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Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate

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Abstract

This paper presents the annual overall energy performance and energy-saving potential of a ventilated photovoltaic double-skin facade (PV-DSF) in a cool-summer Mediterranean climate zone. A numerical simulation model based on EnergyPlus was utilized to simulate the PV-DSF overall energy performance, simultaneously taking into account thermal power and daylight. Based on numerical model, sensitivity analyses about air gap width and ventilation modes have been lead in Berkeley (California) with the aim to optimize unit's structure design and operational strategy of PV-DSF. Via simulation, the overall energy performance including thermal, power and daylighting of the optimized PV-DSF was evaluated using the typical meteorological year (TMY) weather data. It was found that per unit area of the proposed PV-DSF was able to generate about 65kWh electricity yearly. If high efficiency cadmium telluride (CdTe) semi-transparent PV modules are adopted, the annual energy output could be even doubled. The PV-DSF

studied, also featured good thermal and daylighting performances. The PV-DSF can effectively block solar radiation while still providing considerable daylighing illuminance. Due simply to excellent overall energy performance, a PV-DSF at Berkeley can reduce net electricity use by about 50% compared with other commonly used glazing systems. Efficiency improvements of semi-transparent PV modules would further increase the energy saving potential of a PV-DSF and thus making this technology more promising

Keywords: building-integrated photovoltaic (BIPV), energy saving potential, building energy use, double-skin facade, semi-transparent thin-film photovoltaic (STPV)

1. Introduction

In the U.S. during 2010, approximately 41% of total energy consumption was spent in residential and commercial buildings. Heating, ventilating and air conditioning (HVAC) accounted for more than 50% of the total building energy use [1]. Thus, economically and in the interests of sustainability, energy saving in this area is of value. An effective way to reduce building energy consumption, but still ensuring the comfort and convenience of the building users, is by the reduction of heat transfer throughout the building envelope, and thereby reducing cooling/heating loads. Given that windows and glazing facades, for instance, usually have poor thermal insulation properties, the development of energy efficient curtain walls/facades could considerably reduce heat transfer from outside to the inside of buildings. In recent years, semi-transparent thin-film PV (STPV) windows/facades have been a focus of research interest due to their energy efficient performance levels [2-13]. STPV windows/facades not only generates electricity in situ through photovoltaic effect but also significantly reduces the air-conditioning cooling load by blocking solar heat gain [14-19]. Additionally, STPV windows with appropriate transmittance also enable full use of daylighting [15, 20-23]. Much research related to the overall energy performance of STPV windows/facades has been conducted with the objective of determining their energy saving potential. Both experimental and simulation methods have been used and reported.

A comprehensive energy analysis has been conducted for semi-transparent building-integrated photovoltaic (BIPV) windows in Singapore [24]. To evaluate the overall energy performance in this instance, an index of net electrical benefits (NEB) including the generation of electricity, the reductions of cooling energy and artificial lighting energy was introduced. As a result, a better NEB was determined involving high PV efficiency and good thermal properties. In Singapore, when compared with other commonly used glazing systems, semi-transparent BIPV windows were found to be the best in terms of overall energy saving performance providing the window-wall-ratio was optimized in keeping with the various possible orientations. Li et al. [25] investigated the energy performance of a semi-transparent a-Si PV facade for a generic reference office building in Hong Kong. The simulation results showed that semi-transparent PV modules were able to reduce the annual building electricity use and peak cooling load by 1203MWh and 450kW, respectively, if combined with a dimmable lighting control system. Previous study reported that electricity generation of STPV window was relatively small, however, it worked as an efficient sun shading in summer and thus giving a potential for the reduction of investments for cooling equipment and savings on cooling energy use [26].

In Spain, the STPV facade energy saving potential based on different window-to-wall ratios and different transmittances was evaluated by Olivieri et al [27]. The saving ranged from 18% to 59% compared to that of a normal glazing. Didone and Wagner [28] evaluated the energy saving potential of STPV windows in Brazil via simulation. The simulation results indicated that the STPV window has a considerable potential for reducing lighting and air-conditioning energy if used with appropriate control strategies. The impacts of optical characteristics on the overall energy performance of STPV windows have also been investigated by Chae et al [29]. It was found that the optical response at each wavelength could significantly affect the thermal, power and daylighting performance or availability. To maximize the energy saving potential of STPV windows, it seems necessary for the optical characteristics to be customized when fabricating PV laminates. Kapsis and Athienitis [30] examined the impact of various building design parameters on the selection of ideal optical properties for STPV windows. It was reported that STPV windows with 10% visible transmittance had the best energy saving potential.

Previous studies have also reported the thermal insulation performance of single-skin STPV windows to be unsatisfactory because of high heat gain coefficients in summer and serious heat loss during winter nights [31]. A significant reduction of U-value could make PV window become one of the most energy efficient window alternatives [32]. To achieve this goal, ventilated double-skin STPV windows of various types were proposed and their thermal performances studied. Chow et al. [33] investigated the thermal performance of a naturally-ventilated STPV window together with the impact on air-conditioning cooling load reduction. The heat transfer and airflow in the ventilation cavity were simulated using the ESP-r simulation platform, separating the cavity into several thermal zones. The simulation results showed that the naturally-ventilated PV glazing, when compared to the common absorptive glazing window in Hong Kong, could reduce the annual air-conditioning energy use by 28%. Brandl et al. investigated the ventilation effect and thermal behavior of a BIPV façade with 3D CFD models [34]. Due to periphery openings, heat in the cavity was partly transferred to the exterior under the effects of natural ventilation. The thermal performances of single-skin and double-glazing STPV windows were compared using a hot-box designed for that purpose [35]. The experimental results indicated that, in East China, a double-glazing STPV window could reduce the indoor heat gain to 46.5% of that of a single-skin PV window. More importantly, the thermal comfort in the room was obviously better, as the inner surface temperature of the double-glazing STPV window was much lower than that of the single-glazing one. Elarga et al. [36] conducted a dynamic numerical analysis of the cooling energy performance of a ventilated BIPV façade with semitransparent PV cells inside the façade cavity. It was found that the integration of solar cells inside the façade cavity enabled the HVAC system to cool down the PV modules, which not only increased the energy conversion efficiency but also extend the life time of the system.

A novel ventilated photovoltaic double-skin facade (PV-DSF) was developed and has been presented in the authors' previous studies. Its thermal and power performances under different ventilation modes were demonstrated during long term outdoor testing [37-38]. The experimental results showed that the average solar heat gain coefficient (SHGC) of the ventilated PV-DSF was less than 0.15, a measurement which is far less than that of a single-skin STPV window. In addition, it was found that a ventilated PV-DSF could improve the daily energy output by a further 3%, a result based on its lower operating temperature.

From literature reviews, it is evident that although the energy saving potential of single-skin STPV windows has received much attention worldwide, the saving potential of double-glazing STPV windows has, in comparison, rarely been studied and reported. In the study reported in this paper, a comprehensive simulation model based on EnergyPlus is introduced to simulate the year round overall energy performance of a ventilated PV-DSF, situated in the cool-summer Mediterranean climate of Berkeley, California. Weather data, of a typical meteorological year (TMY) was used in the simulation. Based on the simulation model, sensitivity analyses of air gap depths and various ventilation modes were conducted to optimize the design of the PV-DSF structure and the operational strategy. For the optimized PV-DSF, the annual power generation, thermal and daylighting performances were comprehensively investigated. The monthly overall energy performance and net electricity use were also calculated. A study, comparing the PV-DSF and commonly used window glazing, was then conducted, with the aim of revealing the energy saving potential of the PV-DSF in cool-summer Mediterranean climate zones.

2. PV-DSF and Simulation Model

As shown in Figure 1, the PV-DSF consists of an outside layer of semi-transparent a-Si PV panels, an inner layer of an openable window as well as an intermediate 400 mm air ventilation cavity. This PV-DSF possesses the following merits. Firstly, the inside openable window makes air exchange and solar passive heating possible, when needed. Secondly, as the PV panels are semi-transparent, with transmittance of about 7%, thus enabling some natural daylight to penetrate the PV panels and illuminate the room. The upper ventilation louvres can further significantly improve indoor daylighting because daylight can pass through the grille gaps and enter the room. Of final importance is the ventilation design. As shown in Figure 1, cold air can enter the airflow cavity through the bottom inlet louvre, exchange heat with the PV panels as well as the inside windows and finally exhaust a considerable amount of waste heat via the upper outlet louvre. Previous experimental studies demonstrated that such ventilation not only reduces the cooling load by 15%, but also enhances the PV module's energy output by about 3% [37-38]. The key parameters of the PV-DSF are listed in Table 1. More information about this particular PV-DSF is available in [37-38]. The physical characteristics of the semi-transparent PV panels used in the PV-DSF are given in Table 2.

