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MONOFACIAL IV MEASUREMENTS OF BIFACIAL SILICON SOLAR CELLS IN AN INTER-LABORATORY COMPARISON

Michael Rauer[1,*], Karsten Bothe[2], Corrado Comparotto[3], Pi Danzl[4], Maarten Debucquoy[5], Nicolas Enjalbert[6], Jochen Hohl-Ebinger[1], Petra Manshanden[4], Yannik Veschetti[6], Johnson Kai Chi Wong[7]

[1]Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstraße 2, 79110 Freiburg, Germany
[2]Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany
[3]International Solar Energy Research Center (ISC), Rudolph-Diesel-Straße 15, 78467 Konstanz, Germany
[4]ECN Solar, Westerduinweg 3, 1755 LE Petten, The Netherlands
[5]imec, Kapeldreef 75, 3001 Heverlee, Belgium
[6]CEA, LITEN, INES, 50 av. du Lac Léman, 73370 Le Bourget du Lac, France
[7]Solar Energy Research Institute of Singapore (SERIS), 7 Engineering Drive 1, Singapore 117574, Singapore

[*]Corresponding author: phone: +49(0)761/4588-5564, e-mail: michael.rauer@ise.fraunhofer.de

ABSTRACT: Standardizing illuminated IV measurements of bifacial solar cells and modules is a central objective for the introduction of bifacial products into the market. In this paper, the application of monofacial IV measurement conditions to bifacial solar cells is evaluated in an inter-laboratory comparison among seven research institutes in Europe. Bifacial silicon solar cells manufactured at five different sites with five different fabrication technologies were used in this investigation. We demonstrate that several characteristics of the measurement setups which are of minor importance for the measurement of monofacial solar cells can significantly affect bifacial solar cell measurements: (i) the reflectance of the measurement chuck and (ii) the electrical conductance of the chuck implying specific contacting schemes. When dividing the measurement results of this round robin into two groups according to chuck reflectance and conductance, the deviations in the IV parameters among the different partners are mostly within the uncertainty limits commonly reported for monofacial solar cell measurements. For standardization of bifacial solar cell measurements, it is therefore important to define admissible ranges for the chuck reflectance and to specify the contacting scheme in the standard.
Keywords: Bifacial Solar Cells, Standardization, IV Measurement, Round Robin

1 INTRODUCTION

In today's solar cell market, bifacial solar cells and modules are becoming more and more important. Because of their ability to convert light from both front and rear surface, bifacial modules can produce 5 to 25 % more energy than standard monofacial products [1]. Therefore, the market share of bifacial silicon solar cells is estimated to increase to up to 20 % in the next 20 years [2]. Although the current development of bifacial solar cell and module technologies is promising, an essential issue hindering the introduction into the market is the missing IV measurement standardization [3].

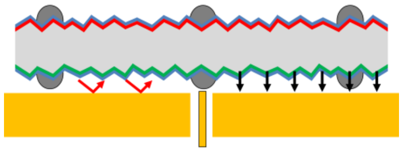
The standards of the International Electrotechnical Commission (IEC) describe the conditions for the measurement of solar cells to ensure inter-laboratory comparability of the solar cell characteristics. However, there is as yet no standard defining the measurement of bifacial solar cells. The most common method to determine the illuminated IV characteristics of bifacial solar cells is the application of monofacial measurement conditions including single-sided illumination. This, however, can lead to additional uncertainties: light that is transmitted through the bifacial solar cell can be reflected at the measurement chuck and reenter the solar cell through its rear surface. Therefore, the chuck reflectivity influences the measured current significantly [4]. In addition, the rear electrical contacting scheme depends on the measurement chuck design as well: whereas reflective chucks are normally made from copper or brass blocks, which electrically contact the entire rear metal grid of the solar cells, non-reflective chucks are commonly covered by non-conducting black foils, so that only the rear busbars are contacted. In general, this leads to the measurement of different fill factors [5]. However, reliable and accurate characterization procedures are essential for solar cell manufactures in order to optimize the solar cell structures for high energy yield.

To clarify the impact of the measurement setup on the illuminated IV characteristics of bifacial solar cells under monofacial conditions, a round robin among seven different research institutes in Europe was carried out. Bifacial solar cells of five different fabrication techniques were investigated. The aim was to evaluate inter-laboratory comparability and to elaborate the reasons for measurement deviations.

