Complex problems require simple solutions: How to measure bifacial devices correctly?

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ABSTRACT

Bifaciality is making significant inroads into the PV market. However, besides further technological developments in cost-effective cells, modules and systems, there are still many other issues that need to be addressed. One of the most important of these is the standardization of bifacial measurements for solar cell and modules. This paper summarizes the actions and status in the area of standardization.

Introduction

LONGi, Jolywood and many other large PV manufacturers claim that bifacial mono c-Si technology is the future [1,2]. Since 2015, bifacial PV installations have been entering multi-MW installation levels [3], and are expected to enter multi-GW levels in 2018. Even now, many companies in India – such as Adani, Vikram Solar and Tata Power Solar – are taking (or planning to take) this route [4]. In addition, several large electrical energy suppliers – such as EDF, Enel and Imelsa – are heading in this direction, and EDF is in the process of installing a 90WMp bifacial system in Mexico [5].

Why are these companies doing this? The answer is simply because the bifacial gain in many cases justifies the additional costs associated with bifacial modules [3,6]. One good example is the 'La Hormiga' PV plant ('BiSoN Farm'), close to St. Felipe in Chile (Fig. 1), with a nominal power of 2.5MWp.

Before conditioning the ground, the bifacial gain at the La Hormiga plant was about 15%; after partial coverage of the ground with white quartz, the gain increased to 27%, but this is estimated to be 30% or more with full coverage. If these rough measurements are superimposed on the graph in Fig. 1(b) of reported bifacial gains for many PV systems (as indicated by the red dots), they lie very close to the expected average gain. At the moment, data are being collected and evaluated to include the real data points in this graph.

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It is very difficult to promote and sell bifacial modules and systems even though real data already exist (as is the case for the 1.25MWp bifacial system built with modules from PVGS in 2013, which has generated an average bifacial gain of nearly 20% during three years' operation [7]). The bankability of bifaciality is still low, one reason being that commercially available PV system simulation programs available on the market (such as PVsyst) cannot model the real bifacial gain correctly. The beneficial impact of the distance of the modules from the ground on the rear-side contribution to the energy yield is generally underestimated. Whereas PVsyst yields a constant bifacial gain from heights exceeding 0.25m, the real values in systems (and using, for example, view factor modelling) are still significantly increasing for heights up to 1.5m, depending on the ground albedo [8].

Another important challenge is the lack of qualification standards for *I–V* measuring and other aspects. One of the reasons is that, because there are a large number of applications and even greater variations in values for ground albedo, it is difficult to define fair standard measuring conditions (STC). In addition, bifacial electrical gain is affected differently in various geographic locations: it very much depends on the availability of diffuse

(a) (b)

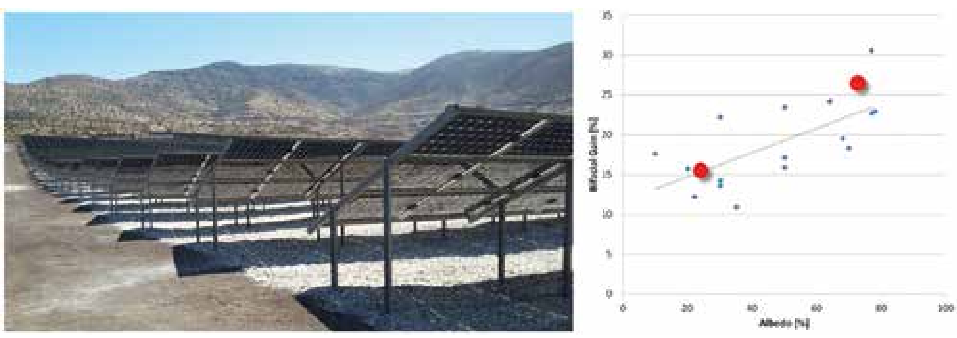

Figure 1. (a) La Hormiga PV plant, where up to 30% bifacial gain has been observed. (b) Reported bifacial gain as a function of albedo for many installed PV systems; the red dots indicate the La Hormiga rough measurements.

