

Energy performance evaluation of bifacial solar photovoltaic modules in Hong Kong

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ABSTRACT

Despite the proven benefits of solar bifacial photovoltaic (BPV) over monofacial PV (MPV) systems, the feasibility of the technology in subtropical climate regions has not been evaluated. Thus, this study provides a comprehensive energy performance evaluation of BPV in Hong Kong using numerical simulation and on-site experimental validation. Three types of solar PV modules, i.e. monofacial PV, framed BPV and frameless BPV, are studied experimentally under different tilt angles, mounting heights and slope orientations. The obtained field measurements and simulation results show that the average bifacial gain (BG) of a BPV system can reach 7.9% and 11.6% when facing south, and up to 167% when facing east. Furthermore, it was observed that an increase in tilt angle also influences the BG performance, and the annual electricity yield can be maximised by increasing the ground albedo through white painting on the roof surface. Finally, the obtained results in this study validate previous studies' assertion that BPV is a viable option over MPV and provides a starting point for the adoption of BPV in subtropical climate regions, especially in Hong Kong.

KEYWORDS Bifacial photovoltaic system; monofacial photovoltaic; energy performance

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1. Introduction

Over the past century, non-renewable energy sources such as fossil fuels have been widely used for electricity generation. The increasing energy demand in the post-industrial-revolution era and the rapid growth of the world's population has resulted in accelerated use of non-renewable energy. Meanwhile, carbon emissions are mainly produced by burning fossil fuels which must be phased out to reduce the greenhouse effect. However, the enormous gap between the consumption rate of non-renewable energy sources and the slow regeneration rate of the resources may lead to an energy crisis as well as climate issues in the foreseeable future. To mitigate the negative effects, the scientific and engineering community must seek breakthroughs in regard to renewable energy and advancements in its adaptation.

In 2014, coal and natural gas accounted for 53% and 22% of power generation respectively in the Hong Kong SAR (Environment Bureau, 2014). However, the HKSAR Government announced Climate Action Plan 2050 and the transition to a low carbon economy with the intention to reduce carbon emissions by 70% in 2020 and the ambitious goal of achieving carbon neutrality on or before 2050. One of the measures is to shift the electricity fuel mix towards renewable energy. In Hong Kong, it is not practical to launch renewable energy programmes and measures that may occupy substantial spaces such as wind energy and hydropower. Due to the limited land resources, solar energy through the use of photovoltaic (PV) technology is the most viable renewable energy option for Hong Kong.

PV power generation technologies have continued to increase over the past few decades, with the global PV capacity reaching 107GW in 2020 (IEA, 2020). Regarding

PV technology, bifacial PV is perceived to be an encouraging solar power generation technology that can absorb solar radiation from its front and rear sides to generate more electricity than monofacial PV modules (Kopecek and Libal, 2018). The two-sided illumination phenomenon as illustrated in Figure 1 and Figure 2, allows the bifacial PV module to produce additional energy output and reduces the Levelised Cost of Energy (LCOE). Moreover, bifacial PV has a higher power density per unit area in comparison to monofacial PV, since monofacial PV modules can only capture solar radiation from its front side. Due to it occupying less area, the area-related cost for the PV installation can also be reduced (Bordin et al., 2010). The capability to absorb reflected radiation, improve energy yield, and reduce the soiling effect demonstrates its potential to be the next solar PV technology (Guerrero-Lemus et al., 2016; Raina and Sinha, 2019). Apart from the energy aspect, previous research suggested that bifacial PV modules have a relatively long lifetime because of the higher durability of the glass-glass structure. The potential degradation due to moisture has been significantly reduced (Sun et al., 2018).

1.1. Research trends on BPV

Several studies have been carried out to investigate the factors that affect the performance of bifacial PV modules. It is suggested that the performance of the BPV module will vary under different environmental conditions (global horizontal irradiance, clearness index, cloud coverage and diffuse fraction) as well as installation parameters (module height, tilt angle, orientation and row spacing) (Baloch et al., 2020; Nussbaumer et al., 2020; Shoukry

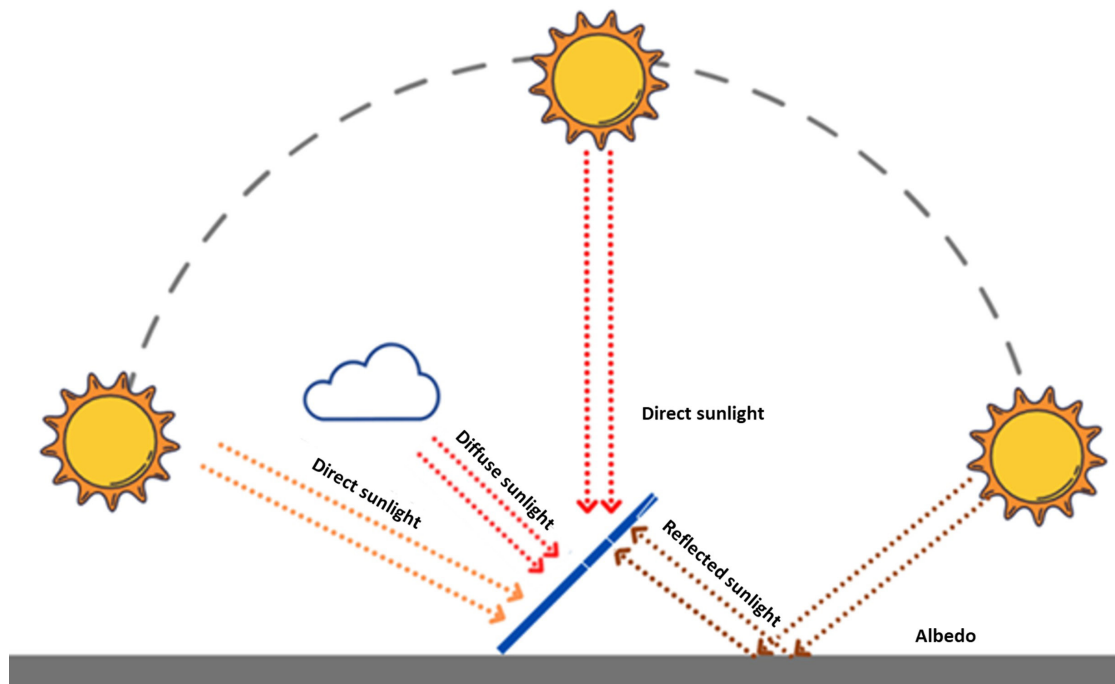


Figure 1. Schematic of bifacial PV module facing west with a double-sided illumination effect.