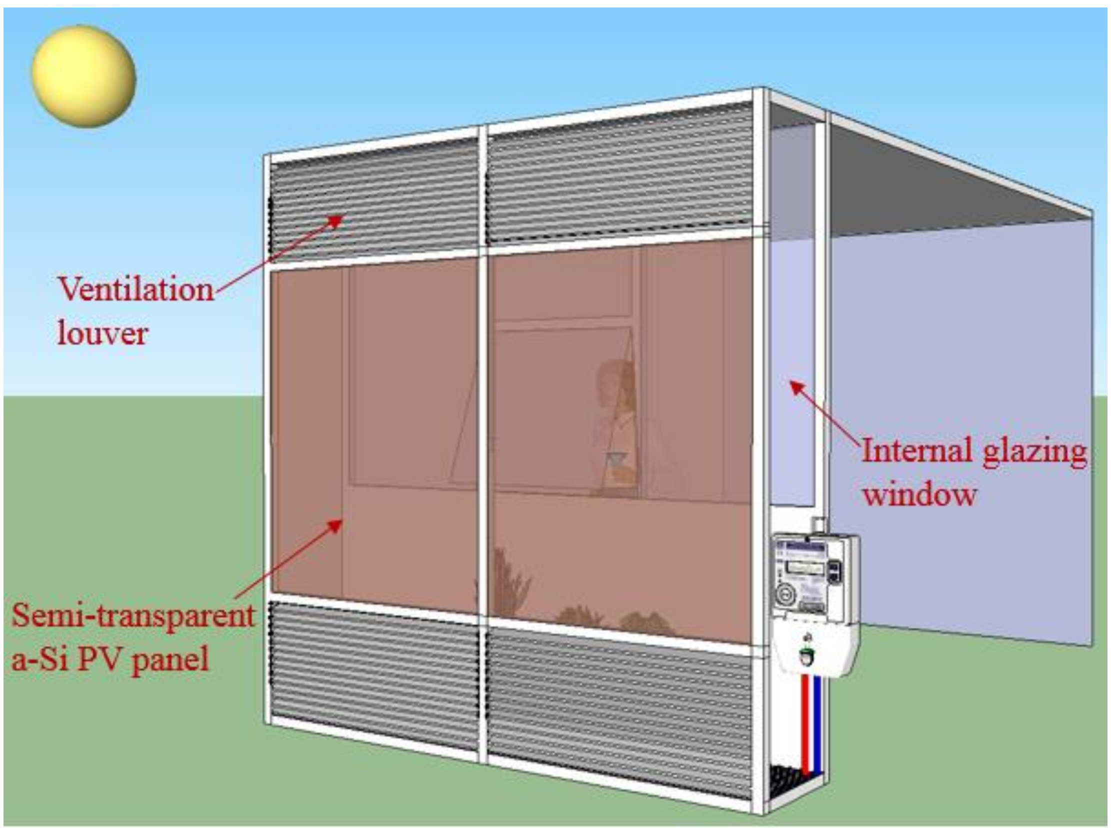

Figure 1 Schematic diagram of the PV-DSF

Table 1 Key dimensions of the ventilated PV-DSF system

Parameters	Values
Width of PV panel	1.1 m
Height of PV panel	1.3 m
Thickness of PV module	0.006 m
Width of louver	1.1 m
Height of louver	0.45 m
Depth of air flow duct	0.4 m
Dimension of office room (W*L*D)	2.3*2.5*2.2 m

Table 2 Physical characteristics of the semi-transparent a-Si PV panel

Parameters	Values
Maximum power under STC (Wp)	85
Open circuit voltage, Voc (V)	134.4
Short circuit current, Isc (A)	1.05
Voltage at the maximum power point, Vmp (V)	100
Current at the maximum power point, Imp (A)	0.85
Efficiency, η (%)	6.2
Power temperature coefficient (Tk)	-0.21%/K
Dimensions (L*W*D), (mm)	1300×1100×7
Transmittance in Visible lighting range	7%
Thermal conductivity, ($Wm^{-1}K^{-1}$)	0.486
Infrared emittance	0.85

To investigate the overall energy performance as well as the energy saving potential of the PV-DSF, a comprehensive simulation model was developed based on EnergyPlus. Figure 2 illustrates the simulation work flowchart. The work was started by measuring the physical characteristics of the semi-transparent a-Si PV module, including its optical characteristics, infrared thermal emissivity and thermal conductivity. The measured physical characteristics were input into the Window program to create a physical characteristics file which can be read by EnergyPlus. The Window program is an example of professional software for calculating the thermal and optical properties of glazing and window systems [39]. The physical characteristics file created by Window was then imported into EnergyPlus together with the PV-DSF geometric dimensions. In EnergyPlus, different models and sub-models, such as the airflow network model, daylighting model, heat transfer model and the Sandia PV power model, were employed to simultaneously simulate the power, thermal and daylighting performances of the PV-DSF.

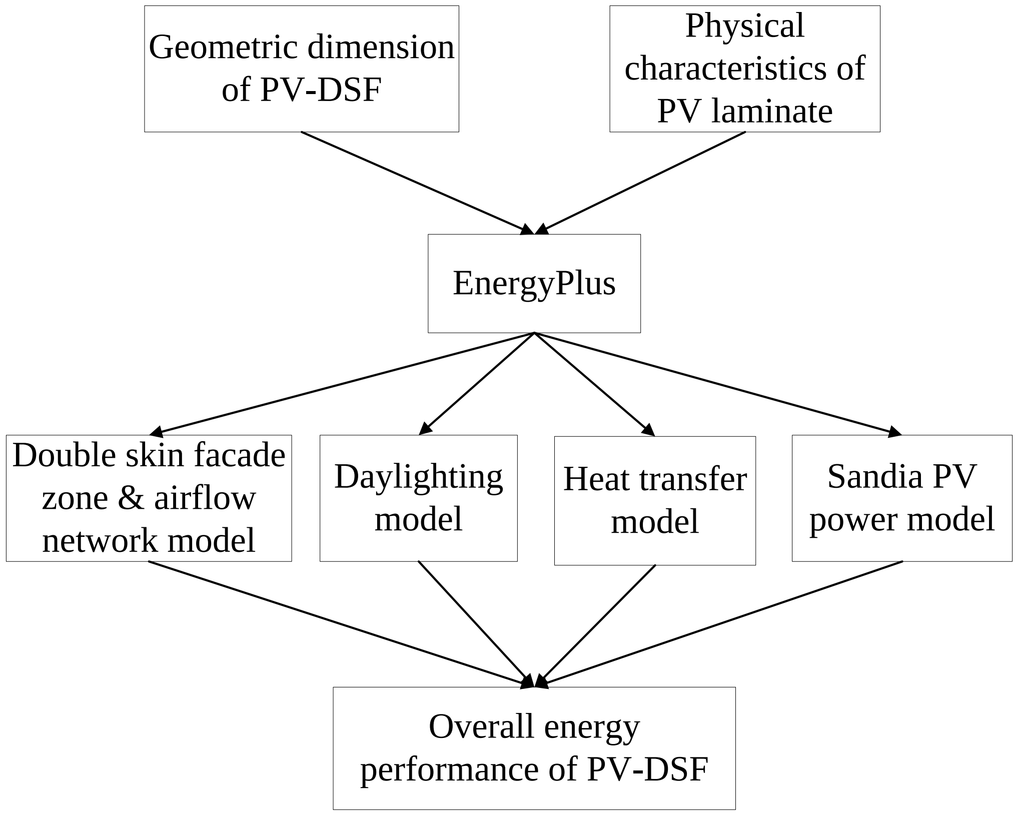

Figure 2 Flowchart of simulating the overall energy performance of PV-DSF

The Airflow Network model was adopted to simulate the heat transfer and air flow in the ventilation cavity to investigate the impacts of ventilation on both the power performance improvement and the cooling load reduction. The Daylighting model in EnergyPlus was chosen to simulate the daylighting performance of PV-DSF under different weather and sky conditions, such as cloudy, overcast, bright sunlight, as well as to investigate the impact on lighting energy use. For power output simulation, the Sandia Array Performance Model (SAPM) was employed. Although the Sandia model is empirically based, it can achieve versatility and accuracy for almost all PV technologies, especially for thin-film solar cells, because all the coefficients used in this model are derived from special tests using the same kind of solar cells [40-41]. In addition, this model also takes into account many factors which considerably affect the power output of PV modules, such as the operating temperature, sunlight incidence angle, solar spectrum and optical effects [42-43].

3. Model Validation

The PV-DSF model developed was then validated against experimental data to verify its accuracy. The outdoor experimental campaign was carried out in the winter of 2012-2013 in Hong Kong. The measured and simulated monthly AC power generations during the experimental campaign were compared in Table 3. To validate the SAPM model's accuracy on predicting annual power generation, the model estimates and measured data were compared using mean-bias-error (MBE), mean-absolute-error (MAE) and root-mean-square-error (RMSE) statistics, and the results are 0.14%, 2.13% and 2.47%, respectively.

Table 3 Comparison of measured and simulated monthly AC power generation

Months	Measured AC power (kWh)	Simulated AC power (kWh)
October	11.46	11.19
November	7.38	7.4
December	9.12	9.27
January	13.56	13.96
February	8.66	8.43

Experimental results in January 2013, a typical winter month in Hong Kong, were chosen to validate against the simulated daily AC energy output. As shown in Figures 3, the SAPM accurately simulated the daily energy output of the PV-DSF with the 39 special pre-determined coefficients. The measured monthly AC energy output was 13.56 kWh in January 2013, while the simulated value was 13.96 kWh, an error of 3%. Such a high level of accuracy for the monthly energy output prediction indicates that the SAPM fully qualifies for use in simulating the annual energy output performance of the a-Si PV-DSF.

