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Optical enhanced effects on the electrical performance and energy yield of bifacial PV modules

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ABSTRACT

In contrast to the conventional monofacial photovoltaic (PV) modules, bifacial PV modules yield more electrical energy by utilizing the reflected or scattered light from the ground and surroundings. The energy generation efficiency of bifacial modules is determined by both the front-side and the rear-side output power. In this study, we compared the IV parameters as well as field performance of different module structures to further realize the influencing factors dominating the energy gain of bifacial modules. Our results show that the glass/glass bifacial modules encapsulated with bifacial solar cells provide over 6% more energy yield compared to the glass/backsheet monofacial modules encapsulated with regular monofacial solar cells. Due to optical enhanced effects of a reflective coating on the rear glass, the energy yield gain of bifacial modules can be increased to above 10%, even though the bifaciality factors were reduced from 72% to 64%. Our study indicates that enhancing the front-side output power of bifacial modules produces more benefits.

1. Introduction

The solar cells with bifacial nature have long been regarded as an effective way to boost power generation by utilizing diffused, scattered and reflected light available to the rear side of field-deployed PV modules assembled with such cells (Guerrero-Lemus et al., 2016). Compared to the standard monofacial PV modules, the regular backsheet is replaced by glass or transparent backsheet in fabrication of bifacial PV modules (Arihara et al., 2018). The back side of the solar cells harvests the albedo through the glass or transparent backsheet with an open metallization grid, which used to be considered as the inherent properties of n-type solar cells. Nowadays the passivated emitter and rear cell (PERC) has become the prevailing technological approach dominating the PV industry (Dullweber et al., 2018), its passivation structure on cells backside also affords them to be made as bifacial cells to have the power output from the backside on module level.

The energy yield gains of bifacial PV modules have been well investigated by researchers via the experimental and simulation studies (Asgharzadeh et al., 2018; Janssen et al., 2015; Liang et al., 2019). In general, installation parameters, such as tilt angle, clearance from the ground, albedo, affect the actual outdoor performance of the bifacial modules (Wang et al., 2015; Yusufoglu et al., 2014). As for the bifacial modules, the rear side power is the key parameter in determining the energy gains, and the index of bifaciality factor (Zhu et al., 2019) is usually used to evaluate the ability of getting extra gain of bifacial modules. Basically, bifaciality factor is an intrinsic property of the cell technology with rear side partially shaded, its module level magnitude is dominated by cell structures, however, different module designs can also lead to different module bifaciality factors with the same cells.

Normally, the bifacial PV modules with the same front-side power and higher bifaciality factors could generate more electrical energy under the same system installation conditions due to the higher conversion efficiency of the back side. When developing the bifacial solar cells or modules, it is reasonable to pursue higher bifaciality factors. However, it should be noted that the way which leads to high output power of the rear side may reduce the output power of the front side. For example, in absence of the internal reflection through the backsheet, the front-side power of glass/glass bifacial modules will be lower than that of glass/backsheet monofacial modules due to the transmittance loss on cell-gap area (Singh et al., 2015). A reflective coating on the rear glass reported in the literature (Min et al., 2017) could improve the front-side power by enhancing optical performance of bifacial modules. But the

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bifaciality factor decreases more or less due to the shading effect on the rear-side surface of bifacial solar cells caused by the reflective coating on rear glass.

Few studies have discussed how to balance the front-side and rear-side power of bifacial modules during the design and manufacture of bifacial PV products. We have been studying the influence of different optical structures on the electrical performance, such as rated power and the bifaciality factors. The field performance of two types of bifacial modules and monofacial reference modules installed in a test field side-by-side are compared to better understand the energy yield of bifacial modules which is related to the electrical performance. The rear-side irradiance influence on bifacial modules is also investigated to further realize the energy gain induced by bifacial design.

2. Experimental

2.1. Bifacial cells and modules

As shown in Fig. 1, p-type PERC cells have two types of electrodes on the backside, which lead to monofacial (Fig. 1a) and bifacial (Fig. 1b) schemes, respectively. Before the metallization, 156 × 156 mm^2 silicon wafers were processed following exactly the same process steps consisting of alkaline texturing, $POCl_3$ diffusion, passivation layers deposition on both sides and laser ablation on the backside (Wu et al., 2018; Hu et al., 2019; Thorsten et al., 2016). Then the wafers were split into two groups. Group 1 were made into monofacial solar cells by screen printing full-Al paste on the rear side, while an open metallization grid (Kranz et al., 2016) was implemented on the rear side of the wafers in group 2 to achieve the bifacial structure, which enables the cells could absorb irradiance from both sides. All cells were tested and sorted under standard test conditions (STC, 1000 W/m^2, 25 °C) with the rear side covered by black sheet to prevent the absorption of the reflected light. We selected the cells in the same classification bin with the conversion efficiency of 20.6–20.8% from Group 1 and Group 2 for module fabrication, respectively.