sunlight compared with direct sunlight. Total electrical production for bifacial modules is therefore more difficult to predict than for monofacial ones; however, because this issue is important for the bifacial roadmap of many large companies, there are currently various actions in progress for standardization. In Asia many (but also uncoordinated) actions in respect of standardization have been reported [4]:

> Earlier this month, the Chinese solar major, Jinko Solar, teamed up with TÜV Rhineland, the German testing, inspection and certifying agency, and a respected name in the solar industry, to evolve testing standards for bifacial modules. Jinko is, however, not the first. Yingli, the supplier to the world's biggest bifacial solar plant of 50MW in China, is evolving standards in-house, while Jolywood (Taizhou) Solar, has tied-up with TÜV Nord for bringing out testing standards.

The European bifacial consortium, led by Pasan, submitted standard measuring conditions to the IEC in October 2016. The IEC committee is scheduled to comment on this by August 2017, after which the procedure can be fine-tuned. The focus of this paper will be on that proposal; before that, however, the different applications on the market of bifacial modules in large systems will be briefly described in the next section.

Bifacial PV systems: different applications

Whereas monofacial modules are limited in terms of their field of application, bifacial modules can be used in many different modes, making standardization much more complicated. Not only does the energy yield of two sides of a module need to be considered, but also the installation of the module in different arrangements leads to different and very interesting applications. Fig. 2 depicts the three most important installation geometries: (a) the classical slanted, sun-oriented set-up; (b) a horizontal mounting; and (c) a vertical installation. All of these installations have different expected bifacial electrical gains; however, they all make sense for different purposes. With a combination of different bifacial installation geometries, the electricity generation peak can be adjusted to match the electrical demand, which means less storage is necessary.

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Standard slanted sun-oriented installation

This arrangement is used for maximum electrical harvesting and results in the highest power density; it can be employed in large field installations and flat rooftop systems. The bifacial gains as a function of ground albedo for these optimal installations were shown earlier in Fig. 1(b). However, low module installation heights may be necessary because of wind loads (e.g. in rooftop systems), in which case the bifacial electrical gain will be reduced. Depending on the ground albedo, this can lead to a very large decrease in bifacial gain [6]. If an albedo of 60% (for example) is assumed, a reduction from 25% to 15% in bifacial gain can be expected when the module height is reduced from 1m to 0.15m.

Horizontal installation

Horizontal installations are used, for example, for carport applications or for building integration on flat roofs. This arrangement is a special case of the previous installation, with an inclination angle of 0°.

Vertical installation

Vertical installations (90° inclination angle) are very attractive options when using bifacial modules. The most interesting case is when the sides of the module are oriented towards the east and the west: in this case a high bifacial coefficient is required, because in the morning, one side faces the sun, while in the late afternoon, the other side assumes this role. Applications for this geometry are manyfold: field installations, flat-rooftop systems, facade applications and even sound-blocking PV systems. As the electrical generation peak is different from that in the south-oriented case, there are many business cases relating to how to make use of this special shape of the electrical generation curve. More electricity can be generated in the morning and late afternoon, and less during the noontime period; therefore less storage is needed.

Bifacial solar cell measurement

The *I–V* measurement of a monofacial solar cell is quite simple: various chucks and various contacting methods can

