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Experimental Evaluation of Double Skin BIPV Façades: Balancing the Energy Performance and Indoor Light Comfort#

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ABSTRACT

To respond to global carbon neutrality goals and promote the sustainable transformation of the building industry, the application of Building-Integrated Photovoltaics (BIPV) is garnering significant attention. High-rise office buildings with glass curtain walls, as landmarks in metropolitan Central Business Districts (CBDs), consume substantial amounts of energy to maintain indoor environmental comfort. To address this issue, the integration of Double-skin Facades (DSF) with BIPV is considered promising, as it can generate clean electricity onsite while simultaneously enhancing the thermal performance of the building envelope and improving indoor environmental comfort.

This paper presents the development of a prototype for a double-skin BIPV facade applied to glass curtain walls, based on modular office units. The prototype incorporates both opaque and semi-transparent photovoltaic (PV) elements. It explores the impact of design parameters on the overall energy performance of the BIPV facade system and the indoor natural light environment. Design optimization is conducted using data obtained from simulations and outdoor experiments. Under conditions where the modular frame size and the area of opaque PV panels are the same, the power generated by the opaque PV in the baseline prototype accounts for approximately 54.7% of the total facade power. By rotating the opaque portion of the facade from the vertical surface by 60 degrees, the total power generation is more than doubled, with the opaque PV contributing over 75% to the total power output. In the closed system (Prototype 1), the surface temperature of the opaque PV is higher than that of the open system (Prototype 2), with an average of 1.19 and 1.26 times that of the baseline. However, the temperatures of the semi-transparent PV in these three prototypes are similar. Furthermore, the amount of side light entering the interior has a significant impact on indoor illuminance; removing the side cover plate results in an increase in indoor illuminance, around 193% to 212% of the pre-removal levels.

Keywords: DSF-BIPV, office unit, power generation, interior illuminance

NONMENCLATURE

Abbreviations	
BIPV	Building-Integrated Photovoltaics
CBDs	Central Business Districts
DSF	Double-skin Facades
PV	Photovoltaic
DNI	Direct Normal Irradiance

1. INTRODUCTION

With the advancement of industrialization and modernization, the level of global urbanization continues to rise, leading to an increasing number of residents migrating to urban areas, which occupy only 2% of the Earth's surface [1]. The world urban population is projected to reach 7 billion by 2050 [2-4]. Housing, infrastructure, and daily activities in cities consume nearly 70% of global energy [4]. In response to the global goal of reducing carbon emissions and the sustainable transformation of the industry, Building Integrated Photovoltaic (BIPV) technology has been regarded as one of the effective solutions. This is due to its dual role as both a building skin and a power generation device [5].

In rapidly developing, densely populated metropolitan areas, high-rise buildings have been commonly constructed for optimizing land use and expanding vertical space [6]. Glass curtain walls are widely used in high-rise facade design due to their transparency, lightweight nature, high strength, and aesthetic appeal. However, the high transparency of glass curtain walls results in significant glare, heat exchange, and thermal conduction, necessitating the

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addition of internal shading to enhance cooling and ensure indoor comfort. To address this issue, double-skin facades have been developed and gradually integrated with emerging technologies to enhance overall wall performance. For BIPV, effective ventilation at the back is often required when integrated into the building envelope to avoid the efficiency loss caused by temperature increase during the operation [7]. Consequently, BIPV integrated double-skin facades (DSF-BIPV) have emerged as a promising new facade technology.

Previous research on DSF-BIPV has primarily focused on the performance of individual types of BIPV, either opaque or semi-transparent, in relation to energy generation and indoor comfort, including ventilation modes, structural design, material integration, transparency, and types of solar cells. However, in practical engineering applications, facade designs often extend beyond two-dimensional planes to meet aesthetic demands. There is a lack of research exploring the design parameters and performance of three-dimensional BIPV modules as the outer layer of DSF. Given that the facades of most office buildings typically consist of repetitive units, this study begins with the fundamental office space unit to explore a novel DSF-BIPV prototype aimed at improving the overall performance of glass curtain wall high-rise buildings, balancing power generation and indoor daylight comfort.

2. METHOD

This study seeks to develop a modular DSF-BIPV prototype that integrates opaque and semi-transparent photovoltaic (PV) elements from the perspective of architectural design. Drawing on existing research and case studies of classic facade patterns, the basic office unit space has been extracted. The performance of the double-skin facade after applying this prototype has been simulated and analyzed, identifying three-dimensional design parameters. Based on simulation results and considerations for actual construction, a full-scale outdoor experiment has been established to measure indicators including solar irradiance, overall BIPV system power generation, PV surface temperature, and indoor illuminance. This investigation aims to explore the impacts of design parameter modifications based on practical data, ultimately leading to optimized designs that enhance overall energy generation and improve the indoor daylight environment.