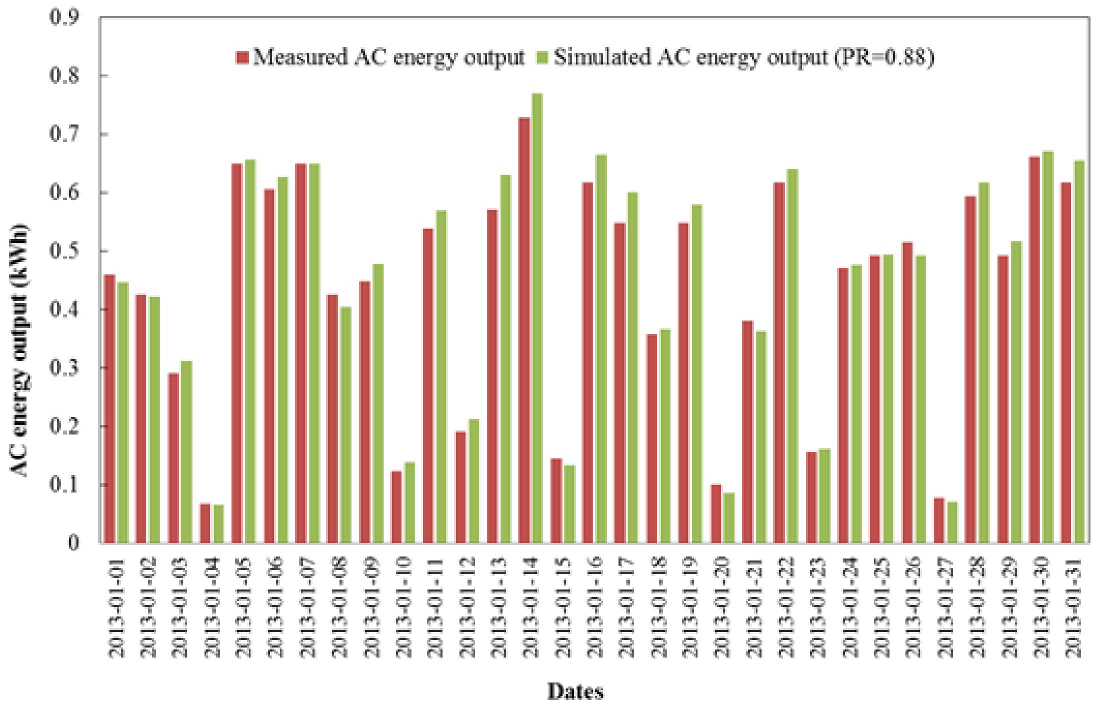

Figure 3 Comparison of the simulated daily energy output and the measured one in January 2013

A comparison of the simulated solar cell temperature and the measured PV module back-surface temperature is presented in Figure 4. The measured PV module back-surface temperature is a little higher than the simulated solar cell temperature, and the back-surface temperature at noon on sunny days, the maximum temperature difference was about 3 °C. On overcast days, the simulated temperatures coincided with the measured temperatures very well. The MAPEs between the simulated PV module back-surface temperatures and the measured results on sunny days (from Dec. 22-24 and Dec.28) and overcast days (Dec.25-27) were 6% and 1.7%, respectively.

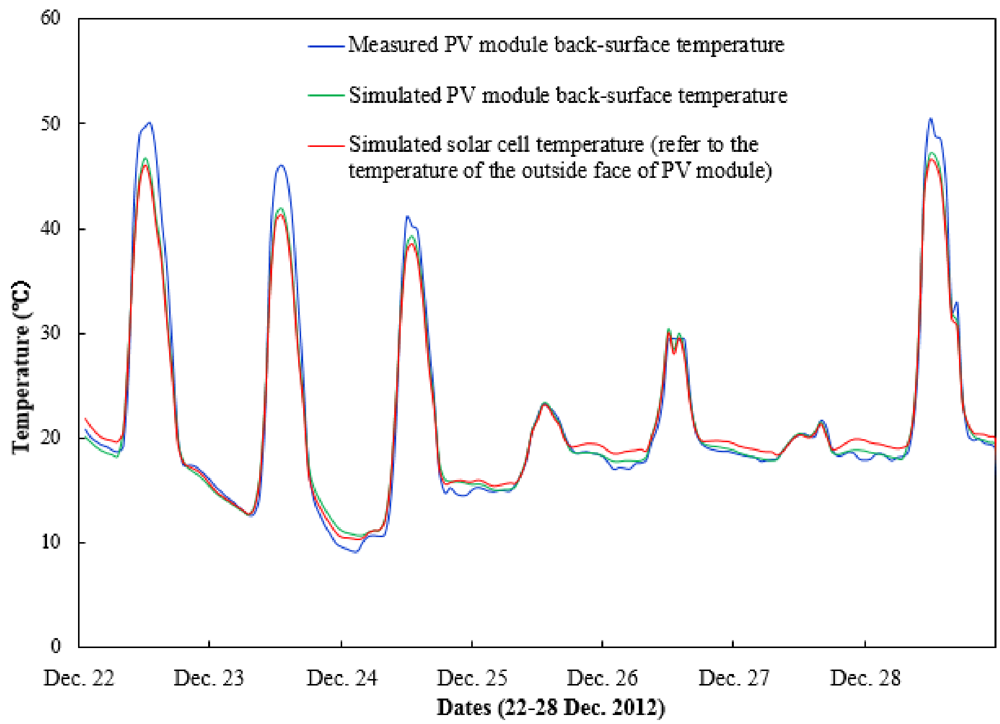

Figure 4 Comparison of the simulated solar cell temperatures and the measured PV module temperature

4. Sensitivity Analysis for PV-DSF in Berkeley

4.1 Sensitivity Analysis of Air Gap Depth

As given above, the PV-DSF studied was a ventilated-type facade, enabling cold air to enter the cavity via the bottom inlet louvre and exhaust from the upper outlet louvre with removing a considerable amount of waste heat in the process. The air ventilation design not only blocks off heat gain from the exterior to reduce the cooling load, but also improves the PV system energy conversion efficiency by cooling the PV module itself. Thus, an optimal design for the air ventilation cavity is beneficial in both reducing building energy use and increasing the energy output of the PV-DSF. In this study, a sensitivity analysis was conducted to investigate the effect of the air gap depth on the overall energy performance of the PV-DSF in Berkeley, California. Figure 5 presents the variation trends of the annual fan, cooling, lighting and net electricity uses as the air gap depth increases. The fan and cooling electricity uses increased as the air gap depth increased to less than 200mm, but decreased when the gap was larger than 200mm. Thus, 200mm proved to be a critical air gap depth at which the least amount of electricity could be saved. This may be because the PV-DSF stack effect was strengthened by the air gap depth decreasing to less than 200mm. This latter situation reinforces the heat convection effect. Under this condition, continually increasing waste heat is removed by the exhaust air via the outlet louvre. When the air gap depth is greater than 200mm, the air thermal resistance then gradually increases in relation to the air gap depth, such that the outside heat gain declines. The lighting electricity use gradually increases with the increasing air gap depth. The distance between outside and inside daylighting reference points increased as the air gap depth increased, resulting in a reduction of daylighting illuminance at the reference points. Thus, more electricity for lighting is needed to compensate for reductions of daylighting illuminance. The inflection point at 225mm might be attributed to the slat angle of outlet louvre, which may block natural lighting penetration to different degrees as the air gap depth changing.

Compared with lighting and cooling electricity uses, the impact of the air gap depth on the PV power generation was very small because the power temperature coefficient of a-Si PV modules is small (about 0.25%). If crystalline silicon PV modules are to be used, the impact would be larger because their power temperature coefficients are about twice that of a-Si PV modules.

