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Integrated CdTe PV glazing into windows: energy and daylight performance for different window-to-wall ratio

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Abstract

When integrated photovoltaics into building windows, the solar cells will absorb a fraction of solar radiation that hit on the window surface to generate electrical power and thus obstruct the solar energy and natural daylight that would have penetrated into inside space. In this paper, a window system integrated with thin film CdTe solar cells with 10% transparency was electrically characterised by Sandia model. The annual energy performance of a typical office with this PV window applied to different façade design was investigated using EnergyPlus under five typical climatic conditions in China. The dynamic daylight performance of the office has been assessed using RADIANCE. The result shows that when compared to a conventional double glazed system, the application of PV window can result in significant energy saving potential if the office has a relative large window-to-wall ratio (i.e. WWR ⩾ 45%). The simulation results also show that this PV window offers better daylight performance than conventional double-glazing.

Keywords: Semi-transparent Solar Cell, Building Simulation; EnergyPlus; RADIANCE

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1. Introduction

Building-integrated photovoltaic (BIPV) is a concept of integrating photovoltaic elements into the building envelope. For glazing application, photovoltaic modules replace conventional glass, taking over the function that glass performs, while also including the additional function of energy production. When integrating different types of PV modules into building window, the variation of thermos-optical properties of the PV glazing may affect the fraction of absorbed, transmitted and re-radiated solar radiation and the amount of penetrated daylight when compared with a conventional glazing window. This will in turn affect the temperature of the PV module and thus influence their electrical power generation. The interaction between the thermal, optical and electrical performance of a PV window, would eventually affect the indoor environment where they applied and the overall building energy consumption. Previous researchers used building simulation tools to reveal the relationship between the overall energy performance and the thermal, optical and electrical characteristics of semi-transparent PV windows [1-5]. A number of those studies focused on exploring the trade-off between the overall energy efficiency and its visible transmittance plus building design parameters (WWR, orientation and lighting design) [2, 3]. However, the inclusion of dynamic building daylight performance predictions with a rigorous method for representing the optical performance of PV windows has been less seen.

In this research, glazing with integrated thin film CdTe solar cells with 10% transparency was under investigation. It worth to note that the transparency of 10% means the proportion of transparent area over the overall glazing area is 10% other than indicating the visible or solar transmittance of the window system. EnergyPlus (v8.1) and RADIANCE (v5.1) were used for energy and daylight performance simulation to demonstrate how the thin film CdTe solar cells integrated into a window system influences the environment in office with different window-to-wall ratio under five distinctive climates in China.

2. Research Methodology

2.1. Prototype office geometry and modelling

A single office room, which is considered as part of a large south-facing façade building with dimensions of 2.9 m × 4.4 m × 3.3 m, was used in the simulation study. Only the south wall of the room was exposed to external conditions. The room is assumed to be used as a private office for two people from 8:00 to 17:00 on weekdays.

2.2. Scenarios of façade design

Window-to-wall ratio (WWR) is the ratio between the area of window and the area of whole façade, which is a fairly important design factor that decides the energy efficient of a building [6]. Due to the low thermal insulation property and the direct transmittance of solar energy and natural daylight of glazing unit, large WWR will expose the indoor space to a higher potential of being influenced by outdoor weather conditions (e.g. over-illuminated, overheating, or increased heating energy consumption).

Semi-transparent PV glazing will absorb a fraction of solar radiation that hit on the window surface to generate electrical power and thus obstruct the overall solar energy and natural daylight that would have penetrated into inside space. Enlarging the covering area of PV glazing on window will lead to more power generation but consequently result in less available daylight and increased lighting energy consumption. Meanwhile, the presence of solar cells on glazing will also reduce the transmitted solar heat gain, which may lead to less cooling demand in summer and more heating demand in winter. Thus, exploring the optimized proportion of window area that covered by PV glazing under different window-to-wall ratio can provide guidance for designers when determining the most energy efficient PV window design.

In this research, four different window-to-wall ratios (WWRs) are considered to represent small, medium, large or extra-large window. Under each window-to-wall ratio group, a variety number of PV glazing's covering ratios are considered, changing from bare to 100% of the window area that is covered by PV glazing. Both normal double-glazing pane and PV glazing pane have a fixed dimension, which is 1200mm by 600mm, to provide modularized variation of façade design scenarios. For same covering rate of each window-to-wall ratio, different architecture designs are considered, where the PV glazing are located at different positions. Totally 28 scenarios were tested as shown in Fig. 1.