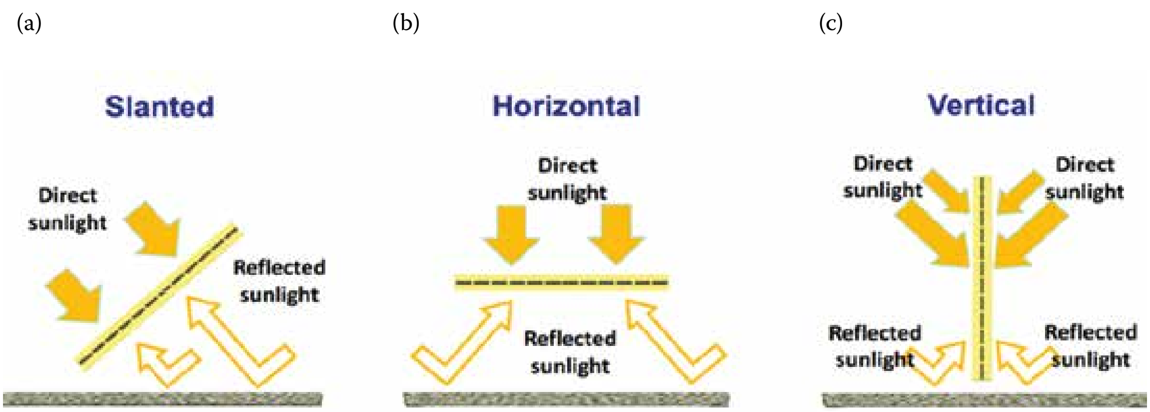

Figure 2. Possible installation geometries for bifacial modules: (a) slanted, (b) horizontal, (c) vertical.

be used, and the same electrical results will be obtained. Even so, round robins at different institutes lead to slightly different electrical parameters I_{sc}, V_{oc} and *FF* and resulting efficiencies. For the most part, the values for *FF* differ as a result of the various contacting methods – if a conducting chuck is employed at the rear side, or if a scissor system (two-sided contact bars with spring-loaded pins) is used.

The measurement of bifacial cells becomes more complicated, since the rear side is open and contributes to the electrical gain. As the rear side of a bifacial cell is more advanced than in the case of standard Al-BSF technology, the efficiencies are currently well in excess of 20%, and even approach 22% for some PERC+ and PERT cells. This goes hand in hand with an increase in the V_{oc} of such cells, and therefore in the electrical capacity of the solar cell. As a consequence, longer light pulses are required for the *I–V* measurement of bifacial cells than those used with Al-BSF solar cells: the standard pulse lengths of 5ms are not sufficiently long to correctly measure the efficiency. For voltages of 660–670mV (screen-printed PERC, PERT), pulse lengths of about 50ms are necessary, whereas for 720mV (passivated contacts, HJT), as much as 200ms is required.

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Fig. 3 shows the different possibilities for the measurement of bifacial solar cells. The differences in all cases are the front- and rear-side contacting, and whether only the front side, or subsequently the rear side, is illuminated. It will be seen later, in the measurement standard paragraph, that bifacial cells too can be measured and the bifacial gain determined using just one illumination source.

In the case of Fig. 3(a), the light source can only illuminate one side, and the rear contact is facilitated via a reflective and conductive measuring chuck. If bifacial modules are used, this case then provides currents that are too high, as the chuck creates additional reflection of the light penetrating through the solar cell. In addition, the fill factor is also too high, as the chuck results in additional lateral conductivity. The solution is to use a black non-conductive chuck, as shown in Fig. 3(b).

The differences in the electrical parameters when using these different chucks are shown in Fig. 4. These measurements, performed on one PERT solar cell at the CalLab at FhG ISE, were presented at the first bifacial PV workshop – bifiPV – in 2012 in Konstanz [9]. The difference in absolute efficiency is about 0.2%$_{abs.}$, mostly resulting from the higher current and fill factor.

Another attractive solution is to use scissor contacts: not only are the results the same as for the black non-conductive chuck, but with this method it is possible to illuminate the solar cell from the rear side as well. One option is to use an additional light source from the rear, as shown in Fig. 3(c), or alternatively an arrangement of mirrors can be employed, as shown in Fig. 3(d). In the latter case, the rear-side illumination, which corresponds to the albedo, can be simulated by using a filter. In the standardization paragraph it will be explained how the arrangements in Fig. 3(b) (one-sided illumination on a black chuck) and in Fig. 3(c) (two-sided illumination with scissor contacts) can both be used at STC for bifacial devices.

