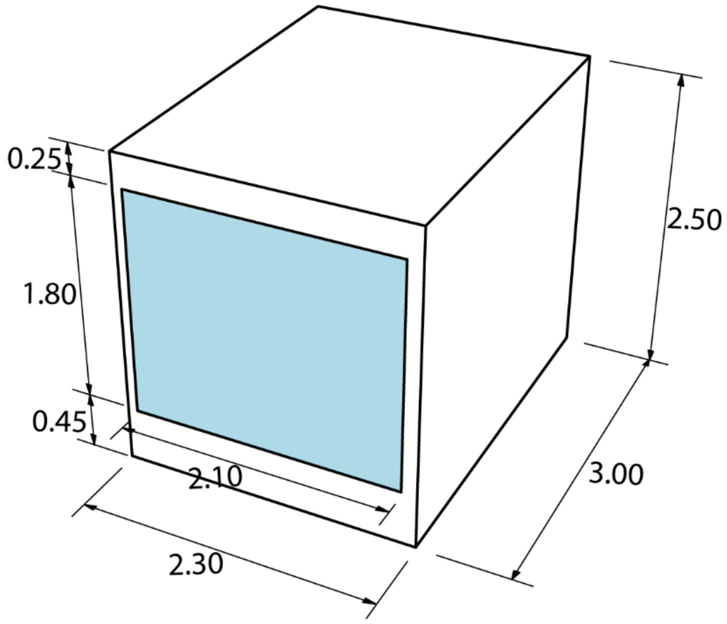


Fig. 4 The EnergyPlus model of a typical small office

Table 2 The locations and weather conditions of the representative cities

City	Climate zone	Location	Summer temperature	Winter temperature
Harbin	Severe Cold	45.8° N, 126.8° E	Maximum: 32.8 ℃ Average: 21.3 ℃	Minimum: -28.7 ℃ Average: -16.1 ℃
Beijing	Cold	39.8° N 116.5° E	Maximum: 37.2 ℃ Average: 25.5 ℃	Minimum: -14.2 ℃ Average: -2.0 ℃
Wuhan	Hot summer and cold winter	30.6° N, 114.1° E	Maximum: 38.8 ℃ Average: 27.6 ℃	Minimum: -3.9 ℃ Average: 7.1 ℃
Hong Kong	Hot summer and warm winter	22.3° N, 114.1° E	Maximum: 32.8 ℃ Average: 28.3 ℃	Minimum: 9.3 ℃ Average: 17.2 ℃
Kunming	Moderate	25.0° N 102.7° E	Maximum: 28.8 ℃ Average: 19.9 ℃	Minimum: -2.1 ℃ Average: 9.2 ℃

3.2 Properties of glazing materials

Double-pane windows, double PV glazing, and vacuum glazing were selected for comparison purpose. The selection of windows comprehensively considered the thermal characteristics and the climatic conditions of different sites. As shown in Table 3, common double-pane windows and exterior walls were applied in different climate regions to meet the national standard of China, "Design standard for energy efficiency of public buildings" (GB 50189-2015) [33]. A double-pane window consists of two glass panes and an air gap. For a low-e glass, a low-e coating deposits on the surface toward the inside. For each site, the double PV glazing was adopted the same a-Si PV glazing as the vacuum PV glazing and the same configuration as the double-pane window. The vacuum glazing is identical to those used in manufacturing the vacuum PV glazing to make a clear distinction between these two thermal insulation glazings. Table 4 shows the critical parameters of the vacuum PV glazing and vacuum glazing adopted in the energy simulations as well as the daylighting simulations.

Table 3 The properties of building envelope of the representative cities

City	Climate zone	Conventional window	U-value of	SHGC of window	U-value of exterior

			window (W/m^{2}K)		wall (W/m^{2}K)
Harbin	Severe Cold	6 mm low-e glass+7 mm air gap+ 6 mm low-e glass	1.50	0.35	0.38
Beijing	Cold	6 mm clear glass+6 mm air gap+6 mm low-e glass	1.90	0.45	0.50
Wuhan	Hot summer and cold winter	3 mm clear glass+3 mm air gap+3 mm low-e glass	2.20	0.45	0.60
Hong Kong	Hot summer and warm winter	3 mm clear glass+1.5 mm air gap+3 mm low-e glass	2.50	0.44	0.80
Kunming	Moderate	3 mm clear glass+1.5 mm air gap+3 mm low-e glass	2.50	0.44	0.80

Table 4 The key parameters of the vacuum PV glazing and the vacuum glazing

Glazing Type	Thickness (mm)	Visible Transmittance	U-value (W/m^{2}K)	SHGC
Vacuum PV glazing	20.8	0.120	0.557	0.143
Vacuum glazing (low-e)	11.5	0.693	0.648	0.391

4. Daylighting simulation modelling and conditions

4.1 Development of the daylighting simulation model

In this study, DAYSIM was used to conduct the annual daylighting simulation for the vacuum PV glazing under different climatic conditions. DAYSIM is a RADIANCE-based dynamic daylight simulation tool based on the backward ray-tracing technique. DAYSIM employs the daylight coefficient (DC) method to perform fast annual daylighting simulation and the climate-based sky model developed by Perez et al. [34] to simulate the sky conditions of a whole year. The daylighting performance of advanced glazing systems can be evaluated by dynamic daylighting metrics such as daylight autonomy (DA), useful daylight illuminance (UDI), and annual daylight glare probability (DGP) [35]. Several studies [35-37] have validated the daylighting simulation model by DAYSIM and indicate that it can predict realistic indoor daylighting illuminance results with high accuracy.

