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LIGHTING PERFROMANCE IN OFFICE BUILDINGS WITH BIPV FACADES: VISUAL AND NON-VISUAL EFFECTS

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Abstract

BIPV facades (integrated with opaque or transparent PV panels) have been accepted as an innovative strategy to provide electricity, reduce peak electrical and cooling demands, improve daylighting utilization, and achieve energy efficiency in buildings. This study presents a preliminary simulation study of impact of BIPV façades on visual and non-visual effects of daylight in an office building. DAYSIM and EVALGLARE, two advanced packages, were used to evaluate daylighting and visual performances. In general lighting and visual conditions can be expressed by the calculated Daylight Autonomy (DA) across the working plane and Daylight Glare Probability (DGP) at vertical planes of specific positions. The non-visual effect of lighting was indicated by the vertical DA at the same vertical positions. It has been found that BIPV facade configurations obviously affect both visual and non-visual performances of daylight. A balance of proper daylighting conditions and visual comfort should be a critical issue in the process of an office façade design.

Keywords: *BIPV façades, Lighting, Visual Performance, Non-visual Effects, Office Buildings*

1. Introduction

Building Integrated Photovoltaics (BIPV) has been generally adopted as one important solution to directly utilize solar energy in buildings, especially for the systems installed at building facades (Farkas et al., 2013). With respect to studies during the last ten years, the BIPV facades (with opaque or transparent PV panels) can provide electricity, reduce peak electrical and cooling demands, improve daylighting utilization, and achieve energy efficiency in buildings (Quesada et al., 2012). A case study in two modern buildings showed that PV facade systems significantly benefit fossil energy savings and the reduction of CO_2 emission in a hot and highly luminous climate (Alnaser et al., 2008). According to simulations in northern, central and southern Europe, urban factors (obstruction and orientation) would impact the energy performance of opaque PV façade and determine its optimal configurations composed of glazing and solid wall (Yun and Steemers, 2009). However, semi-transparent PV has actually received more attentions from designers and engineers for the modern façade systems. In Hong Kong such a transparent PV facade was investigated in an office building (Li et al., 2009), which has been proved to produce a clear decrease of electrical lighting and cooling energy consumption. Another study in a cold climate also expressed that semi-transparent PV façade has a large potential to improve overall energy efficiency than opaque façade due to its ability to utilize daylighting (Robinson and Athienitis, 2009). A German simulation enhanced the fact that lighting, heating and cooling loads in an office with semi-transparent PV glazing façade could be partially displaced through the electricity produced by the PV systems (Mende et al., 2011). In contrast to this study, a Brazil research found that a PV window works more efficiently in terms of artificial lighting and cooling loads under a tropical climate than the central European climate (Didone and Wagner, 2013). Recently, a more complicated façade design integrated with PV panels has occurred at the locations with warm climates. Two studies of PV facade in a sub-tropical climate presented that a ventilated double-skin structure could improve both PV performance and indoor thermal comfort in summer (Chow et al., 2009; Han et al., 2013). The

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combination of shading devices and PV panels has been regarded as another interesting research topic. A movable shading device integrated with PV panels was proved as an efficient way to achieve the largest potential of energy savings for cooling and lighting use under central and southern European climates (Janak and Kainberger, 2009), while a similar result has been found in a study of fixed shading device at a Mediterranean location (Mandalaki et al., 2014).

Visual performance is also a crucial research focus of the PV façade in office buildings. An earlier investigation has preliminarily studied the visual amenity (glare, view, contrast and lighting model) and aesthetic quality of indoor spaces with various transparent PV windows at a Scandinavian location (Lien and Hestnes, 2000). The assessment of visual performance in this study was basically focused on qualitative aspects. Later, one study implemented under a similar climate has adopted quantitative methods including lighting measurements and subjective survey to evaluate lighting performance and visual comfort in a room with various transparent PV glazing facades (Markvart et al., 2012). It has been concluded that the integration of transparent thin-film PV in glazed facades could significantly influence occupants' perception of daylight in the room and the view to the outside. Based on a complicated simulation method, the impact of solar cell density of PV facade on indoor visual comfort was analyzed in an office building (Mende et al., 2011). The finding showed that the transparent solar cells in glazing façade might have a limited effect to keep a proper visual comfort and a supplement shading device might still be required.

Apart from the visual aspects, the non-visual effects of daylight (e.g. psychological and physiological issues) in an office have actually become a new research trend due to an increasing requirement for a healthy indoor working environment (Boyce et al., 2003). Even though daylight availability is generally accepted as a standard to justify a proper design, it is still necessary to implement more investigations in an office with various facades since there are still many unknown areas of human behavior related to daylighting (Aries et al., 2015).

Thus, it can be found that energy performance is only one of important issues in office buildings with PV facades. Directly and significantly influenced by the indoor lighting, occupants' health, well-being and work productivities in such a space could be more critical. This article therefore aims to study the visual and non-visual performances of daylight in an office building with various PV façade systems. A dynamic lighting and visual simulation was completed in an office at two locations of Beijing (China) and London (UK).

