Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: D-102

Experimental investigation on the performance evaluations of the bifacial photovoltaic modules

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ABSTRACT

Bifacial photovoltaic (bPV) technology can output more power than conventional mono-facial PV (mPV) technology by absorbing sunlight from both sides, which attracts increasing attention and its market share is predicted from 15% in 2019 to 70% in 2030. However, there are still no unified plans on what type of the mPV modules should be taken as reference. Therefore, in this study, the similar structure (double glass) of bPV and mPV modules are employed not only validate the previous numerical simulation results, but also to estimate the bPV performance. Furthermore, the daily bPV and mPV electrical and thermal performance is measured and compared under the same conditions. Results show that the bPV modules obviously outperform the mPV modules, and the average bifacial gain can be up to 17.33%. At the same time, the bPV module is cooler than the mPV due to the absence of the back surface field. In addition, some important factors on the bPV performance are discussed by simulation. Results indicates that it is better to install a bPV module with high albedo, elevation, tracking technology at an optimum tilt angle to obtain high power output.

Keywords: Bifacial photovoltaic (bPV) modules; Experimental investigation; Performance estimations; Bifacial gain

NONMENCLATURE

Abbreviations	
bPV	Bifacial photovoltaic
DHI	Diffuse horizontal irradiance
GHI	Global horizontal irradiance
MPP	Maximum power point
mPV	Mono-facial photovoltaic
PV	Photovoltaic
Symbols	
E_p	Elevation
I	Current
N_s	Cell numbers connected in a module
P	Power
T	Temperature
u_w	Wind speed
V	Voltage
Y	Energy yield
Superscripts	
a	Ambient
c	Cell
F	front side
mpp	Maximum power point
oc	Open circuit
R	rear side
ref	Reference conditions, i.e. standard test conditions
sc	Short circuit
Greek symbols	
α	Current temperature coefficient
β	Voltage temperature coefficient
β_p	Photovoltaic panel tilt angle
γ	Power temperature coefficient
γ_p	Photovoltaic panel azimuth angle
ρ_p	Ground albedo

1. INTRODUCTION

Energy is rather crucial to supply people with plenty of cool, heat and electricity, which can be produced by

Selection and peer-review under responsibility of the scientific committee of CUE2020

various fossil energy. However, the world is facing energy crisis, global warming and air pollution due to the burning of the fossil energy [1]. Faced with these urgent challenges, utilization of renewable energy resources are regarded as a promising alternative, especially photovoltaic (PV) systems due to the abundance of solar energy. The global PV circulative installation has expanded to 627 GW at the end of 2019 [2]. The PV module can be classified into mono-facial PV (mPV) and bifacial PV (bPV) according to the receiving method. Besides lower LCOE, the bPV modules have longer lifetime than the traditional mPV module due to special glass-glass structure. In addition, bPV modules are more flexible and widely-used in some special conditions, such as noise barriers [3] and the facade of a building [4].

Under these circumstances, the fascination of PV market and academic circles has turned from mPV to bPV, whose market is predicted from 15% in 2019 to 70% in 2030 [5].

The history of bPV technology is apparently short, but the first work can date back to a patent of Hiroshi in 1966 [6], followed by some articles about efficiency calculation and applications. The bPV field began to boom from 2009, as renewable energy demand increases, especially from China, USA, Germany and Japan. Various mathematical models were developed to estimate the bPV performance. Bifacial gain of 30% is achievable by estimation of Sun et al. [7] when the albedo and elevation is 0.5 and 1 m ,respectively. More power output contributes to 2-6% lower Levelized Cost of Energy (LCOE) [8] at high latitude. Besides numerical simulation, a series of filed experiments were also undertaken to compare the bPV performance with the mPV [9]. Stein et al. [10] installed bPV modules in convectional PV systems under various installation conditions for exploring the effects of tilt angles, heights, orientations, and track methods on the bPV performance. Results show that bPV modules obviously outperform mPV modules and performs better with the high albedo and low ground shading. Bifacial gains of 15% and 30% on sandy and snowy land also indicate that albedo has positive effect on the high power output gain [11]. Numerous similar bPV technology research studies, including simulation and experiments, about have been done in scientific circles. However, there are still no unified plans on what type of the mPV modules should be taken as reference. Therefore, in this study, the similar structure (double glass) of bPV and mPV modules are employed not only validate the previous numerical simulation results, but also to estimate the bPV performance. In addition, the daily bPV and mPV performance is measured and compared under the same conditions. Furthermore, some important factors on the bPV performance are also discussed.