The three-dimensional model was built up in Rhino 6 [38]. Rhino 6 provides a platform, namely Grasshopper [39], for various functional plugin tools, such as Ladybug and Honeybee. Ladybug was used to import weather files of Harbin, Beijing, Wuhan, Hong Kong, and Kunming as five reprehensive cities of different climate zones in China. Honeybee was used to develop the daylighting simulation models using DAYSIM as the engine. The simulation results of daylight illuminance can be visualized in Rhino/Grasshopper environment. The daylight glare comfort level can be evaluated dynamically on an annual basis. For ensuring the consistency with the building energy simulation model, a daylighting model was conducted based on the same boundary conditions, which include the building geometry and building envelope material. The daylighting performance of a south-facing office mounted with the vacuum PV glazing in different climate regions were compared with the application of the vacuum glazing to investigate how the integration of the vacuum glazing and PV glazing affects daylight availability and visual comfort. The simulation parameters of the daylighting simulation model are listed in Table 5 as follows.

Table 5 Details of DAYSIM simulation parameters

Ambient bounces	Ambient accuracy	Ambient divisions	Ambient resolution	Ambient super-samples	Direct threshold	Direct sampling
2	0.25	512	16	128	0.5	0.15

4.2 Daylighting performance metrics

To fully evaluate the daylighting performance of the vacuum PV glazing, two assessment metrics, Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP) were used in this study to represent the daylight availability and the visual comfort level. UDI was developed by Nabil and Mardaljevic [40] to assess the available daylight illuminance for a whole year based on occupant preference and behaviour. For a specific point on the working plane, this metric divides the daylight illuminance values during the working hours of a whole year into three ranges. The working hours are determined by the occupancy schedule, which is applicable to both the daylighting simulation model and the building energy simulation model. $UDI_{<100\ lux}$ is the percentage of the time when the undersupply daylight occurs. The illuminance level lower than 100 lux indicates that the daylight is insufficient to be the sole source of light or to contribute significantly to artificial lighting. $UDI_{>2000\ lux}$ is the percentage of the time when the oversupply daylight occurs. The illuminance level higher than 2000 lux suggests that it is likely to generate visual or thermal discomfort. $UDI_{100\text{-}2000\ lux}$ represents the time when the daylight illuminance is in range of 100-2000 lux, which is considered as the useful daylighting supply for occupants. In this study, 10 points along the central line from the window to the rear wall were selected as the indicators to estimate the interior illumination distribution. Those points were located at the working plane with a height of 0.8 m and the interval between adjacent points was 0.3 m.

Daylight Glare Probability (DGP) was proposed by Wienold and Christoffersen [37, 41] to evaluate the probability of daylight glare discomfort based on the vertical illuminance at the viewpoint of an occupant. The levels of daylight glare comfort are divided into four ranges by the thresholds of DGPs. DGP lower than 0.35 is ‘imperceptible’ glare, in the range of 0.35 – 0.4 is ‘perceptible’ glare, in the range of 0.4 -0.45 is ‘disturbing’ glare, higher than 0.45 is considered as ‘intolerable’ glare. DAYSIM can obtain the hourly DGPs by using a simplified annual method. Therefore, the DGP values for all the daytime hours can be recognized as the annual glare profile. The viewpoint was located at the same location as the reference point in the EnergyPlus model. The view vector was set vertically towards the window.

5. Results and discussion

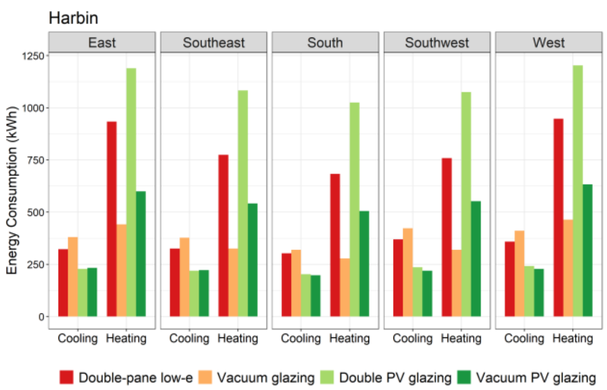
5.1 Thermal performance

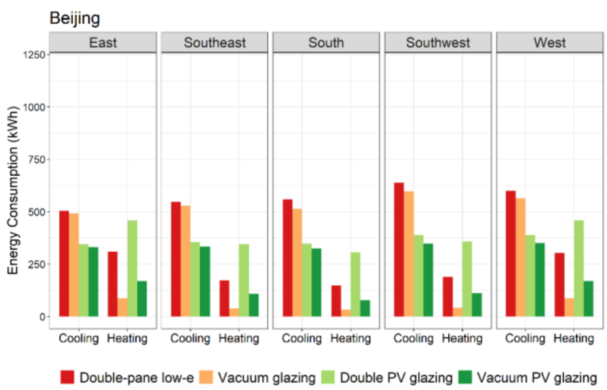
One of the primary motivation of the development of the vacuum PV glazing is to maximize the thermal performance of BIPV windows by conserving the energy for cooling and heating. The energy-saving potential due to the thermal performance was evaluated by comparing the annual cooling and heating consumption of the vacuum PV glazing with which of other alternatives. The selected double-pane windows were used as the baseline for different climate conditions. As part of the vacuum PV glazing components, the PV glazing with a relatively low SHGC and the vacuum glazing with an extremely low U-value would perform different thermal behaviours under different climate backgrounds. The double PV glazing and the vacuum glazing were used to indicate the thermal behaviour of the two components of the vacuum PV glazing, respectively. Therefore, the comprehensive thermal behaviour of the vacuum PV glazing can be discussed in depth.