Bifacial module measurement

As illustrated in Fig. 5, bifacial modules can be measured in a very similar way to that described above for bifacial solar cells. Fig. 5(a) shows the measurement of a bifacial module at STC with one-sided illumination from the front side and undesired reflection from the rear side. Fig. 5(b), on the other hand, shows the set-up with no illumination from the rear side, used for a monofacial-like set-up for the determination of the front-side P_{max} at STC. Fig. 5(c) and (d) show two different possibilities for implementing two-sided illumination of a bifacial module with defined rear-side irradiance levels, by using either rear-side reflectors or an additional light source for illuminating the rear side of the module.

Bifacial measurement standards

This section will cover the most important points from the proposal for a bifacial *I–V* measurement standard submitted to the IEC committee in October 2016 [8], which will be commented on by the IEC committee in August 2017. The text uses in part the exact formulation from Fakhfouri [10].

The bifacial *I–V* characterization procedure, under consideration for the potential future IEC standard, defines two cases:

1. Measurements by PV laboratories
2. Measurements in PV production environments

The possibilities and the needs of these are different, but the measurement results provided are complementary. The combination of laboratory and production measurements allows good information to be gleaned, at a reasonable cost and complexity, about bifaciality and the expected bifacial power gain.

Measurements with two-sided illumination

A solar simulator with the possibility of simultaneously illuminating the bifacial device on both sides can be used (see Fig. 6(a)). Such simulators are able to provide irradiance at variable levels on the two sides, by using either two light sources or one light source in combination with mirrors and grey filters. At the irradiance levels used for the characterization of bifacial devices, the non-uniformity of irradiance must be below 5% on both sides. The proposal for the new IEC standard stipulates:

- At least three different irradiance levels (G_{Ri}) on the rear side are required, each with simultaneous illumination of the front side with 1,000W/m^2.
- At least two specific P_{max} values, $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$ for G_{R1} = 100W/m^2 and G_{R2} = 200W/m^2 respectively, must be reported.
- If the irradiance levels on the rear side do not correspond to G_{R1} and G_{R2}, $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$ must be obtained by linear interpolation of the data series P_{max} versus G_{Ri}.

Measurements with one-sided illumination

Determination of bifacial coefficient

To determine the bifaciality

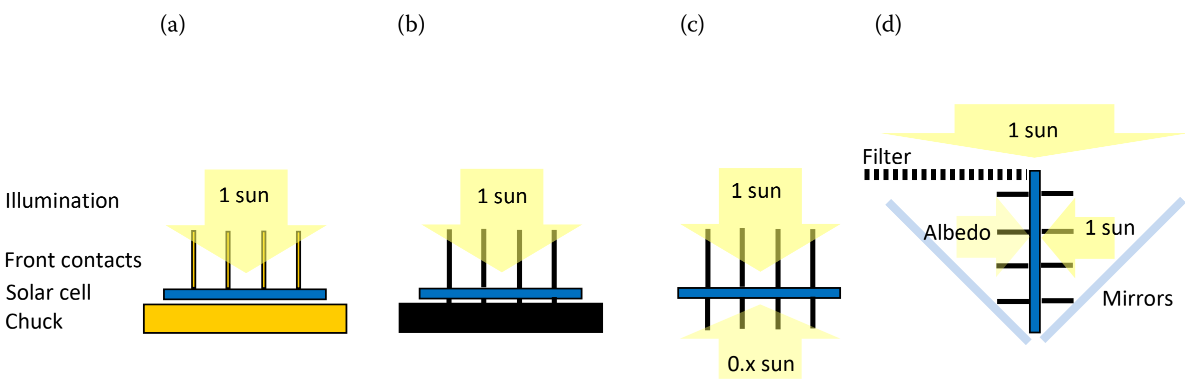
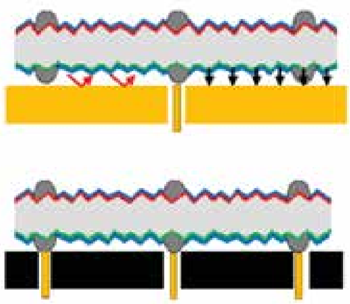


Figure 3. Possible measurement arrangements for bifacial solar cells.