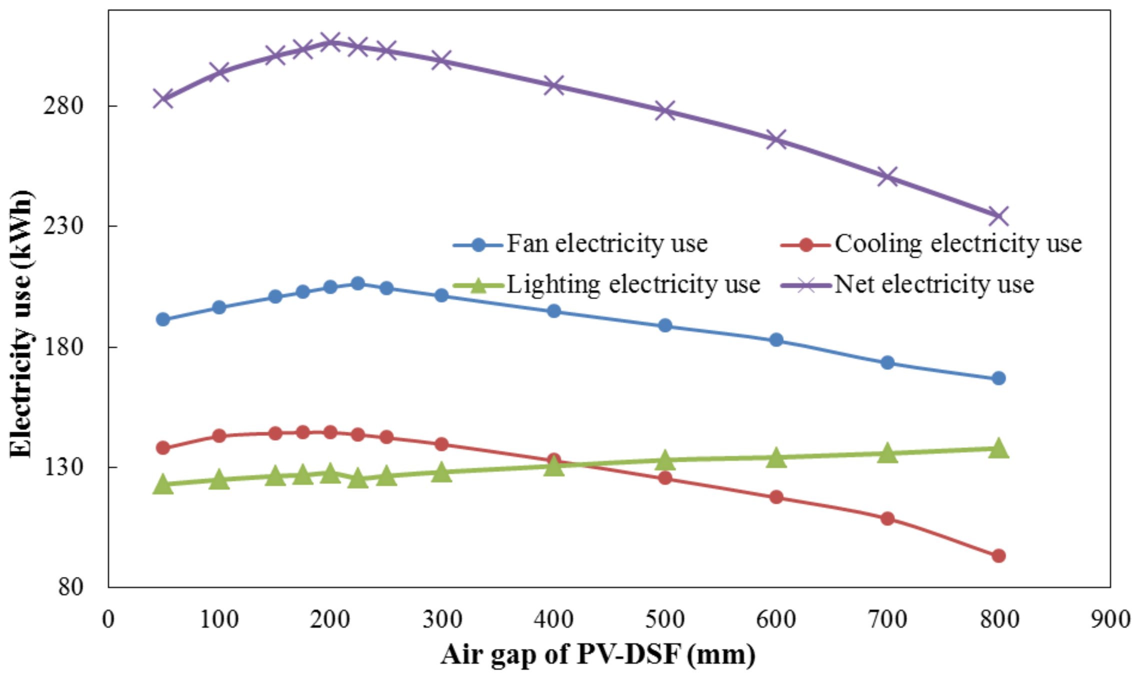

Figure 5 The impact of air gap depth on the annual electricity uses

The impact of air gap depth on the net electricity use of an office room fitted with a PV-DSF is also illustrated in Figure 5. It was found that the worst air gap depth for a PV-DSF installation in Berkeley is 200 mm, at this distance the room consumes the largest amount of annual net electricity. Thus, PV-DSF installations at Berkeley should avoid this air gap depth. When the air gap depth was larger than 200mm, the net electricity use decreased as the gap increased. Although the net electricity use decrease continues to parallel the air gap increase, a tradeoff can be achieved with regard to space provision in the building and electricity saving. Thus, after comprehensively considering all aspects, including energy use, costs, facade cleaning and maintenance, 400 to 600mm is recommended as an 'optimal' air gap range for such as Berkeley conditions. The annual net electricity use would be reduced by 15% if the air gap depth is chosen to be 600mm rather than 200mm.

3.2 Sensitivity Analysis of Ventilation Modes

In order to investigate the impact of air ventilation on the electricity end-uses, the electricity generated by the PV-DSFs and the electricity used when operating in the three ventilation modes: non-ventilated, buoyancy-driven ventilated and naturally-ventilated, were calculated and are shown in Figure 6. It was found that the naturally-ventilated PV-DSF had greater ability than the non-ventilated PV-DSF to reduce the fan, cooling and lighting electricity demands. Its usage, however, needs to be somewhat greater in the case of heating. It is worth noting that the ventilation mode effect on the PV energy output was not obvious because the power temperature coefficient of a-Si PV modules is small. Figure 7 illustrates the energy use breakdowns of PV-DSFs under different ventilation modes. There is no doubt that among the three modes, the naturally-ventilated PV-DSF consumes the lowest amount of electricity, followed by the buoyancy-driven ventilated PV-DSF. The non-ventilated PV-DSF was the least efficient. Compared with the non-ventilated PV-DSF, natural ventilation saves about 35% of electricity per year in Berkeley. This powerfully makes the point that ventilation design is a necessary and effective component for PV-DSF in terms of energy saving.

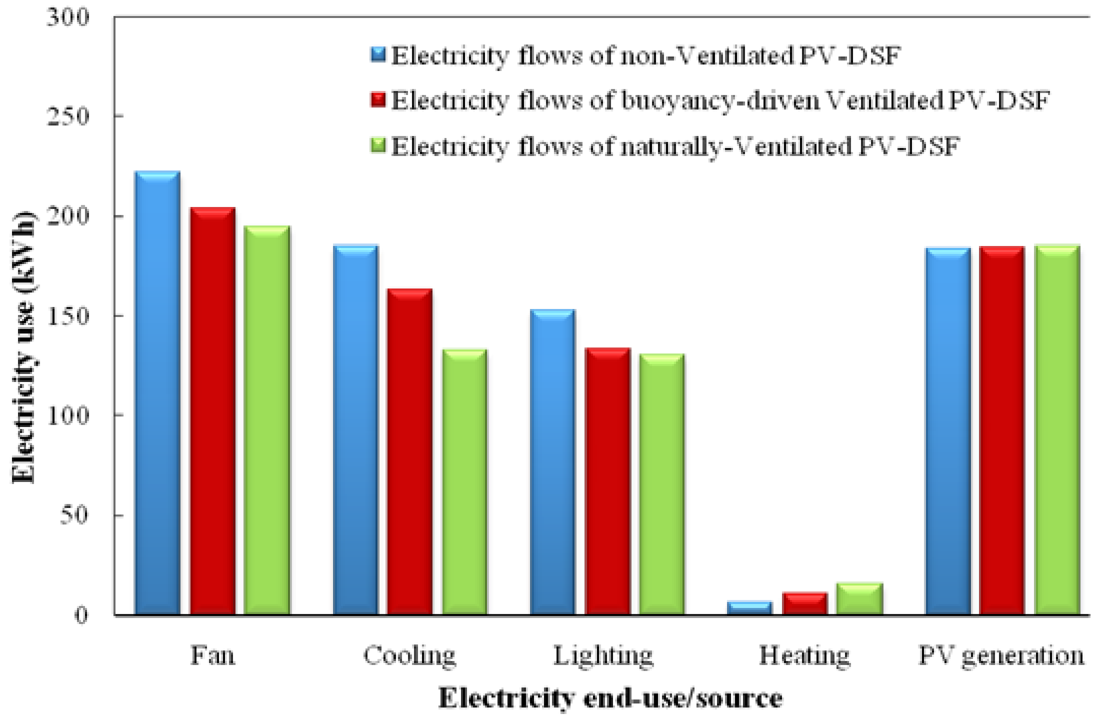

Figure 6 Electricity generated and used by PV-DSFs under different ventilation modes in Berkeley

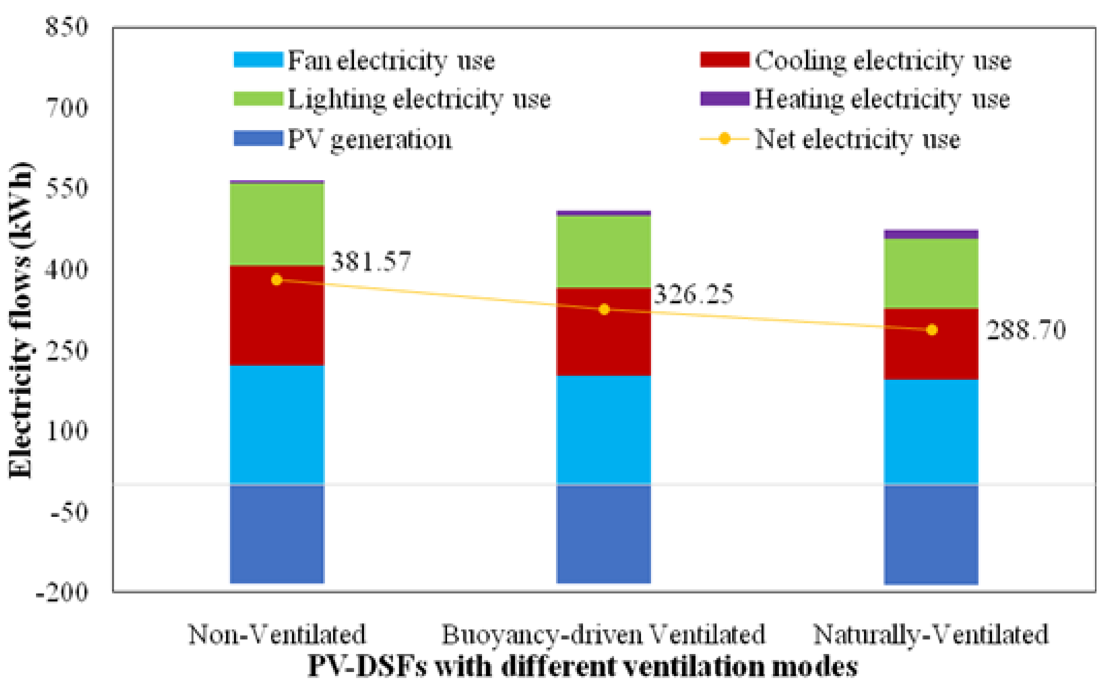

Figure 7 Annual net electricity use of PV-DSFs under different ventilation modes in Berkeley

5. Overall Energy Performance of PV-DSF in Berkeley

5.1 Power Performance

Based on the sensitivity analysis results given above, the optimized PV-DSF should have an air gap depth ranging from 400mm to 600mm and operate in the naturally-ventilated mode. Thus, in this study, a naturally-ventilated PV-DSF with a 400 mm air gap depth was modeled to investigate the corresponding annual overall energy performance in Berkeley. The weather data of the typical meteorological year (TMY) were adopted for the simulation. The annual global solar radiation was about 1692 kWh/m^2 on the horizontal surface and the incident solar radiation upon the south-facing facade was about 1114 kWh/m^2.