2. METHOD

2.1 Experiment setup

It is significant to set up the bPV experiment, which can be used not only to estimate the bPV performance, but also validate the bPV mathematic models, namely the optimal model, electrical model and thermal model. Fig. 1 presents a framework for simulating the bPV performance, in which view factor model, 5-parameter model and heat transfer network is employed in optical, electrical and thermal models, respectively [12]. Weather parameters and installation parameters are the inputs of the framework. Onsite weather parameters includes global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), ambient temperature (T_a) and wind velocity (u_w), which can be obtained from some meteorological data companies, such as SolarGIS [13] or calculated simply from clear sky model [14]. Installation parameters consist of tilt angle (β_p), azimuth angle (γ_p), elevation (E_p) and albedo (ρ_p).

Weather and installation parameters are input into the optical model to calculate the front- and rear-side irradiances, which are combined with ambient temperature T_a and wind velocity u_w in thermal model to obtain cell temperature T_c. Combined together, the outputs of the optical model and thermal model are fed as input to the electrical model, and lastly the bPV power output can be obtained [7].

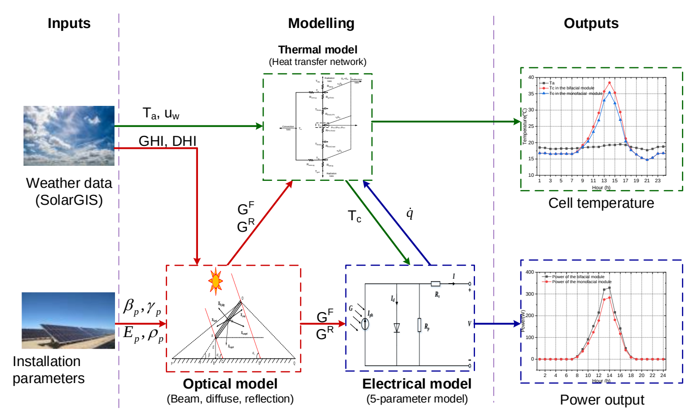

Fig. 1 A framework for simulating the bPV performance [12].

In the experiment, a bPV module and a mPV module as the reference module are installed on the roof as shown in Fig. 2.

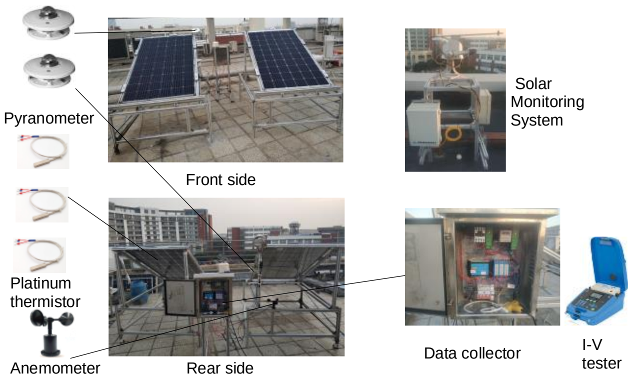

Fig. 2 Configuration of the bPV experimental system.

Key parameters of the bPV and mPV modules under standard test conditions in the experiment are listed in Table 1, which can be obtained from the manufacturer. For simplification, all PV modules are assumed to be under the same working conditions, namely at maximum power point (MPP) all the same.

Table 1 Key parameters of PV modules.

Specification	bPV		mPV
Side	Front side	Rear side	/
$V_{oc,ref}$	39.92 V	39.54 V	39.92 V
$I_{sc,ref}$	9.73 A	7.83 A	9.78 A
$V_{mpp,ref}$	32.73 V	32.35 V	32.73 V
$I_{mpp,ref}$	9.32 A	7.05 A	9.32 A
$P_{mpp,ref}$	305 W	228 W	305 W
α	0.0282 %/℃		0.027 %/℃
β	0.281 %/℃		0.286 %/℃
γ	0.397 %/℃		0.39 %/℃
N_s	60 (6×10)		
Dimension	156.75 mm×156.75 mm		

2.2 *Performance index*

The concept of bifacial gain, relative percentage of bPV module energy yield compared with mPV under the same conditions is often employed to show the bPV advantage in bPV field as presented in Eq. (1):

$$\text{Bifacial gain (\%)} = (Y_{bPV} - Y_{mPV}) / Y_{mPV} \times 100 \tag{1}$$

where Y_{bPV} and Y_{mPV} is energy yields of bPV and mPV modules, respectively.