3. PROTOTYPE DEVELOPMENT

In the prototype design process, the visual appeal of the facade is also a crucial consideration. The facade serves as the face of commercial buildings and significantly influences the aesthetic perception of urban spaces. To promote the practical application of BIPV in real projects and enhance stakeholders' acceptance of BIPV technology, it is essential to develop facade geometric solutions that align with mainstream architectural aesthetics. This study has initially gathered existing project cases involving high-rise office buildings, summarizing and analyzing classical geometric forms that possess both practical significance and aesthetic expression (see Fig.1).

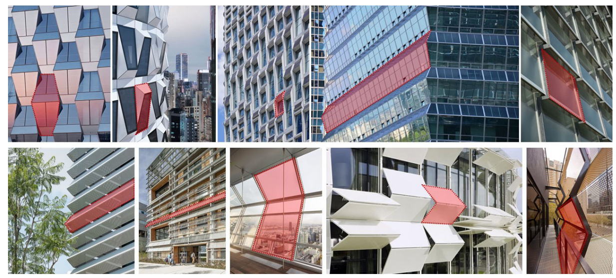

Fig. 1 Case study of geometric forms of high-rise buildings

Moreover, the building envelope acts as a medium connecting the internal and external environments, providing a stable and comfortable interior space while ensuring unobstructed views. Therefore, incorporating BIPV into the facade design of commercial buildings facilitates the rational utilization of solar energy, enhancing clean electricity generation through light capture while improving the thermal performance of the envelope and the indoor lighting environment through shading. Based on case analyses and previous research on DSF-BIPV [8, 9], geometric forms have been summarized and simplified into the prototype shapes, as shown in Fig.2.

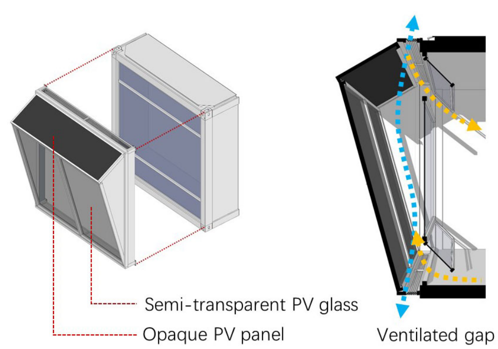

Fig. 2 DSF-BIPV prototype design

Research indicates that in a humid subtropical climate, the depth of the air gap in double-skin BIPV facades has a minimal impact on overall performance [10]. Considering the experimental setups in existing studies [10-12] and production processing requirements, the air gap depth for this prototype has been designed to be 25 cm.

To understand the performance of facades with varying folding angles, simulations assessed solar energy potential, indoor lighting conditions, and cooling loads based on a modular office unit measuring 3m x 6m x 3m. The southern facade is composed entirely of glass, simulating an office unit within a glass curtain wall building. A double-skin BIPV facade was installed on the exterior. Opaque PV panels were positioned in the upper third of the facade to block excessive direct sunlight. The double-skin facade inherently provides significant shading; therefore, the lower two-thirds of the facade was fitted with PV glass with a transparency of 60% to prevent insufficient natural light indoors. During the adjustment of the facade's geometry, the area of the opaque PV panels was kept constant. In practical engineering applications, achieving high precision when installing inclined facade panels is challenging; thus, simulations were conducted within a range of 0 to 90 degrees, with 5-degree intervals to analyze all potential scenarios. The simulation results are presented in the Table. 1. The angles in the table represent the angles between the tilted PV panel and the vertical plane.