Fig. 5(a) – (e) present the annual cooling consumption and heating consumption of the simulation model adopted different glazing systems in different climate regions. As shown in Fig. 5(a), the heating energy is much higher than the cooling energy in Harbin due to the severe cold climate. For the heat consumption in Harbin, it can be found that the applications of the vacuum glazing can reduce the heating energy dramatically. The vacuum PV glazing can achieve 26.0% - 35.7% heating energy saving while the vacuum glazing can save 51.0% - 59.3% energy consumption for heating compared with the double-pane window. Meanwhile, the applications of the PV glazing may have a particularly negative impact on the heating consumption. It is because the direct transmitted solar heat will be blocked by the solar cells, which results in the low SHGC of the PV glazing. Consequently, the reduction of the solar heat gain leads to more energy for space heating in winter. The heating consumption of the double PV window is 27.0% - 50.0% higher than the baseline. In terms of cooling consumption, the vacuum PV glazing has the best performance by saving 27.6% - 40.6% cooling energy in different orientations. The double PV glazing is also beneficial in the cooling seasons by providing the energy-saving potential of 29.3% - 36.1% for cooling. However, the vacuum glazing performs the adverse effects in summer since the cooling consumption of the vacuum glazing increases by 5.5% - 18.1%.

As shown in Fig. 5(b) - (d), for the regions have a hot summer, it is found that the vacuum PV glazing and the double PV glazing perform higher energy-efficiency in terms of the cooling consumption than the vacuum glazing and double-pane window. In Beijing, Wuhan and Hong Kong, the energy-saving for cooling by adopting the vacuum PV glazing are 34.6% - 45.7%, 21.9% - 34.1%, and 20.4% - 29.0%, respectively. In addition, the application of the vacuum PV glazing and the vacuum glazing greatly reduce the heating consumption compared with the use of the double PV glazing and the double glazing in the regions with a cold winter. The energy-saving for heating when using the vacuum PV glazing is 37.1% - 47.2% in Beijing and 69.8% - 78.3% in Wuhan. However, as shown in Fig. 5(e), the vacuum glazing and the vacuum PV glazing are not suitable for Kunming due to the additional consumption of cooling compared with the double-pane window and the double PV glazing. The double PV window is recommended for moderate climate due to the best thermal performance.

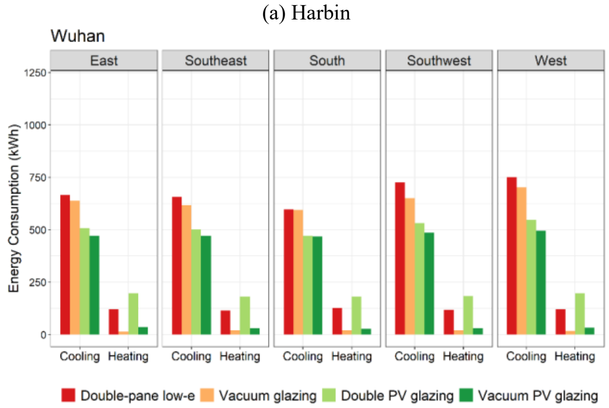
With regard to the thermal performance, the vacuum PV glazing can be considered as the best fenestration product under different climatic conditions. It combines the energy-saving potential for cooling by the PV glazing and the energy-saving potential for heating by the vacuum glazing. Therefore, the applicability of this innovative BIPV window is greatly enhanced. Compare with the common double-pane window, the vacuum PV glazing can save 28.7% - 34.0%, 38.6% - 44.6%, 31.8% - 39.3%, 20.7% - 29.2%, and 23.0% - 43.1% of the total energy for cooling and heating in Harbin, Beijing, Wuhan, Hong Kong, and Kunming, respectively.