The monofacial solar cells were encapsulated into the glass/backsheet modules. These regular monofacial modules (REG PERC) were used as the reference samples for the evaluations on the bifacial modules. As shown in Fig. 2, the bifacial solar cells were integrated into two module structures: (1) Glass/Glass, (2) Glass/Glass (with lattice pattern on the rear glass). The bifacial modules with Glass/Glass (DG Bi-PERC) have the full-area transparent rear glass. A lattice pattern reflective coating, which is made of white ceramic on the rear glass, was adopted on the cell-gap area for another type of bifacial modules (DG Bi-PERC/RC). The reflective coating line is 6-mm, which is wider than the standard cell-gap of 2-mm. This design could make sure reflective coating fill in all cell-gap areas, even if there is a small alignment error between the cell strings and the rear glass during the lay-out process. Consequently, there was a 2-mm overlap between the reflective coating and the rear side of each cell, which resulted in the shading effect on the rear side of bifacial cells.

I-V characteristics of finished modules were carried out under STC (1000 W/m^2, 25 °C and AM1.5G) with HALM module tester. During the I-V measurements of bifacial modules, the non-illuminated side of the bifacial modules was covered by a non-reflective black cover to ensure that there are no reflections from the test surroundings entering the non-illuminated side. By this method, the power of the front side and rear side could be measured independently. Then the bifaciality factors were defined by the ratio of the rear-side power and the front-side power of bifacial modules.

2.2. Field test system

Three types of module strings, REG PERC, DG Bi-PERC, and DG Bi-PERC/RC, were mounted on the same rack next to each other in one of the outdoor testing fields in Yangzhou, China (N32°23′; E119°24′), and each array consisted of 11 modules. The modules were installed at 25°-tilt, facing south on cement paved ground. The energy generation data of the module strings were extracted from the grid-connected inverters. Moreover, three single-module of each type were installed on the next rack to validate the data collected from module strings. The Multi-Tracer 5 system (MT5) was used to track the maximum power point for each module by the electronic load and collect their real-time IV data per minute under the real-operating conditions. The data collection resolution is 3 mV for voltage measurement, and 0.61 mA for current measurement. The testing accuracy of voltage and current are 0.1% for both 2 parameters. All racks were in a standard test field designed for regular monofacial modules. The installation conditions, such as the rack distance, module clearance were not practically optimized for bifacial modules.

To monitor the in-plane irradiance, two pyranometers (Meteo Control SR20-D2) were installed, one was parallel to the module front side, and the other one was installed parallel to the module rear side for albedo measurement. Blue'log X-3000 was used for the Data logger. Compact weather station (WS600-UMB) was installed for climate monitoring, such as temperature, humidity and wind speed. The outdoor data was obtained in a period of 22 months from July 2017 to April 2019.

3. Results and discussion

3.1. IV characteristics on modules

Table 1 lists the average electrical parameters of three module types, totally 45pcs modules were tested, 15pcs for each group. Fig. 3 present typical I-V curve plots of three module structures. Both front and rear I-V

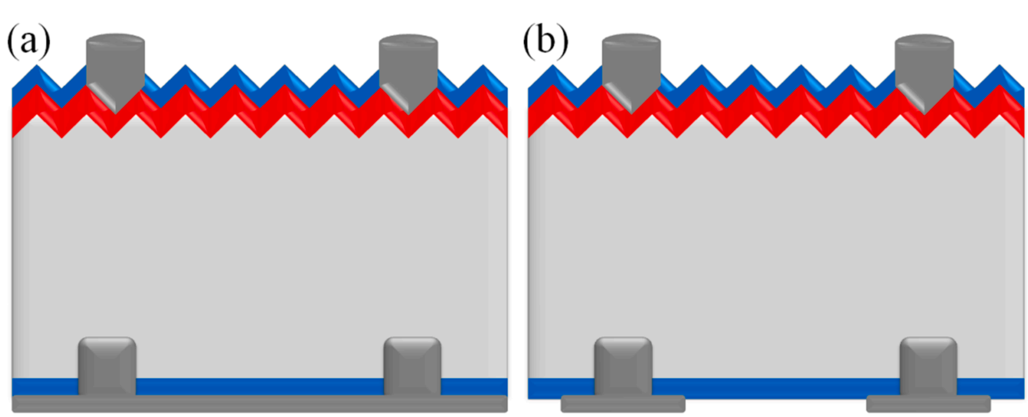

Fig. 1. Schematic illustrations of the (a) monofacial and (b) bifacial PERC cell structures.