2. Methods

This section presents locations and climates, office and façade models, as well as simulation settings.

2.1 Locations and Climates

The simulation study was based on two locations with different climatic conditions: Beijing (39.9167° N, 116.3833° E) and London (51.5072° N, 0.1275° W). Beijing has a continent climate with cold winter and hot summer, while a typical temperate climate dominates at London. The annual sunshine hours for Beijing and London are 2707 and 1460 respectively (of a possible number 4383) (Database of World Climate & Temperature, 2015). Beijing has clearly 29% more sunny days than London.

2.2 Office and Façade Models

In this study a single office room has been chosen as a typical model (Fig.1), with a dimension of 5.4×3.6×2.85m (depth, width and height). The office room has one fully-glazed window facade, which the PV panels were integrated with. The window façade has a south-facing orientation. Five various façade configurations were studied as follows: bare window (no PV panels), façades with opaque PV panels (small and large areas), façade with semi-transparent PV panels (small and large areas). For the facades with bath types of PV panel, the large PV area means the ratio of glazing area to wall area is 30% (PV area: 70%), while the value for the small PV area is around 60% (PV area: 40%) (Fig.1). The surface reflectances of each room element are: 0.8 (ceiling), 0.6 (wall), 0.3 (floor) and 0.1 (glazing). The visual transmittance of façade glazing is 0.72 (clear float glass). The part of PV façade is made of the glass laminate thin film PV units with two outer layers (clear float glass, thickness 4mm, visual transmittance 0.9) and one middle layer (PV encapsulation panel, 0.8mm). The opaque PV encapsulation panel has a diffuse reflectance 0.1 whilst a diffuse transmittance 0.3 was set for the semi-transparent PV encapsulation panel. An average diffuse transmittance of semi-transparent PV panel could be around 0.24.

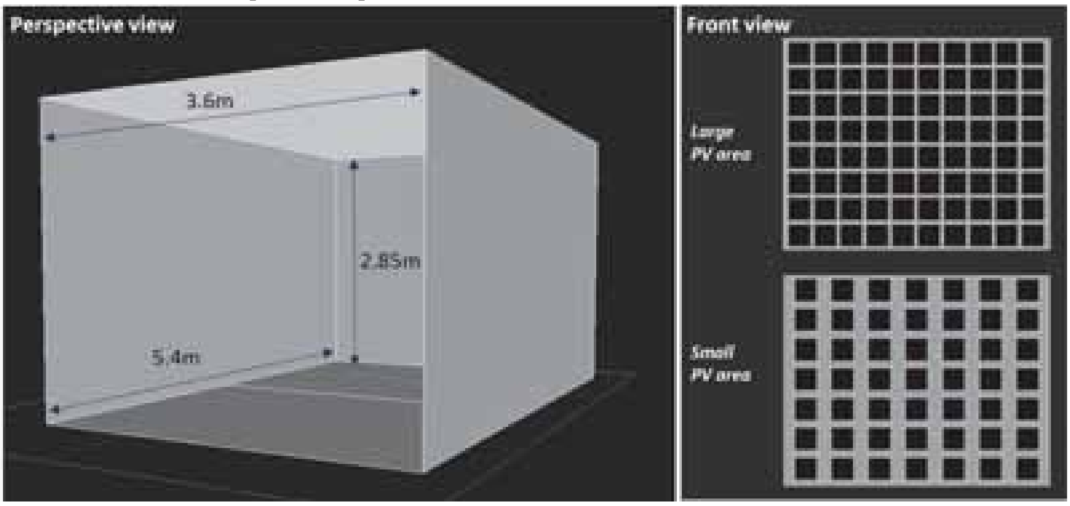


Fig. 1: Dimensions of office model (left: perspective) and configurations of two PV facades (right: front view).

2.3 Simulations

As for the basic daylight availability in this office, Daylight Autonomy (DA) and Daylight Factor (DF) across horizontal working plane (0.8m above floor) were calculated using a climate-based dynamic daylighting modelling tool DAYSIM (Reinhart and Herkel, 2000). A calculation grid with a 0.5m distance between two adjacent positions was used to get an average value of DA or DF. Also, eight positions were selected along the centre line of room from window to back wall, with a distance to window as follows: No.1-8 (0.51m, 1.18m, 1.86m, 2.53m, 3.21m, 3.88m, 4.56m and 5.23m). The design illuminance for DA assessment at the working plane is 500lux within a daily time period from 8am to 17pm.

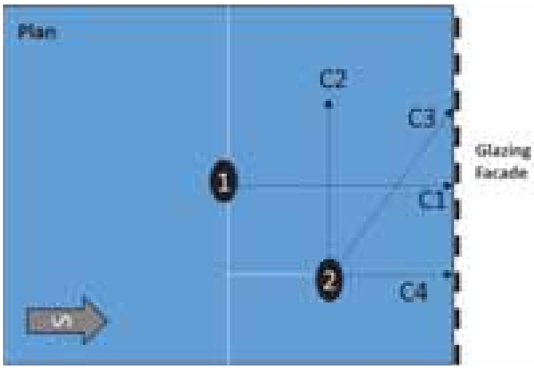


Fig. 2: Two positions and four view directions studied in this office (plan view).