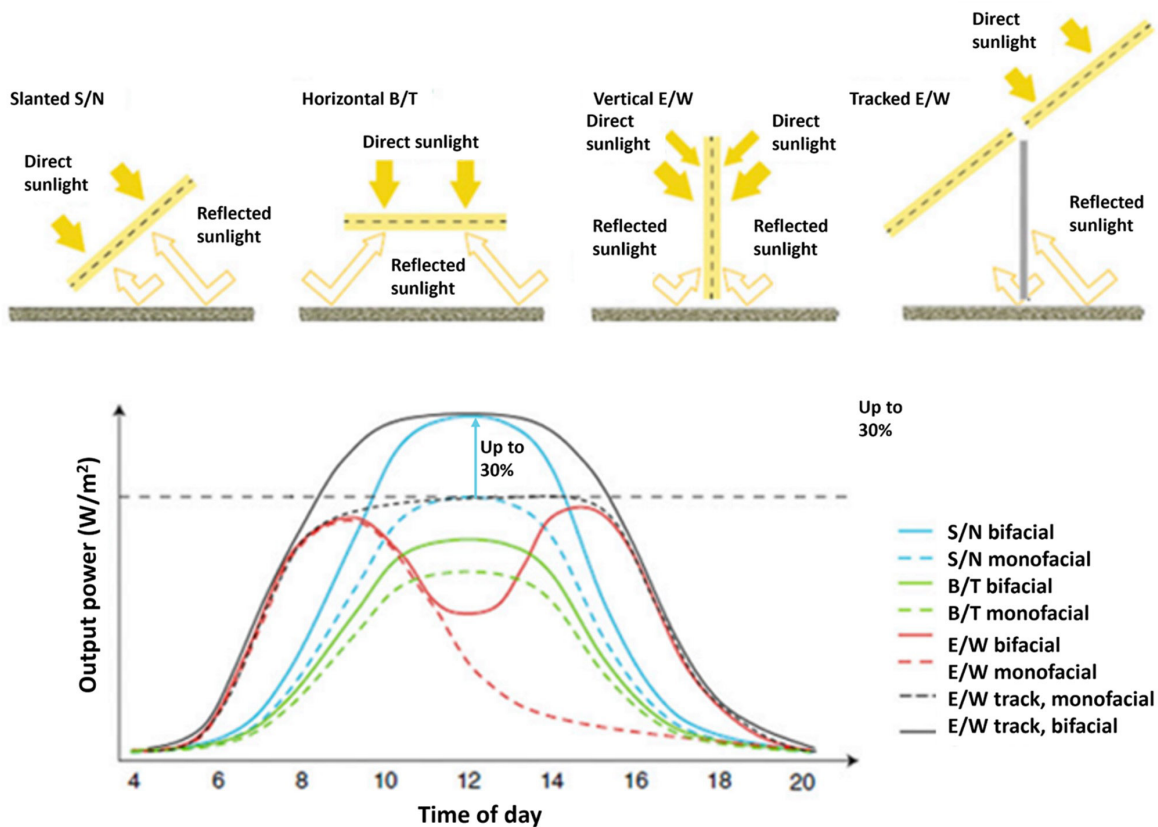


Figure 2. Energy production characteristics of bifacial PV modules.

and Ismail et al., 2016; Wang et al., 2015). Regarding the module's operating temperature, one study has shown that the operating temperature of the BPV module completed with a white painted diffuse reflector is estimated to be 5-9°C higher than that of a standard monofacial PV module (Moehlecke et al., 2013), as a result of higher solar radiation received on the rear side of the cells and the convective heat transfer in an enclosed space formed by glass, reflector and aluminium frames. The higher operating temperature will result in less power output because of the characteristic of PV solar cells (Moehlecke et al., 2013). However, it is observed that the additional energy yield on the rear side can offset the losses due to higher cells' temperature (Moehlecke et al., 2013). Another study shows similar insights on the temperature effect, and it is believed that BPV modules will generally have a higher temperature because of the rear side irradiation due to the diffuse irradiance from the cloud or irradiance reflected from the ground surface (Lamers et al., 2018).

In addition, an outdoor experiment was performed, and the results show that the Bifacial Gain of BPV (BG) that is estimated in Equation (1) is still larger than the losses due to the slight heating of the module (Lamers et al., 2018). In contrast, Khan et al. (2017) opined that this PV technology has a lower operating temperature because of its glass-glass structure, with no metal back sheet at the back, hence leading to a lower temperature coefficient of solar cells. Shading effects on the BG are also investigated from previous studies, and are classified into three categories, namely self-shading, structural frame shading, and mutual shading from adjacent panels (Khan et al., 2017; Marion et al., 2017; Yusufoglu et al., 2015). Self-shading is caused by the module shadow on the ground and leads to a reduction of the rear side's performance. Yusufoglu et al. (2015) reported that the maximum BG is less than 10% due to the self-shading effect, and they conducted economic analysis with consideration of the shading effect. It is suggested that the energy performance in real-life application is not ideal, as the soiling effect and shading effect will make the actual energy yield deviate from the theoretical power output. For large-scale solar farms, mutual shading between PV modules is found to occur easily. The shadow will block the reflected irradiance, especially in the early morning when the sun position is at a low elevation (Khan et al., 2017).

$$\text{Bifacial Gain (\%)} = \frac{E_{\text{bifacial}} - E_{\text{monofacial}}}{E_{\text{monofacial}}} \times 100\%, \quad (1)$$

where E_{bifacial} and $E_{\text{monofacial}}$ are the energy yield of the bifacial PV module and monofacial PV module respectively.

From the above key influencing parameters, the energy yield of a bifacial PV system varies a lot with different conditions; therefore, the BG is not easily quantified and it should be considered case by case. Therefore, to investigate the BG on the bifacial PV module, it is vital to observe

the performance of bifacial PV modules with different PV system configurations in order to further evaluate the energy performance of bifacial PV modules under other installation conditions (ground albedo, elevation and tilt angle) and PV module specification (module efficiency, bifaciality factor, and temperature coefficient).

In recent years, various researchers have explored BPV technology, and many studies can be found in the literature on the development of BPV. However, there is insufficient on-site field research data that relate to BPV applications in a subtropical climate region. As suggested by previous studies, the amount of cloud and clearness index will affect the diffuse solar radiation (Nussbaumer et al., 2021). In a humid subtropical region like Hong Kong, heavy rain is a common issue during the southwest monsoon. This will affect the electricity generation of the PV system significantly. Research also suggested that locations with a latitude of less than 30° are considered not economically feasible for BPV installation because the maximum BG is below 5% (Patel et al., 2020). Therefore, it is necessary to carry out a field experiment under subtropical climate conditions to investigate the feasibility of the BPV application. Furthermore, previous studies have focused on the impact of the individual influencing factors, so analysis of the effects of different parameters is limited. Among these influencing parameters, very few studies are dedicated to the effects of module temperature effect and shading effect. Thus, this study newly presents an overview of BPV module performance under various conditions within a subtropical climate region. A field experiment is carried out to study the critical performance parameters on the BPV module. The effects of different parameters are also considered. In addition, the energy performance of the BPV module is compared with the monofacial PV module (reference case in this study). BG and bifaciality are used to evaluate the performance of the PV module.

1.2. Research gaps and contributions of the study

The aforementioned review indicates that BPV technology has several advantages, such as generating additional electricity from the rear side, reducing the space occupied by the PV module, and the flexibility to install it in any direction to absorb solar irradiance from all directions. However, there is a lack of application study on the energy performance of the BPV system in Hong Kong. The research gaps based on the literature review are listed as follows:

- A few studies have been conducted on the research of BPV technologies worldwide, but there is a severe lack of local simulation and experimental research in Hong Kong.
- Among the different influencing parameters, very few studies are dedicated to the effects of module temperature effect and shading effect. The impact on the rear side's energy production by the

influencing factors and various climate conditions needs to be experimentally examined.

Based on the research gap, comprehensive experimental and simulation research on bifacial PV technology was conducted in Hong Kong. This analysis aims to show the practical performance of the BPV system in Hong Kong. Influencing factors are also investigated to fully understand how to maximise the energy yield in the BPV system. In this study, field testing and energy simulation are adopted to look at the BPV system's performance in Hong Kong. This study may provide experience for the application of BPV technology in Hong Kong as well as in other subtropical climate regions.

2. Research method

An outdoor experiment and simulation approach is adopted in this study to investigate the feasibility of BPV technology in Hong Kong. Figure 3 shows the proposed methodology to assess BPV adoption in the subtropical climate region through practical energy performance assessment.

2.1. Outdoor experiment procedure

First of all, three PV modules are chosen for the energy performance comparison in this study, including a monofacial PV module as a reference case, a framed BPV module, and a frameless BPV module. A PV module catalogue is included in Appendix B. The detailed PV specifications are shown in Table 1.

During the measurement, the results were compared to a reference case to assess the BG. Framed and frameless bifacial PV modules were selected to evaluate the shading effect due to the frame structure in terms of electricity generation. The shading effect due to soiling, supporting structure, and shadowing was also investigated. Apart from the shading effect, other influencing parameters such as ground albedo, module temperature and the tilt angle were examined in the study.

A prototype of the supporting structure was built to support the weight of the PV panel. The tilt angle can be adjusted from 0° (horizontally) to 90° (vertically). The PV module is connected to the pyranometer, I-V checker and thermocouples in order to monitor the energy performance under different operating conditions. During the whole experimental testing, we designed different types of system configuration as shown in Appendix C. Figure 4 describes the outdoor experimental measurement setup of the BPV system and MPV system respectively, while the equipment and instrument used during the experiment are summarised in Table A4 and A5.