Fig. 1. Façade design scenarios

2.3. Weather data in building simulation

The whole country of China has been divided into five climate zones according to their distinct meteorological characteristics. In this research, five cities have been selected to represent those five different climate conditions (Table 1). The building performance simulations were performed in one-hour time steps for an entire year using the IWEC (International Weather for Energy Calculation) weather data of these cities.

Table 1. Latitude, longitude, summer and winter average temperatures and solar irradiance of 5 cities.

	Climate zone	Latitude	Longitude	Summer avg. temp. (°C)	Winter avg. temp. (°C)	Annual avg. solar irradiance (kWh/m2)
Harbin	severe cold	45.7° N	126.7 ° E	21.5	-16.5	1250-1350
Beijing	cold	39.9° N	116° E	25.4	-1.1	1400-1500
Shanghai	hot summer cold winter	31.2° N	121.4° E	27	5.3	1300-1400
Guangzhou	hot summer warm winter	23.1° N	113.3° E	28.3	14.7	1350-1450
Kunming	temperate	25° N	102.3° E	8-18		1600-1700

2.4. Simulation methods and conditions

- *EnergyPlus for energy simulation*

Sandia model, which uses empirically determined coefficients of a PV panel to predict its electrical performance, was used to electrically characterise the window system with integrated CdTe solar cells. Sandia model can is tightly coupled to the surface heat balance and uses the result of surface temperature as the solar cell's operating temperature [4]. The BSDF file that derived from a ray-tracing technique was also input to EnergyPlus for optically characterising the CdTe window system. The loads for equipment and lighting were assumed to be 13W/m^2 and 16W/m^2 respectively [7]. The set-points of thermostat are 21°C for heating and 25°C for cooling.

- *RADIANCE for daylight simulation*

The generation of dynamic daylight performance metrics can be performed using annual hourly simulation results obtained from RADIANCE [8]. The 'Three-phase method' was used to conduct the dynamic annual daylight simulation of applying CdTe window in the office. The daylight matrix and view matrix were obtained based on the model's orientation, surrounding environment, geometry and surface properties of the indoor space using an embedded command in RADIANCE. Sky matrices were obtained from weather data for these five cities. The transmission matrix for the window systems with CdTe solar cells was expressed using Bidirectional Scattering Distribution Functions (BSDFs). A BSDF file, which defines coefficients to allocate light from each exterior direction to each interior direction, was generated by a ray-tracing program genBSDF in RADIANCE based on their geometry and material properties. 9 points along the central line with 0.5 m interval between each other were used to estimate the illuminance distribution on a working plane positioned at a height of 0.75 m above floor level.

3. Result and discussion

3.1. Energy consumption for different PV covering rate under different WWR

The first question in this study sought to determine the effect of the CdTe glazing on the overall energy consumption of the office with different WWRs under different climates. The predicted heating, cooling and lighting energy consumption, electrical power generation and the total energy consumption of the office can be found in Fig. 2. For each PV covering rate with more the one design scenarios, an average value is presented in Fig. 2. When compared with normal double glazing under all the tested climates, fully applying CdTe glazing (100% PV) for 30% WWR cannot give rise to a lower energy consumption, while replacing 50% of the window area by CdTe glazing results in a minimal difference of overall energy consumption. With the increase of WWR from 45% to 75%, the energy saving potential of using CdTe glazing increases. Covering 67%, 75% and 80% of the window area by PV glazing gave rise to the lowest overall energy consumption for 45%, 60% and 75% WWRs, respectively. The most significant energy saving potential of applying CdTe window exist when coving 80% of the window area by PV glazing for 75% WWR, as reductions in energy consumption of up to 73% or 1016.8 kWh per annual can be achieved under the tested climates. Thus, considering the investment of solar cells, applying CdTe glazing with 10% transparency is only recommended for middle-size to extra-large window-to-wall ratios (i.e. WWR⩾45%).

