

CHARACTERIZATION OF BIFACIAL SILICON SOLAR CELLS AND MODULES: A NEW STEP

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ABSTRACT: Being interested in the characterization of bifacial solar cells and the maximizing of their potential, we studied how the sample holders add an external current mainly due to the reflectance properties of their surface. We found that this influence can be higher than one percent relative with respect to current. Using the same type of cells, mini modules were encapsulated using different back sheets. An increase of up to 8% in power output is visible before and after encapsulation if the back sheet is highly reflecting. Larger modules were laminated using transparent back foils with 16 of these cells and outdoor measurements performed. We changed the reflectance of the underlying surface and so the bifacial performance of the module varied, in a proportional manner. We have observed a relative increase in relation to monofacial averaged value of 7.9% of current if the reflectance of the surface is high, with major peaks up to 20%. The underlying area must be optimized to reveal the real potential of these devices. We have found a difference of about 30% relative comparing a small underlying area vs. a bigger area. There is also a saturation point when the underlying area is six times the area of the module. For this size or larger areas, the surface can be considered as infinite because its contribution will not change the performance of the module.

Keywords: Characterization, Bifacial, Module

1 INTRODUCTION

To assure the return of the warranted annual yield of photovoltaic outdoor installations along with the cost-saving potential of reduced tolerance specifications of photovoltaic modules, cell and module manufacturers worldwide pursue an in-depth understanding of measurement procedures to minimize their uncertainties and gather benefits of accurate performance predictions. Current-voltage (I-V) ratings and internal spectral quantum efficiencies (IQEs), representing the most important characteristics of a readily fabricated solar cell or module, are of special interest within this approach.

Bifacial and rear side passivated open rear contact solar cells present difficulties when measured due to their bilateral properties and hence external contributions from the measurement systems itself. One approach to eliminate these contributions from the rear side would be to measure these devices on a setup and especially a sample holder with a non reflective surface [1]. The resulting measurement would give an absolute value for a one side illuminated bifacial device. Because of a lack of appropriate non reflective and at the same time conducting surface material, the technical implementation is challenging and causes difficulties.

Bifacial solar cells are employed in double-sided transparent modules, taking advantage of the natural albedo from the place where they are mounted in order to increase their power output. It is also possible to laminate these cells in a module with a high reflecting, and hence non-transparent back sheet to get the rear contribution on a constant compared to monofacial solar cells elevated level. Different back sheets have been tested in mini modules, investigating the IV and IQE characteristics in every case.

2 PREREQUISITES FOR MEASUREMENTS

Before performing the experiments, several considerations were necessary. When using solar cells, it is very important to have a long time stable device and characterize its properties. In our case, the important

characteristics are not just the I-V curves, but also the IQE performance and transmission among others, for both sides. Temperature coefficients play an important role when using the cells in a laminated module for outdoor measurements.

Reflecting surfaces and back sheets have previously been characterized with respect to their properties of reflection, absorption and transmission [2].

2.1 Measurement of temperature coefficients

Temperature coefficients for cells are typically measured by placing the cell on a temperature controlled test fixture, illuminating the cell with a solar simulator, measuring the cell's current-voltage (I-V) curve over a range of cell temperatures, and then calculating the rate of change of the desired parameter with temperature [3].

Coefficients for modules can be measured either indoors with a solar simulator or outdoors under operational conditions [3].

In our outdoor measurements, these coefficients are needed to correct the measured values according to a standardized temperature.

2.2 Reflectivity of different surfaces

We have characterized different foils, used for subsequent experiments, some for indoor and others for outdoor measurements. Most of the foils are especially designed for photovoltaic approaches and for this reason they are quite stable in their reflection, absorption and transmission properties over the whole visible wavelength range, as shown in Fig. 1. We have searched for materials with reflecting characteristics that are similar to what can be found in nature [4]. The first foil is black (A) and the reflectivity of this foil varies from 6% to 8%, similar to what is observed for dark wet soil. Two white foils with reflectivities varying from 65-74% (B) and from 78-83% (C) respectively correspond to reflectivities of fresh snow. Finally, the reflectivity of the beige foil (D) shows a strong wavelength dependence. It can vary from 20-60% approximately and this reflection range is comparable to the reflection generated by sand in a desert.