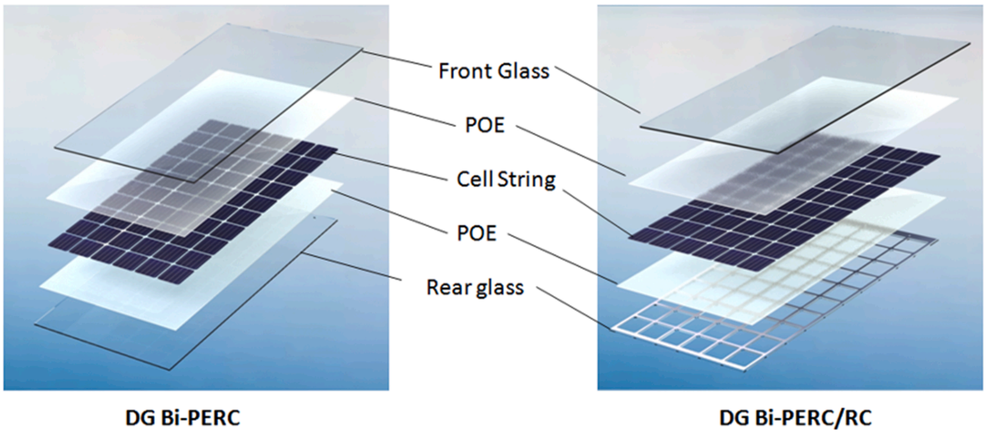

Fig. 2. Schematic diagram of DG Bi-PERC and DG Bi-PERC/RC modules.

Table 1
Electrical parameters of the monofacial modules and the bifacial modules assembled with different rear glass.

Module Types	$I_{mp, front}$ (A)	$V_{mp, front}$ (V)	$P_{mp, front}$ (W)	$P_{mp, rear}$ (W)	Bifaciality factors (%)	Power gains (%)
REG PERC	9.19	32.11	295	–	–	–
DG Bi-PERC	9.04	32.17	291	209	72	−1.4
DG Bi-PERC/RC	9.29	32.33	300	192	64	1.7

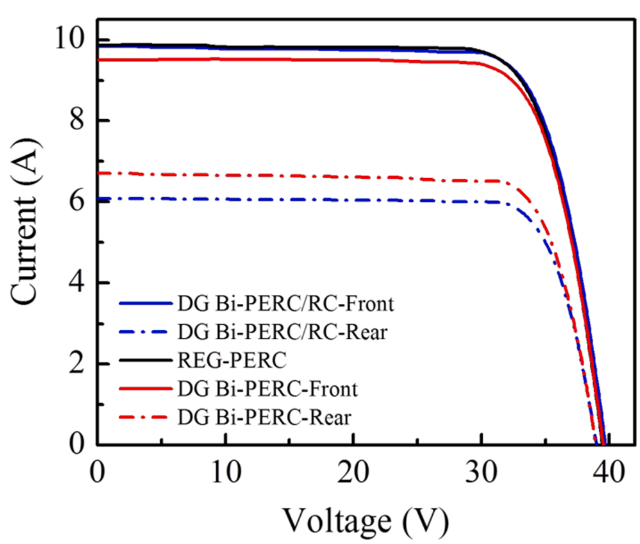

Fig. 3. I-V curve plots of different module structures.

curves are demonstrated for DG modules. It can be seen that it has a big difference on the front maximum current ($I_{mp,\ front}$), which is the primary cause differs the front maximum power ($P_{mp,\ front}$). Normally, the optical gain has the first importance to the current of solar device. The low $I_{mp,\ front}$ of DG Bi-PERC modules is attributed to the transmittance loss on the cell-gap areas (Lopez-Garcia et al., 2019).

By implementing the reflective coating on the rear glass, the incident light is scattered back at various angles and absorbed by the front side and rear side of bifacial cells in DG Bi-PERC/RC modules. A highest $I_{mp,\ front}$ of 9.29A is achieved by the efficient light absorption. With regard to the REG PERC modules, the incident light between the cell-gap could also be scattered back due to the backsheet scattering and reflection properties. The scattering and reflection properties of reflective coating and backsheet have studied by researchers (Min et al., 2017). Because the scattered light of REG PERC module could only be absorbed by the front side of monofacial cells, the $I_{mp,\ front}$ of REG PERC modules is lower than that of DG Bi-PERC/RC modules.

The DG Bi-PERC modules have the lowest $P_{mp,\ front}$ of 291 W within three module types due to the transmittance loss. The $P_{mp,\ front}$ of 295 W for REG PERC modules is obtained by the internal reflection of the backsheet and the light absorption by the front side of monofacial cells. The $P_{mp,\ front}$ of 300 W (~1.7% higher than REG PERC modules) is achieved due to the optical enhanced effects of the reflective coating applied in DG Bi-PERC/RC modules. Nevertheless, the reflective coating causes a shading effect on the rear side of bifacial cells, which decreases the rear maximum power ($P_{mp,\ rear}$) from 209 W to 192 W, then lowers the bifaciality factors from 72% to 64%.