Experimental results are widely-used to validate the related mathematic models with some performance indexes, especially the coefficient of determination (R^2) as is presented as Eq. (2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - f_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{2}$$

where y_i is the measured data, $\bar{y}$ is the average value of total measured data, and f_i is the model simulated data. It can be seen that the smaller these values are, more accuracy the proposed models are.

3. RESULTS AND DISCUSSION

3.1 *Validation*

For validation, the linear relationships between the measured power and simulated power for bPV and mPV modules are presented in Fig. 3. It is obvious that all points are closely attached along the y=x line, and the slope of the fitting curve is 0.96 and 0.89 for bPV and mPV modules (R^2 is 0.98 and 0.96), respectively, meaning that there was a very good linear correlation between simulated power and the measured one. It is noted that there are some deviating points at near 150 W, which can be accounted for the rapid change irradiance under the fluctuated cloudy day [15].

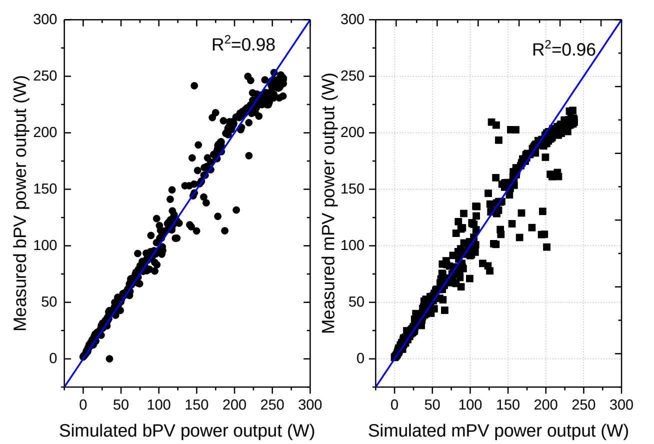

Fig. 3 Validation of bPV and mPV performance.

3.2 *Daily performance*

To characterize the daily bPV performance on the day, mPV is taken as a reference module as presented in

Fig. 4. It can be seen that the bPV module obviously produces more electricity than the mPV due to receiving the sunlight from both sides.

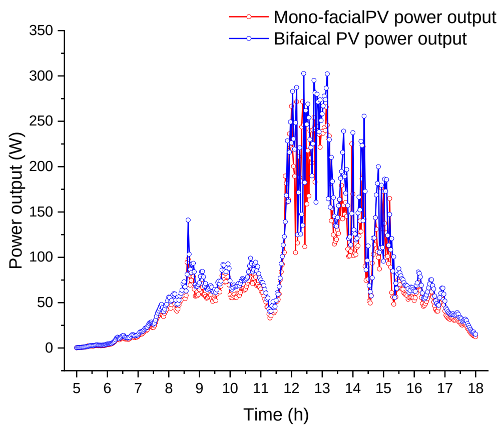

Fig. 4 Power output of mPV and bPV modules on the day.

For better characterization, bifacial gain versus time is presented in Fig. 5 to show the advantage of bPV technology. The bifacial gain is fluctuated and ranged from 0-40% on the day. The average bifacial gain is up to 17.33%.

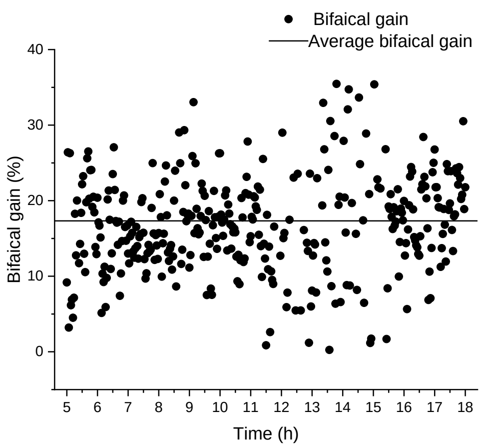

Fig. 5 The bifacial gain of the bPV module on the day.

Apart from electrical performance, bPV and mPV thermal performance cannot also be neglected, which can be represented as cell temperature. It can be noted from Fig. 6 that the bPV cell temperature is lower than the mPV although the former receives more irradiance than the latter. This phenomena can be accounted for the reason that there is a layer of back surface field behind the mPV cell, resulting in that high percentage of absorbed sunlight and the rise of cell temperature.