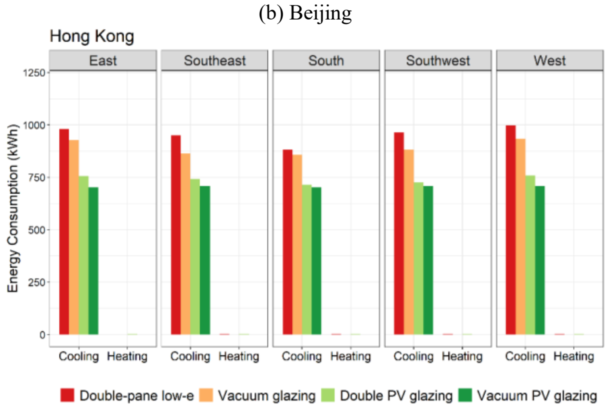


(a) Harbin

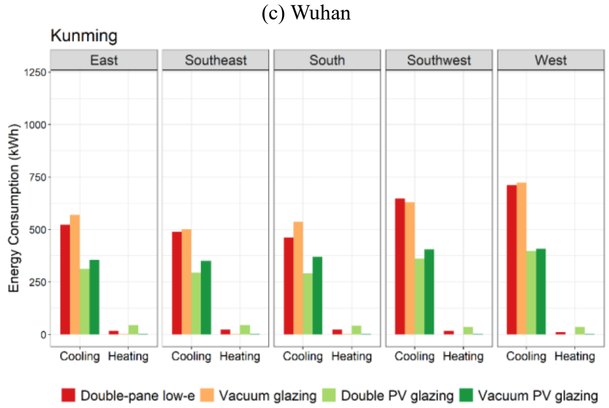
(b) Beijing



(c) Wuhan



(d) Hong Kong



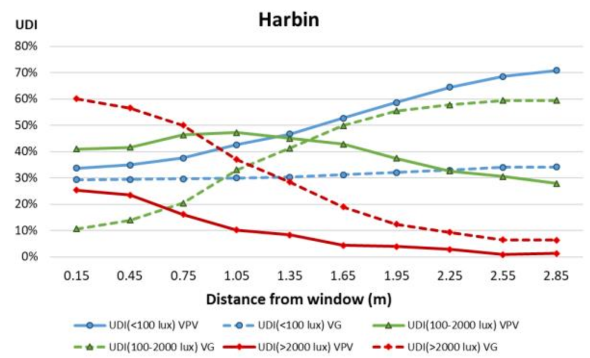
(e) Kunming

Fig. 5 Annual consumption for cooling and heating in different climate regions

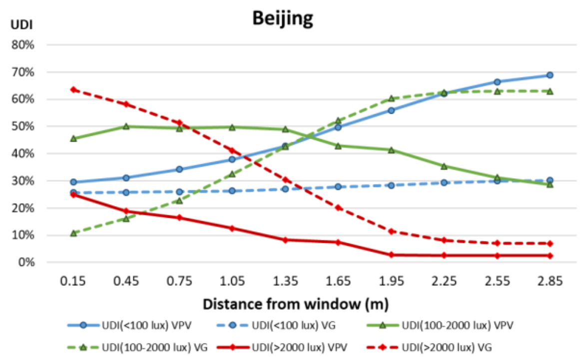
5.2 Daylighting performance

From the thermal performance analysis in the previous section, both the vacuum PV glazing and the vacuum glazing show the excellent thermal performance, especially when adopting in the cold regions. However, the daylight behaviour of the vacuum PV glazing is materially different from which of the vacuum glazing since the solar cells cause the semi-transparent appearance of the insulated glass unit. On account of the visual transmittance, the vacuum glazing is similar to the typical double-pane window. In this section, the daylighting performance of the vacuum PV glazing in different climates was investigated in terms of daylight availability and visual comfort. The comparisons of the daylighting performance between the vacuum PV glazing and the vacuum glazing were conducted to indicate the advantage and limitation of the application of the PV glazing integrated with the vacuum glazing.

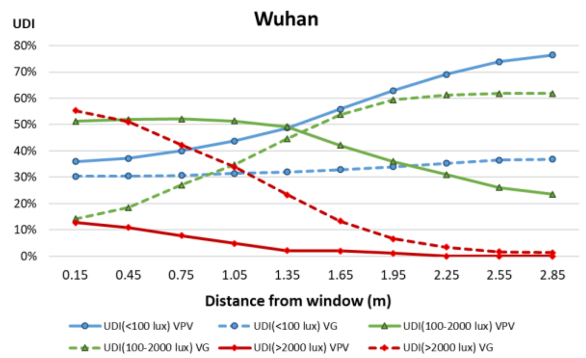
Fig. 6(a) – (e) show three UDI bins of the vacuum PV glazing and the vacuum glazing in different climates. For the case in the Harbin, as shown in Fig. 6(a), it can be seen that the $UDI_{<100\ lux}$ of the vacuum PV glazing, which ranges from 34% to 71%, are larger than the $UDI_{<100\ lux}$ of the vacuum glazing which increases from 29% to 34% with the increment of the distance from the window. When adopting the vacuum PV glazing, the undersupply daylight along with the depth of the room increases much faster than the application of the vacuum glazing. On the contrary, the $UDI_{>2000\ lux}$ of the vacuum PV glazing is much lower than which of the vacuum glazing. For the vacuum glazing, the $UDI_{>2000\ lux}$ is 60% in the region near the window and dramatically decreases to 6% in the rear area of the office. The $UDI_{>2000\ lux}$ of the vacuum PV glazing decreases from 25% to 1%. It suggests that the vacuum glazing provide a higher likelihood of the oversupply daylight illuminance than the vacuum PV glazing, especially in the area close to the window. In the aspect of the useful daylight illumination, the $UDI_{100\text{-}2000\ lux}$ of the vacuum PV glazing varies from 28% to 47%, while the $UDI_{100\text{-}2000\ lux}$ increases from 11% to 59% as the distance from the window increases. In the region near the window, the $UDI_{100\text{-}2000\ lux}$ of the vacuum PV glazing is 41%, which is much higher than the $UDI_{100\text{-}2000\ lux}$ of the vacuum glazing as 11%. However, the $UDI_{100\text{-}2000\ lux}$ of the vacuum glazing surpasses which of the vacuum PV glazing at the point near the centre of the office. In the deepest area, the $UDI_{100\text{-}2000\ lux}$ of the vacuum PV glazing and the vacuum glazing are 28% and 59%, respectively. From Fig. 6(b) to (e), the similar distribution of three UDI bins of these two types of glazing can be observed in Beijing, Wuhan, Hong Kong, and Kunming. It is worth noting that more oversupply daylight occurs near the rear wall in the sites with high latitudes, such as Harbin (45.8° N). It is because the south-orientated window will receive more direct sunlight in the high latitude regions in winter. It can be concluded that, in the anterior half of the room, the oversupply of daylight ($UDI_{>2000\ lux}$) is more serious when the vacuum glazing was adopted, while the application of the vacuum PV glazing can offer more useful daylight ($UDI_{100\text{-}2000\ lux}$). In the rear half of the room, the vacuum PV glazing tends to undersupply the daylight illuminance ($UDI_{<100\ lux}$), and the vacuum glazing is highly likely to provide useful daylight ($UDI_{100\text{-}2000\ lux}$).



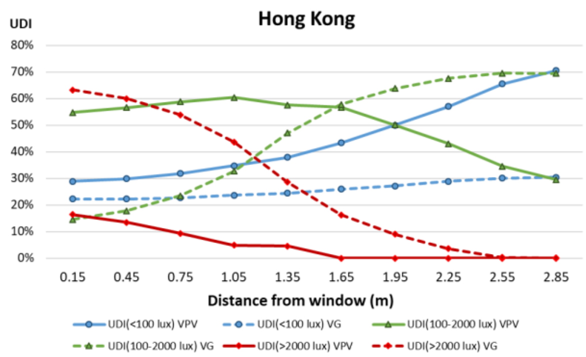
(a) Harbin



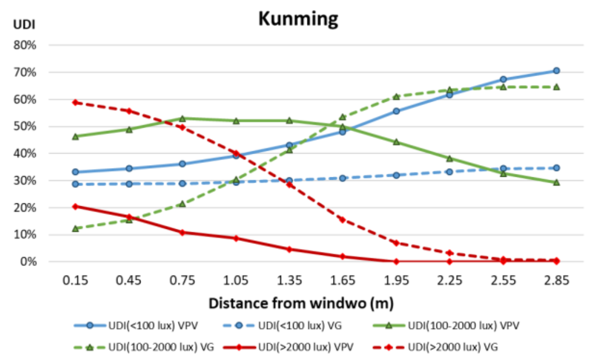
(b) Beijing



(c) Wuhan



(d) Hong Kong



(e) Kunming

Fig. 6 Useful Daylight Illuminance of the vacuum PV glazing and the vacuum glazing under different climates