In today's PV market, the sellable power is determined by the front-side rated power, even for the bifacial modules, and the rear side power act as a bonus to customers, thus many people focus a lot on the importance of module bifaciality factors. In this study, we detailed compare the field performance of different module types and investigate the influence factors on module energy yield to find the most feasible way on modules selection for PV power plant.

3.2. *Comparison of accumulated energy*

The power plant is located in Yangzhou, Jiangsu province, its subtropical monsoon climate, not too cold not too hot, with four distinct seasons. Fig. 4 presents the accumulated energy of three module types mounted in arrays and stand-alone system, respectively. Both the long-term field data collected from inverters and Multi I-V tracer clearly demonstrate that glass/glass modules with bifacial cells, DG Bi-PERC and DG Bi-PERC/RC, generate more energy than regular modules with monofacial cells, REG PERC. Side-by-side comparison shows about 6% gains on the energy generation by DG Bi-PERC modules in the past 22 months even with a slightly lower $P_{mp,\ front}$ compared to REG PERC modules. The contribution of the rear side makes up the less output power of the front side and further brings more energy generation. The outdoor energy generation data also unequivocally show that incorporating the rear glass with the reflective coating pattern into glass/glass modules with bifacial cells further boosts energy generation with over 10% energy gains compared to the REG PERC modules.

It is reported that bifacial modules have 10–30% energy yield gains (Pelaez et al., 2018; Shoukry et al., 2016) compared to the regular monofacial modules. The energy yield gains vary according to the different installation conditions as mentioned above. In our study, all modules were installed on a large-scale concrete ground surface with the

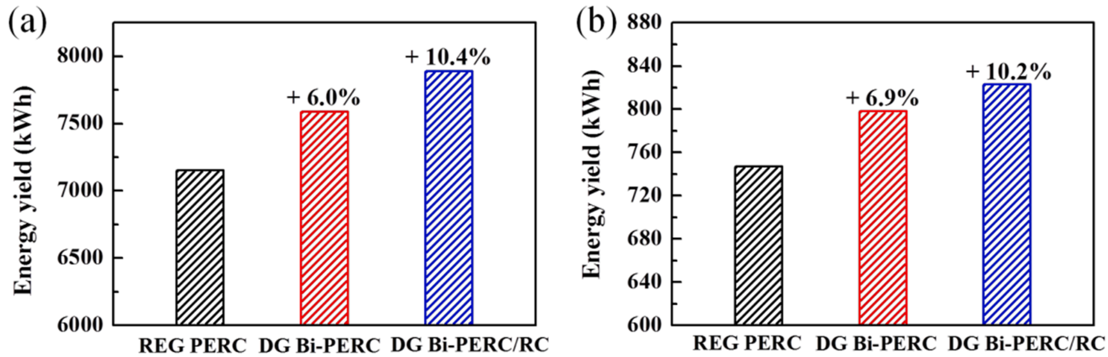

Fig. 4. Energy yield comparison of three module types in two monitoring systems: (a) Module strings connected to Inverters, (b) Individual modules monitored by Multi I-V Tracer.

average albedo of 16.7% in the period of 2 years and the installation conditions were not optimized to harvest more reflected and diffused light for bifacial modules. Therefore, the energy yield gains of bifacial modules in this work are likely lower than most of reported results. It is in agreement with the lower energy generation in larger system caused by horizon blocking and large shadowing area of module rows (Asgharzadeh et al., 2018).

3.3. Comparison of performance ratio

Performance ratio (PR) has been used widely to evaluate the field performance of PV modules, which was defined as the performance relative to STC power (IEC, 2017):

$$PR = \frac{Y_f}{Y_r} = \frac{Eout/P_0}{H_i/G_{i,ref}} \tag{1}$$

where Y_f is the final system yield, Y_r is the reference yield, E_{out} is the energy output, P_0 is the rated power of the array, H_i is the in-plane irradiation, $G_{i,ref}$ is the irradiance at which P_0 is determined.

Due to the complex installation conditions, and thus uncertain energy gain of the rear side, the module manufactures could only measure and rate bifacial modules with illumination from the front side to set the sellable power for marketing. So we use the $P_{mp,\ front}$ to calculate PR and evaluate the energy yield performance. Fig. 5 illustrates the accumulated PR comparison of three module types individually. As expected, double glass bifacial modules show much higher performance ratio due to extra collecting of diffused and scattered lights from module rear side. One remarkable result is that we see DG Bi-PERC/RC modules present comparable PR (100.8%) versus DG Bi-PERC modules (100.5%) even with lower bifaciality factors. This result indicates that the slightly shading on cell rear side and less module transparent have negligible influences on the energy generation of bifacial modules. We attribute this to the IAM benefits in the gap of solar cells with reflective coating. Light incident to the reflective coating can be scattered or reflected to both sides of the bifacial cells. At the high angles of incidence, there will be more internal reflection and less optical loss for the front-side irradiance.