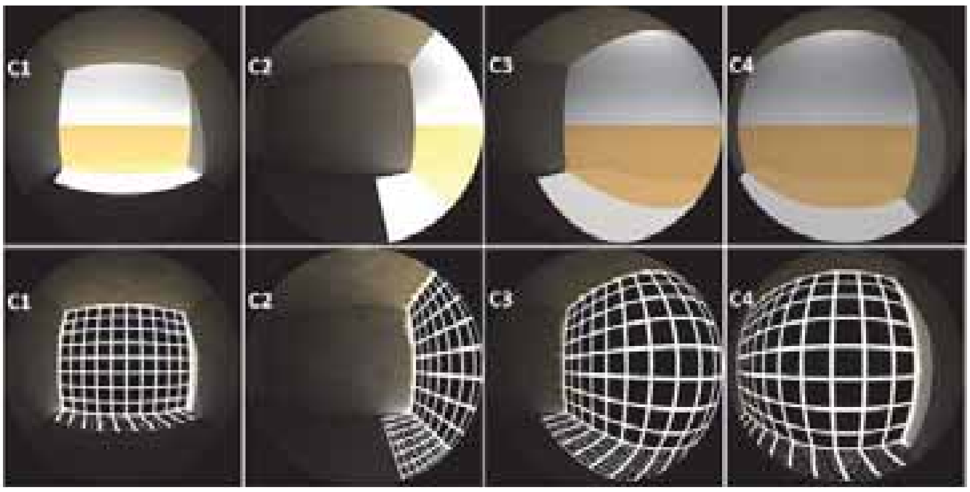


Fig. 3: Examples of rendering fish-eye images of four various views (up: glazing façade; bottom: PV façade).

In addition, two positions in the office were studied in terms of visual and non-visual lighting performances: No.1 & 2 (Fig.2). Position No.1 is exactly located at the room centre. Position No.2 is at the area near window, which could be regarded as a common place for a working station. The distances of position No.2 to window and side wall are 1.35m and 0.9m respectively. Four view directions were also defined at the two positions: C1 (at No.1, facing south), C2 (at No.2, facing east), C3 (at No.2, facing south east) and C4 (at No.2, facing south). C1 and C2 were the main views in this study. According to previous studies (Aries et al., 2015; Borisuit et al., 2014), the non-visual effect of daylight could be evaluated by the vertical illuminance received at the eyes of occupants. Thus, the daylighting availability at the two positions and along the four view directions has been assessed to indirectly indicate the effect. Similarly, two vertical DA values (illuminance threshold: 1000lux and 2000lux) were calculated at a height 1.2m (normal eye level of a sitting human being) using the DAYSIM for each view. In order to achieve a comprehensive visual performance of PV façade, a more complicated analysis was carried out in terms of Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006). Different from a conventional model Daylight Glare Index (DGI), DGP could be more suitable for assessing visual comfort in a real daylit space, especially for the window with a non-uniform surface luminance. Based on fish-eye images rendered by Radiance (Fig.3), DGP values were calculated at each view in a software package EVALGLARE (Wienold and Christoffersen, 2006). The glare metrics of DGP method are: DGP < 35%, imperceptible; 35% < DPP < 40%, perceptible; 40% <DGP < 45%, disturbing; DGP > 45%, intolerable. The dates for visual comfort evaluation were: spring equinox 20/03/2015; autumn equinox 23/09/2015; summer solstice 21/06/2015; winter solstice 22/12/2015. For each date, also, only three times 9am, 12pm and 15pm were analyzed.

Following a method to model PV glazing system (Didone and Wagner, 2013), BSDF (Bidirectional Scattering Distribution Function) of PV façades in this study was achieved according to various materials used for each layer. A software OPTICS (version 6.0) and International Glazing Database (version 29.0) from Lawrence Berkeley National Lab were the tools to produce Radiance material files used in all simulations.

3. Results and Discussions

This section includes a preliminary analysis of daylighting performance across the working plane, visual and non-visual performances in the office model with various PV façade systems. The five façade systems are named as: BW (bare window), LOP (large opaque PV facade), LTP (large semi-transparent PV facade), SOP (small opaque PV facade) and STP (small semi-transparent PV facade).

3.1. Daylight performance at the working plane

The daylighting level at the working plane is generally adopted to show a basic daylighting condition. Table 1 presents average DF and DA values at the working plane in various models. DF is a daylight metric to show a basic daylighting condition under CIE standard overcast sky condition.

Tab. 1: Average Daylight Factor and Daylight Autonomy in the office with various façade systems.