Tilted Angle of the Opaque PV panel	Annual Solar Irradiance_Opaque (kWh/m²)	Annual Solar Irradiance_Glass (kWh/m²)	Area of the BIPV Skin (m²)	Interior Lights Electricity (kWh)	Daylight Uniformity Ratio (%)	Annual Cooling Loads (kWh)
0° (Vertical)	65.29	65.29	9.00	674.05	21%	3387.38
5°	70.34	63.42	9.02	688.75	21%	3361.44
10°	74.85	61.47	9.07	703.24	20%	3333.34
15°	79.24	59.51	9.15	714.35	21%	3319.64
20°	83.82	57.58	9.27	723.61	22%	3301.98
25°	88.09	55.75	9.41	727.74	24%	3291.33
30°	92.50	54.18	9.58	729.99	24%	3278.16
35°	96.68	52.94	9.77	729.48	23%	3267.73
40°	100.80	51.90	9.97	726.44	26%	3259.55
45°	104.65	51.08	10.20	721.09	27%	3252.93
50°	108.27	50.42	10.44	713.59	26%	3247.32
55°	111.70	49.91	10.68	704.15	26%	3242.92
60°	114.66	49.56	10.94	692.98	27%	3239.35
65°	117.50	49.34	11.20	680.32	30%	3236.67
70°	119.70	49.27	11.46	671.61	27%	3240.09
75°	121.74	49.31	11.72	653.70	28%	3229.54
80°	123.13	49.47	11.98	636.69	28%	3239.17
85°	124.01	49.73	12.24	620.83	28%	3228.20
90° (Horizontal)	124.54	50.08	12.49	584.17	28%	3242.98

Table. 1 Simulation results of different tilted BIPV options

As the rotation angle of the opaque PV panels increases relative to the vertical plane, the solar irradiance also increases, although the rate of increase slows after reaching 65 degrees. During this process, due to self-shading effects in the lower portion of the facade, solar irradiance continuously decreases and stabilizes after 55 degrees. The indoor lighting energy consumption peaks at a rotation angle of 30 degrees and subsequently declines. However, the daylight uniformity ratio stabilizes after 60 degrees, peaking at 30% at 65 degrees. The cooling loads decrease rapidly with the rotation of the PV panels at the beginning, stabilizing after reaching 60 degrees. As the opaque PV panels rotate from the vertical to the horizontal plane, the required area for BIPV increases, consequently expanding the space occupied by the double-skin facade. Based on the consideration of cost and performance, the final design for the DSF-BIPV prototype was selected with the opaque PV panels rotated 60 degrees from the vertical plane.

4. EXPERIMENTAL RESULTS

4.1 Experiment Set-up

According to the case studies and simulation results presented in Chapter 3, the developed DSF-BIPV is designated as Prototype 1. For comparative analysis, two additional DSF-BIPV prototypes were established for the experiment. Given that the energy generation of opaque PV panels dominates the facade system, the areas of the opaque PV panels across all prototypes were kept consistent, while the areas of the semi-transparent PV panels were adjusted according to the facade design. A conventional two-dimensional vertical BIPV facade was established as the baseline. To improve the ventilation and heat dissipation of the PV panels and increase flexibility, Prototype 2 was configured as a fully open dynamic system, eliminating the side covers. Research has shown that the spacing between PV panels significantly contributes to reducing surface temperatures and enhancing energy generation efficiency [13]. Therefore, in Prototype 2, the complete PV panel was divided into four sections, with a 50 mm gap introduced between each section. Additionally, the folding angles of Prototype 2 can be adjusted to facilitate subsequent experimental validation and optimization exploration (see Fig. 3).

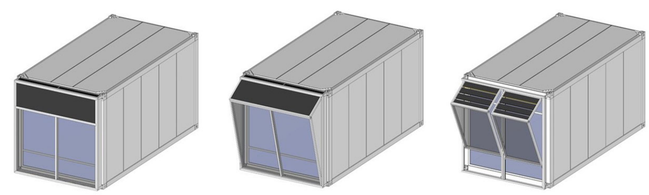

Fig. 3 Prototypes demonstration for the experiment

In July 2025, all three prototypes were completed and installed on the southern facade of a 3m x 3m x 6m modular unit in a factory. The entire southern facade of the unit consists of single-layer glass, with operable windows positioned above and below. The three experimental units featuring DSF-BIPV were transported to an outdoor testing site in Shenzhen, free from shading obstructions. Subsequently, relevant parameters were tested and data were collected, including solar irradiance received by the PV panels, BIPV power generation, surface temperatures, and indoor illuminance. The configuration of the equipment for office units is illustrated in Fig. 4. The information of the equipment