As shown in the schematic diagram (Figure 4), pyranometers are connected to the data logger to measure

the horizontal solar irradiance, and solar irradiance of the front side and rear side. Thermocouples were mounted on the BPV and MPV panels to measure the operating temperature, as well as one more thermocouple to measure the ambient temperature. The supporting structure can adjust the tilt angle from 0° to 90°. Figure 4 shows the experimental setup of the BPV and MPV systems with a tilt angle of 40° with a south-facing orientation.

(a)



(b)

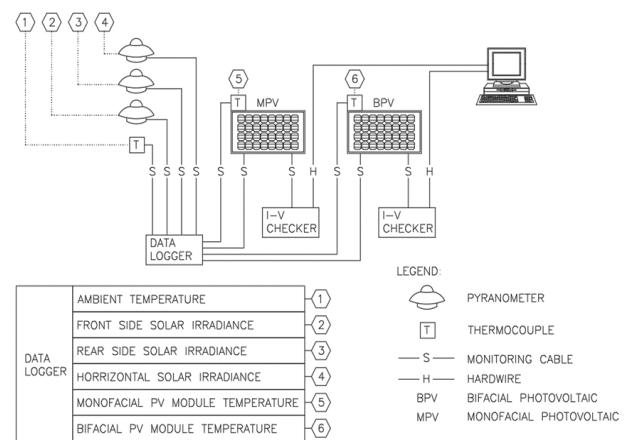


Figure 4. (a) Picture of outdoor experimental setup for the BPV system and MPV system; and (b) schematic diagram of the experimental system.

The experiment was conducted in Hong Kong, a region with a subtropical climate (22.18°N, 114.10°E). In this study, data were collected from January to April of 2021 to evaluate the energy performance of the BPV system. The experiments were conducted on the roof of a six-storey building inside The Hong Kong Polytechnic University campus without significant blockage from the neighbouring buildings or tall objects. The site is located in urban areas surrounded by existing buildings of different heights. Figure 5 shows the photomontage established by google earth and auroscope.

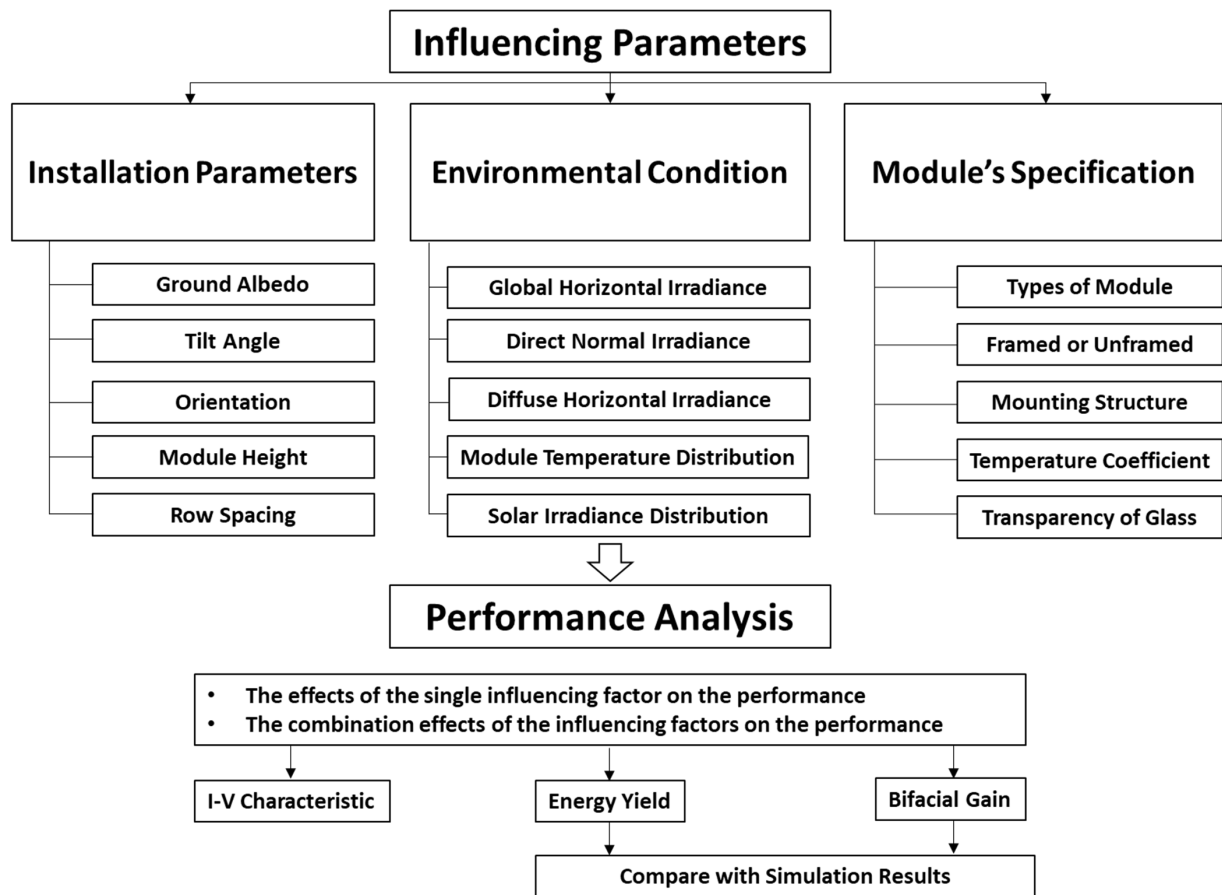


Figure 3. Flowchart of the research methodology.

Table 1. PV module's performance rating under (STC).

Specification	Monofacial module (Reference case)	Bifacial module 1 (Framed)	Bifacial module 2 (Frameless)
Type of solar cells	Monocrystalline	Monocrystalline	Monocrystalline
Dimensions (mm)	1650 × 991 × 35	1664 × 997 × 40	1676 × 994 × 6
Maximum power P_{max} (W)	315	300	320
Open circuit voltage V_{oc} (V)	40.53	39.6	40.79
Short circuit current I_{sc} (A)	9.98	9.58	10.09
Maximum voltage (V)	33.16	32.9	33.49
Maximum current (A)	9.98	9.11	9.56
Module efficiency (%)	19.3	18.1	19.2
Temperature coefficient of P_{max} (%/°C)	-0.38	-0.38	-0.37
Temperature coefficient of V_{oc} (%/°C)	-0.3	-0.3	-0.3
Temperature coefficient of I_{sc} (%/°C)	0.06	0.06	0.06

(a)



(b)



Figure 5. (a) 3D satellite view of the project building; and (b) 3D satellite view of experiment location.

2.2. Energy simulation

In this study, PVsyst was chosen as the energy simulation software. It can edit the geographical location, weather data profile and also installation parameters. Moreover, it is able to simulate the energy performance of the BPV module system. View factor models are adopted to illustrate the fraction of sunlight due to diffusion and scattering from the cloud. Both direct and indirect components can be assessed, combining the module's total incident effective irradiance. Furthermore, yearly energy yield and BG can be obtained from this modelling tool (Mermoud and Wittmer, 2018; Varun and Manikandan, 2020).

During the experimental measurement, GHI, ambient temperature, and module surface temperature were recorded in 60s intervals. The data were further processed and input into typical meteorological year (TMY) data of Hong Kong developed by City University (Chan et al., 2006). The installation parameters, including module height, albedo, tilt angle and module specification, were collected as input data for simulation variables. Weather data of the simulation model are shown in Figure 6. Also, a six-storey building was developed to investigate the energy performance of a BPV system installed on the roof. Figure 7 shows the virtual image of a building with different PV system configurations.

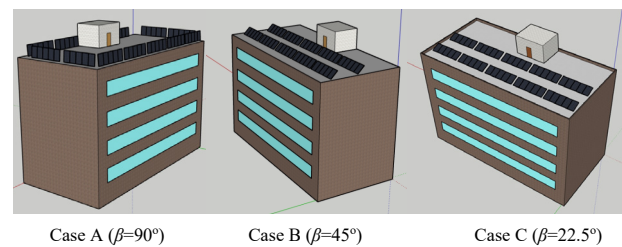


Figure 7. The virtual image of a building with different PV system configurations.