Figure 8 presents the monthly energy output of a south-facing PV-DSF. The monthly energy output in the winter was about twice that in summer. The maximum monthly energy output was about 20kWh in November, and the minimum was only 10.3kWh in June. The total annual energy output of the PV-DSF in Berkeley was about 185kWh. Figure 8 also presents the maximum transient power output of the PV-DSF for each month. The results show that the maximum power output, given in December, was 155W, a figure close to the rated power output of the PV-DSF under standard testing conditions (170W). The annual energy output per unit area of PV-DSF was 65kWh/m^2 in Berkeley. The maximum monthly energy output was about 7kWh/m^2. It is worth noting that the energy conversion efficiency of the a-Si PV modules used in the PV-DSF was only 6.2%.

If high efficiency cadmium telluride (CdTe) PV modules had been adopted, the efficiency of which is approximately 10% with a visible light transmittance of 20%, the annual energy output of the PV-DSF could be doubled.

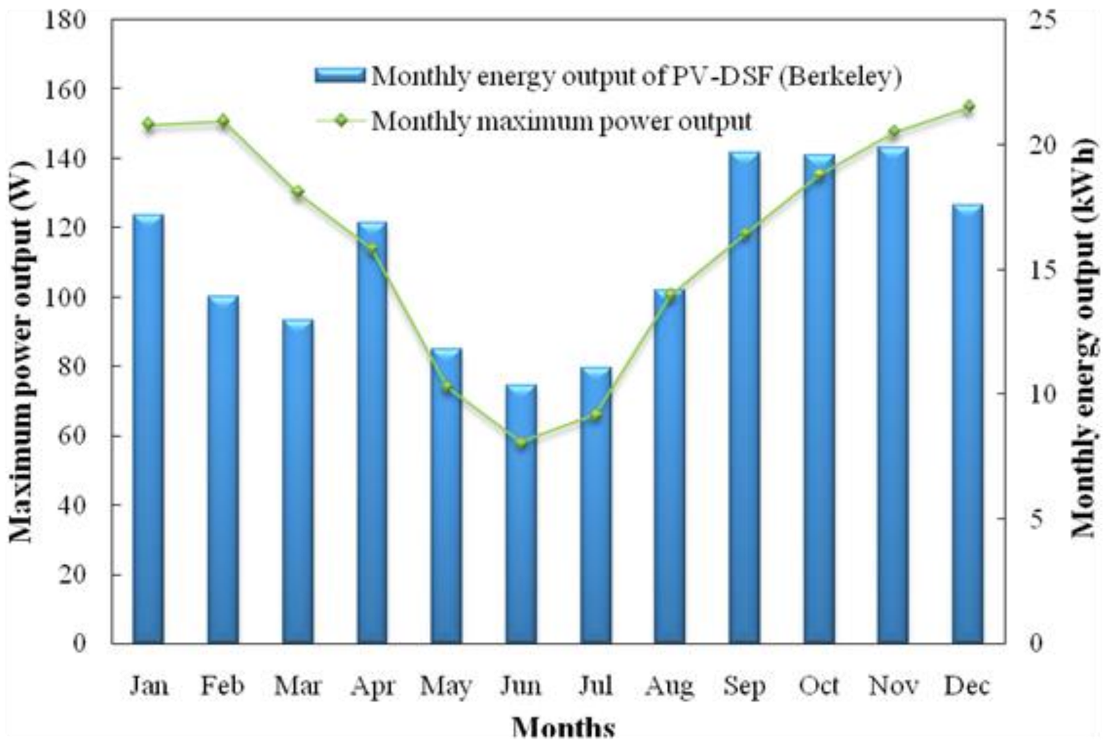

Figure 8 Monthly energy output and the maximum power output of PV-DSF

The best orientation for PV-DSF installation in Berkeley was also determined by simulating the annual energy output for different orientations. As shown in Figure 9, if evaluation is based only on the power generation performance, the best PV-DSF installation orientation for Berkeley is 30 degrees south west, at which the PV-DSF generates the most electricity, at about 67kWh/m^2/yr. In addition, west-facing orientations for PV-DSFs in Berkeley have been found to be more suitable for power generation, than those which face east.

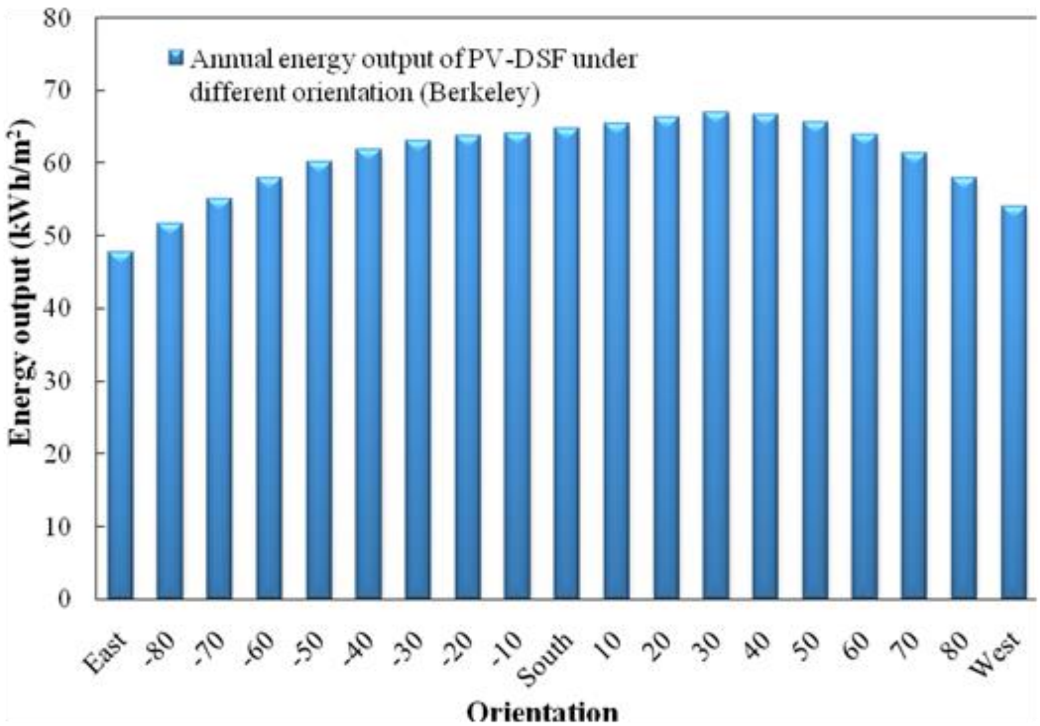

Figure 9 Annual energy output of per unit area of PV-DSFs under different orientations

5.2 Thermal Performance

Due to the high absorptivity and low transmittance of PV modules, the PV-DSF can significantly reduce solar heat gain. It was found that the solar energy passing through the PV-DSF was only one seventh of the incident solar energy. Without considering convection and thermal radiation, the direct solar heat gain coefficient (DSHGC) of the PV-DSF was as low as 0.15 caused by much solar heat gain being blocked by the PV modules.

Figure 10 presents the monthly demand for cooling energy and heating energy of the office room with a PV-DSF installed. Compared with the situation in Hong Kong, the monthly demand for cooling energy is much lower in Berkeley. In the latter, the incident solar radiation is much higher than that in Hong Kong, but the ambient air temperature is much lower in summer as Berkeley has a cool-summer Mediterranean climate. Weather data of a typical summer day in each location was chosen for comparison. Although the solar radiation quantities were close, as shown in Figure 11, the ambient air temperature in Berkeley was much lower than that in Hong Kong and the minimum temperature difference was larger than 13°C. The highest temperature on the typical summer day in Berkeley was lower than 25°C, which is the same as the HVAC cooling design temperature. Thus, the lower ambient air temperature resulted in a smaller cooling load in Berkeley. In addition, the low ambient air temperature aids improvement of the PV module's energy efficiency.

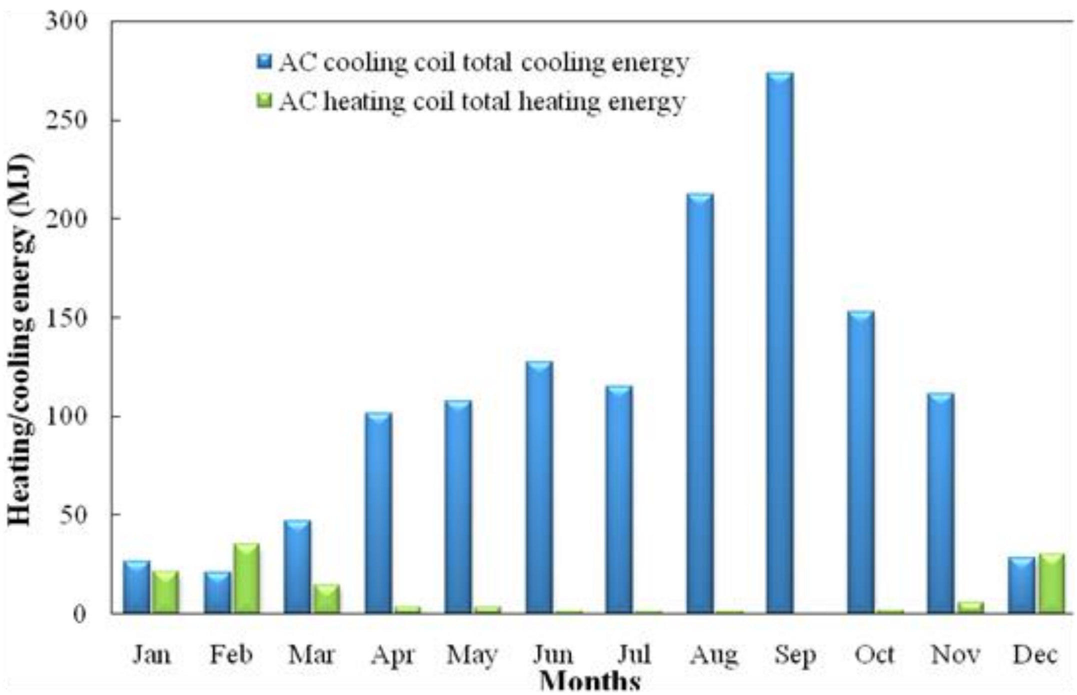

Figure 10 Monthly demand of cooling energy and heating energy of the office room installed with PV-DSF

