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IV MEASUREMENT OF BIFACIAL MODULES: BIFACIAL VS. MONOFACIAL ILLUMINATION

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ABSTRACT: Bifacial modules are able to use light incident on both sides und thus have the potential for significantly increasing the yield of PV Power plants. However, as current testing procedures do not respect gains from rear side illumination, the bifacial technology comes along with new challenges considering a reproducible and comparable characterization of the modules. Currently a draft for a new standard is in preparation, including different measurement methods with front side only and bifacial illumination. In this paper, we compare measurement results of these different approaches to characterize bifacial modules. The differences between single sided and bifacial illumination are investigated. The role of the light incident side and the influence of module properties on the resulting measured power are analyzed. Additionally, as most labs do not have the possibility to measure the IV curve under bifacial illumination, a method is presented to calculate the power under bifacial illumination based on monofacial measurements.
Keywords: Bifacial, Calibration, Characterisation, PV Module, Performance

1 INTRODUCTION

For the measurement of bifacial modules different methods are currently under discussion. As the existing standards for the IV measurement of photovoltaic devices do not consider gains from rear irradiation, nor define the measurement conditions for the module rear side, it is often not clear how the nominal power of commercial modules is determined. The labeled values are often extrapolated from frontside STC measurements, assuming a linear power boost, or measured with an undefined reflector behind the module. In any case, the comparability of datasheet values is poor.

A new standard for the IV measurement of bifacial modules is already in development, allowing for different options for the assessment of the bifacial gain: frontside measurement under elevated irradiance, measurement under bifacial illumination and outdoor measurement with different rear intensities.

In this paper, measurement results of different indoor approaches for the determination of power of bifacial modules are compared: measurements under single sided illumination, under elevated front side illumination as proposed in [3], and under simultaneous bifacial illumination. It is analyzed in which cases the results are in good agreement, and which module properties cause deviations between the different approaches, with respect to irradiance intensity regimes.

2 METHODS

2.1 STC under single sided illumination

For a basic characterization of bifacial modules, it is necessary to measure each side separately at STC, while the other side has to be protected from incident stray light. For the measurements in this work, the module´s rear side was covered by a black curtain. The spectrally weighted reflection of the material is 4.3% and rather constant over the relevant wavelength range between 300-1200nm. Along the module`s long edges a mask prevents light from passing by the module, so the incident light on the rear cover is reduced to transmission through the module and light passing by the short egdes of the module. This way the electrical module parameters of each side are determined with maximum precision. With these results the bifaciality φ of current and power can be calculated:

$$\varphi_{Isc} = \frac{I_{sc,rear}}{I_{sc,front}} \quad (1)$$

$$\varphi_{Pmpp} = \frac{P_{mpp,rear}}{P_{mpp,front}} \quad (2)$$

The bifaciality is needed for the calculation of the elevated irradiance Ge, as described in the next section. The single sided STC parameters are also the basis for the calculations in section 3.3, and for yield simulations of bifacial PV systems [7].

For framed modules, special care has to be taken for the module position in the rear side measurement. The module surface is shifted by the frame width behind the normal measurement plane. Thus the intensity has to be adjusted to obtain one sun in the plane of the rear module surface.

2.2 Front side under elevated irradiance

Since the module's behavior in bifacial operation and the bifacial gain cannot be directly assessed from the single sided STC measurements, Fakhfouri et al. [3] propose additional front-side measurements at higher irradiances $G_{e,i}$. $G_{e,i}$ is calculated by the short-circuit current bifaciality coefficient φ:

$$G_{e,i} = 1000W/m^2 + \varphi \cdot G_{r,i} \quad (3)$$

At least three different irradiances $G_{r,i}$ have to be measured and the results interpolated to G_R = 100 and 200 Wm^{-2}. With this method, the increased resistive loss due to series resistance is considered, as the generated current is equal to the current under the respective bifacial illumination.

2.3 Bifacial illumination

As bifacial modules in real applications operate under simultaneous front and rear side illumination, it is advisable to characterize this module type under bifacial illumination For determination of parameters under bifacial operation and the bifacial gain, a new measurement set up was developed at CalLab PV Modules, which enables bifacial illumination of full size modules up to 1x2m in irradiation quality better than AAA. Two mirrors in 45° angle to the lamp are directing the light of the solar simulator simultaneously on both sides of the module, like described in [6] for cells. The mirrors are made from a silver coated reflector sheet, with a reflectance over 95% in the wavelength range 300-1200nm, so the reflected spectrum remains A+ quality. The reflector sheets are attached to glass panes to get a smooth surface for maintaining good irradiance homogeneity.