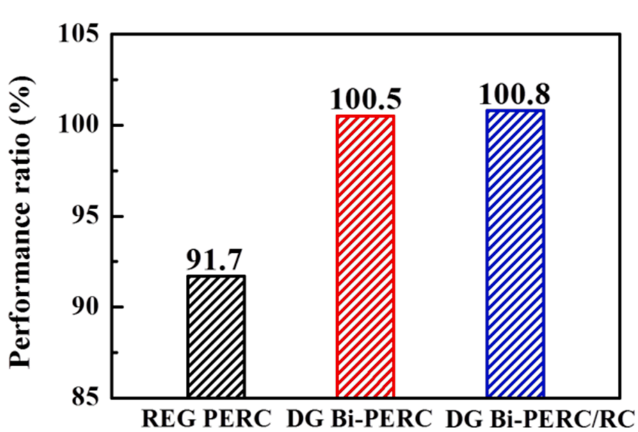

Fig. 5. Accumulated PR comparison of three module types.

Fig. 6 presents brief diagrams of the paths of light (exclusive diffused light) in different module structures: (1) front incident light, (2) cell reflected light, (3) cell-gap transmitted light, (4) RC reflected light, (5) background reflected light. Besides the light path 1, 2 and 5, DG Bi-PERC/RC modules gains extra reflected light through the light path 4 thanks to the existence of reflective coating. With regards to the light path 3, researchers from NREL, SANDIA, etc. have conducted detailed sensitivity studies on the deployment height and light transmitted through the modules. They consider "with sufficient ground clearance (e.g. $z > 1$ m), G_{rear} (rear side irradiance) is impacted only slightly by module transparent area" (Deline et al., 2016). In this study, the module center height to ground is 1.5 m (bottom to ground is 1.15 m) and the cell-gap is only 2 mm, thus the G_{rear} influence by transparent area could be negligible, which means the transmitted light through path 3 has little influence on the energy comparison between DG Bi-PERC/RC and DG Bi-PERC modules.

The PR comparison results indicate that the bifacial modules have better power generation performance than monofacial modules with ~10% extra energy yield gains. With regards to two types of bifacial modules, enhancing the internal reflection in cell/string gaps leads to a higher $P_{mp,\ front}$ and comparable PR value, even though the bifaciality factors are reduced. It is prefer to choose the DG Bi-PERC/RC modules in the investment of PV power plant, as which could reduce the balance of system (BOS), as well as the levelized cost of energy (LCOE) because of the higher energy output density of each module.

In Fig. 7, we see there is a very strong seasonal variation of the performance ratio of all the modules. Basically, modules present higher PR in winter while lower in summer, which can be ascribed to the adverse effect of temperature influence on module performance. In addition, we observe that DG Bi-PERC/RC modules present obvious higher PR value than DG Bi-PERC modules in the month of Jan 2018 and Feb 2019. The common point of these two months is the weather condition rich of cloudy and snowy days, DG Bi- PERC/RC module show even better performance at such days due to better response on diffused light. We will further compare the module performance under different weather conditions in the next paragraphs.

3.4. Effect of irradiance

The energy yield gains of bifacial modules are highly related to the rear-side irradiance (Zhu et al., 2019). We investigate the characteristics of module rear irradiance in this study. Fig. 8 illustrates the irradiance distribution at the rear side of a module string at different times during a

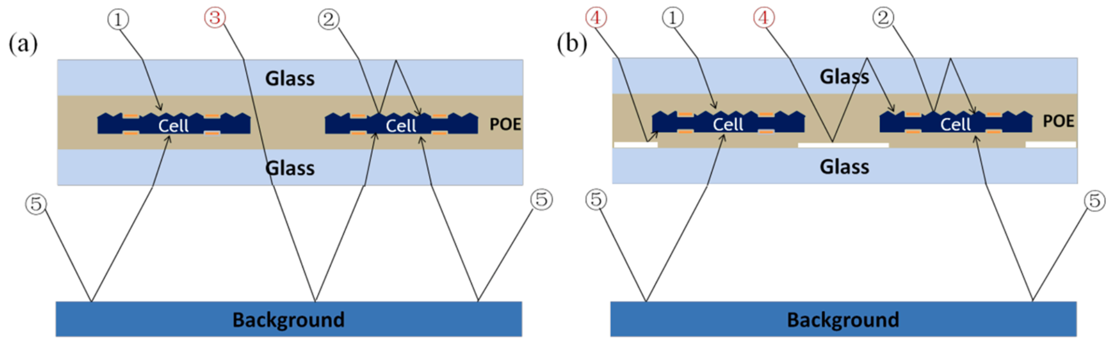

Fig. 6. Brief diagrams of the path of light (not to scale) in (a) DG Bi-PERC module and (b) DG Bi-PERC/RC module.