Chuck	Jsc [mA]	Voc [mV]	FF [%]	eta [%]
Golden*	39.12	647.5	79.47	20.13
Black*	38.69	647.1	79.35	19.86
Combined	39.12	647.5	79.35	20.10
Δ	1.1%	<0.1%	0.2%	1.3%

(*ISE CalLab measurements)

Figure 4. Differences in electrical parameters when using different chucks [7].

coefficients of the test specimen, the main I–V characteristics of the front and rear sides must be measured at STC (G = 1,000W/m^2), as shown in Fig. 6(b1) and (b2). A non-reflecting background must be used in order to avoid the illumination of the non-exposed side. The non-exposed side is considered to be non-irradiated if the irradiance is measured to be below 3W/m^2 on at least two points of the non-exposed side of the device, while also fulfilling the requirement of a non-uniformity of irradiance of less than 5% for the front and rear sides.

Short-circuit current bifaciality coefficient φ_{Isc}, usually expressed as a percentage, is the ratio between the short-circuit current generated exclusively by the rear side of the bifacial device and that generated exclusively by the front side:

$$\varphi_{Isc} = \frac{Isc_r}{Isc_f} \qquad (1)$$

where Isc_x is the short-circuit current at STC under one-sided illumination, with index x = 'f' for front side and 'r' for rear side. Both currents are measured at STC (1,000W/m^2; 25°C; IEC 60904-3 reference solar spectral irradiance distribution).

The spectral mismatch correction shall be applied to the measurement of Isc_f and Isc_r in accordance with IEC 60904-7, unless it is known that the front and the back of the bifacial device have identical spectral responsivities.

Other bifaciality coefficients shall be reported and are calculated from:

$$\varphi_{Voc} = \frac{Voc_r}{Voc_f} \qquad (2)$$

$$\varphi_{Pmax} = \frac{Pmax_r}{Pmax_f} \qquad (3)$$

where φ_{Voc} is the open-circuit voltage bifaciality coefficient, φ_{Pmax} is the maximum power bifaciality coefficient, Voc_x is the open-circuit voltage, and $Pmax_x$ is the maximum power. Both of the last two are obtained with one-sided illumination at STC, where the index x again indicates front-side (f) or rear-side (r) illumination. Spectral mismatch corrections shall be applied in accordance with IEC 60904-7 in the above-mentioned calculations.

Measurement at equivalent irradiance levels

To carry out indoor measurement of the power generation gain, a standard solar simulator with adjustable irradiance levels for one-sided illumination can be used. At least three different irradiance levels on the rear side are required. Two specific $Pmax$ values, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ for G_{R1} = 100W/m^2 and G_{R2} = 200W/m^2 respectively, must be reported. Again, if the irradiance levels on the rear side do not correspond to G_{R1} and G_{R2}, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be obtained by linear interpolation of the data series $Pmax$ versus G_R.

The quantities $Pmax_{Bifi10}$ and $Pmax_{Bifi20}$ for the device must be measured by illumination of just the front side with equivalent irradiance levels G_{Ei}; these levels depend on the bifaciality coefficient, corresponding to 1,000W/m^2 on the front side, plus different rear-side irradiance levels G_{Ri} (see Fig. 6(b3)). The equivalent irradiance levels are thus:

$$G_{Ei} = 1{,}000 + \varphi \cdot G_{Ri} \qquad (4)$$

where φ is equal to the smaller of φ_{Pmax} and φ_{Isc}. For example, a device with a maximum power bifaciality of φ_{Pmax} = 80% must be irradiated on the front side at the level G_{E2} = 1,160W/m^2 in order to provide the equivalence of G_{R2} = 200W/m^2. The $Pmax$ measured under this illumination level G_{E2} corresponds to the quantity $P\max_{BiFi20}$.