	BW	LOP	LTP	SOP	STP
DF (%)	9.49	2.2	4.06	5.26	6.32
DA (%): Beijing	86.96	43.64	64.34	72.87	78.04
DA (%): London	78.74	42.18	61.73	68.4	71.98

The façade with a large PV area normally gives rise to the minimum average DF, while the highest average value is found with the bare window. Taking the average DF of bare window as reference, the percentage DF differences of other façade systems are the following: -76.8% (LOP), -57.2% (LTP), -44.6% (SOP) and -

33.4% (STP). Interestingly, small opaque PV façade would still bring in more diffuse daylighting than the large semi-transparent PV facade. Based on the climate-based daylight modelling, nevertheless, DA is used to assess the daylighting availability taking into account locations and climates. Clearly, a higher average DA of Beijing can be found for each façade system than London, due to a better sky condition for daylight utilization. In response to the DF analysis, large opaque PV facades at both locations receive the lowest DA at the working plane, whilst small opaque PV facades would still lead to a relatively higher DA than large transparent PV facades. Reducing PV transmittance or increasing PV size would significantly lower the average DA in the office. Similarly, taking the DA of bare window as reference, the relative DA differences of PV facades are: LOP (Beijing: -49.82%; London: -46.43%), LTP (Beijing: -26%; London: -21.6%), SOP (Beijing: -16.2%; London: -13.13%) and STP (Beijing: -10.25%; London: -8.59%). Compared with London, Beijing sees a slightl ... rally, a 43% decrease in PV size would reduce th ... or 15% for transparent PV panels. However, a 0 ... would lead to a reduction of relative DA differenc

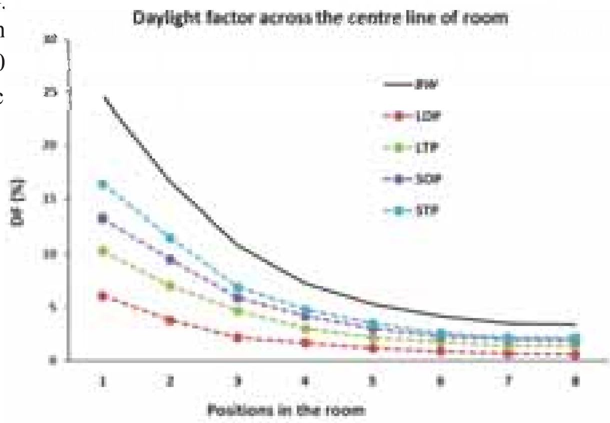


Fig. 4: Daylight Factors at the eight positions in the office with various façade systems.

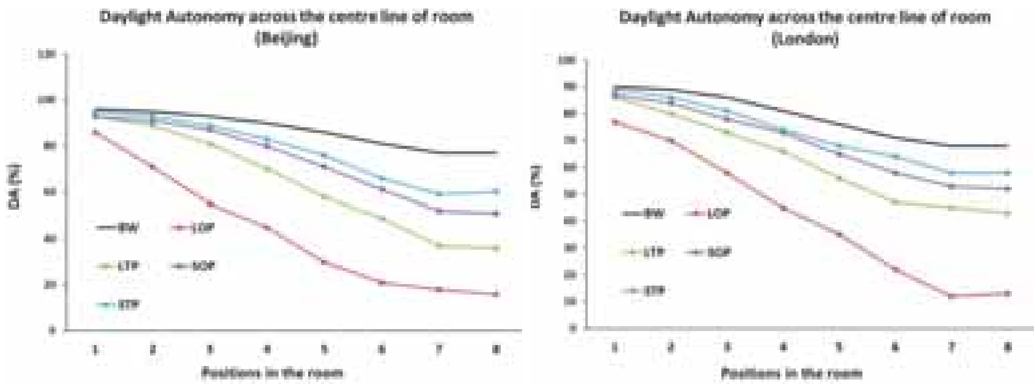


Fig. 5: Daylight Autonomy at the eight positions in the office with various façade systems (Beijing and London).

Fig 4 indicates variations of DF along centre line of the room with the five façade systems. An exponential decay of DF could be found for each façade system. With PV panels in the glazing facade, DF values have been clearly reduced along the room centre, especially for the area near window (distance to window < 2.7m). Normally, small PV size and transparent PV panel will give rise to a higher DF value than large PV and opaque panel from the window to back wall. The average DF values of the eight positions are: 9.49% (BW), 2.2% (LOP), 4.06% (LTP), 5.26% (SOP) and 6.32% (STP). In general, a 43% decrease in PV size would get an over doubled DF value for opaque panel and a 56% higher DF value for transparent panel, whilst a 0.24 increase in absolute transmittance value of PV panels would increase 100% and 20% DF value for large and small PV panels respectively. Similarly, variations of DA along the centre line of room have been displayed in Fig 5. Compared with other PV façade systems, large opaque PV façade has a much lower DA at both locations and only the perimeter area (No.1-3) has a DA >50%. Except for large opaque facade, however, the first position No.1 (with a distance 0.51m to window) sees a similar DA value between bare window, while a DA divergence increases with the position moving towards back wall. For both Beijing and London, small PV facades could keep a DA > 50% at each centre position. Similar to average DA, the relative differences of DA between PV facades and bare window along centre line are smaller at London than Beijing.