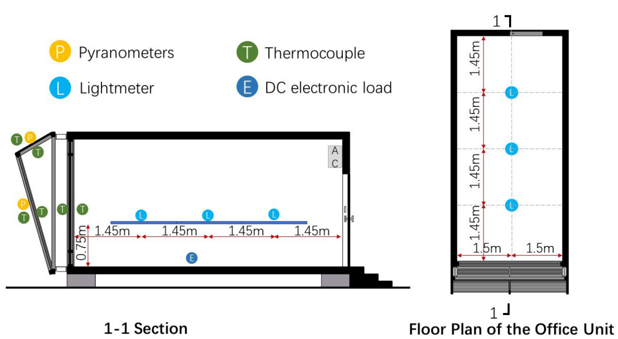

Fig. 4 Configuration of the equipment

Equipment	Function	Manufacturer	Accuracy
Weather Station	Weather condition recording	Shandong Renke Control Technology	Temperature: ±0.5°C(25°C) Wind speed: ± (0.2+0.03V) m/s,@ (0~30m/s,25℃)
Pyranometers	Solar irradiance measuring	EKO Instruments (ML-02)	Sensitivity: 50 μV/W・m-2
DC electronic load	Power measuring	HAOYI Tech (HY 8212)	± (0.3%Vin/Rset+0.2%IF.S)
Thermocouples	Temperature testing	KAIPUSEN (K-type thermocouple)	±(0.3%t+0.40)°C
Lightmeters	Indoor illuminance	BENETECH	± 3%rdg
Data logger	Data collection	Graphtec (midi Logger GL840-M)	Voltage: ± 0.1% of F.S.

Table. 2 Basic information of the equipment

used in the experiment are detailed in the Table. 2.

4.2 Experimental Results

Fig. 5 Photos of the experimental office units

After a period of testing, experimental data were collected. The three experimental units were designated as Room 1, Room 2, and Room 3, as illustrated in Fig. 5.

4.2.1 Analysis of system power generation

The analysis focused on power generation data from July 25-28, August 7-13, and August 16, totaling 11 days. The testing was conducted from 7:50 AM to 5:50 PM, covering standard working hours, with data recorded at 20-minute intervals. From Fig. 6-8, it is evident that, from

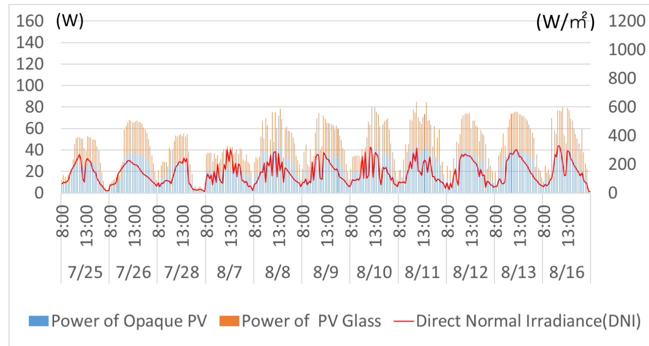

Fig. 6 Power and solar irradiance of Room 1

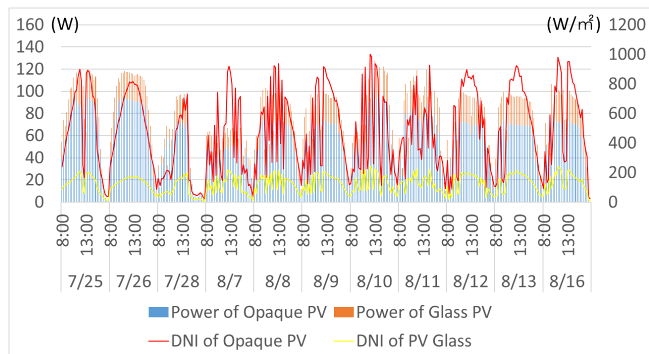

Fig. 7 Power and solar irradiance of Room 2

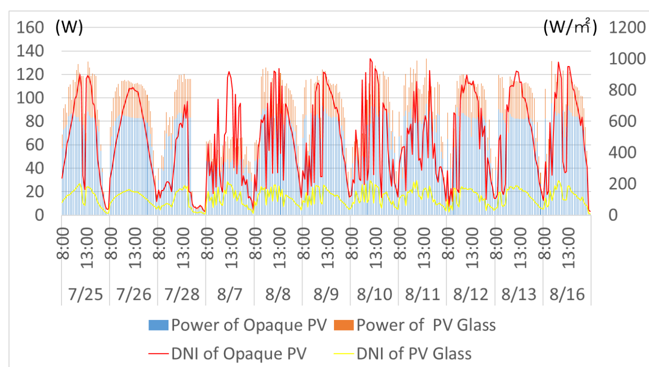

Fig. 8 Power and solar irradiance of Room 3

a system-wide perspective, Rooms 2 and 3 exhibited significant enhancements in power generation compared to Room 1. The power output of Room 2 was approximately 1.8 times that of Room 1, while Room 3's power output was about 2.2 times that of Room 1. After rotating the opaque PV panels 60 degrees from the vertical plane, the average solar irradiance received by the surface reached 3.3 times that of the vertical surface. Following the folding design of the facade, the lower PV glass experienced self-shading, resulting in a slight decrease in solar irradiance; however, on average, the PV glass in Rooms 2 and 3 still achieved 92.4% and 85.6% of the solar irradiance received by the vertical surface of Room 1, respectively. Considering that the PV glass area in Room 2 is smaller than that in Room 3 due to the facade and structure design, it is reasonable for Room 2's overall power generation to be slightly lower than that of Room 3.