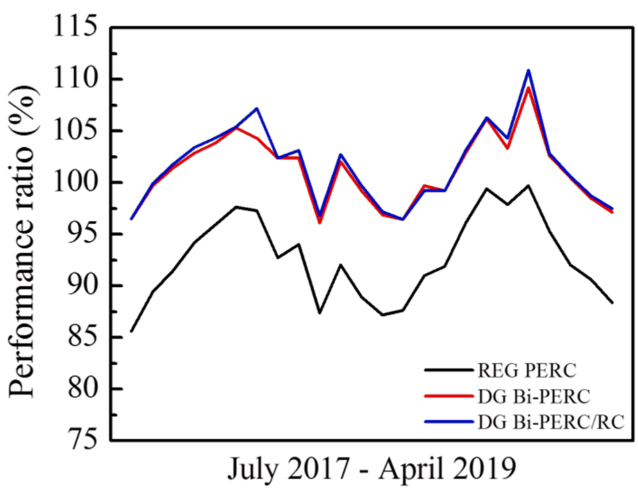

Fig. 7. Monthly PR comparisons of three module types.

given cloudy and sunny day. A portable Newport 91150V with calibrated reference solar cell was used to test the front and rear irradiance at different positions of a module string (110 points per string). Nine points (3 × 3) on the rear side of each module spreading over from top to bottom and left to right, as well as one point on the front side were measured. The ratio between rear and front irradiance (R) was used to represent the level of rear irradiance at each point. The non-uniformity of rear irradiance is defined as:

$$\text{Nonuniformity} = \frac{\text{maxR} - \text{minR}}{\text{maxR} + \text{minR}} \tag{2}$$

As can be seen in Fig. 8, the irradiance behind the rear side of module strings is inhomogeneous due to the shading effect of modules (Zhang et al., 2019) and depends greatly on the weather conditions. The nonuniform backside irradiance will cause the mismatch loss of the output power for bifacial modules (Wang et al., 2019). On the rear side of module string, the irradiance distribution keeps changing at different time as the movement of sun azimuth and zenith angle. The nonuniformity is ~28% on cloudy day, which is better than that of ~33% on sunny day due to the increased shading effects (morning sunlight from rear side leads to higher nonuniformity of ~49% due to the direct shading of other strings in test field). This property makes it highly difficult to predict the energy yield of bifacial modules from the rear side, even though the rear side power has been measured under STC.

The energy gains of bifacial modules vary both on a daily and seasonal basis, due to increased air mass at sunrise and sunset compared to noon, and in winter compared to summer. Fig. 9 demonstrates the current comparison of three module types and the current ratio of bifacial modules versus regular PERC modules under specific weather conditions: (a) sunny winter; (b) cloudy winter; (c) sunny summer; (d) cloudy summer; (e) sunny day after snow. Table 2 lists the detailed information of energy yield gains of bifacial modules versus monofacial modules, as well as the accumulated irradiance of each day measured by the pyranometers.

The energy yield gains of bifacial modules are primarily related to the rear irradiance ratio affected by solar altitude and weather conditions. The dynamic changes of solar altitude in seasons lead to different rear irradiance ratios for the fixed module tracks. On the sunny day, the rear irradiance ratio could reach to ~20% due to the increased reflection area at large solar altitude angles in summer (Chieng and Green, 1993). The rear irradiance ratio decreases because of the shading effect at relatively small solar altitude angels in winter. On the cloudy day, it has comparable rear irradiance ratio between summer and winter. At then

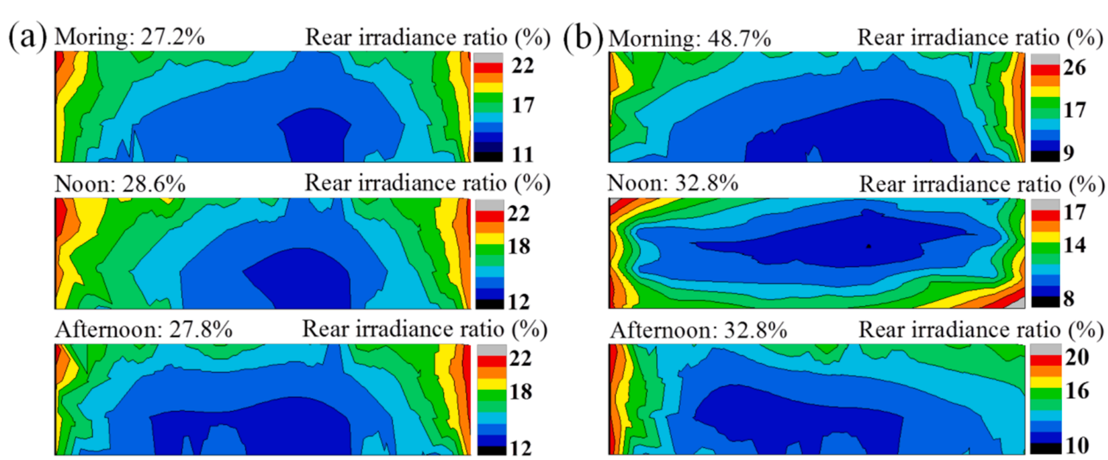

Fig. 8. In-plane irradiance distribution on the rear side of a module string at different times on (a) a cloudy day and (b) a sunny day.