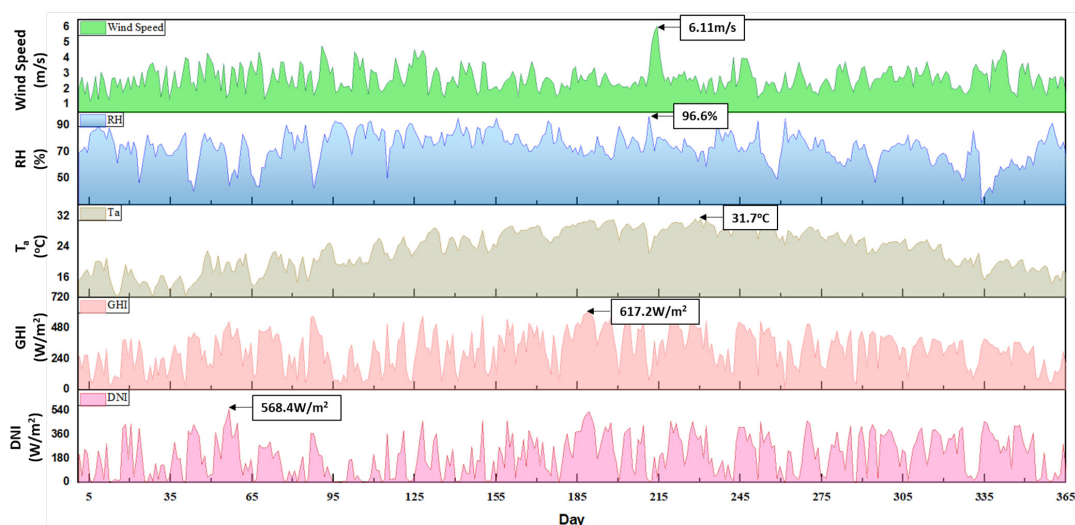


Figure 6. TMY weather data in Hong Kong.

In PVsyst, the concept of the View Factor is applied to analyse the effective solar irradiance reaching the front side and rear side of BPV modules. This method is recognised as the most common way to simulate bifacial performance. It is necessary to evaluate the total solar irradiance received from the rear side of BPV. The solar irradiance on the BPV module is represented by a View Factor model $F_{s \rightarrow r}$ as follows:

$$F_{s \rightarrow r} = \frac{1}{A_s} \int_{A_s} \int_{A_r} \frac{\cos \theta_s \cos \theta_r}{\pi d^2} dA_s dA_r, \quad (2)$$

$$0 \leq F_{s \rightarrow r} \leq 1, \quad (3)$$

$$\sum_{r=1}^N F_{s \rightarrow r} = 1, \quad (4)$$

$$A_s F_{s \rightarrow r} = A_r F_{r \rightarrow s}, \quad (5)$$

where $F_{s \rightarrow r}$ is the view factor from “a” surface toward “b”; it describes the fraction of flux leaving surface A_s and reaching surface A_r . A_s is the area of sending surface, A_r is the area of receiving surface, and d is the distance between two surfaces. θ_s and θ_r are the angles between the surface normal and viewing direction of the sending/receiving surface respectively.

The total solar irradiance that reaches the rear side is computed by the formula below which is multiplied by the area ratio of the ground area to the PV module area.

$$I_r = I_g F_{g \rightarrow r} \frac{A_g}{A_{pv}}. \quad (6)$$

In the simulation process, it is necessary to input the diffuse solar radiation. However, it is difficult to obtain the diffuse solar radiation data directly from the Pyranometer. Thus, a prediction model is referenced to estimate the direct and diffuse components through regression equations as follows (Lam and Li, 1996):

Table 2. Energy modelling input summary.

K_t region	Whole year	Cooling season
$K_t \leq 0.15$	$K = 0.977$	$K = 0.975$
$0.15 < K_t \leq 0.5$	$I_{dn} = -3581K_t^3 + 5992K_t^2 - 1896K_t + 178$	$I_{dn} = -3240K_t^3 + 5509K_t^2 - 1698K_t + 158$
$0.5 < K_t \leq 0.7$	$K = 1.237 - 1.361K_t$	$K = 1.227 - 1.350K_t$
$0.7 < K_t$	$K = 0.273$	$K = 0.272$

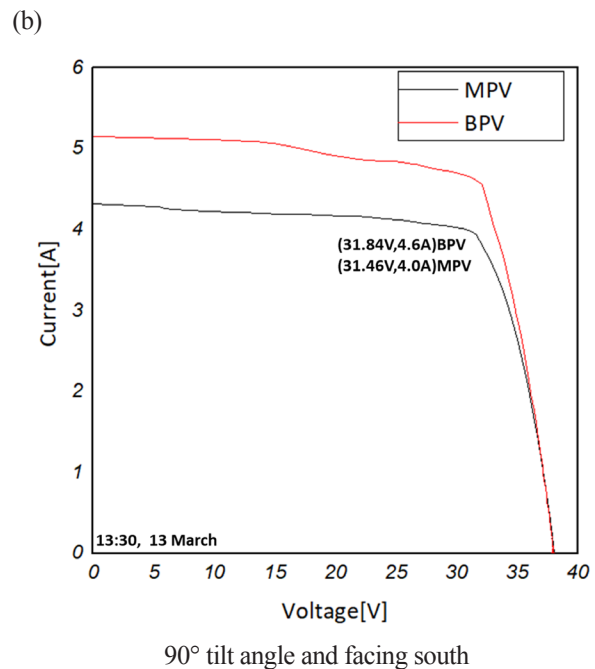
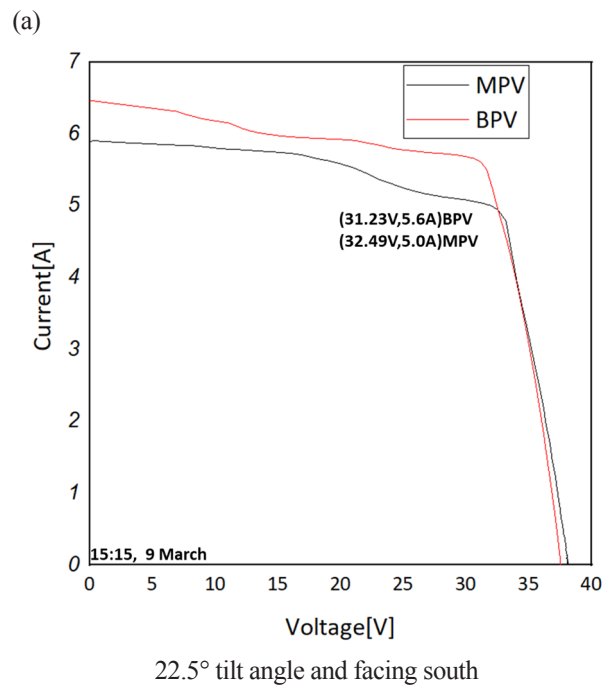
Where K_t is the Clearness index, it represents the global solar radiation/extra-terrestrial solar radiation; K is the diffuse solar radiation/global solar radiation.

3. Results and discussion

In this section, experimental testing results and simulation results of the BPV system are presented. The data collected from the experiments were analysed and the relationship of influencing parameters was investigated and discussed.

3.1. I-V Characteristic of BPV and MPV modules

The I-V curves of the four scenarios (seen Table A8) are illustrated in Figure 8. The power generation and maximum power point of the installed modules were monitored by ECO, MP-11 and 170 I-V checker. The analysis of I-V characteristics is based on the maximum power generation of that day. The I-V status was recorded every 60s. Remarkably, similar I-V curve shapes were obtained for the different setup configurations. It should be noticed that Scenario 2 (90° facing south) has the largest P_{max} difference (up to 16% difference of the electricity generation) which indicates that the orientation is the best location for maximum power generation.