3.2. Daylight availability applying PV window under different WWR

Useful daylight illuminance (*UDI*) was used to evaluate daylight availability for the window system with and without PV glazing with the best covering rate for their energy performance. Fig. 3 shows the predicted *UDI* along the central line of the office between the window to the end wall. Generally, when a normal double glazed window is used, over-illuminated conditions are dominated for the zone near to the window, especially for larger WWR. The use of CdTe PV glazing can effectively eliminate the oversupply of daylight. Using WWR 75% as an example, in the half office near the window, the percentage of hours where the UDI is in the useful range (100-3000 lux) increase from 30~ 55% for the conventional DG to 40~90% for the window with CdTe PV glazing. For the rear area in the office, $UDI_{100\text{-}3000\ lux}$ increases from 55~ 80% for the conventional DG to approximately 90% for the window with CdTe PV glazing

4. Conclusion

In this research, EnergyPlus has been used to predict the impact of CdTe glazing on building heating, lighting and cooling energy consumption. RADIANCE has been used to predict detailed daylight performance of a space served by CdTe PV windows. Our results clearly demonstrated that application of PV window can result in energy saving at large window to wall ratio. The daylight availability that offered by window with integrated CdTe PV glazing is also better than that of conventional double-glazing.

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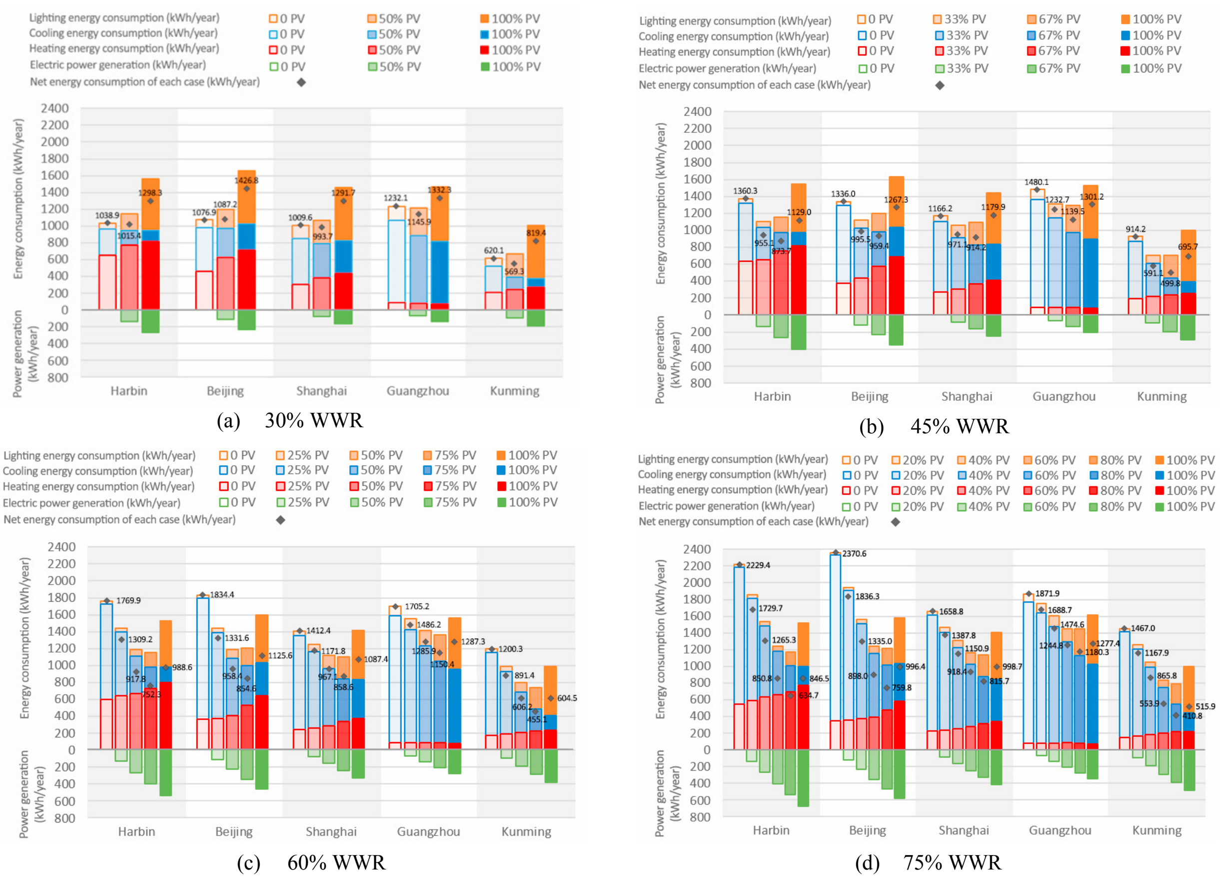