Figure 1 shows a schematic of the set-up. The lamp power can be adjusted between 100-1000W/m^2, and by inserting attenuation filters the rear intensity can be reduced. With this variable light intensity and variable front-to-rear intensity, typical irradiation conditions for different installation geometries (e.g. south, east-west) can be simulated.

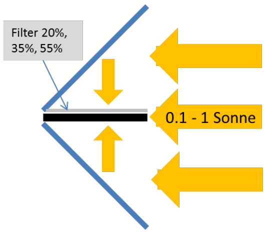

Figure 1 schematic of the bifacial measurement set-up: 2 mirrors in 45° angle to the lamp are directing the light on both sides of the module

The attenuation filters used for this work are made of woven wire mesh. This material shows spectrally neutral transmission and good spatial homogeneity on big areas, as shown in [1]. The currently available transmissions are 20%, 35% and 55%. For reaching lower transmissions of 10-20%, representing the range of realistic installation conditions, new filters of different materials are currently under design.

As this mirror set-up is installed in the same sun simulator where the normal single sided measurements are performed, all the general measurement procedures are not affected. All measurements are carried out as section and hysteresis measurements.

2.4 Devices under test

The described measurement procedures were compared for different commercial bifacial modules, consisting of 60 or 72 cells. Since a module`s fill factor (FF) is always influenced by different effects of the serial connection of single cells, like current mismatch, standard size commercial modules as well one-cell modules were investigated for a closer FF analysis.

3 RESULTS

3.1 single sided vs. bifacial measurement

In the first step, single sided measurements over a wide intensity range of 100W-1000W/m^2 are compared to bifacial measurements. In the following figures, the irradiance is always symmetrical (frontside irradiance = rearside irradiance). In figure 2, the sum of Isc of front and rearside is compared to the Isc measured under bifacial illumination. The deviation is below ±0.3% for all intensities. From this good agreement, it can be concluded that in this intensity regime the assumption that the current is linear is applicable. Further, the bifacial illumination quality is sufficient for reproducing the expected current based on the single sided precision measurements.

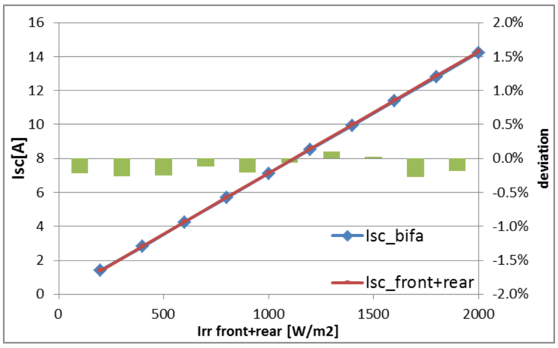

Figure 2 Sum of Isc of front and rearside compared to bifacial Isc

Figure 3 shows the Vocs measured for frontside, rearside and bifacial illumination. The x-axis refers here to Isc instead of irradiance, in order to compensate the bifaciality. At the same current level, Voc is independent of light incident side in the complete irradiance range.

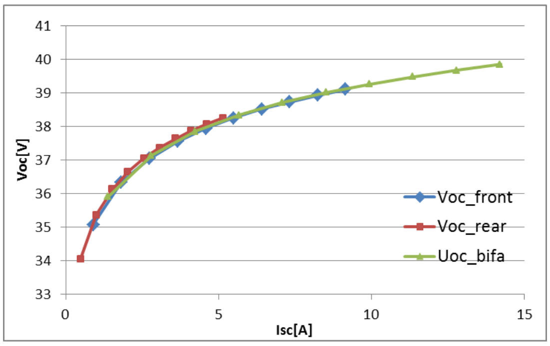

Figure 3 Voc measured on frontside, rearside and bifacial , with respect to Isc

While Isc and Voc for bifacial operation can be calculated based only on the single sided measurements for any given irradiance condition, like shown in [4], the bifacial Pmpp is affected by resistive losses due to series resistance and shunt resistance. Figure 4 shows the deviations of the bifacial Pmpp and the sum of Pmpp of front and rearside.