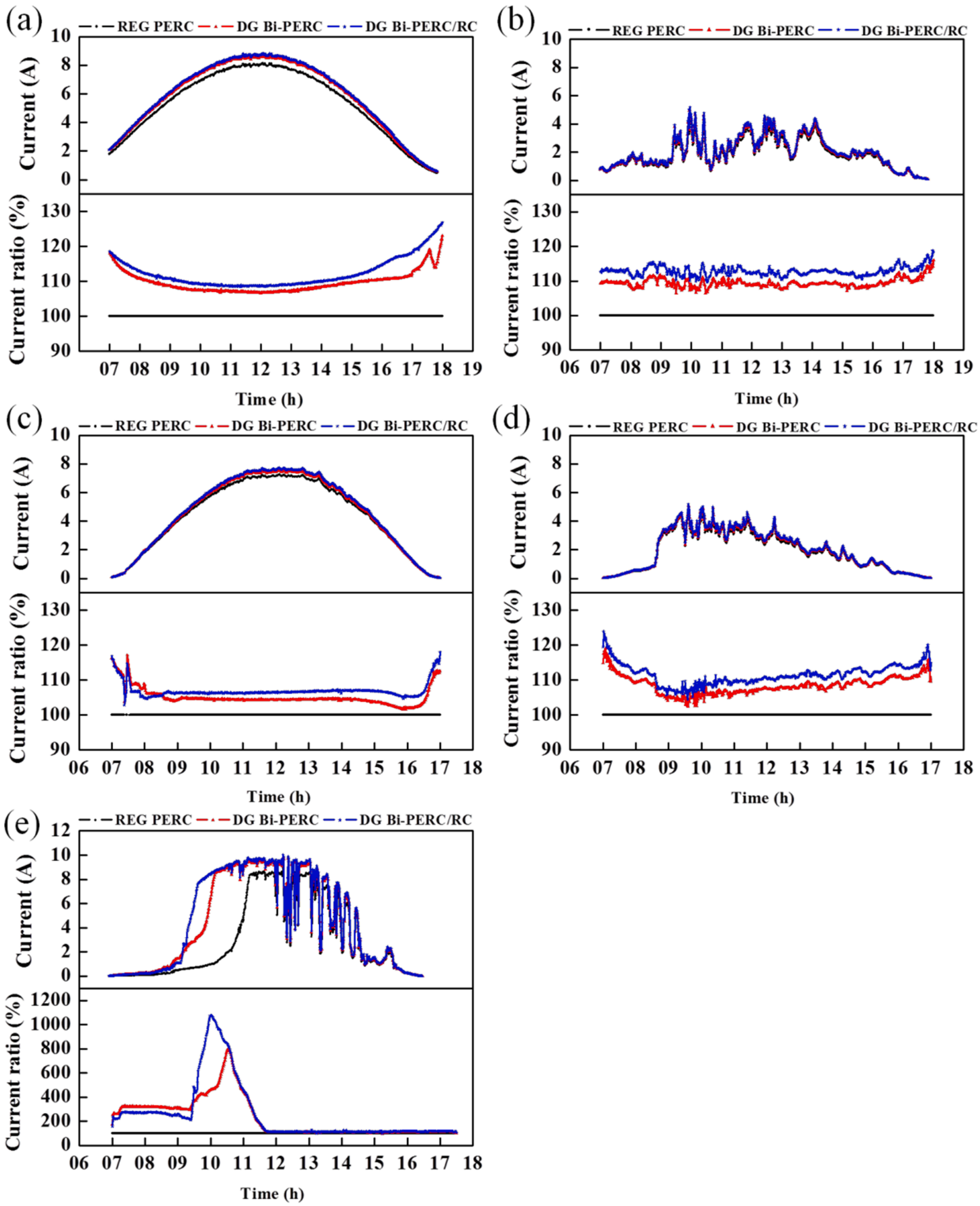

Fig. 9. Current comparison of three module types under specific weather conditions: (a) sunny winter, (b) cloudy winter, (c) sunny summer, (d) cloudy summer, (e) sunny day after snow.

Table 2
Detailed information on the module performance under different weather.