Besides the daylight availability, the visual comfort level of the vacuum PV glazing and the vacuum glazing under different climate conditions were evaluated by using the DGP technique, as shown in Fig. 7. The frequency distribution of four DGP bins was calculated by classifying all hourly DGP values of the daytime. The percentage of $DGP_{\leq 0.35}$ of the vacuum glazing in Harbin, Beijing, Wuhan, Hong Kong and Kunming is 54.6%, 52.2%, 57.8%, 53.1%, and 49%, respectively. Meanwhile, the hours of 'intolerant glare' ($DGP_{\geq 0.45}$) account for 22.1% - 28.6% when the vacuum glazing is adopted under different climate backgrounds. The results suggest that it is unlikely to recommend using the vacuum glazing alone (without any shading devices) due to the daylight glare problem. For the daylight visual comfort of the application of the vacuum PV glazing, remarkable improvement can be observed in all climate regions. When applying the vacuum PV glazing, the 'imperceptible glare' ($DGP_{\leq 0.35}$) dominates the majority of the daytime. The percentage of this figure is 88.3%, 92.1%, 98.8%, 99.9%, and 99.9% in Harbin, Beijing, Wuhan, Hong Kong and Kunming, respectively. According to the glare rating classification proposed by Wienold [37], the requirement of the 'Best' class is 95% of daylight glare during the office working time weaker than 'imperceptible'. It can be seen that the better daylight glare performance can be attained by the vacuum PV glazing in the regions with a lower latitude, such as Wuhan (30.6° N), Hong Kong (22.3° N), and Kunming (25.0° N). Therefore, the vacuum PV glazing can be recognized as the 'Best' class in those cities. In conclusion, the daylight glare can be largely prevented by the utilization of the vacuum PV glazing, especially in the low latitude regions.

From the analysis of the UDI and the DGP of the vacuum PV glazing and the vacuum glazing, it can be concluded that the vacuum PV glazing can provide sufficient daylight without visual discomfort occurring. In view of the occupant preference in daylit offices [42], visual discomfort is more intolerant than insufficient daylight supply since the latter one can be substituted by artificial lighting. In this regard, the vacuum PV glazing has a better daylighting performance than the vacuum glazing. Therefore, the combination of the semi-transparent PV glazing and the vacuum glazing provides the potential to make a balance between the daylight availability and visual comfort level.

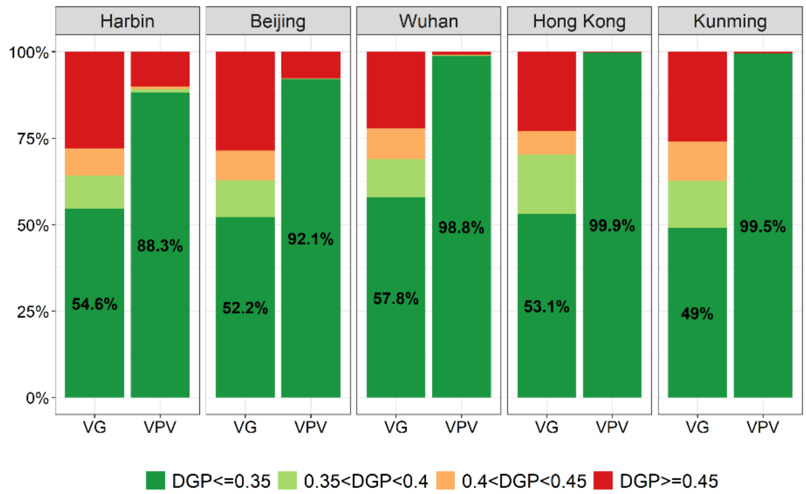


Fig. 7 Daylight Glare Probability of the vacuum PV glazing and the vacuum glazing under different climates

5.3 Overall energy performance

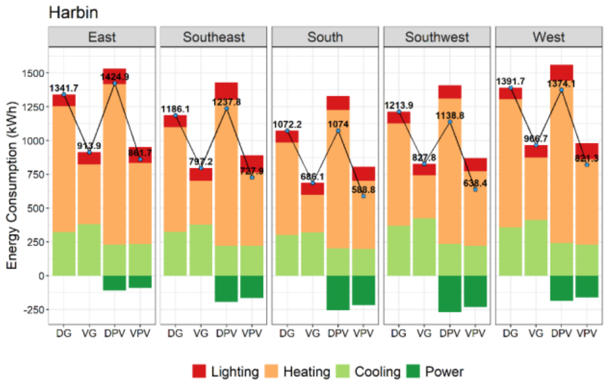
The overall energy consumption of different glazing systems in different climates indicate the total energy saving potential of the application of the proposed vacuum PV glazing, which takes into account the power generation from solar energy. Based on the above discussion in Section 5.1, the adoption of the PV glazing has a huge energy-saving potential regarding the cooling consumption and the vacuum glazing can contribute immensely to saving energy regarding the heating consumption. However, the PV glazing may increase the energy consumption in the heating season, and the thermal insulation performance of vacuum glazing might be an unfavourable factor in the transition season. Moreover, as discussed in Section 5.2, the vacuum PV glazing may compromise the supply of daylight in the rear half of the room. The solar cells of the PV glazing not only generate renewable energy but also lead to additional lighting consumption due to the semi-transparent effect. Therefore, it is necessary to investigate the influence on the overall energy consumption when using the vacuum PV glazing in different climatic zones.