Regards as the analysis above, a diffuse incident skylight under overcast sky could be heavily blocked by the large opaque PV panels. However, changing the size of semi-transparent PV panels would not bring in the difference as big as the opaque PV panels, due to a fact that the increased transmittance could significantly supplement one part of blocked diffuse daylight. For the DA analysis, nevertheless, the direct sunlight would be more difficult to block than the diffuse skylight by the application of PV panels in facades.

3.2. Visual performance of various facades

This section discusses the visual performance along four view directions in the office model with various façade systems at Beijing and London. The DGP was evaluated under a clear sky at the locations in order to investigate the worst visual condition with direct sunlight.

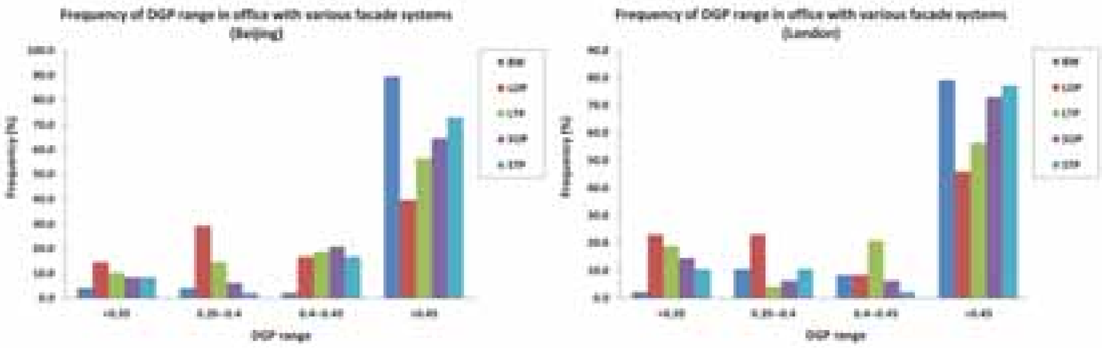
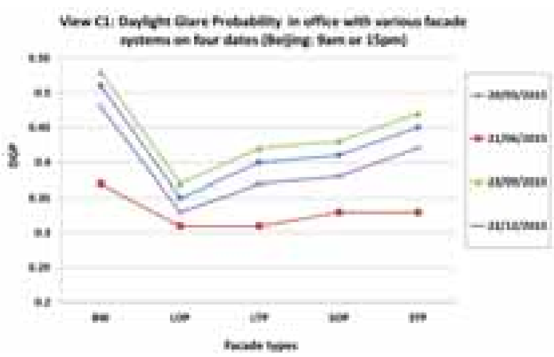


Fig. 6: Frequency distribution of four DGP ranges in the office with various façade systems

(Left: Beijing; Right – London).

First, a general visual performance has been discussed through a statistical analysis. Fig 6 shows the frequency distributions of four DGP ranges (see section 2.3) on four dates (20/03/2015; 21/06/2015; 23/09/2015; 22/12/2015) and three typical times (9am, 12pm and 15pm). The frequency was averagely analyzed with all four views (C1, C2, C3 and C4). Clearly, the biggest frequencies occur at DGP>0.45 (intolerable glare). DGP metrics show 0.4 is the threshold to justify visual comfort in a space (Wienold and Christoffersen, 2006). For the DGP>0.4 (visual discomfort), however, various façades have an occurrence frequency: Beijing – 91.7% (BW), 56.3% (LOP), 75% (LTP), 85.4% (SOP) and 89.6% (STP); London – 87.5% (BW), 54.2% (LOP), 77.1% (LTP), 78.4% (SOP) and 79.3% (STP). Accordingly, the potential to bring in a comfort visual environment in the office follows an order of lowest to highest as: BW>STP>SOP>LTP>LOP. In addition, the absolute differences of the frequency (DGP>0.4) between Beijing and London are: 4.17% (BW), 2.08% (LOP), -4.16% (LTP), 6.25% (SOP) and 10.41% (STP). Thus, Beijing office sees a relatively higher potential of visual discomfort than London office with bare window, large opaque PV and two small PV facades, whereas the large transparent PV façade would lead to a bit higher possibility to get visual discomfort in London office.

Second, as a main view facing outside, C1 has been specifically assessed with respect to visual comfort (DGP variations) in the model with five various façade systems (Fig 7 and 8) as below.



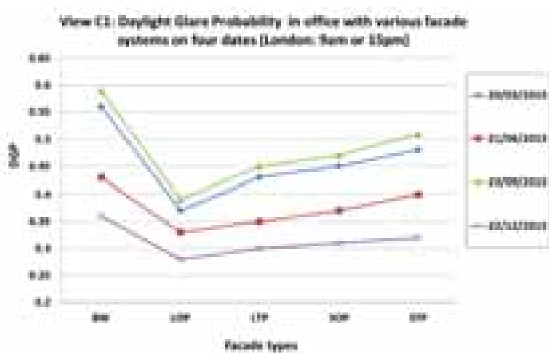


Fig. 7: Variations of Daylight Glare Probability in the office with various façade systems at 9am or 15pm (C1; Beijing: left; London: right).