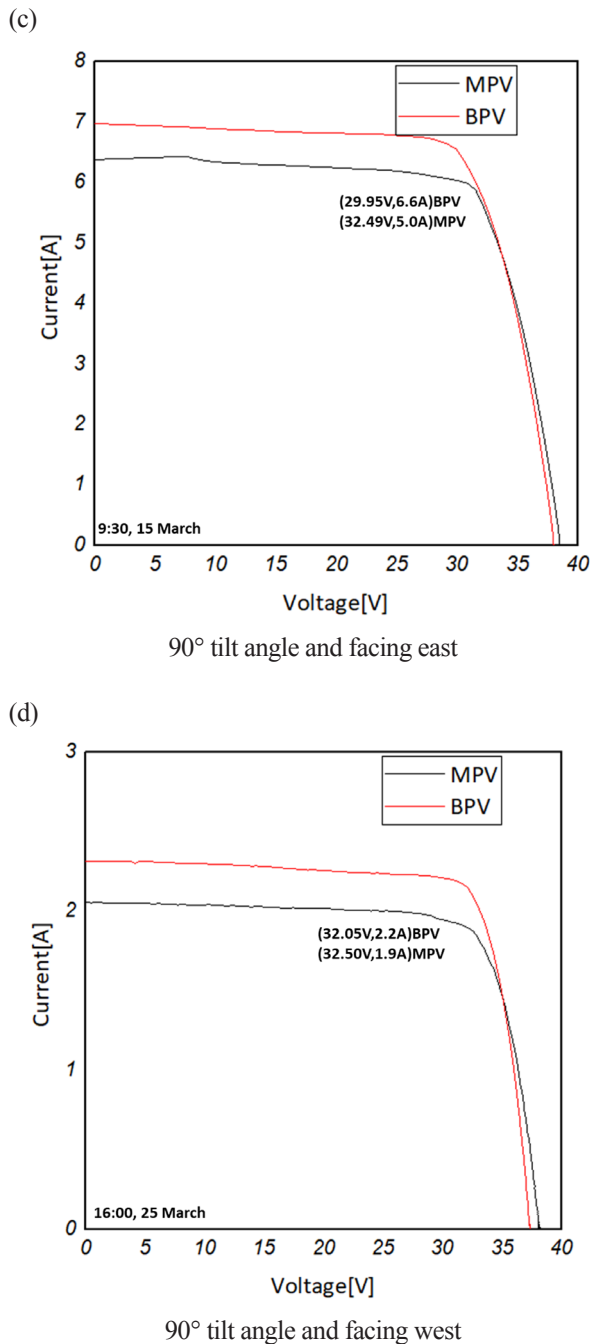


Figure 8. I-V Characteristic comparisons.

3.2. Comparison of the module temperature of BPV and MPV modules

Figure 9 illustrates that the operating temperature of the BPV module is relatively higher than the MPV module by approximately 5 degrees, which is due to additional solar irradiance received at the rear side of the BPV module that increases the module temperature. Although the electricity generation performance of BPV is affected by higher operating temperature, the bifacial gain of BPV can still overcome this shortage. If the tilt angle of the

PV installation increases, the module temperature will be increased because of more incoming sunlight at the back surface. Nonetheless, such effects will not have a significant impact on the energy yield performance, as can be seen from previous I-V characteristic comparisons. Hence, the BPV module always outperforms the MPV module under any circumstances.

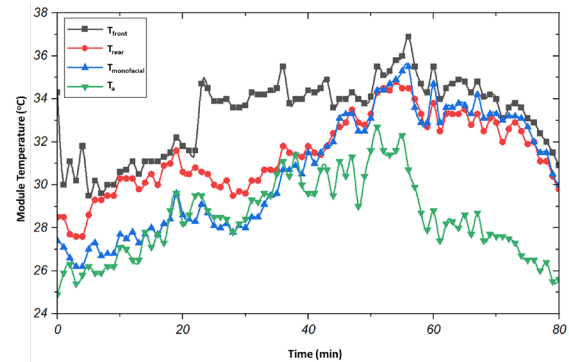


Figure 9. Relationship of the module temperature with time.

3.3. Relationship of the GHI and BG

Considering the measured horizontal irradiance and the measured power output for a 22.5° tilted installation at a height of 0.25 m and ground albedo of 0.3 (the ground was made of concrete, and the ground albedo was set as having an empirical value of 0.3 as suggested by PVsyst) as described in Figure 10. Bifacial gain (BG) of the BPV module was estimated in the range of 0.8-8.6%. It is worth mentioning that the BG exhibits an inverse relationship with global horizontal irradiance. This occurs as a result of the dual side illumination effect of the bifacial solar module which can benefit from diffuse solar radiation even when there are low irradiance conditions.

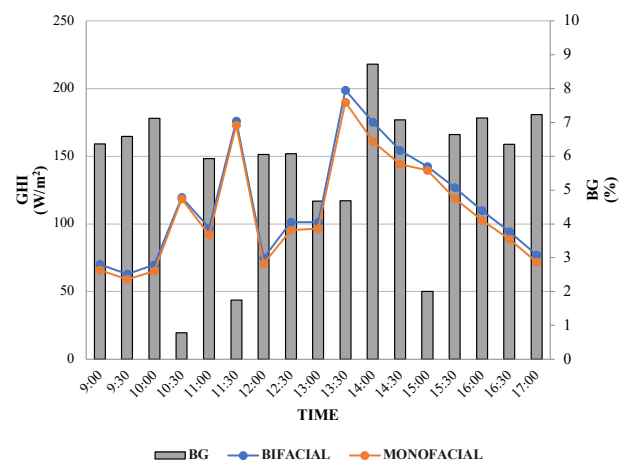


Figure 10. Relationship of the GHI and BG with a 22.5° tilt angle and facing south.

3.4. Relationship of the BG and different orientation/tilt angle

Figure 11 summarises the impact of changing the orientation of PVs. It is observed that the vertical installation facing south would not have a significant benefit with regard to bifacial gain. This is influenced by the climate condition as recorded on 9 March and 13 March which were cloudy days (with low irradiance conditions). It is observed that bifacial gain ranges within 5-12%. It is also noticed that the energy output in scenarios 3 and 4 are encouraging since solar irradiance is absorbed from both sides. There were two daily peaks of electricity generation observed throughout the duration of sunrise and sunset. Direct sunlight will hit the BPV module two times per day. In summary, the obtained results of four scenarios field measurements are presented in Tables A4-A8.

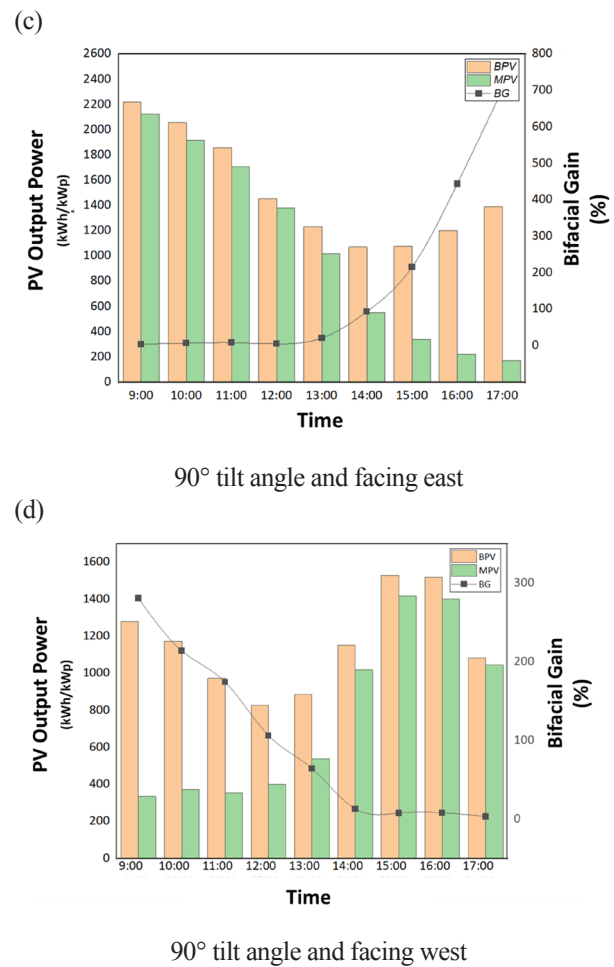
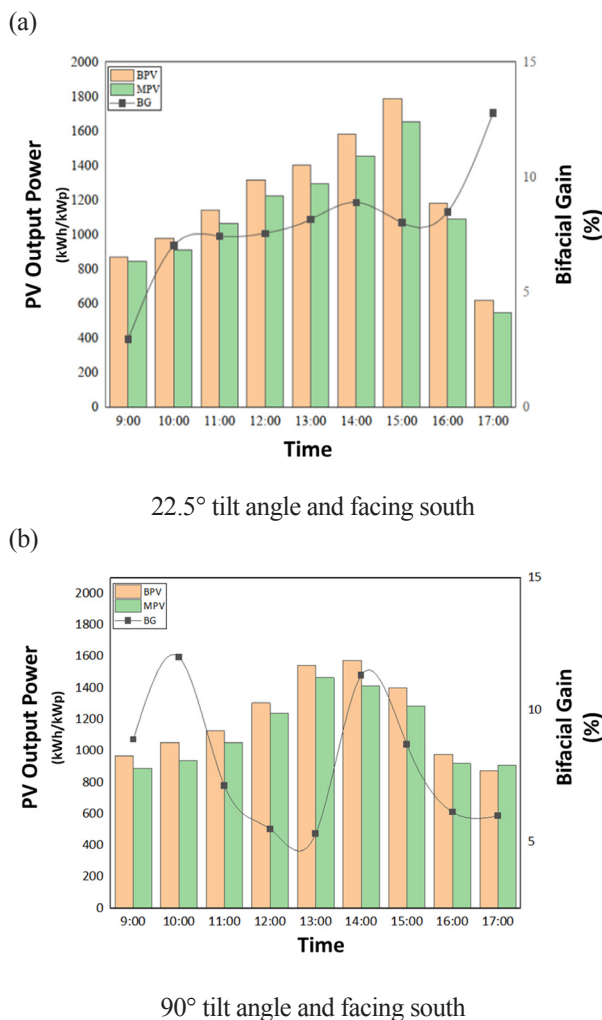