As shown in Fig. 8(a) – (e), the relative proportions of cooling consumption and heating consumption are quite different in different climate regions. It shows the predominance of heating consumption in Harbin, which represents the severe cold region, while the cooling consumption is becoming more and more dominant from the cold region to the hot summer and warm winter region. As a reference baseline, the proportion of cooling consumption of the double-pane window is 24.0%~30.4% in Harbin and 56.5%~71.0%, 73.4%~78.3%, 91.4%~92.4% and 81.4%~88.3% in Beijing, Wuhan, Hong Kong, and Kunming, respectively. On the other hand, when adopting the PV glazing, the power generation can fully compensate for the additional lighting consumption. For instance, comparing the lighting consumption of the vacuum glazing with the vacuum PV glazing in Harbin, the additional lighting consumption ranges from 11.1 kWh to 33.3 kWh. On the other hand, the annual power generation of the vacuum PV glazing is 91.0 kWh~231.0 kWh. For the application of double PV glazing, the power generation is 108.5 kWh~269.5 kWh, which is much higher than the additional lighting consumption, 11.1 kWh~41.7 kWh.

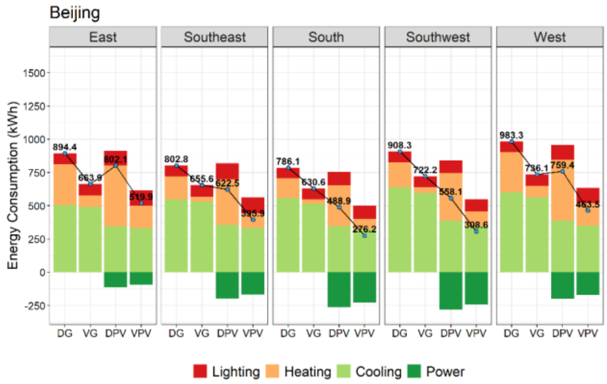
In Harbin, where the heating season is much longer than the cooling season, although the double PV glazing can reduce the cooling consumption, it consumes much more heating energy in the severe cold climate. As shown in Fig. 8(a), although the double PV glazing can generate electricity, the overall energy consumption is 6.2%, 12.5%, 8.9%, 1%, and 5.2% higher than that of the double-pane glass when the room oriented east, southeast, south, southwest and west, respectively. On the contrary, despite the vacuum glazing requires the most cooling consumption, it has the best thermal insulation performance, which can reduce 26.0% - 31.9% overall energy consumption compared with the baseline. As the combination of the PV glazing and the vacuum glazing, the overall energy consumption of the vacuum PV glazing is 33.8% - 43.4% lower than that of the double-pane window, which is superior to the results of the vacuum glazing. It can be concluded that the vacuum PV glazing can improve the overall energy performance of the application of PV glazing, especially in the heating-dominated region.

As shown in Fig. 8(b) - (c), in the cities which have cold winter, such as Beijing and Wuhan, the applications of PV glazing perform better than the PV glazings in the severe cold region. It is because the cooling consumption in those areas takes a bigger bite out of the overall energy consumption. The double PV glazing can save 10.3% - 38.6% and 16.1% - 30.5% of the total consumption in Beijing and Wuhan, respectively. The vacuum glazing can reduce 18.3% - 25.8% of the total consumption in Beijing and 13.3% - 18.2% of the total consumption in Wuhan. It was found that the double PV glazing has a better performance in Wuhan and the vacuum glazing has a better performance in Beijing with regards to the total consumption for cooling and heating. These results are also related to the weather condition of these two types of climatic zones. Although the total consumption in Beijing and Wuhan have the same level, it requires more heating energy and less cooling energy in Beijing than that in Wuhan. The energy-saving of the vacuum PV glazing in Beijing is higher than the one in Wuhan, which is 41.9% - 66.0% in Beijing and 36.8% - 48.8% in Wuhan. The main reason is that the PV glazings can produce more power in Beijing. The vacuum PV glazing is arguably the best glazing system in the cold region and the cold winter and hot summer region.

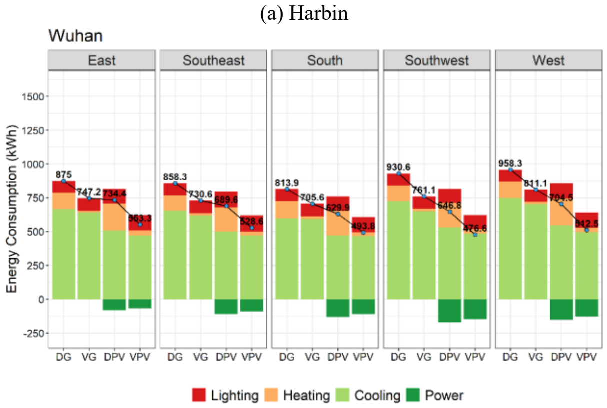
As shown in Fig. 8(d) – (e), it can be found that the heating consumption is negligible in Hong Kong and Kunming. Therefore, the advantage of the vacuum glazing becomes insignificant. Compared with the overall energy consumption of the double-pane window in Hong Kong, the vacuum glazing can only reduce 4.7%, 8.3%, 2.6%, 8.0% and 5.9% when the room was set facing east, southeast, south, southwest, and west, respectively. In Kunming, the vacuum glazing requires more energy than the double-pane glazing. For instance, the energy consumption of the vacuum glazing is 10.8% higher than the baseline of the south-facing room in Kunming. For the vacuum PV glazing, the energy conservation is 29.4% - 35.6% and 36.4% - 66.4% in Hong Kong and Kunming, respectively. The double PV glazing has a similar thermal performance. It is seen that 29.1% - 35.0% of the overall energy consumption can be saved when using the double PV glazing in Hong Kong. Moreover, the double PV glazing is considered as the best choice of windows for the moderate region like Kunming as it can reduce 39.1% - 73.8% of the overall energy consumption. This suggests that the vacuum PV glazing improves the overall energy performance of the application of vacuum glazing in the cooling-dominated region. However, it is preferably using the double PV glazing in the moderate region like Kunming.