Fig 7 displays varying DGP values of various facades in the morning (9am) or in the afternoon (15pm). Normally, a similar variation could be found on spring and autumn equinoxes: only large opaque PV façade could keep an acceptable visual environment; other façade systems would just bring in visual discomfort. Apparently, lower DGP values can be found on winter and summer solstices. All façade systems at Beijing office see a proper visual condition (DGP<0.4) on summer solstice, while a similar trend at London can be only found on winter solstice. Except for the bare window and small transparent PV façade at Beijing, other three facades have a DGP<0.4 on winter solstice. Interestingly, the summer solstice gives rise to an acceptable visual performance in the London office on the condition of using large opaque, large transparent and small opaque PV facades.

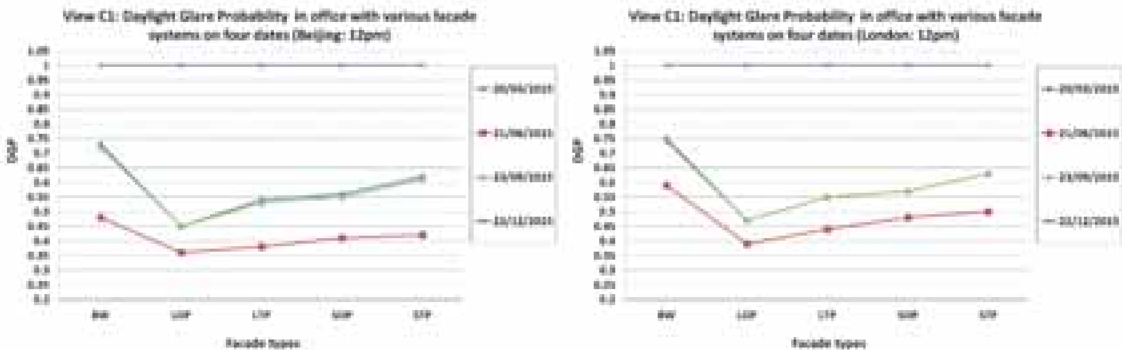


Fig. 8: Variations of Daylight Glare Probability in the office with various façade systems at 12pm (C1; Beijing: left; London: right).

The varying DGP values of various facades at noon (12pm) can be found in Fig 8. In general, it could be very hard to achieve a comfort visual environment in the office through the integration of PV panels in the glazing façade at Beijing and London. Even though the large opaque PV can block a lot of direct sunlight, DGP of LOP façade is still kept in a range of 0.35 — 0.4 (glare: perceptible). Beijing and London have a similar DGP varying trend: the highest value is found on winter solstice while summer solstice sees the lowest value; spring and autumn equinoxes have a middle value in between.

Third, view direction C2 (facing east) is commonly found in a typical office. The DGP assessment along this view is displayed in Fig 9, 10 and 11.

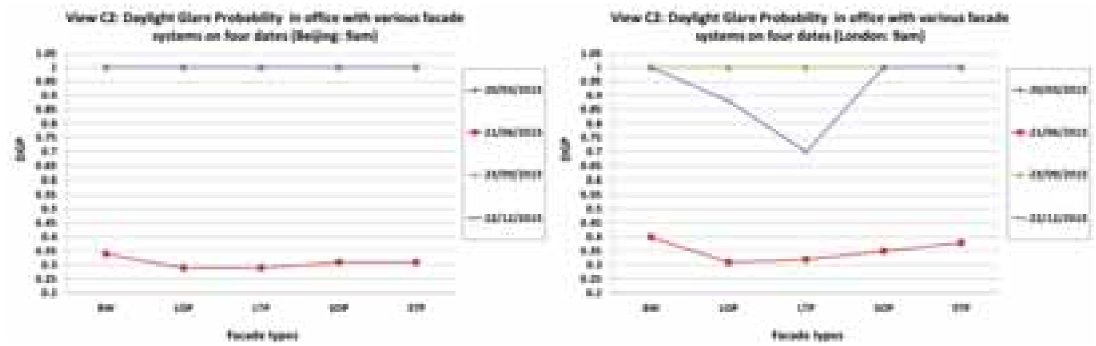


Fig. 9: Variations of Daylight Glare Probability in the office with various façade systems at 9am (C2; Beijing: left; London: right).