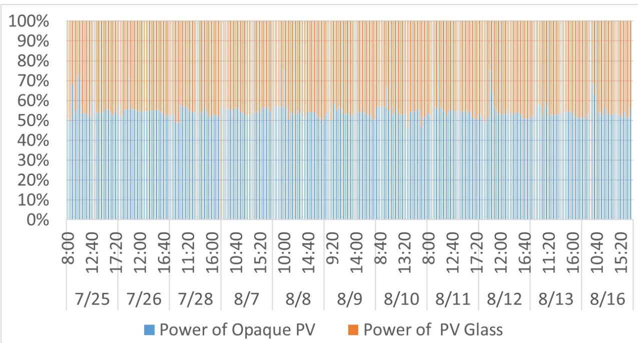

Fig. 9 Power generation percentage of Room 1 opaque PV and PV glass

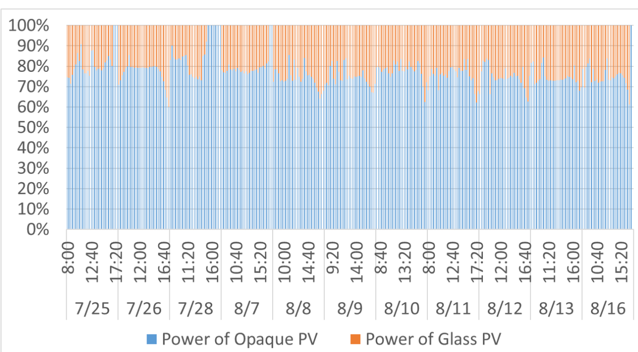

Fig. 10 Power generation percentage of Room 2 opaque PV and PV glass

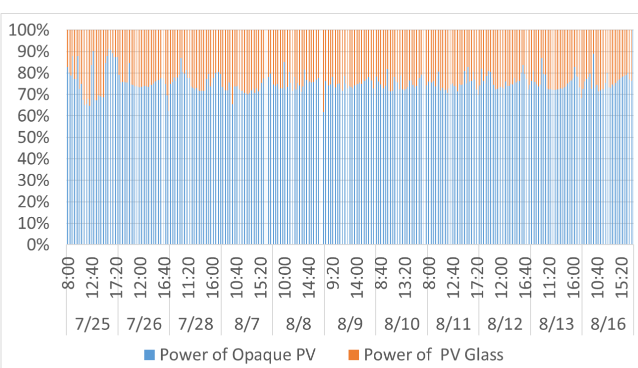

Fig. 11 Power generation percentage of Room 3 opaque PV and PV glass

From Fig.9-11, the power generation percentages of the three systems are illustrated. In the vertical DSF-BIPV prototype, the opaque PV contributes approximately 54.7% of the total power generation, which is comparable to the contribution of the PV glass. In contrast, for the tilted BIPV systems in Rooms 2 and 3, the contribution of the opaque PV to the total power generation greatly increased, reaching 77.5% and 75.6%, respectively. Although the power generation of the PV glass in Room 3 increased by 10% compared to Room 1, its overall contribution to the total power generation within the system decreased from 45.3% to 24.4%.

<u>4.2.2 Analysis of power generation per unit area</u>

As illustrated in Fig.12, a comparison diagram of the power generation per unit area of opaque PV panels across the three prototypes is demonstrated. It reveals that the average power of Room 2's PV panels reached