Figure 11. PV hourly output power comparisons.

3.5. Simulation results analysis

TMY weather files were adjusted based on the measured global horizontal irradiance and input into the simulation software, PVsyst. The annual energy yield of the BPV system and MPV system results are presented in Tables 3 and 4 respectively. To compare the simulation results with the field measurement results, PV modules with the same specifications were input into the simulation model. The results show that up to 11.6% of bifacial gain can be achieved for the rooftop PV system. For vertical installations facing east/west, the average daily bifacial gain can reach up to 167%.

Table 3. BPV annual production simulation results.

40 pieces 300 Wp bifacial PV module			
Annual production			
		Output	% Delta
Irradiance (kWh/m ²)	Annual global horizontal irradiance	1305.8	
	POA irradiance	1341.9	2.8%
	Shaded irradiance	1325.5	-1.2%
	Irradiance after reflection	1281.7	-3.3%
	Irradiance after soiling	1256.1	-2%
	Total collector irradiance	1256.3	0.0%
Energy (kWh)	Nameplate	19262.42	
	Output at irradiance levels	18967.75	-1.5%
	Output at cell temperature derate	18068.28	-4.7%
	Output after mismatch	17509.07	-3.1%
	Optimal DC output	17468.29	-0.2%
	Constrained DC output	17468.29	0.0%
	Inverter output	17118.94	-2.0%
	Energy to grid	17033.32	-0.5%
Temperature metrics			
Average operating ambient temperature			23.9°C
Average operating cell temperature			30.9°C
Simulation metrics			
Operating hours			4458

Table 4. MPV annual production simulation results.

40 pieces 315 Wp monofacial PV module			
Annual production			
		Output	% Delta
Irradiance (kWh/m²)	Annual global horizontal irradiance	1305.8	
	POA irradiance	1341.9	2.8%
	Shaded irradiance	1325.5	-1.2%
	Irradiance after reflection	1281.7	-3.3%
	Irradiance after soiling	1256.1	-2.0%
	Total collector irradiance	1256.3	0.0%
Energy (kWh)	Nameplate	17261.29	
	Output at irradiance levels	17039.22	-1.3%
	Output at cell temperature derate	16187.51	-5.0%
	Output after mismatch	15679.86	-3.1%
	Optimal DC output	15657.39	0.1%
	Constrained DC output	15678.69	-0.1%
	Inverter output	15355.96	-2.1%
	Energy to grid	15267.93	-0.6%
Temperature metrics			
Average operating ambient temperature			23.9°C
Average operating cell temperature			29.4°C
Simulation metrics			
Operating hours			4458

Figure 12 presents the annual electricity yield of BPV and MPV systems under three different cases, i.e., tilt angle of 22.5°, 45° and 90°. According to the simulation results, it is noticed that a larger tilt angle results in better bifacial energy performance. The bifacial gain is magnified at larger tilt angles. According to the simulation results, the annual average BG for the three cases is 15.1%, 6.9% and 5.8% respectively. Case A has the largest BG, while Case C has the maximum annual energy yield.

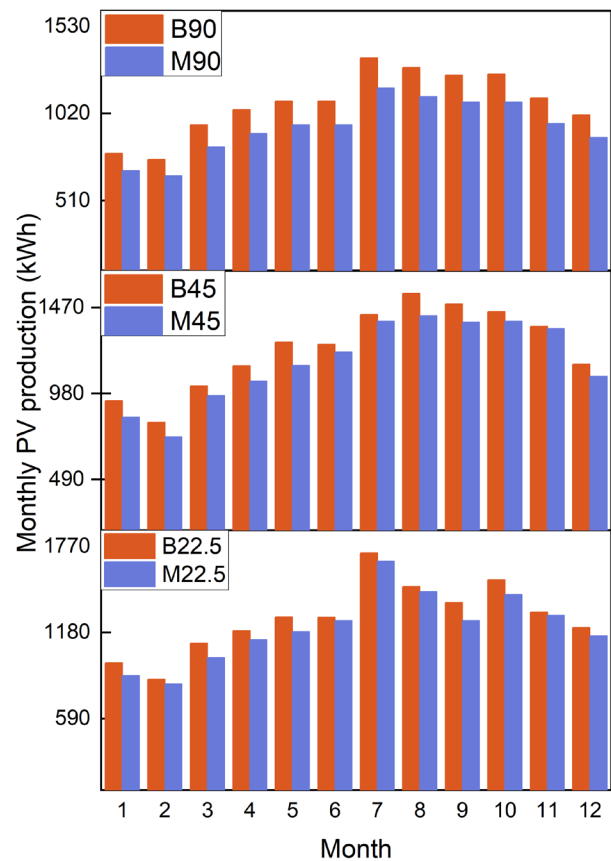


Figure 12. Annual electricity production comparison.

3.6. Comparison of simulation results and experiment results

In order to verify the accuracy of the measurement results, simulation results and measurement results are compared and the deviation between the measurement results and simulation results are shown in Figure 13. The shadow of the supporting structure may cause a significant reduction in energy yield which makes the results deviate from the simulation results. Furthermore, such data with a huge difference are considered to be due to the ambient conditions of the site experiment measurement, and also due to the variation of ground albedo.

As discussed in the introductory section, albedo measurement should be conducted as it will vary throughout the day. So this should be done to further improve the accuracy of the simulation results/measurements results.