The “natural” values show a large inhomogeneity and they are valid for certain climatic conditions. Nevertheless these values are typical for certain areas of the planet and have been measured during years under different circumstances [4].

The foils used in our case differ from these variations. Especially the impact of humidity, playing an important role in nature is eliminated and therefore stable reflection properties can be supposed during the time of the experiments.

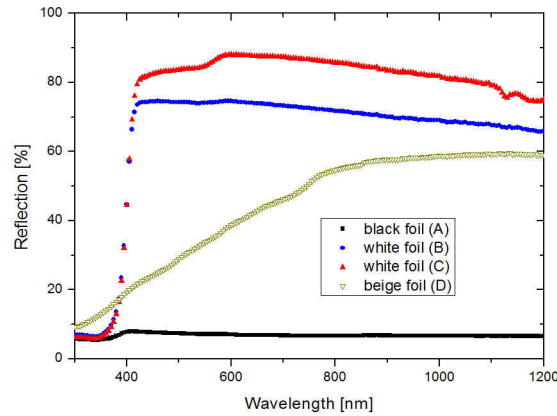


Fig. 1: Reflectivity of some of the foil surfaces used for our experiments.

2.3 The data collection system for outdoor measurements

We used an integrated system which allows us doing simultaneous measurements for several modules. The measured parameters for all data points are module performance and I-V curves, the temperature of the cell in the module and the solar radiation chosen perpendicular to the module surface.

With this data and the temperature coefficients (2.1) it is possible to normalize the measured values to standard test conditions (STC). All the presented data in this work were analyzed and corrected to STC: 1000 [W/m²] for irradiance and 25°C temperature.

3 INDOOR MEASUREMENTS

When a bifacial module is mounted in a highly reflecting environment, the light conversion and power generation will not only be driven by the illumination from the front side of the device, but also from reflected light which is penetrating the module from the rear side.

If these conditions are not fulfill and there is no space between the module and the reflecting surface (for example on a roof) an alternative could be to laminate the module with a highly reflecting surface instead of a transparent back sheet. With this, the rear contribution will be constant and comparable to monofacial modules with an elevated level.

In this part of the investigation, the aim is to predict how a bifacial module will behave for unusual lamination conditions.

3.1 What is really contributing from the rear side of a bifacial solar cell in a standard test measurement?

Previous results [2] show that the back reflectivity and the contact configuration of the sample holders strongly influence the generated current and the fill factor.

We consider a bifacial solar cell as quoted in [5], with 55 Ω/sq phosphorous emitter and 60 Ω/sq boron diffused back surface field based on a p-type substrate with a resistivity of 1.5 Ohm·cm and 200 μm thickness, leading to a n+pp+ asymmetric structure. Even for exclusive illumination of the front side, an extra contribution compared to monofacial samples is observed due to the device structure. This contribution considers the interaction of the system cell chuck, which is given by the light passing through the cell, but being reflected on the chuck surface and re-entering back the rear side of the cell. To calculate this influence, it is necessary to consider the transmission through the solar cell and the reflection of the chuck surface along the light spectrum. The graph in Fig. 2 shows the spectral response for front side illumination of the bifacial solar cell including the rear contribution. Since it is an integrated measurement we can hardly differentiate the contribution from the rear side effect. The red dots in Fig. 2 show the analogous calculation for the rear contribution caused by the chuck.

As the calculation indirectly includes the spectrum of the incident light, this is just an approximation to show graphically the influence of the rear side. In the measurement part of this article (3.2), this effect will be shown numerically.

Note that the data for this calculation is based on measurements where no space is between the cell and the chuck surface.