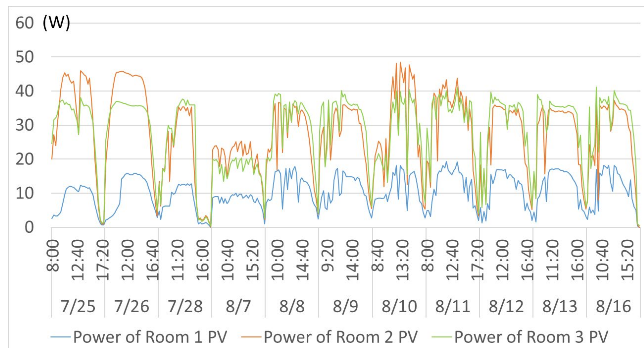

Fig. 12 Comparison of power per square meter of opaque PV

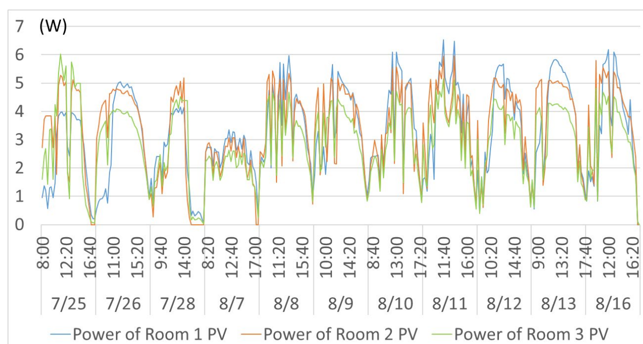

Fig. 13 Comparison of power per square meter of PV glass

2.93 times that of Room 1, while Room 3's average was 3.08 times that of Room 1. When the power per unit area ranged from 30 to 40 W, the opaque PV power in Room 3 was slightly higher than that in Room 2; however, when the power per unit area fell below or exceeded this range, Room 2's opaque PV performance was superior.

Similarly, as illustrated in Fig.13, the average power of Room 2's PV glass was 1.10 times that of Room 1, while Room 3's was 0.97 times that of Room 1. During the time period from 8 AM to 10 AM, when the solar altitude angle was low, the folded PV glass surfaces in Rooms 2 and 3 received much higher solar irradiance compared to the vertical surface, resulting in higher power generation. Overall, the power per unit area in the whole day was comparable to that of Room 1. These findings indicate that folding the outer skin of the DSF-BIPV notably enhances the overall system performance. Compared to vertical PV glass, the power loss of the self-shaded PV glass after folding is minimal, while the power increase of the opaque PV is substantial. The PV glass area of Room 3 was maximized for realizing the closed system, followed by Room 1, while Room 2 had the smallest PV glass area due to the panel spacing and added sliding frame structure. The impact of area reduction is greater than the loss of power generation due to self-shading. Thus, the power per unit area in Room 2 was higher, even exceeding that of Room 1, which experienced no self-shading.

4.2.3 Analysis of surface temperature

During the experiment, the surface temperatures of the operating PV panels were measured, and data were collected. After preliminary data organization and processing, erroneous data were removed, retaining temperature data from July 25, 26, 28, and August 10, 11 for analysis.

As shown in Fig. 14, the surface temperatures of the opaque PV and PV glass in Room 1 were relatively close to the ambient temperature. In contrast, the opaque PV panels in Rooms 2 and 3 received more solar radiation and exhibited higher power generation, resulting in elevated operating temperatures that were, on average, 1.19 times and 1.26 times that of Room 1's opaque PV, respectively. The surface temperature of Room 3's

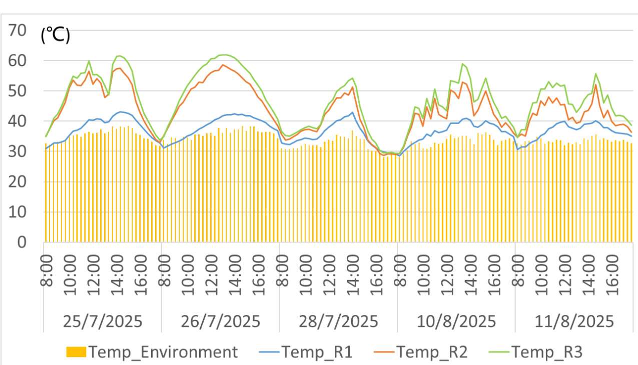

Fig. 14 Surface temperature comparison of opaque PV panels

opaque PV was slightly higher than that of Room 2, averaging 1.06 times that of Room 2. This suggests that the open system of Room 2 and the designed spacing of the PV panels contributed to the system's heat dissipation.