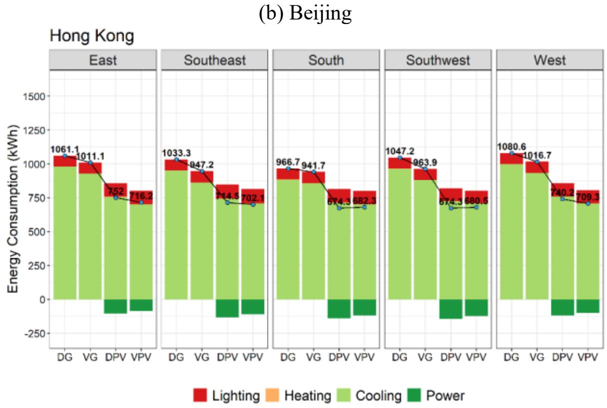
(a) Harbin



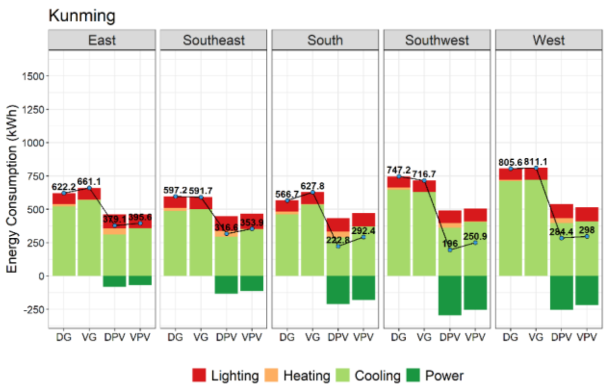
(b) Beijing



(c) Wuhan



(d) Hong Kong



(e) Kunming

Fig. 8 Overall energy consumption of different glazing systems in different climate regions

5.4 The reversed and reversible types of the vacuum PV glazing

Based on the discussion in the previous section, the vacuum PV glazing can be considered as an excellent fenestration product in the light of thermal performance and can provide a large amount of energy-saving potential when adopting in all types of climates. However, the vacuum glazing can be the better choice when applied in the severe cold climate zone. It is mainly due to the original design of the vacuum PV glazing set the PV glazing as the outer layer. The solar heat gain of PV glazing, which could contribute to being part of indoor heating energy in the daytime of the heating season, will be blocked by the vacuum glazing, which is the inner layer. The reversed vacuum PV glazing is referred to the vacuum PV glazing which has the reversed structure, namely, the outer layer is the vacuum PV glazing and the inner layer is the PV glazing. The thermal behaviour of the reversed vacuum PV glazing should be quite different from the vacuum PV glazing. The PV glazing as the inner layer may increase the cooling load in summer. However, it will be beneficial to solar space heating in the heating season. Fig. 9 demonstrates the monthly consumption for cooling and heating of the vacuum PV glazing and the reversed vacuum PV glazing in Harbin when facing southwest. It can be observed that the vacuum PV glazing consumes less energy from April to October while the reversed vacuum PV glazing can save more energy than the vacuum PV glazing in the heating season from November to March.

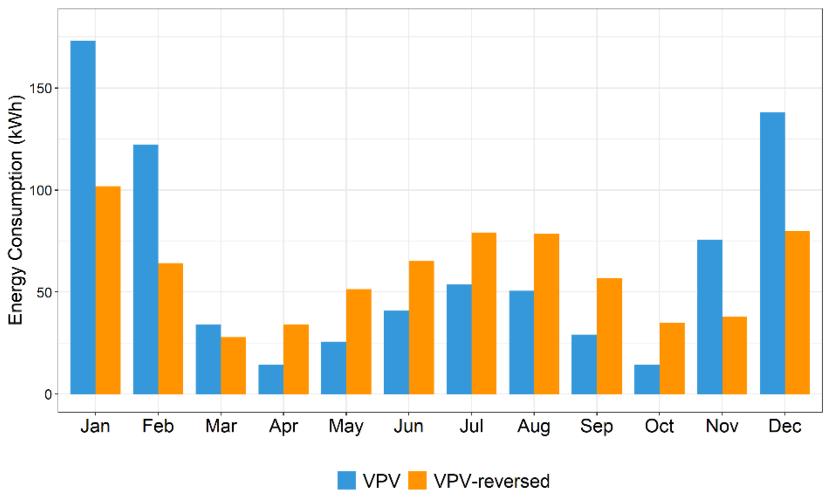


Fig. 9 Monthly consumption for cooling and heating of two types of VPV in Harbin

Based on the adequate understanding of the thermal behaviour of the combination of the PV glazing and the vacuum glazing, the concept of the reversible vacuum PV glazing is proposed to fully utilize the advantage of the solar control ability of the PV glazing and the outstanding thermal insulation performance of the vacuum glazing.

Several new types of solar cells, such as PERT (Passivated Emitter Rear Totally-diffused) solar cell [43] and PERC (Passivated Emitter and Rear Cell) solar cell [43, 44], can convert solar energy into electricity from both front side and rear side. These types of solar cells could be adopted in the reversible vacuum PV glazing system to maintain the function of photovoltaic power generation in both the vacuum PV glazing mode and the reversed vacuum PV glazing mode. Hence, the reversible vacuum PV glazing could be realized by integrating the PV glazing that was made up of PERT or PERC modules with the vacuum glazing into a commercial reversible window frame [45].