Fig. 2. Heating, cooling and lighting energy consumption and electrical power generation of the office under different climates

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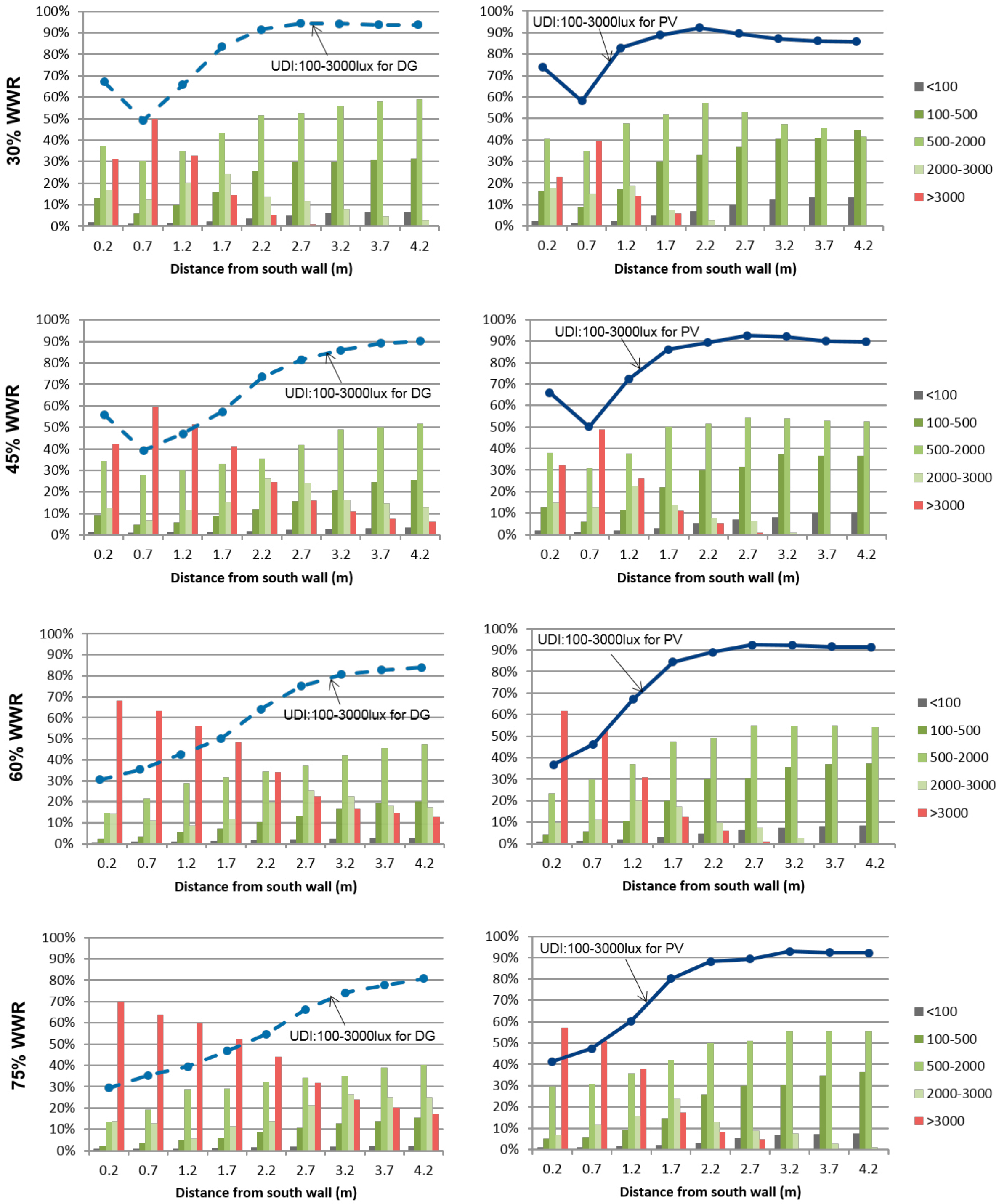

Fig.3. UDI distribution in the office for the window system with and without CdTe solar cells