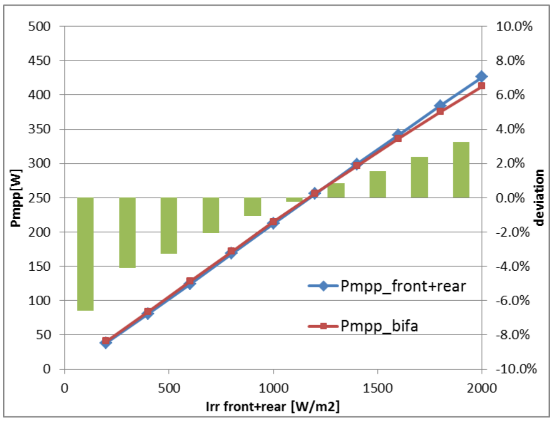

Figure 4 Sum of Pmpp of front and rearside comp. to bifacial Pmpp

For low irradiances, the Pmpp of the single sided measurements is more affected by the shunt resistance as under bifacial irradiation, as the module operates at a higher injection level because of the simultaneous illumination. For high irradiances, the measured power for simultaneous illumination is lower than the sum of the single sided measurements, due to the increased series resistance loss. These effects cause a deviation of linear superposition in Pmpp of up to 6% for extreme irradiance combinations.

3.2 Ge method vs. bifacial measurement

For comparing single sided and bifacial measurements of commercial modules, it is important to consider the form of the IV curves. Most bifacial modules have distorted rear I-V-curves, due to partial shading by the junction box, cabling, frame or label, or due to cell sorting by frontside current only.

As in the Ge method a modules IV curve is measured only under elevated front irradiance, the distortion of the rear IV curve will not be detected, as can be seen in figure 5. While the IV curve of the Ge measurement is as smooth as the frontside STC, the IV curve for the bifacial measurement is affected by the partial shading of the module´s rearside.

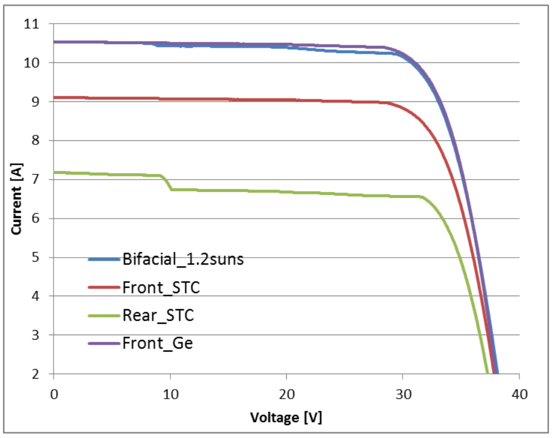

Figure 5 IV curves of a typical commercial module under front and rear STC, bifacial and Ge for 200W rear irradiance

Depending on the rear intensity and the severity of the distortion, this leads to a deviation between measured power and FF for Ge and bifacial measurement. Figure 6 shows measured FFs for different illumination conditions for a typical module. FF_bifa refers to symmetrical irradiation for front and rear side. Additionally, the FFs for the Ge and bifacial measurement, corresponding to $1000W/m^2$ front and $200\ W/m^2$ rear intensity are shown.

For all bifacial modules measured with the bifacial set-up and with the Ge-method, the deviation of measured Pmpp was calculated. Table 1 shows the mean deviations for commercial modules and for single cell modules.

Table 1: mean deviation of measured Power for bifacial and Ge measurement, for irradiance condition 1000W/m2 front and 200 W/m2 rear:

	Commercial Modules	One cell modules
Mean deviation	0.54%	0.15%
stdev.	0.24%	0.20%

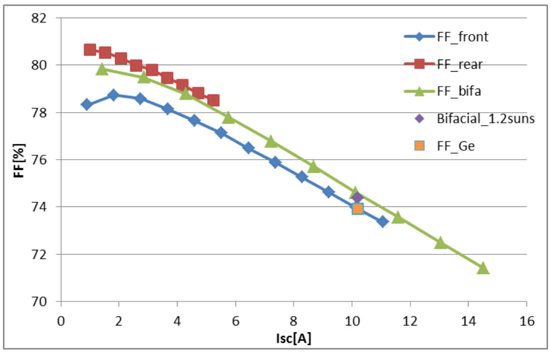

Figure 6 FF measured on frontside, rearside and bifacial, with respect to Isc. Additionally the FF for the Ge and bifacial measurement with 200W rear intensity are shown

For the measured commercial modules a mean deviation of 0.5% in Pmpp between Ge and bifacial measurement was found for the irradiance condition 1000W/m2 front and $200\ W/m^2$ rear intensity.

In order to have a closer look at the FF and to separate the effects of the serial interconnection of the cells from the single cell behavior, we used one cell modules for further investigation of the FF. Three different bifacial cell technologies were investigated.