I–V characterization of bifacial devices in practice

Two cases are to be considered for the I–V characterization of bifacial devices. The first case is where the bifaciality coefficients of the test specimen are not known, which is common for newly developed or modified devices, and when the measurements are performed by PV laboratories or accredited agents. The second case is where the bifaciality coefficients of the test devices are known, which is typical in PV manufacturing environments, when reference devices of the same technology as the devices to be tested are available.

In PV laboratories the procedure is as follows. First, I–V measurements under STC are performed separately for both sides of the test device. From these I–V curves, the bifaciality coefficients of the test device are determined. When the test device is to be used as a reference device, the key data is reported for both sides under STC with monofacial irradiance. To report the bifacial power gain, it is necessary to determine $P\max_{BiFi10}$ and $P\max_{BiFi20}$, either directly from measurements or from linear interpolation of measurements at other equivalent irradiance levels.

To determine the bifacial power gain in PV production facilities, where reference devices are available, the PV panels are measured under STC at an irradiance level of 1,000W/m^2 only on the front, yielding monofacial-like values. To report the bifacial power gain, the values of $P\max_{BiFi10}$ and $P\max_{BiFi20}$ are calculated, at the appropriate equivalent irradiance levels, by applying the bifaciality coefficients of the reference device. The main differences are summarized in Table 1.

In addition to the indoor measurement procedures described here, the proposal for the new I–V measurement standard for bifacial modules describes also the possibility of obtaining $P\max_{BiFi10}$ and $P\max_{BiFi20}$ from outdoor measurements and appropriate extrapolations.

It is important to standardize not only the parameters from the I–V characteristics, but also the qualification procedures followed by quality-assurance institutions, such as TÜV. In the latter, it is even more difficult to agree on standardization procedures, since the bifacial cell and module manufacturers (as already mentioned) work with different institutions [4].

Some of the most crucial procedures to be agreed upon (which differ from those for the classic double-glass module) include testing bypass diodes at maximum current (which has to be defined), and measuring potential-induced degradation (PID), which can now affect both sides. Depending on the specific application, even hail-

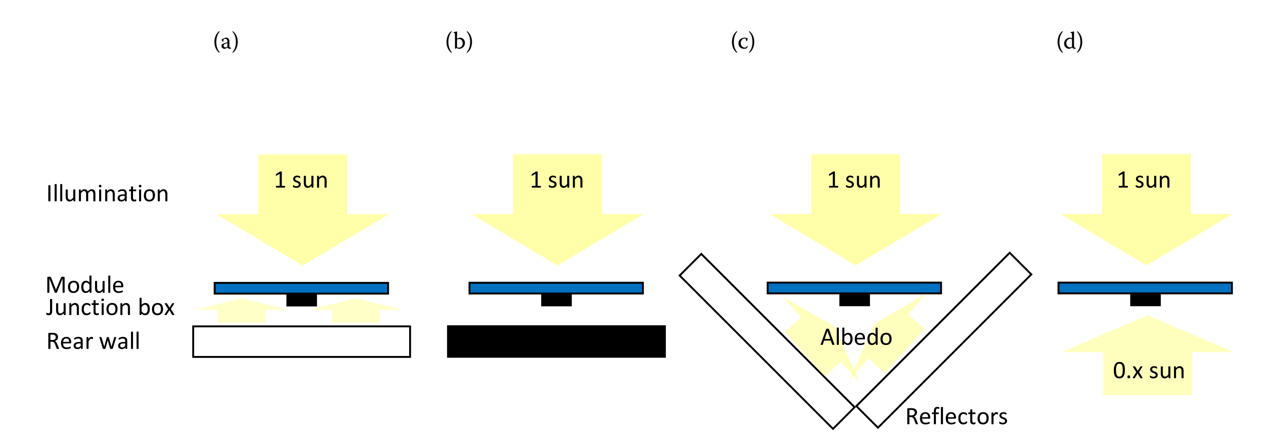


Figure 5. Possible measuring arrangements for bifacial modules.