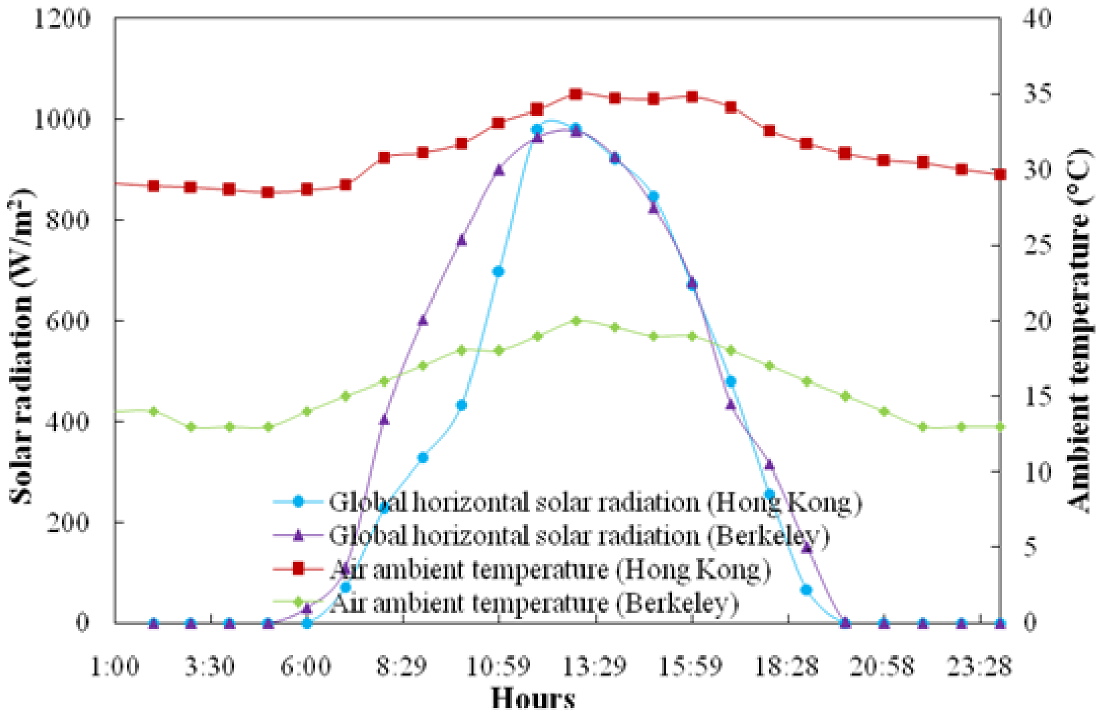

Figure 11 Comparison of weather conditions on a typical summer day in Hong Kong and Berkeley

5.3 Daylighting Performance

Figure 12 presents the indoor monthly average daylighting illuminance with the PV-DSF. The maximum monthly average daylighting illuminance was about 300 lux, in November. Such a high daylighting illuminance significantly reduces the artificial lighting energy use.

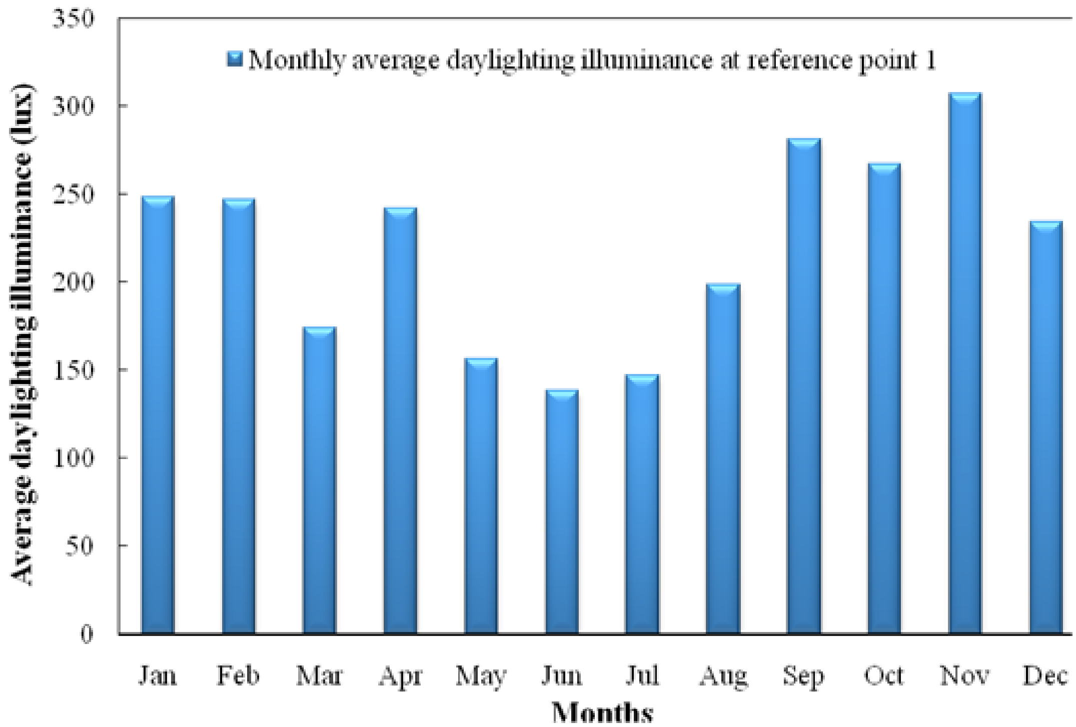

Figure 12 Monthly average daylighting illuminance of PV-DSF in Berkeley

Figure 13 presents the monthly average daylighting lighting power multiplier together with the minimum power multiplier for each month. The daylighting lighting power multiplier in winter is obviously lower than in the summer, and about 50% of the lighting electricity can be saved in the winter season. In addition, the minimum daylighting lighting power multiplier, viz. 0.1, appeared in many months.

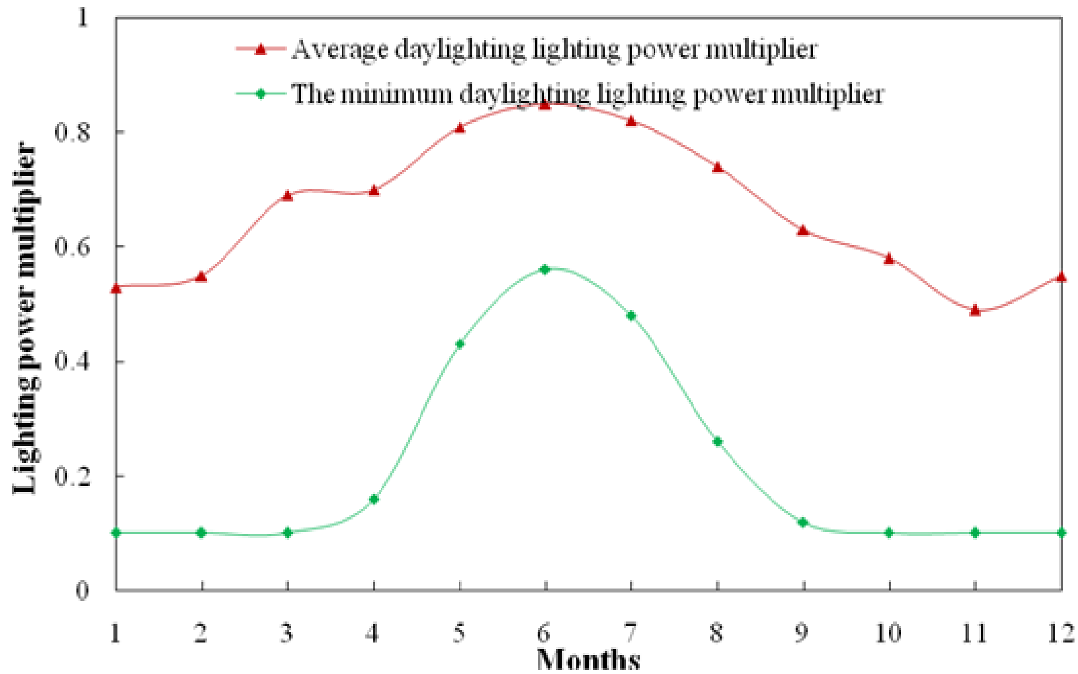

Figure 13 Monthly average daylighting lighting power multiplier and the minimum lighting power multiplier

The monthly lighting energy use for the office room installed with PV-DSF was calculated and is presented in Figure 14. For comparison, the monthly PV-DSF energy output is also presented. It is seen that the monthly energy output in all months, except for the period May to July, is higher than that of the energy for lighting. Specifically, the energy output in winter is about twice that of the lighting energy used. Thus, in Berkeley the electricity generated by the PV-DSF is sufficient to power the lighting system for most of the year. The total annual energy output of the PV-DSF was about 185kWh, which is higher than the annual lighting energy use by 54kWh.