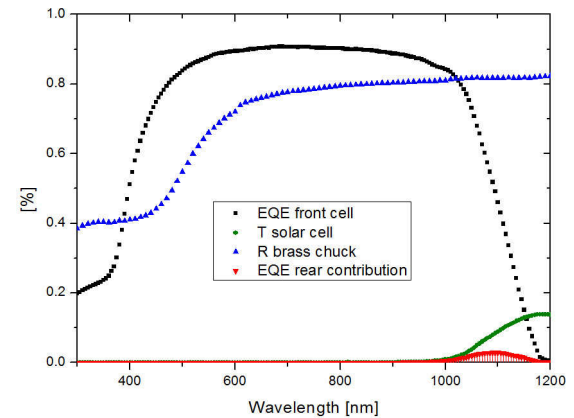


Fig. 2: Spectral response measurement for the front side of a bifacial solar cell (black). Transmission of the same cell, measured from the front (green). Reflectivity of a brass chuck surface (blue) and the rear contribution calculated due to the bifacial structure of the device (red).

3.2 I-V measurements for bifacial cells, different sample holders

A set of rear full area BSF bifacial and standard industrial monofacial silicon solar cells was chosen for IV characterization. Their transmission properties have been measured previously.

Different surfaces and back sheets have also been characterized with respect to their properties of reflection, absorption and transmission.

It is important to note that only the optical properties of our measurement system were changed and the electrical properties were kept constant.

The influence considers the effective reflection of the system cell-chuck as graphically shown in Fig. 2.

To test this, a long term stabilized bifacial solar cell was measured with a flash solar simulator, maintaining

the contact configuration and altering the optical properties of the chuck surface where the cell is placed. The following table shows the average results of these measurements, including short circuit current density variations compared to the standard chuck of the flasher.

Table I: Bifacial cell measured on different chuck surfaces.

| Chuck surface | V_{oc} [mV] | J_{sc} [mA/cm ²] | FF [%] | η [%] | Rel. variation J_{sc} [%] |
|----------------|---------------|--------------------------------|--------|------------|-----------------------------|
| Standard Chuck | 622.7 | 36.8 | 75.1 | 17.2 | N/A |
| Black A | 622.8 | 36.6 | 75.1 | 17.1 | -0.38 |
| White B | 623.3 | 37.1 | 75.0 | 17.3 | +0.84 |
| White C | 623.3 | 37.1 | 74.9 | 17.3 | +1.01 |

The rear side of this cell was also measured, showing the same variation range for the low reflecting back sheet and over +1% in J_{sc} variation for the high reflecting back sheets [2].

3.3 I-V measurements of mini modules with different back sheet encapsulation

A set of bifacial solar cells was long term stabilized and characterized. Before lamination in single cell mini modules the cells were sorted in three groups of five cells each. For the front side standard tempered glass 15.0x15.0 cm² with a thickness of 3.0 mm was used while for the rear side a non-transparent back sheet was applied. EVA served as encapsulant.

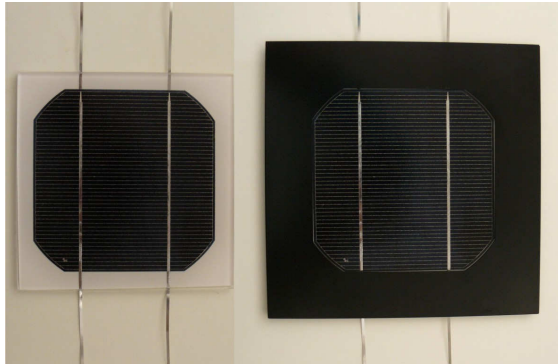


Fig. 3: One cell mini module and frame to cover the non-active area.

The solar cell presents a pseudo square shape with a size of 12.5x12.5 cm² and a diagonal of 15.0 cm. The resulting mini module has a size of 15.0x15.0 cm². The solar cell is laminated in the middle of the mini module.

A frame was built to cover the non-active area of the mini module, as depicted in Fig. 3.

With this device it is possible to measure in two modes: only by the illumination of net the cell area or illuminating the complete area of the mini module. Each group was measured before and after lamination. Table II presents the parameters of one representative sample for each lamination back sheet.

For the black foil a reduction in power output is observed. As values before lamination refer to

measurements on a standard brass chuck, the reduced reflectivity of the foil explains the deviation.