For the measurement under single sided illumination on front and rear side, we found a slightly higher FF for the rear side illumination even for the single cell modules. Figure 7 shows the FFs for rear and front irradiation for different intensities.

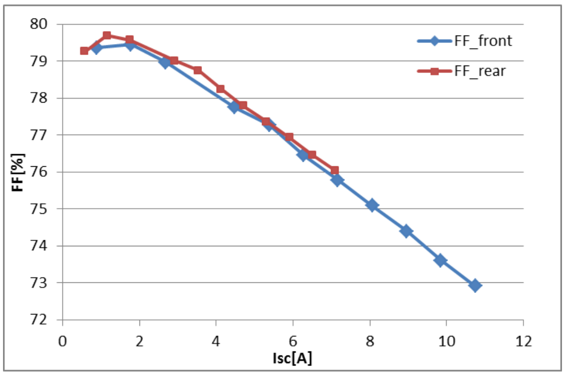

Figure 7 FF for front and rear irradiation with respect to Isc for a one cell module.

To calculate the FF difference at the same current level, three one cell modules were measured under a front intensity $G_{r,STC}$, defined as

$$G_{r,STC} = 1000W/m^2 \cdot \varphi_{Isc} \quad (4)$$

Under this intensity the same current is generated on the front side as on the rear side at STC. In Table 2 the results are listed. The FF for rear illumination is found to be 0.3% abs. higher than for frontside illumination. This result suggests that the FF is dependent on the light incident side. The cause for this effect is currently under further examination.

Table 2: differences in FF for frontside and rearside illumination for 3 one cell modules:

	Isc_[A]	FF_[%]	delta FF
Mod1_front_$G_{r,STC}$	5.881	77.966	
Mod1_rear STC	5.882	78.122	**0.20%**
Mod2_front_$G_{r,STC}$	5.916	76.677	
Mod2_rear STC	5.914	76.936	**0.34%**
Mod3_front_$G_{r,STC}$	7.785	76.991	
Mod3_rear STC	7.791	77.344	**0.46%**
mean:			**0.33%**
stdev:			0.13%

3.3 Calculation of bifacial power

As most labs and module producers do not have the possibility to measure a module`s IV curve under bifacial illumination, it is desirable to get reliable results for the bifacial gain based on monofacial measurements.

Singh et al. introduced in [2] a method to calculate the bifacial efficiency based on monofacial STC measurements of front and rear side. For different commercial modules, the results of this method were found to underestimate the measured bifacial power. Therefore, instead of using the ideal value for n=1, and an empirical relation for the pseudo fill factor pFF as proposed by Singh, these values were determined from a SunsVoc measurement [5] of the front side.

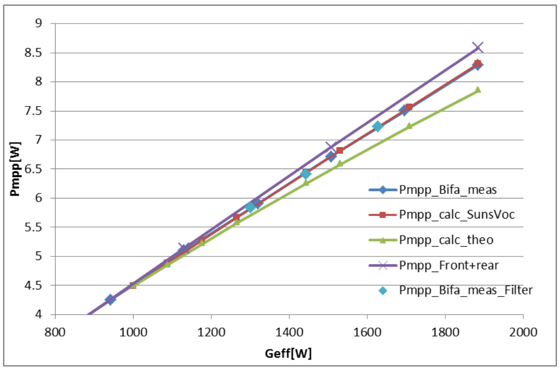

Figure 8 different approaches for measurement and calculation of bifacial Pmpp

With this modification, very good agreement with the results of the bifacial measurements could be reached, as is shown in figure 8 and Table 3. For the extreme case of 1000W/m^2 on front and rear side the mean deviation of measured and calculated power is 0.2%.

Table 3: mean deviation of measured bifacial power and calculated values for 1 sun front and rear intensity:

	meas-calc SunsVoc	meas-calc theo
Mean deviation	0.2%	-3.7%

4 CONCLUSIONS

For the basic characterization of bifacial modules, single sided STC measurements are required to assess the module parameters for each side. A comparison of different methods for the determination of the bifacial gain shows slightly different results. For modules with severe distortion of the rear IV curve, the measurement under real bifacial illumination is recommended to assess the correct IV curve for realistic operating conditions. In the Ge-method, the effects of partial shaded rear sides on the IV curve are not detected.

However, for low rear irradiances up to 200W/m^2 , the different approaches are in good agreement of about 0.5%.

Further, it is shown that based on single sided STC measurements and an additional SunsVoc measurement, the bifacial efficiency can be calculated. The results are in very good agreement with the measurement under bifacial illumination.

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