At time 9am in the morning (Fig 9), all façade systems could bring in a proper visual comfort (DGP<0.4) on summer solstice while a high possibility to be seriously disturbed by glare are found on other three dates. Two large PV facades would produce a good daylighting condition according to visual comfort

(DGP< 0.35; ‘imperceptible’ glare). For the time at noon (12pm), however, a more complicated DGP variation has been given regarding the Fig 10: the lowest DGP can be found on summer solstice at Beijing and on winter solstice at London, whereas both Beijing and London see the highest DGP on spring equinox. At Beijing, a proper visual condition (DGP<0.4) only occurs on summer solstice for PV facades. Also, the winter solstice and autumn equinox have a similar DGP performance. At London, large opaque façade can help achieve the lowest DGP and proper visual comfort (DGP≤0.4) on each date. With PV panels (both opaque and transparent), also, a very good visual environment is found on winter solstice (DGP≤0.35) at London office. Generally, London office has a relatively lower DGP value than Beijing office. In the afternoon (15pm, Fig 11), DGP variations of various façade systems are similar to those at noon (12pm, Fig 10). Spring equinox has the worst visual condition, whilst Beijing and London offices see the best visual comfort on summer solstice and winter solstice respectively. Besides, large opaque PV panel would bring in a proper visual comfort (DGP≤0.4) on all dates and at both locations. The use of PV panels (both opaque and transparent) could ensure the basic visual comfort (DGP<0.4) on winter and summer solstices at London office. However, a similar effect can be only found on summer solstice at Beijing. In terms of the analysis of three times 9am, 12pm and 15pm, an order of the potential to achieve visual comfort for all PV facades from highest to lowest is: LOP, LTP, SOP, and STP.

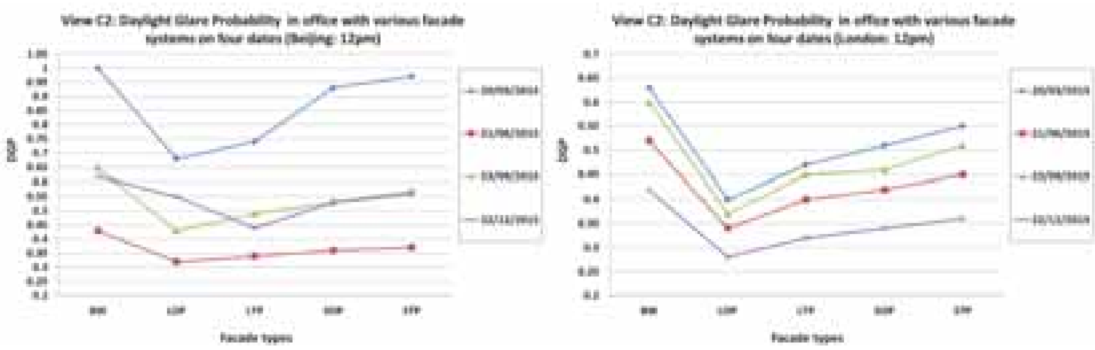


Fig. 10: Variations of Daylight Glare Probability in the office with various façade systems at 12pm (C2; Beijing: left; London: right).

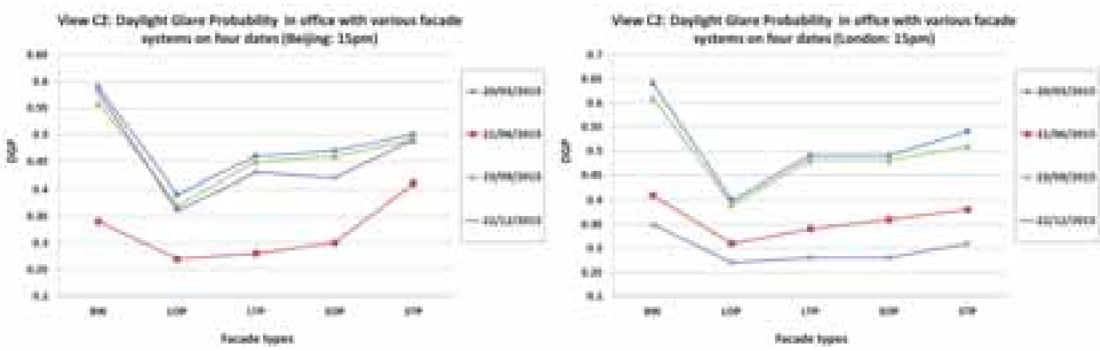


Fig. 11: Variations of Daylight Glare Probability in the office with various façade systems at 15pm (C2; Beijing: left; London: right).

From the analysis above, DGP variations could be explained by the combined effect of solar geometry and façade configurations. Compared with small PV panels, the large panels could block more direct sunlight that gives rise to a higher potential of visual discomfort. For the view facing south (C1), a higher solar altitude of summer solstice at noon results in a smaller daylighting level at the vertical surface of glazing façade, whereas the vertical daylighting level will go up with a lower solar altitude in winter. These could directly decide if a proper visual condition is achieved. When sunlight arrives from the side (9am or 15pm) on spring or autumn equinox, the lower solar altitude would lead to a higher daylighting level at the opposite side wall, which would make the wall brighter. Following this way, the view facing east (C2) will get a similar visual performance at 9am and 12pm as the south-facing view at noon and in the afternoon respectively.

3.3 Non-visual performance of various facades

As mentioned in section 2.3, Daylight Autonomy (threshold: 1000lux and 2000lux) at four vertical positions was used to expressed the non-visual effects of daylighting with the occurrence of various façade systems. Tab 2&3 give the calculated DA values at the offices of Beijing and London. The larger is the DA, the higher is the possibility to active a positive non-visual effect of daylight.