To validate the simulation results' accuracy, the Coefficient of Variation Root Mean Square Error (CVRMSE) was estimated using the following equation.

$$\text{CVRMSE}(\%) = \frac{\sqrt{\frac{1}{N} \sum (S_i - M_i)^2}}{\frac{\sum (M_i)}{N}}, \quad (7)$$

where N is the number of data, S_i is the simulation results

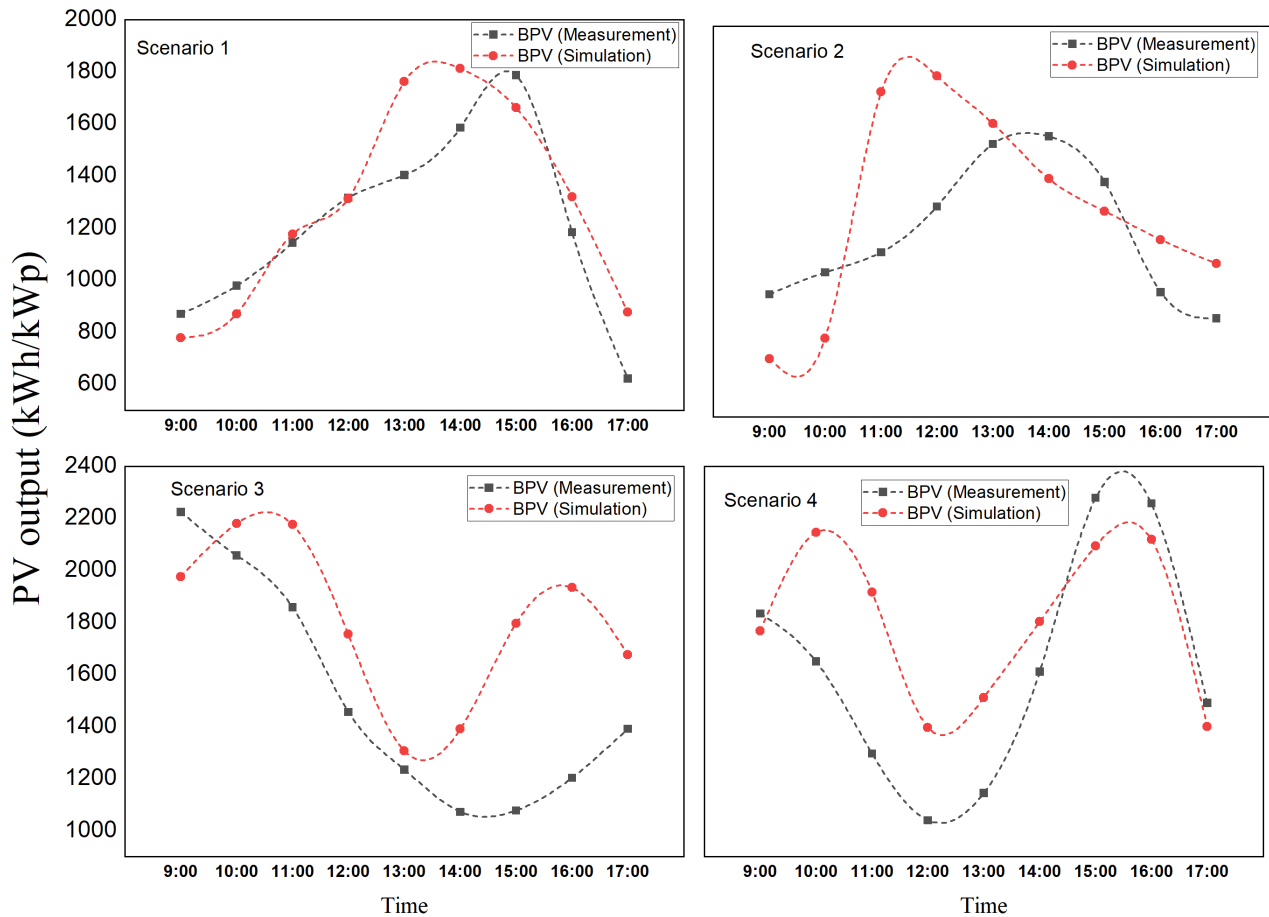


Figure 13. Hourly output power comparison of the simulation results and experiment results.

from PVsyst, and M_i is the measurement results. Energy simulation modelling errors are summarised in Table 5.

Table 5. CVRMSE of energy simulation model under different scenarios.

Scenario	Simulated average BPV output (kWh/kWp)	Measured average BPV output (kWh/kWp)	Coefficient of Variation Root Mean Square Error (%)
Scenario 1	1285.5	1210.0	14.5%
Scenario 2	1297.7	1205.3	23.7%
Scenario 3	1798.1	1508.0	22.5%
Scenario 4	1256.8	1159.2	15.0%

It is shown in Table 5 that the Coefficient of Variation is lower than 24%, which is basically satisfactory in this work. The relative error of simulation results in Figure 14 is also shown. As can be seen in the figure, the relative error of most data is within $\pm 25\%$, and the simulation values are relatively high as compared with the experimental values. A possible reason for this is that the ground albedo may be overestimated. To improve the accuracy of the model, the ground albedo should be more accurately measured. Also, more accurate models, such as the anisotropic diffuse models for the rear side, will be considered in future work.

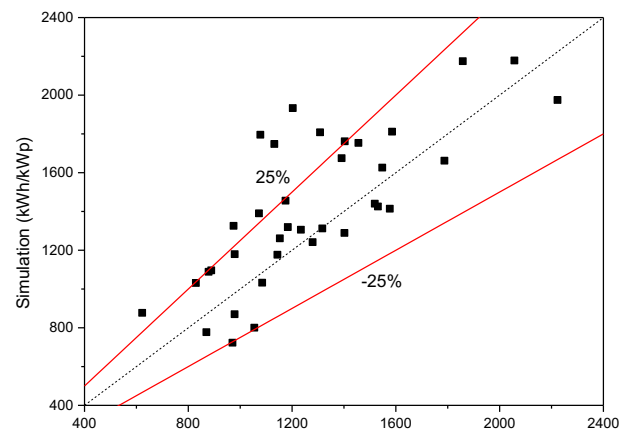


Figure 14. Relative error of simulation results.

4. Conclusion

The potential of the Bifacial PV system in Hong Kong is explored. The BPV system is perceived to be an encouraging solar power generation technology that can implement more renewable energy with limited land. Both the experiment's measurement results and simulation results reveal that the average bifacial gain of the BPV

module with a south-facing orientation is 7.9% and 11.6% respectively. If the BPV module is installed vertically and facing east or west, the bifacial gain can reach a minimum of 8% and a maximum of 167% even when the ground albedo is low (0.3). If we further improve the ground albedo by painting the roof white, it can increase the annual electricity yield. This study newly examined the BPV application through outdoor measurements and simulation. The results indicate that the BPV system seems to be a viable option over MPV.

Remarkably, the shading effect due to supporting structures, aluminium frame and internal shading effect needs to be investigated in the future as it has a huge impact on the energy production and accounts for bifacial technology's feasibility study. Thus, in the future study, the mutual shading effect on the PV string connection with field measurement will be considered to obtain a more precise result. A deeper understanding of the PV array installation due to the shading effect is recommended.

Appendix A: Experimental data record

Table A1. Experimental setup of different design configurations.

Date	Tilt angle	Mounting height	Orientation	Albedo
5 January	15°	0.25 m	Facing south	0.3 (Concrete)
6 January	30°	0.25 m	Facing south	0.3 (Concrete)
7 January	90°	0 m	Facing south	0.3 (Concrete)
13 January	22.5°	0.25 m	Facing south	0.3 (Concrete)
9 March	22.5°	0.25 m	Facing south	0.3 (Concrete)
13 March	90°	0 m	Facing south	0.3 (Concrete)
15 March	90°	0 m	Facing east	0.3 (Concrete)
23 March	40°	0.25 m	Facing south	0.3 (Concrete)
25 March	90°	0 m	Facing west	0.3 (Concrete)

Table A2. Instrument range and accuracy.

Measurement type	Equipment	Model	Measurement range	Accuracy
GHI, Albedo	Pyranometer	EKO MS-802	0-4000 W/m ²	±0.23%
Ambient/ Module temperature	Thermocouple	CRZ-1632R-100-1/3B	-20 - 150°C	±0.4%
I-V characteristics & energy yield	I-V Checker	EKO MP-11	10-1000 V 0.1-30 A	±1%
		EMO MP-170	10-1000 V 0.1-10 A	±1%

Table A3. Summary of all the assumptions made during the energy modelling.

Description	Condition set 1											
Weather dataset	TMY, Hong Kong, CityUHK-45007 (epw)											
Solar angle location	Meteo Lat/Lng											
Transposition model	Perez Model											
Temperature model	Sandia Model											
Temperature model parameters	Rack type	a			b			Temperature delta				
	Fixed tilt	-3.56			-0.075			3°C				
	Flush mount	-2.81			-0.0455			0°C				
Soiling (%)	J	F	M	A	M	J	J	A	S	O	N	D
	2	2	2	2	2	2	2	2	2	2	2	2
Irradiation variance	5%											
Cell temperature spread	4°C											
Module binning range	-2.5% to 2.5%											
AC system derate	0.5%											
Module characterisations	Module 1						Module 2					
	JAM60S01-315/PR (MPV)						LR6-60BP-300M (BPV)					

Table A4. Hourly output power of 22.5° tilt angle and facing south.