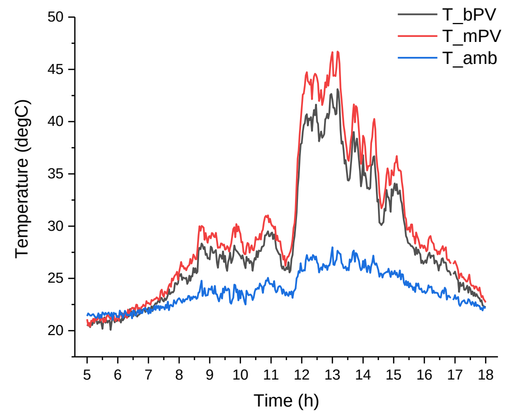

Fig. 6 Ambient temperature and PV cell temperature.

3.3 *Parametric analysis*

As Fig. 7 shows, the bPV performance is affected by various factors, which can be divided into three categories, namely bifacial technology, local meteorological and geographical information (sun position, soiling, shading, diffuse coefficient, and ground albedo) and installation information (orientation, tilt angle, row distance, and module elevation). In this subsection, some of them will be discussed by simulating method in detail.

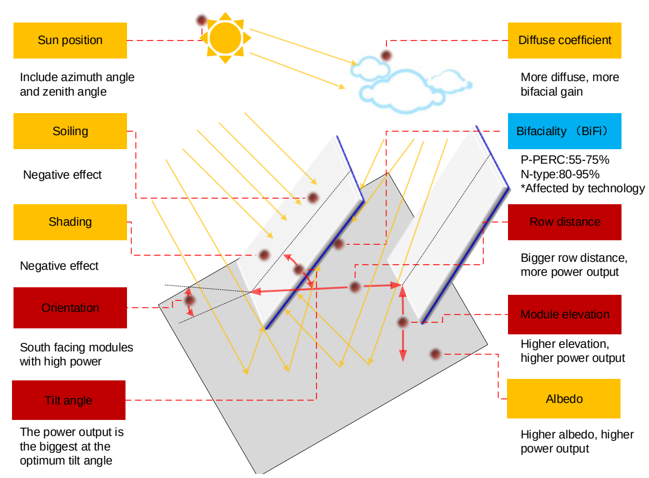

Fig. 7 Various factors on the bPV performance.

3.3.1 *Albedo*

To investigate the effect of albedo on the bPV performance, the albedo value ranges from 0.1 to 0.9 with interval of 0.2 as presented in Fig. 8. It can be seen that albedo has a strong positive effect on the rear irradiance, resulting in that bPV energy yield grows linearly with the increasing of albedo. Therefore, the bifacial gain also faces linear growth under almost constant front irradiance, indicating that the bPV module can take advantage of its property to output more electricity in the areas with higher albedo, such as snowy and white painted field.

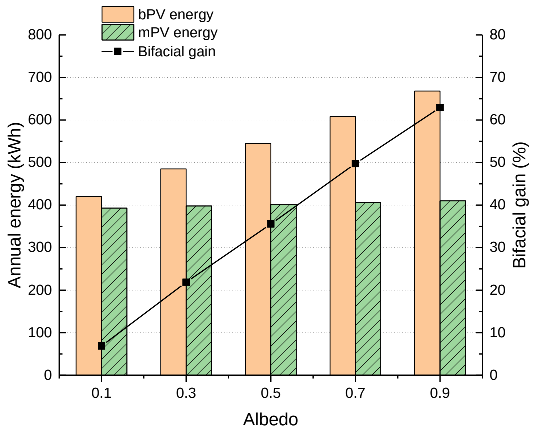

Fig. 8 The effect of ground albedo on the PV performance.

3.3.2 *Orientation*

Bifacial PV performance also varies with the orientation greatly as the received irradiance on the bPV panel is affected (Fig. 9). It is known that tracking technology is good for more power output than the fixed because of more received irradiance. However, tracking technology has deeper effect on front-side irradiance than the rear-side, resulting in lower bifacial gain with a tracking system. For the fixed one, the PV modules facing south can obtain higher energy yield. When facing east or west, the modules produce a little lower energy yield, but with higher bifacial gain, indicating that bPV technology is more flexible compared with the mPV.