Date	Weather	Front irradiance (kWh/m^2)	Rear irradiance ratio* (%)	Energy yield gains (%)	
				DG Bi- PERC	DG Bi- PERC/RC
19/12/2017	sunny winter	4.8	13.9	4.5	7.8
23/12/2017	cloudy winter	2.0	18.3	7.5	11.0
20/07/2018	sunny summer	6.9	20.3	8.7	11.7
07/07/2018	cloudy summer	2.2	19.5	9.8	13.8
26/01/2018	Sunny day after snow	5.2	20.5	53.0	64.7

* Daily irradiance ratio of the rear to the front plane.

the rear irradiance is dominated by the diffused light which is less dependent on solar altitude instead of the reflected light. It can be seen that DG Bi-PERC/RC modules have 3% ~ 4% absolute value of energy yield gains higher than DG Bi-PERC modules in the above all weather conditions. We attribute this to the domination of the front side output which is scarcely influenced by the rear irradiance.

On the sunny day after snow, bifacial modules present extremely better performance than regular monofacial modules due to the ability of snow melting. Fig. 9(e) depicts the energy curves of different modules under a sunny day after a heavy snow, which perfectly demonstrates this advantage. Before 9:30 am, the output power of bifacial modules was dominated by the rear side contribution. DG Bi-PERC module shows higher current because of the higher bifaciality factors compared to DG Bi-PERC/RC module. Once the snow began to melt after then, the current of DG Bi-PERC/RC module raises faster than that of the DG Bi-PERC module due to the optical enhanced effect of reflective coating. The speed of snow melting has been greatly enhanced by better utilizing of the front side irradiance.

To better understand the relationship between the energy yield gains and the rear irradiance ratio of bifacial modules, we plot the daily energy gains as a function of the daily rear irradiance ratio as depicted in Fig. 10. It can be seen that the energy yield gains of bifacial modules are linear with the rear irradiance ratio.

DG Bi-PERC/RC modules with reflective coating present obvious higher energy gain than DG Bi-PERC modules caused by higher front side power due to optical enhance effect. The slight shadowing of the reflective coating on the edges of backside of cells has a negligible effect on the extra energy gain yielded by the DG Bi-PERC/RC modules in comparison with DG Bi-PERC modules. In addition, the slope should be related to the bifaciality factors, and there is no obvious difference between two types. With regarding to the discussion on the nonuniformity of rear irradiance and the influence of weather conditions, we can conclude that the bifaciality factors in a certain range is not a key factor of outdoor performance of bifacial modules due to the insufficient utilization on the rear irradiance. Combining with the comparison results of performance ratio, putting the front-side power first rather than bifaciality factors is profitable for both modules venders and PV power plant developers.

As for the bifaciality factor, there are several ways to elevate it for modules. On cell level, reducing the finger width or increasing the roughness on backside surface will increase the short circuit current for the rear side, then leads to higher bifaciality factors. But these ways may affect the front-side performance due to the degradation on the fill factor or the open circuit voltage. On module level, the fully transparent rear glass leads to higher bifaciality factors, but the lower front-side power and energy yield compared to the rear glass with latticed pattern. In our opinion, the effectively utilization of front side irradiance is more important. It's better to increase the bifaciality factors without sacrificing the front side output power during developing bifacial PV modules. Quantitative analysis is beyond the scope of this work and will be discussed in a future study.

4. Conclusions

Two types of bifacial modules have been studied in comparison with monofacial modules on their electrical performance and energy yield in this work. The glass/glass bifacial module has about 1.4% lower front-side power compared to monofacial reference module due to the optical loss in cell-gap area. Appling the lattice pattern on the rear glass boosts the front-side power by about 1.7%, but lowers the bifaciality factors by about eight percentages from 72% to 64%. The energy yield gain of glass/glass bifacial module is about 6% during the period of investigation. However, it can be increased to above 10% with optical enhanced effects of the reflective coating on the rear glass. The study on the irradiance reveals that bifacial modules with reflective coating present better energy yield performance under different weather conditions. When developing or manufacturing bifacial PV modules, we suggest increasing the front-side power as the first priority, then the bifaciality factors, especially in the utility scale application.

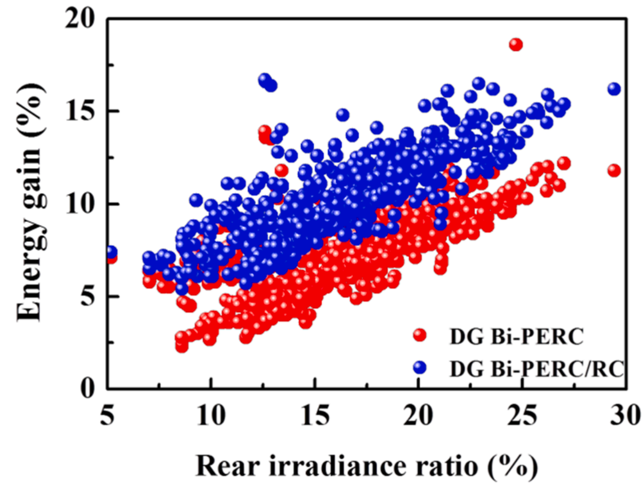

Fig. 10. Energy gains of bifacial modules as a function of daily rear irradiance ratio.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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