Table II: I-V measurements for different back sheets. Before lamination, illumination of the cell area only and illumination of the complete mini module. Relative variation to the measurements before lamination.

| | V_{oc} [V] | J_{sc} [A] | FF [%] | P_{out} [W] | Rel. P_{out} variation [%] |
|--------------------------------|--------------|--------------|--------|---------------|------------------------------|
| Cell before lamination | 0.603 | 5.20 | 66.6 | 2.09 | N/A |
| <i>Lamination Black foil A</i> | | | | | |
| Illumination Cell area | 0.602 | 4.97 | 67.1 | 2.01 | -3.9 |
| Illumination Module | 0.602 | 5.06 | 66.8 | 2.03 | -2.7 |
| Cell before lamination | 0.588 | 4.86 | 67.9 | 1.94 | N/A |
| <i>Lamination White foil B</i> | | | | | |
| Illumination Cell area | 0.590 | 4.87 | 67.9 | 1.95 | +0.4 |
| Illumination Module | 0.592 | 5.27 | 67.2 | 2.1 | +7.4 |
| Cell before lamination | 0.587 | 4.84 | 67.7 | 1.93 | N/A |
| <i>Lamination White foil C</i> | | | | | |
| Illumination Cell area | 0.588 | 4.85 | 68.0 | 1.94 | +0.6 |
| Illumination Module | 0.591 | 5.28 | 67.4 | 2.1 | +8.2 |

For the white foils an increase in power output of up to 1% is visible if the illuminated area is restricted by the mask to the active area of the solar cell. In the case that the mini module is completely illuminated, the elevated reflections on the surface of the glass and the back foil boost the power output up to 8.2%.

The open circuit voltage and the fill factor remain almost constant, while the determinant parameter is the short circuit current. It is important to mention that the solar cell was measured before lamination with the same contacts as after lamination and therefore we have expected that the fill factor remains unchanged.

4 OUTDOOR MEASUREMENTS

Bifacial modules are designed to capture the existing albedo of a region using the front side as well as the rear side of the device to increase the performance. This type of module is not commonly installed on roofs, and shows best suitability for ground mounting areas where light can be reflected by a surface and can be collected at the rear side.

It is also known that the space between the module and the reflecting surface plays an important role in the power output gain [6] and that this distance increases the homogeneity of the collected reflected light [7].

In this work we have used three types of bifacial modules and three different reflecting ground back sheets, representing surfaces similar to what can also be found in nature, to give the reader an idea about the applied potential of these devices.

4.1 Bifacial module for different reflecting surfaces

The used module has similar characteristics as quoted in [5]. Standard module glass has been used on the front side, while a clear transparent back sheet was applied to the rear side and standard EVA served as encapsulant.

The measurements were performed in the city of Konstanz (coordinates 47°49'N 8°53'E) in south Germany during one week in August. The presented values are averaged during one day. The module was facing south with an inclination angle of approximately 30°. The underlying surface cannot be considered as infinite, but it was large enough to reflect a appropriate amount of light.

Three measurements were recorded for every reflecting surface: a) only front side (monofacial) by covering the rear side of the module, b) only rear side, covering the front side of the module and c) bifacial. Table III presents a summary for J_{sc} and a comparison for monofacial (only front) vs. bifacial.

Table III: Module measurements of J_{sc} for different reflecting surfaces and the percentage difference between monofacial and bifacial measurements for front side illumination.

| Reflecting surface | Rear [A] | Front [A] | Bifacial [A] | Difference [%] |
|--------------------|----------|-----------|--------------|----------------|
| Black A | 0.27 | 4.62 | 4.77 | 3.2 |
| Beige D | 0.33 | 4.60 | 4.84 | 5.0 |
| White C | 0.46 | 4.65 | 5.05 | 7.9 |

The increase in current has a linear dependence vs. reflectivity of the underlying surface. Major peaks are detected during different irradiation conditions showing up to 20%, not visible in the standardized and averaged results.

It is also possible to notice an effect, since the direct addition of front and rear current is always higher than the measured bifacial value. This mismatch varies inversely with the reflectivity of the underlying surface.

4.2 Small module, influence of the underlying area size

Fig. 4 presents the lateral view of a scheme to measure the underlying area effect on bifacial solar cells. A small module with area $A_1 = a \cdot b$ was placed in a fixed distance $z = a$ from the underlying surface, keeping the module always parallel to the surface. This surface is highly reflecting as presented in Fig. 1, white C.