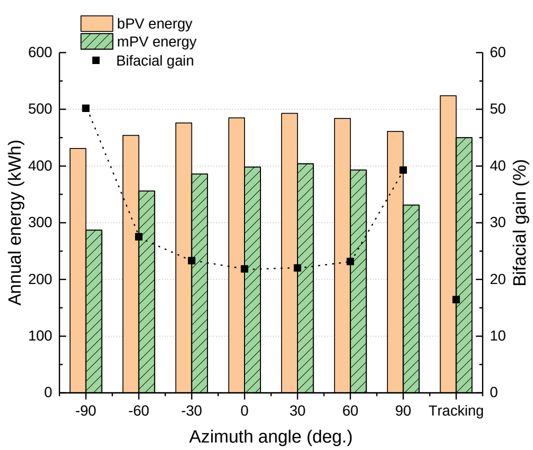

Fig. 9 The effect of orientation on the PV performance.

3.3.3 *Tilt angle*

Besides albedo, tilt angle also affects bPV performance greatly as presented in Fig. 10. The annual energy generation of the bPV and mPV modules increases slightly until optimal tilt angles and then decreases sharply. It is noted that the bPV optimal angle is larger than the mPV under the same weather and installation conditions [7, 8]. Tilt angle has less effect on the rear-side energy yield compared to the front-side. This is due to negligible effects on the diffuse and reflected irradiances from the sky and ground, demonstrating total bifacial energy yield with less reduction and corresponding continuous increase in bifacial gain. It is highlighted that high bifacial gain at a large tilt angle can account for the fact well that vertical bPV technology is more recommended in some building and transportation scenarios, such as for the facade of a building and for noise barriers.

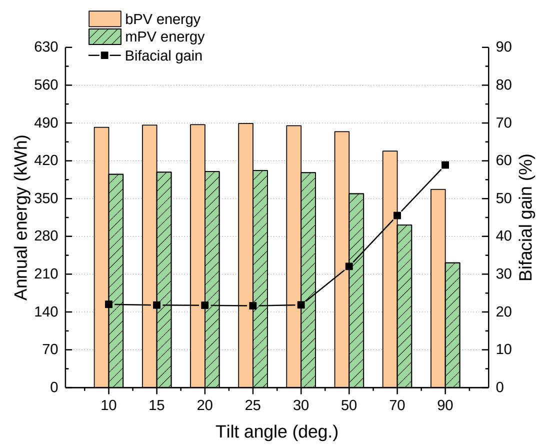

Fig. 10 The effect of tilt angle on bPV and mPV performance.

3.3.4 *Elevation*

Elevation also affects the bPV performance by affecting the rear irradiance as presented in Fig. 11. Due to more reflected irradiance from the ground and less self-shading, bifacial energy yield and bifacial gain accelerate at high elevation, but with a small growth rate. Therefore, it is usually suggested to set the elevation of the bPV modules as 0.5- 1.5 m above ground level, to comprise electrical gain with the size of space.

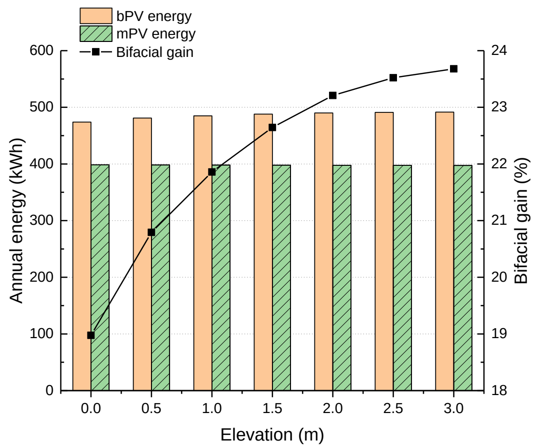

Fig. 11 The effect of elevation on bPV and mPV performance.

4. CONCLUSIONS

In this study, some mathematic models and experiment setup for estimating the bPV performance are described. The daily bPV performance is measured and the mPV performance is taken as a reference. In addition, some important factors, including ground albedo, tilt angle, elevation and orientation on the bPV performance are discussed. The main conclusions are listed as below:

- The bPV modules obviously outperform the mPV modules, and the average bifacial gain is 17.33%.
- The bPV cell is cooler than mPV cell due to the absence of back surface field.
- It is recommended to install a bPV module with high albedo, elevation, tracking technology at an optimum tilt angle to obtain high power output.

ACKNOWLEDGEMENT

The authors would appreciate the financial supports provided by National Natural Science Foundation of China (NSFC) through the Grant No. 51976124 and Shenzhen Technology Innovation Commission (STIC) through the Grant No. JSGG20180504165907910.

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