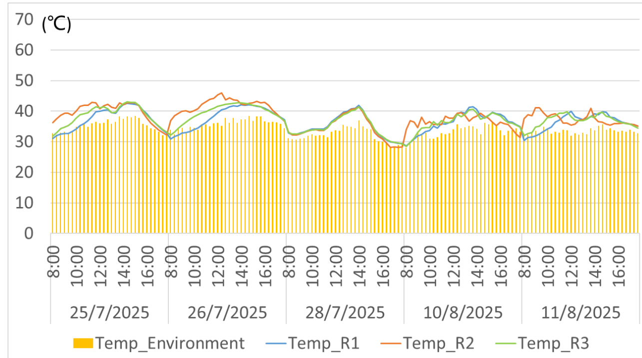

Fig. 15 Surface temperature comparison of PV glass panels

As indicated in Fig. 15, the surface temperatures of the semi-transparent PV in all three rooms were relatively similar, with Room 2's and Room 3's PV glass averaging 1.04 times and 1.02 times that of Room 1, respectively. Collectively, these data results demonstrate that despite the self-shading effect of the folded PV glass, both power generation and surface temperatures remain comparable to those of the vertical PV panels, further validating the feasibility of this prototype design approach.

4.2.3 Analysis of interior illuminance

One day from the testing period, specifically August 16, was selected for indoor illuminance data analysis. Testing occurred from 7:50 AM to 5:50 PM, with data recorded at one-minute intervals. The three indoor testing points were sequentially numbered from the side closest to the window to the side closest to the interior as Point 1, Point 2, and Point 3. By combining the minute-by-minute power generation data of the BIPV systems, Fig. 16-18 were generated. Compared to the baseline Room 1, the indoor illuminance in Room 3 exhibited a notable decrease due to the increased cavity volume between the two layers of the folded facade, which had a stronger diminishing effect on incoming daylight. However, for the testing points closest to the windows in both Room 1 and Room 3, illuminance levels often failed to reach 300 lx, which is the minimum illumination level required for office spaces according to the Standard for Lighting Design of Buildings issued by the Ministry of Housing and Urban-Rural Development of China [14]. In contrast, Room 2 exhibited a significant improvement in indoor illuminance compared to Room 1, with the average illuminance levels of the three testing points being 375%, 251%, and 310% of those in Room 1. Although the opaque PV panels in Rooms 2 and 3 were set at the same rotation angle, the areas and angles of the PV glass in the two rooms differed slightly, resulting in substantial differences in indoor illuminance due to the open system design of Room 2, which reduced shading from lateral light.