On account of the simulation results of the vacuum PV glazing and the reversed vacuum PV glazing in Harbin, the optimal operation strategy of the reversible vacuum PV glazing should be making the vacuum glazing facing inside from April to October and maintaining the reversed mode for the rest of the year. Fig. 10 presents the annual total energy consumption for cooling and heating of three alternatives of vacuum PV glazing as known as the vacuum PV glazing, the reversed vacuum PV glazing, and the reversible vacuum PV glazing. It can be seen that the reversed vacuum PV glazing is superior to the vacuum PV glazing in terms of the thermal performance. Compared with the results of the vacuum PV glazing, the reversed vacuum PV glazing can reduce the total consumption for cooling and heating by 3.0% - 17.5%. However, the reversible vacuum PV glazing can save the thermal energy dramatically. The annual consumption for cooling and heating of the reversible vacuum PV glazing is 22.6% - 32.2% less than which of the vacuum PV glazing. The results indicate that the reversible vacuum PV glazing acts energy response more efficiently and exerts the full energy-saving potential of the integration of the PV glazing and the vacuum glazing.

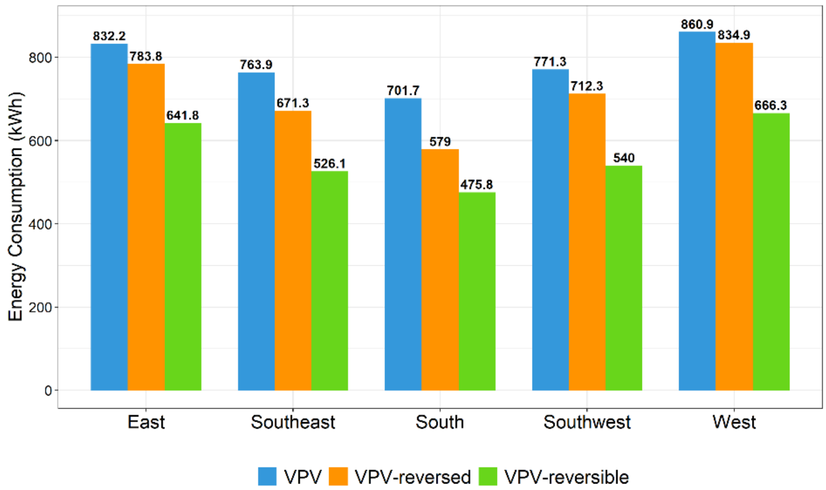


Fig. 10 The annual total consumption of cooling and heating in Harbin

6. Conclusions

In this study, a comprehensive investigation was conducted to evaluate the daylighting, thermal and overall energy performance of a novel semi-transparent PV vacuum glazing in different climate regions. The main conclusions of this study are as follows:

(1) In the severe cold, cold, and hot summer and cold winter regions, the vacuum PV glazing can effectively conserve the heating energy. In the hot summer and cold winter region, and hot summer and warm winter region, the vacuum PV glazing provides the most energy-saving for cooling. In terms of the total annual energy consumption for cooling and heating, the vacuum PV glazing can save 28.7% - 34.0%, 38.6% - 44.6%, 31.8% - 39.3%, 20.7% - 29.2%, and 23.0% - 43.1% in Harbin, Beijing, Wuhan, Hong Kong, and

Kunming, respectively. However, the application of the vacuum PV glazing requires additional cooling energy in the moderate climate zone like Kunming.

(2) The vacuum PV glazing can provide more useful daylight illumination in the anterior region of the room, and avoid the daylight glare for the occupants of the space. On account of the preference of the occupants on the luminous environment, it is suggested that the adoption of the vacuum PV glazing can balance daylighting availability and visual comfort compared with the vacuum glazing solely. The vacuum PV glazing can be classified as the ‘Best’ fenestration product in terms of daylight visual comfort in the low latitude regions, such as Wuhan, Hong Kong and Kunming.

(3) In terms of the overall energy performance, the vacuum PV glazing has superior performance than other competitors, including the double-pane window with low-e coating, the double PV glazing and the vacuum glazing. The power generated by the solar cells can sufficiently recover the additional lighting consumption. The vacuum PV glazing provides the energy-saving potential of 33.8% - 43.4%, 41.9% - 66.0%, 36.8% - 48.8%, 29.4% - 35.0%, and 36.4% - 66.4% in Harbin, Beijing, Wuhan, Hong Kong, and Kunming, respectively. It was noteworthy that the vacuum glazing is not preferable for Kunming, which represents the moderate region in China.

(4) In order to fully utilize the energy-saving potential of the combination of the PV glazing and the vacuum glazing, the reversed vacuum PV glazing and the reversible vacuum PV glazing have been proposed. It is found that the reversed vacuum PV glazing serves better than the vacuum PV glazing in the severe cold region and the reversible vacuum PV glazing can achieve the maximum energy saving potential by taking proper operation strategy.

The results of the energy simulation and daylighting simulation indicate that the PV glazing, which has the solar controlling and harvesting ability, can be beneficial to the reduction of the cooling demand. Meanwhile, the vacuum glazing, which provides the best thermal insulation performance, can be beneficial to saving heating energy. With respect to the requirement of the luminous environment, the vacuum PV glazing has a better daylighting performance than transparent glazings. The reversible window concept can enhance the applicability of the combination of the PV glazing and the vacuum glazing in different climate regions. This paper demonstrated the complex interactions between the daylighting performance and energy performance of the integration of the PV glazing and the vacuum glazing. For future work, a mathematical heat transfer model can be developed and validated by experiments to study the heat transfer mechanism of the vacuum PV glazing. Moreover, the influence of different PV coverage and transparency could be investigated to identify the optimum design of the vacuum PV glazing with regard to the daylighting and overall energy performance.

Acknowledgement

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