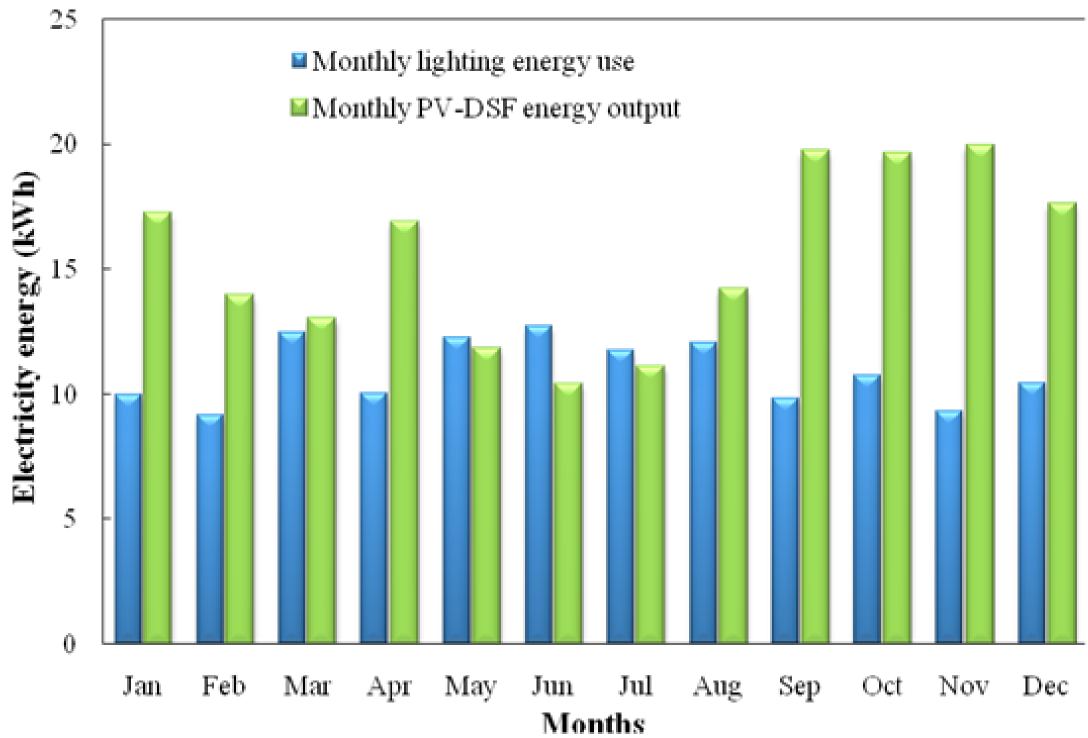

Figure 14 Monthly lighting energy use and energy output of the PV-DSF in Berkeley

5.4 Overall Energy Performance

The overall energy performance of the PV-DSF, including the thermal, power and daylighting performances, are illustrated in Figure 15. It is seen that the largest energy consumer over most of the year is the fan. Heating electricity use was very small and can be ignored in most months. Two features are also observed in Figure 15. On the one hand, the cooling electricity use in Berkeley, is seen to be very low in summer due to the low ambient air temperature and on the other hand, the monthly energy output of the PV-DSF is high in winter because of the high level of incident solar radiation. The sum of the two features given above contributed to the much lower monthly net electricity use for a PV-DSF in Berkeley. The minimum monthly net electricity use in January, was only

2.6kWh/m^2. The annual net electricity use in the office was 289kWh, and the net electricity use for that room per unit area was only 54.5 kWh/m^2/yr.

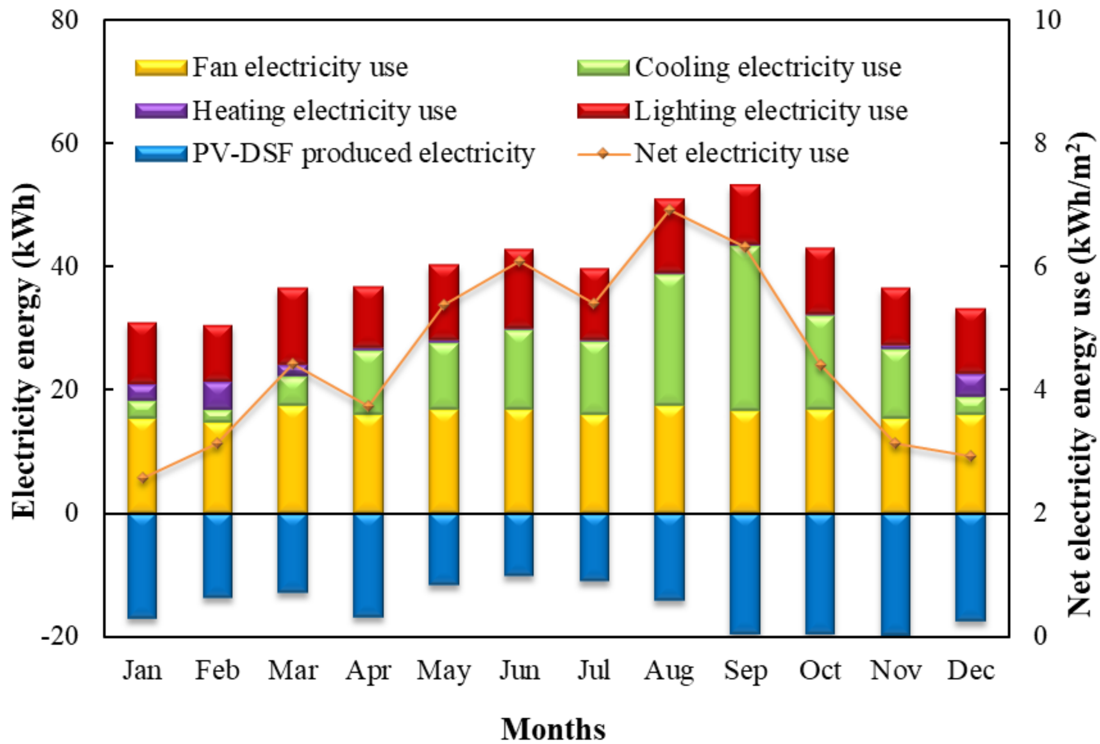

Figure 15 Overall energy performance and net electricity use of the PV-DSF

As reported above, the summer ambient air temperature in Berkeley, is not high and the cooling load is mainly derived from solar heat gain. However, the PV-DSF studied, was just sufficiently effective to block solar radiation in the provision of daylighting illuminance, therefore greatly reducing the air-conditioning energy use. Apart from its passive reduction in energy consumption, PV-DSF can also actively generate enough electricity in situ to mitigate the load on the utility grid and further reduce the total net electricity use of buildings.

The optimum orientation in terms of power generation for a PV-DSF installation in Berkeley was found to be 30 degrees south west. It is necessary to find the best orientation to enable the overall energy consumption for a PV-DSF installation to be achieved. The annual HVAC & lighting electricity uses of PV-DSFs for different orientations in Berkeley is presented in Figure 16. It is found that an office room facing due south consumes the least electricity. The room's annual net electricity use was calculated by taking the total annual energy output into account. As shown in Figure 16, due south is the optimum orientation for a PV-DSF installation because this orientation requires the lowest net electricity use. Compared with the worst orientation, viz. 10 degrees east by south, a due south facing PV-DSF could save 107kWh electricity per year in Berkeley, about 37kWh/yr. for per unit area.