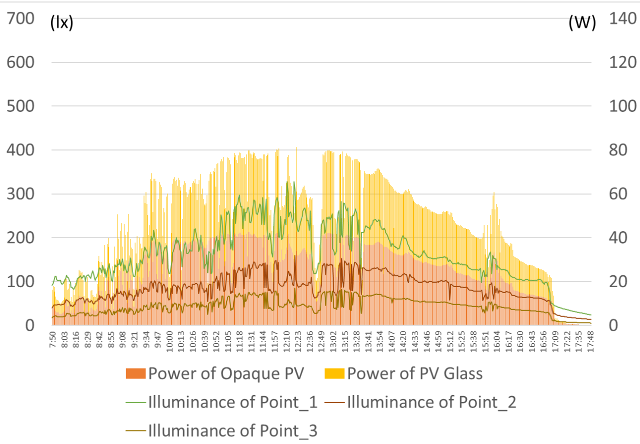

Fig. 16 Interior illuminance and BIPV power of Room 1

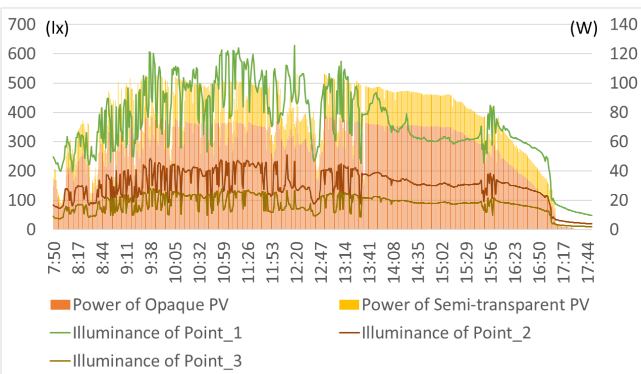

Fig. 17 Interior illuminance and BIPV power of Room 2

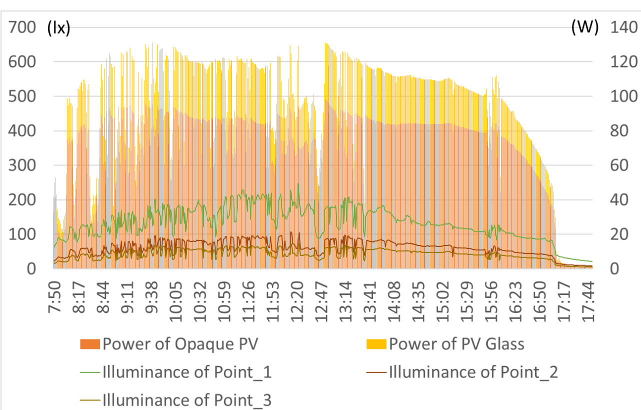

Fig. 18 Interior illuminance and BIPV power of Room 3

Consequently, the side covers of Room 3's DSF-BIPV were removed. Two days with similar climatic conditions were selected for analysis—August 15 and September 2—during which indoor illuminance data were compiled and analyzed, resulting in Fig. 19 and Fig. 20. With the increased lateral light penetration, the internal lighting environment improved, with average illuminance values at the three testing points reaching 212%, 202%, and 193% of the pre-removal values. The proportion of time during the period from 7:50 AM to 5:50 PM that met the office space illuminance standard increased from 1.3% to 53.3%.

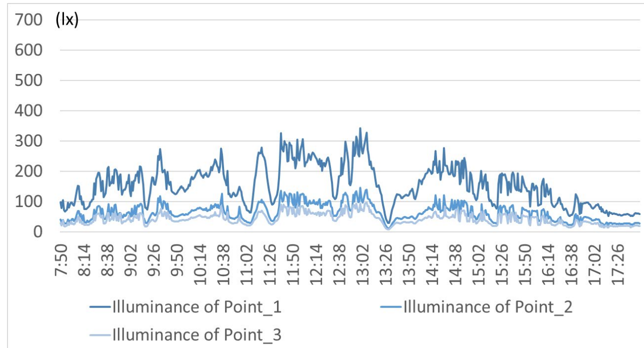

Fig. 19 Interior illuminance of Room 3 with side panels

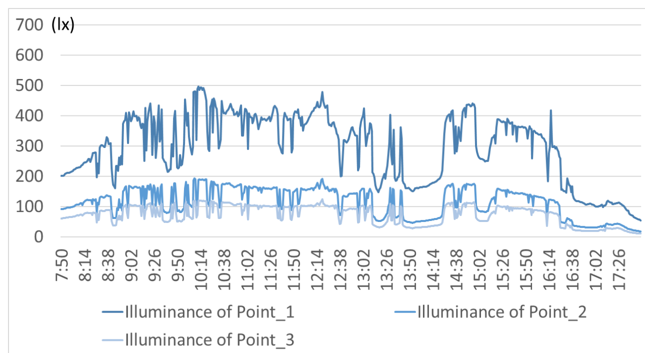

Fig. 20 Interior illuminance of Room 3 without side panels

5. CONCLUSION

This study developed a novel modular folding DSF-BIPV prototype that integrates opaque PV and semi-transparent PV, aimed at application in high-rise office buildings to enhance clean energy generation and improve indoor lighting conditions while ensuring aesthetic appeal in facade design.

Using a basic office unit measuring 3m x 6m x 3m as the research object, simulations were conducted to explore the balance of multiple performance parameters in relation to the facade's folding angle. Following the optimization results, full-scale rooms with DSF-BIPV were constructed for outdoor testing. The vertical BIPV system served as the baseline (Room 1), allowing for comparative analysis of the performance of the 60-degree folded DSF-BIPV in the open system (Room 2) and closed system (Room 3).

Experimental data indicated that the overall power generation of BIPV in Rooms 2 and 3 was 1.8 times and 2.2 times that of Room 1, respectively. Although the folded PV glass experienced self-shading, Rooms 2 and 3 with different tilt angles still achieved solar irradiance levels equivalent to 92.4% and 85.6% of the vertical surface. The results demonstrate that the increase in power generation of the opaque PV after folding far exceeds the power loss of the glass PV.

The surface temperatures of the opaque PV panels in Rooms 2 and 3, due to higher solar radiation exposure, were approximately 1.19 times and 1.26 times that of Room 1, respectively, indicating that the open system and panel spacing contribute to PV heat dissipation.

The folded-open DSF-BIPV system markedly improved the indoor lighting environment, with illuminance levels at the three testing points being 375%, 251%, and 310% of those in the room installed with vertical BIPV. The experiments underscored the importance of lateral light penetration, as the removal of the side covers in Room 3 resulted in illuminance values at the three testing points reaching 212%, 202%, and 193% of the pre-removal values.

In future experiments, this study will further explore the performance of dynamically folding BIPV facades based on the structure of the Room 2 prototype. In addition, the research will investigate the processes and methods for applying modular DSF-BIPV to facade designs in office buildings based on a further case study, thereby advancing the sustainable renovation of glass curtain wall commercial buildings.

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