To simplify matters, we kept the incident angle α always constant and approximately 30° with respect to the reflecting surface. To do this, the measurements have to be fast, so the natural movement of the sun does not affect the measurements. The angle was calculated from the projection of the shadow of the module over the reflecting surface.

Once we achieved the desired position we changed the size of the underlying surface A_2 in a proportional mode to the module area A_1 . For every area A_2 the I-V characteristics of the module were measured under three

conditions: front side only, rear side only and bifacial mode. The summary of these results for J_{sc} is shown in Fig. 5, including also a comparison with the mathematically added values front plus rear.

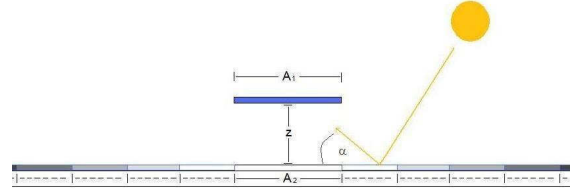


Fig. 4: Scheme of the lateral view for the area experiment.

While the area A_2 increases, the front side measurement remains constant and only the rear and therefore the bifacial mode changes. There is a saturation point observed, approximately at six times A_1 the area of the module. For values of power output the same saturation behavior is observed.

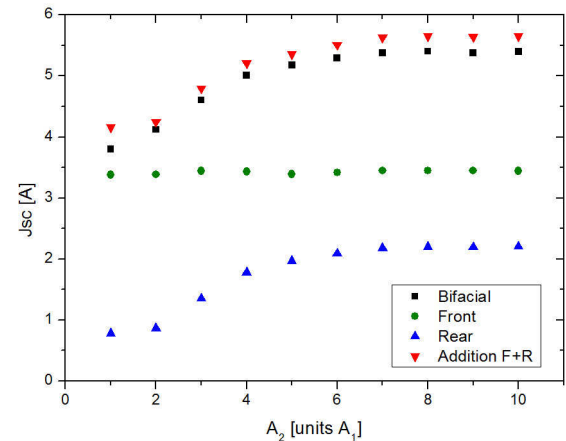


Fig. 5: Current of the mini module for different underlying areas in three modes: bifacial, front and rear. Front plus rear side addition as reference.

The visible gain is up to 29% relative from a small underlying area compared to an area larger than six times the area A_1 ($A_2 = 6 \cdot A_1$). From this value on, the surface can be considered as “infinite” since a larger area will not affect the results.

The comparison between monofacial and large underlying area in bifacial mode shows an increase in current up to 35% relative.

It is also interesting to note that once again, the addition of the values front and rear side is higher than the measured bifacial mode. This is due to a saturation effect of the device, as it is impossible to convert all the light simultaneously.

This study suggests to be extended to a non parallel position of the module with respect to the surface. This would be a more real case since PV modules are not mounted parallel to the surface, but at a certain angle. Our case is a simplified model, but new experiments are planned to study this effect in a more real situation.

5 CONCLUSIONS

To characterize bifacial solar cells realistically it is necessary to consider the structure of the devices. It is important to know how the measurement system will influence the results to benefit from the bifacial structure and ambient conditions and to optimize the performance of the system.

The contribution of the rear side has been measured and it can be up to 1% in J_{sc} . To take advantage of this effect, bifacial solar cells can be laminated using a high reflecting back sheet. In this case the increase can be higher than 8% comparing the cell before and after lamination. When we use a black foil for lamination, a reduction of about 3% relative in efficiency is observed.

Depending on the reflectivity of the underlying surface, an average increase of up to 7.9% (relative) of the bifacial mode compared to the monofacial mode can be observed. However, higher values of up to 20% have been measured in our experiment.

Comparing the reflectivity of our foils with naturally occurring reflectivities, we can predict an increase of up to 3% relative in the bifacial mode compared to monofacial mode with dark soil as a reflector. For sand or fresh snow the corresponding numbers are expected to be 5% and 8% respectively.

The size of the underlying area exposed to direct sunlight plays also an important role. We have found that the usable area to reflect the light is six times the area of the module size. For this type of modules it is important to consider a wide separation for installation to take advantage of the reflection of the natural surface.

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