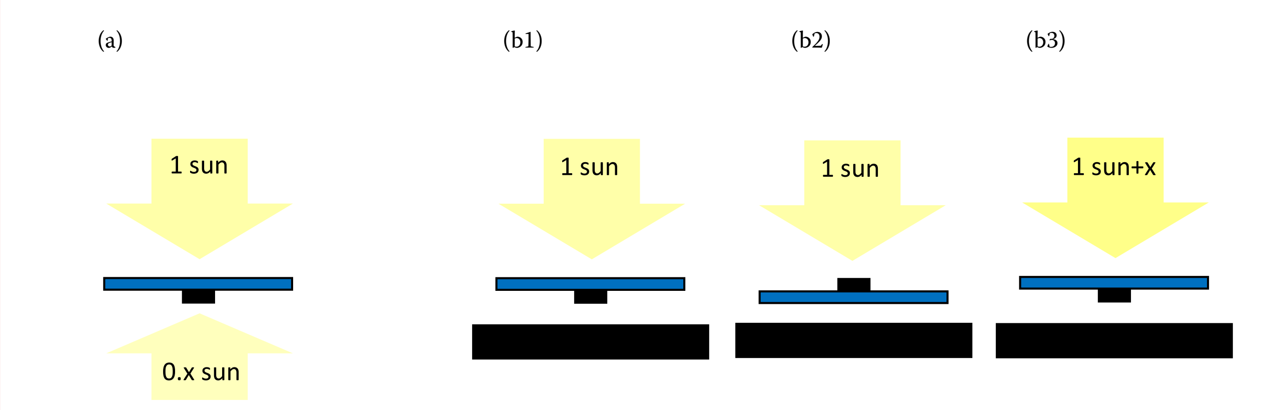


Figure 6. Possible standardized measurement methods for bifacial modules.

	PV laboratories	PV production	
I–V measurements	STC front STC rear Possibly front @ G_E	STC front
Bifaciality coefficients	Calculate φ	Use φ (reference device)
Bifacial gain	Measurement or calculation: P_{max} = f(G_R or G_E)	Calculation: $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$
Reporting	Key data at STC P_{max} = f(G_R or G_E)	$P_{max_{STC}}$ $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$

Table 1. Differences in bifacial *I–V* characterization in practice.

impact tests will have to be performed on the rear side (such as in the case of vertical installations). It is therefore expected to take a long time to define qualification standards.

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How to sell bifaciality?

It is still extremely difficult today to sell bifacial solar cells and modules, as installers are not used to this product. Large PV systems are installed by electricity providers (EDF, Enel, Imelsa, Yingli, etc.) who have gained experience with bifacial installations on a small scale and have themselves proved the bifacial gains.

The difficulty is also due to the absence of reliable commercially available bifacial simulation programs on the market, as well as the lack of standards for bifacial measurements. So far, no bifacial module manufacturer has used the proposed measurement standard described earlier. There is a great deal of reported in-house data on bifacial gains, which is extremely confusing to customers. The question has arisen during bifacial workshops as to whether a certain bifacial gain must be guaranteed in order to be able to sell bifaciality. From these discussions, a bifacial gain guarantee of 10–15% is considered to be realistic, as this represents the lowest value when some basic installation rules are fulfilled.

Summary and outlook

The bifacial technology share of the market is rapidly growing; indeed, the ITRPV predicts that in 2024 about 20% of the market will use bifacial products [11]. As discussed in this paper, however, the bifacial community still has to work on many issues, such as standards and qualifications, simulations and bankability. All these topics are scheduled for discussion at the 2017 bifiPV workshop in October 2017 in Konstanz [12], where everyone is invited to participate and cultivate the future of bifaciality. .

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