Tab. 2: Daylight Autonomy at four vertical positions in an office with various façade systems (Beijing)

Daylight Autonomy (%) - Beijing						
Vertical Illuminance Threshold	**View**	**BW**	**LOP**	**LTP**	**SOP**	**STP**
	C1	91	45	75	81	82
	C2	89	36	65	76	79
1000lux	**C3**	94	64	84	88	89
	C4	94	72	86	90	90
	C1	77	17	44	53	61
	C2	71	12	35	45	54
2000lux	**C3**	87	26	60	71	77
	C4	89	38	65	75	80

Similar to the general daylighting performance at working plane, vertical DA values (1000lux and 2000lux) at the four positions of Beijing office in Table 2 follow a trend: LOP < LTP < SOP < STP < BW. Taking the bare window as reference, four PV facades have average percentage differences of vertical DA (threshold: 1000lux) as: -41% (LOP), -15.8% (LTP), -8.96% (SOP), -7.6% (STP) and vertical DA (threshold: 2000lux) as: -71.3% (LOP), -37% (LTP), -24.7% (SOP), -16.1% (STP). Increasing PV size would significantly reduce the vertical DA, especially for the large vertical illuminance 2000lux. For opaque PV panels, a 75% increase in PV size (from 40% to 70% wall area) would cause a fivefold percentage DA difference with 1000lux and a tripled percentage DA difference with 2000lux. However, transparent PV panels see a lower impact of the size change: a 75% increase in PV size will just get a doubled percentage DA difference for both thresholds. Normally, facing east (C2) receives the lowest vertical DA values with each façade system. With the small vertical illuminance 1000lux only the two positions (C1 and C2) with large opaque PV have a vertical DA < 50%, whereas more lower DA values can be found with the large vertical illuminance 2000lux: all positions (LOP), C1 & C2 (LTP), C2 (SOP).

Tab. 3: Daylight Autonomy at four vertical positions in an office with various façade systems (London)

Daylight Autonomy (%) - London						
Vertical Illuminance Threshold	**View**	**BW**	**LOP**	**LTP**	**SOP**	**STP**
	C1	80	48	67	71	75
	C2	76	40	58	65	69
1000lux	**C3**	85	58	73	78	80
	C4	86	65	77	80	83
	C1	68	21	47	53	60
	C2	62	9	36	48	52

2000lux	**C3**	76	36	56	64	68
	C4	78	43	61	68	72

Tab. 3 shows the vertical DA values in London office. A similar varying trend as Beijing office could be found here. The average percentage differences of vertical DA of PV facades to the bare window are as follows: for threshold 1000lux, -35.5% (LOP), -15.9% (LTP), -10.1% (SOP), -6.12% (STP); for threshold 2000lux, -61.6% (LOP), -29.6% (LTP), -18% (SOP), -11.3% (STP). With a 75% increase in PV size, the large opaque PV panel sees a 3.5 times percentage DA difference of small opaque panel, whereas the large transparent panel has a value slightly higher than the doubled percentage difference of small transparent panel. The large PV would give rise to a lower vertical DA (<50%), in particular for the vertical illuminance 2000lux or at the position facing east. Compared with Beijing office, it could be found that London office receives a smaller impact of PV panels on the vertical DA.

4. Conclusions

This simulation study was completed in an office with various PV façade systems, which focused on the impact of indoor daylighting on visual and non-visual performances of occupants. Several findings are given as follows:

(1) In modern office buildings, the energy efficiency could not be the only core issue considered by the BIPV façade designers and engineers. It would be necessary to implement a comprehensive daylight design in such buildings in terms of visual and non-visual effects.

(2) It could be possible to adopt a proper BIPV façade as a feasible design strategy in office buildings to achieve energy efficiency, a good general daylighting performance at the working plane, as well as an acceptable vertical daylighting level relating to non-visual performance at typical working stations.

(3) For a glazing façade with uniformly distributed PV units, size and transmittance of PV cells could be critical in terms of visual and non-visual daylighting design in office buildings. When considering opaque PV cells, it could be still possible to produce a relatively worse daylighting performance (visual and non-visual aspects), even with the occurrence of large glazing (e.g. 30% wall area).

(4) It would be difficult to keep a proper visual comfort at typical working times in office buildings with the vertical BIPV façade system. Extra shading devices (e.g. venetian blind, overhang, louvre, ect) would be strongly recommended in order to avoid glare and complete a normal office work in day time.

(5) For the vertical BIPV system integrated with building fenestrations, it could be possible to achieve a higher indoor daylighting performance at both horizontal and vertical planes, which are used to indicate a basic daylighting condition and a potential to active non-visual effect. However, a proper balance between horizontal and vertical daylight levels and visual comfort would be a big challenge.

Limitations: this study was based on a preliminary simulation with simple office and BIPV models. More complicated building spaces and façade systems will be studied in the next stage.

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