Tilt angle	Mounting height	Orientation	Albedo
22.5°	0.25 m	Facing south	0.3 (Concrete)
Hour	9 March	MPV output (kWh/kWp)	BPV output (kWh/kWp)
	9	844.62	869.73
	10	914.16	978.43
	11	1064.28	1143.48
	12	1223.92	1316.49
	13	1297.2	1403.09
	14	1455.69	1585.36
	15	1654.31	1787.14
	16	1091.05	1183.69
	17	551.62	622.18

Table A5. Hourly output power of 90° tilt angle and facing south.

Tilt angle	Mounting height	Orientation	Albedo
90°	0 m	Facing south	0.3 (Concrete)
Hour	13 March	MPV output (kWh/kWp)	BPV output (kWh/kWp)
	9	891.05	970.34
	10	941.33	1054.38
	11	1056.14	1131.62
	12	1239.52	1307.78
	13	1469.17	1547.58
	14	1416.43	1576.79
	15	1289.45	1401.81
	16	922.13	978.87
	17	828.53	878.32

Table A6. Hourly output power of 90° tilt angle and facing east.

Tilt angle	Mounting height	Orientation	Albedo
90°	0 m	Facing south	0.3 (Concrete)
Hour	MPV output (kWh/kWp)	BPV output (kWh/kWp)	Bifacial gain (%)
9	2125.71	2223.12	4.58
10	1919.54	2057.00	7.16
11	1710.63	1858.08	8.62
12	1381.94	1455.80	5.34
13	1018.86	1233.92	21.11
14	553.37	1072.32	93.78
15	340.80	1077.72	216.23
16	220.91	1202.68	444.41
17	173.37	1391.04	702.35

Table A7. Hourly output power of 90° tilt angle and facing west.

Tilt angle	Mounting height	Orientation	Albedo
90°	0 m	Facing south	0.3 (Concrete)
Hour	MPV output (kWh/kWp)	BPV output (kWh/kWp)	Bifacial gain (%)
9	335.79	1279.20	280.95
10	373.96	1174.80	214.15
11	355.13	974.40	174.38
12	401.67	829.20	106.44
13	539.90	888.40	64.55
14	1018.97	1152.80	13.13
15	1417.08	1530.80	8.02
16	1401.61	1518.80	8.36
17	1046.94	1084.80	3.62

Table A8. Summary of hourly output power of four scenarios.

Date	Tilt angle	Mounting height	Orientation	Scenario	Average bifacial gain
9 March (Cloudy)	22.5°	0.25 m	Facing south	Scenario 1	7.9%
13 March (Cloudy)	90°	0 m	Facing south	Scenario 2	7.9%
15 March	90°	0 m	Facing east	Scenario 3	167%
25 March	90°	0 m	Facing west	Scenario 4	97%

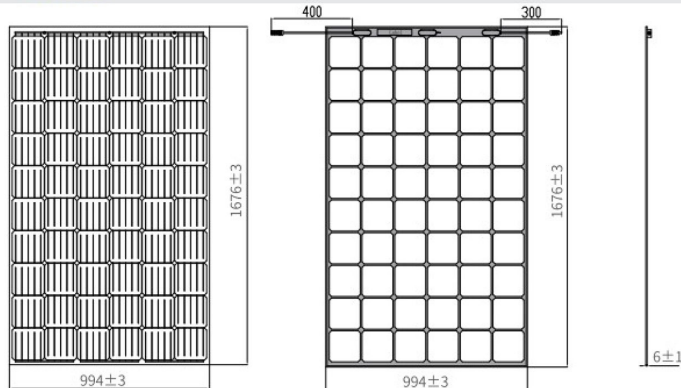
Appendix B: Bifacial module catalogue

LR6-60BP 290~310M

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Figure B1. Module 1– Bifacial (Framed).

工程图纸



产品规格

电池类型	单晶
组件重量	23.3kg±3%
组件尺寸	1676±3mm×994±3mm×6±1mm (含接线盒厚度25mm)
线缆截面积	4mm ²
电池片数量	60(6x10)
接线盒	IP68, 3个二极管
连接器	QC 4.10-35
包装信息	32块每托

STC下的电性参数

型号	JAM60D09 -305/BP	JAM60D09 -310/BP	JAM60D09 -315/BP	JAM60D09 -320/BP	JAM60D09 -325/BP
最大功率 (Pmax) [W]	305	310	315	320	325
开路电压 (Voc) [V]	40.01	40.27	40.53	40.79	41.05
最大功率点的工作电压 (Vmp) [V]	32.68	32.97	33.23	33.49	33.75
短路电流 (Isc) [A]	9.87	9.94	10.01	10.09	10.16
最大功率点的工作电流 (Imp) [A]	9.34	9.41	9.48	9.56	9.63
组件效率 [%]	18.3	18.6	18.9	19.2	19.5
功率公差 (正面)	0~+5W				
短路电流温度系数 (α _{Isc})	+0.060%/°C				
开路电压温度系数 (β _{Voc})	-0.300%/°C				
最大功率温度系数 (γ _{Pmp})	-0.370%/°C				
标准测试条件 (STC)	辐照度1000W/m ² , 电池温度25°C, 光谱AM1.5G				

注: 在该产品目录中的电性能参数并不单指一块组件, 也并不是合约中承诺内容。电性参数只用做不同组件类型间比较之用。
组件在低辐照光强下的输出效率是标准光强下输出效率的98%。
*背面率=背面STC峰值功率/铭牌标称功率

Figure B2. Module 2 – Bifacial (Frameless).

Appendix C: Experiment equipment for measurement

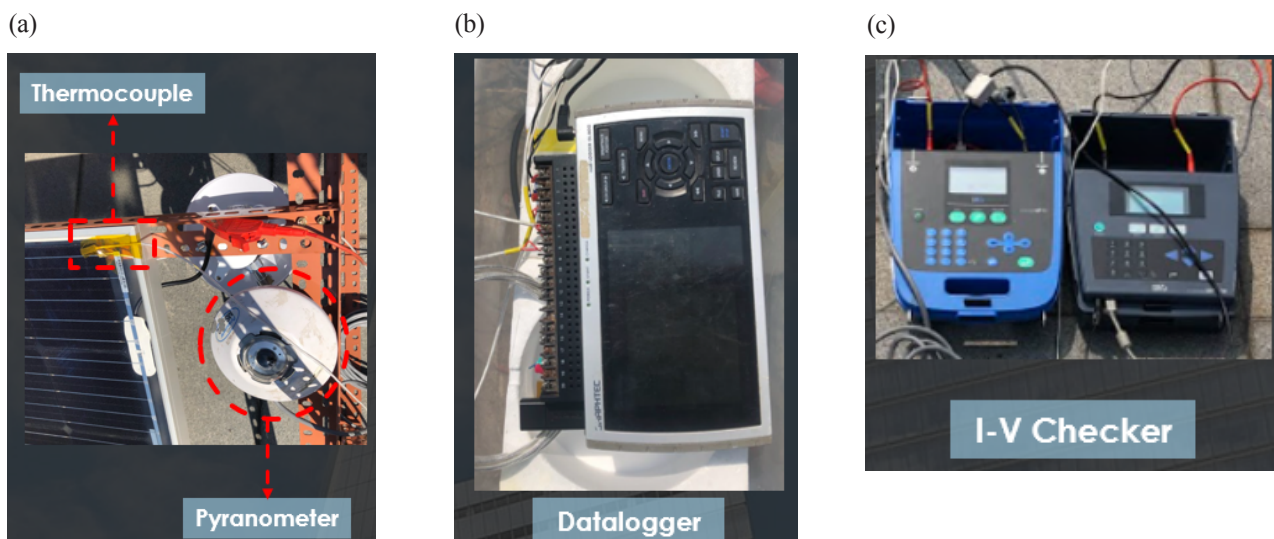


Figure C1. Experimental equipment used during the experiment.

(a)



(b)



Figure C2. Photos of experimental installations and measurements: (a) Vertical installation; and (b) inclined installation.

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