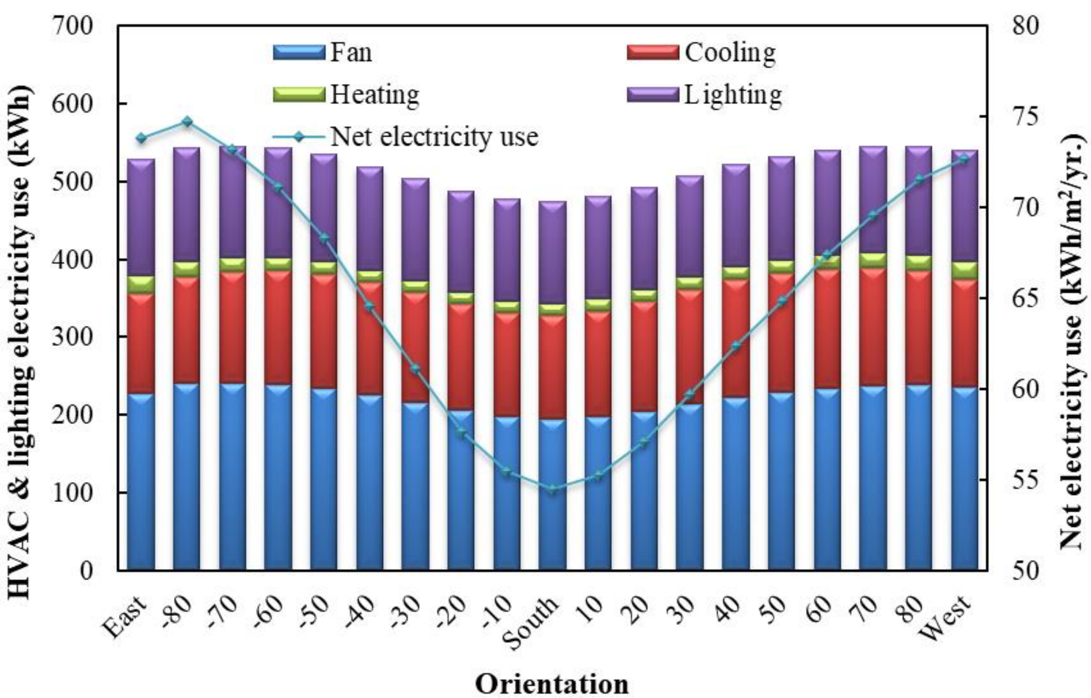

Figure 16 The total and net electricity uses of PV-DSFs under different orientations in Berkeley

6. Energy Saving Potential of PV-DSF

Although the annual overall PV-DSF energy performance has been demonstrated above, the energy saving potential of a PV-DSF compared with other types of windows and facade systems is still unclear. Thus, a study was conducted to compare the overall energy performances of a PV-DSF and six commonly used glazing systems (windows and facade systems). The glazing systems and the corresponding scenarios chosen for this study are listed in Table 4. The structures of various glazing systems as well as the glass IDs, as in the international glazing database (IGDB), are also given in Table 4.

Figure 17 presents the annual electricity use of office rooms fitted with different types of windows and facades in Berkeley. It is seen that Scenarios E and G (PV-DSF) consume much less cooling electricity, and their total electricity uses were much lower than the others. Even without taking the PV power generation into account, the PV-DSF (Scenario G) was almost the most energy efficient choice in Berkeley. Its annual total electricity use was 473kWh, just a little higher than that of Scenario E. However, if the annual PV power generation of about 185kWh is also counted, the annual net electricity use of the PV-DSF (Scenario G) was as low as 288.7kWh, much lower than the other types of windows and facades. As mentioned above, if high efficiency semi-transparent CdTe PV modules were to be adopted in this kind of PV-DSF, the annual energy output could be doubled. With the improved efficiency of semi-transparent PV modules, the advantages of PV-DSF will become larger in the future, making this a very promising energy-efficient facade for Berkeley.

Table 4 Information of the chosen glazing systems

Scenarios	**Glazing name**	**Structure**	**ID in IGDB**	**Note**

A	Double bronze	Bronze(5.61mm)+Air gap(12.7mm)+Clear(5.66mm)	898/9804	
B	Double low solar low-e clear	SB60 clear(5.66mm)+Air gap(12.7mm)+Clear(5.66mm)	5284/9804	
C	Double clear with shading always on	Clear(5.72mm)+Air gap(12.7mm)+Clear(5.72mm)	103/103	"always on" means the VB always cover the window
D	DSF clear glass with shading always off	Clear(5.72mm)+Air ventilation duct(400mm)+Clear(3mm)	103/412	"always off" means the VB always cover none of the window
E	DSF clear glass with shading always on	Clear(5.72mm)+Air ventilation duct(400mm)+Clear(3mm)	103/412	
F	DSF clear glass with shading on if high glare	Clear(5.72mm)+Air ventilation duct(400mm)+Clear(3mm)	103/412	"on if high glare" means the VB cover the window when the glare is high
G	**PV-DSF** PV laminate	a-Si PV laminate(8mm)+Air ventilation duct(400mm)+Clear(3mm)	60900/412	

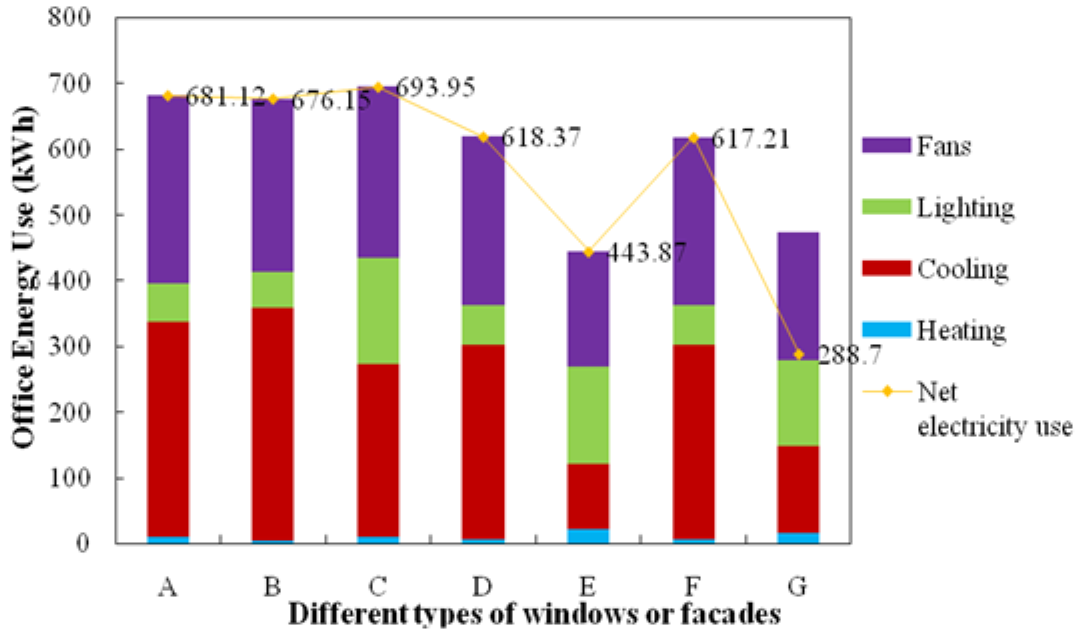

Figure 17 Net electricity uses of office rooms fitted with different types of windows or facades in Berkeley

7. Conclusions

A comprehensive simulation model based on EnergyPlus has been developed and introduced in this paper. The model can be used to simulate the annual overall energy performance of a ventilated PV-DSF in a cool-summer Mediterranean climate zone. Using the simulation model, sensitivity analyses of air gap depths and modes of ventilation were conducted to investigate their impact on overall energy performance. It was found that the least efficient air gap depth for PV-DSF installation was 200 mm. At this gap depth the most electricity was consumed by the room. After a comprehensive analysis of all aspects relating to energy generation, cost, space utilization and maintenances, it was concluded that thicknesses between 400 and 600mm could be recommended as the optimal air gap range for a PV-DSF installation in Berkeley. About 15% of the annual net electricity use could be saved if an air gap depth of 600mm rather than 200mm was chosen. It was found that ventilation modes also significantly affect the overall energy performance of a PV-DSF. When compared with a non-ventilated PV-DSF, the naturally-ventilated PV-DSF saves about 35% of electricity use per year in Berkeley, a situation which is a powerful indication that the consideration of ventilation design is a necessary undertaking in the production of the most effective PV-DSF solution in terms of energy saving.

The PV-DSF was able to generate about 65kWh per unit area, electricity yearly in Berkeley. If high efficiency cadmium telluride (CdTe) semi-transparent PV modules were to be adopted, the annual energy output of the PV-DSF could be doubled. The PV-DSF studied also produced good thermal and daylighting performances. Except for providing considerable interior daylight, the PV-DSF was able to effectively block solar radiation from the interior. The direct solar heat gain coefficient (DSHGC) of the PV-DSF was as low as 0.15, without considering convection and thermal radiation. The maximum monthly average daylighting illuminance was about 300 lux, enabling about 50% of lighting electricity to be saved in winter. The electricity generated by the PV-DSF was sufficient to power the lighting system for most of the year.

The overall energy performance of the PV-DSF in Berkeley was evaluated and two specific features were observed. On the one hand, cooling electricity use was low in summer due to the low ambient air temperature; and on the other hand, the monthly energy output was large over the whole year because of the abundance of solar radiation. The above two factors, together, contributed to the low net electricity use figure for a PV-

DSF in Berkeley. The annual net electricity use per unit area in the office room was only 54.5 kWh/m^2, and the minimum monthly net electricity use was only 2.6kWh/m^2.

A comparative study was also conducted to evaluate the energy saving potential of various window and facade designs in Berkeley. The results showed that the PV-DSF used about 50% less net electricity than other commonly used glazing systems. With the improved efficiency of semi-transparent PV modules, it appears clear that the energy saving potential of PV-DSFs will become increasingly attractive in future. Thus, it appears clear that PV-DSF provides promising energy-efficient facade for Berkeley and therefore possibly, for other areas with the characteristics of abundant solar energy resources and a cool-summer Mediterranean climate.

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