2 EXPERIMENTAL

Twenty-seven industrial bifacial *n*-type silicon solar cells with edge lengths of 156 mm and three busbars were provided by five participants of this round robin. The investigated solar cells thus comprise five different fabrication technologies. The illuminated IV characteristics of the solar cells were independently measured by the different partners under standard testing conditions (25°C, 1000 W/m^2, AM1.5G spectrum) using single-sided illumination. Separate measurements of front and rear characteristics were carried out. The measurement chucks used by the partners can be grouped into (i) "reflective and conductive chucks", which are generally realized by metal chucks with reflective surface and electrical contact to the entire rear metal grid of the solar cells, and (ii) "non-reflective and non-conductive chucks", which are chucks with black foils and electrical contacts only to the rear busbars of the solar cells (see

(a) Reflective and conductive chuck



(b) Non-reflective and non-conductive chuck

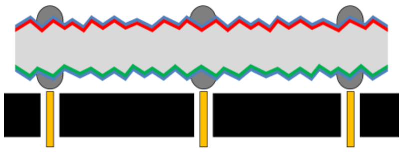


Figure 1: Schematics of the two different measurement setups applied in this study. The figures are adapted from [5].

Figure 1).

Table 1 gives an overview of the chucks applied by the partners. For simplicity, reflective/conductive chucks are referred to as "*reflective chucks*", non-reflective/non-conductive ones as "*non-reflective chucks*" in the following.

Partners 1, 5 and 6 carried out additional spectral response measurements for the spectral mismatch correction, thereby using corresponding identical measurement chucks. Partner 5 measured the IV characteristics with a non-reflective chuck at the beginning and at the end of the round robin. The accordance of the measured IV parameters was within the uncertainty limits given by the partner.

In order to assess the inter-laboratory comparability, the non-area-related IV characteristics, namely the short-circuit current I_{sc}, the open-circuit voltage V_{oc}, the fill factor FF and the absolute power P_{mpp}, were evaluated. To investigate the influence of the series resistance of the metal grids, the busbar-to-busbar resistances were additionally measured.

3 DEVIATIONS IN THE MEASURED IV PARAMETERS

In order to compare the IV parameters measured by the different partners of this round robin, median values were calculated for each cell, thereby distinguishing between reflective and non-reflective chucks. The relative differences of the parameters measured by the partners to the respective cell medians were determined. To eliminate the effect of outliers, median instead of average values were used for the evaluation.

Figure 2 shows the deviations of the short-circuit current, the open-circuit voltage and the fill factor from the respective medians. For reasons of clarity, the deviations in power are not depicted. The dashed lines indicate the expanded measurement uncertainties (coverage factor 2) for the measurement of monofacial solar cells as given by partners 1 and 5.

The distributions can be used to investigate the random and the systematic deviations between the partners for each IV parameter. Random variations are quantified by the standard deviations of the

Table 1: Measurement setups used by the partners of this round robin for the determination of the illuminated IV characteristics. "x x" means that two different, independent setups of the respective configuration were applied.

Partner	Reflective and conductive chuck	Non-reflective and non-conductive chuck
1	x	x
2	x	
3	x	
4		x
5	x x	x
6	x x	x
7	x	

distributions, *i.e.* by the widths of the distributions, systematic variations by the absolute deviations from the median, *i.e.* by the offsets of the distribution averages [6].

3.1 Short-circuit current deviations

The I_{sc} deviations observed for bifacial solar cells between the partners in this round robin are within the uncertainty limits commonly reported for monofacial solar cell measurements (see dashed lines in Figure 2), if the measurements are differentiated by the two chuck types. No significant differences in the random and systematic variations were thereby found between measurements on reflective and on non-reflective chucks: The distributions of the I_{sc} values show that, for both chuck types, the random variations at each partner's setup are in the same order or larger than the systematic deviations among the different partners.

In this study, the random deviations are more pronounced than in other round robin evaluations published before [6]. We attribute this discrepancy to the use of solar cells of different technologies together with the partial omission of the spectral mismatch correction in the present round robin. As the solar cells investigated here exhibit diverse spectral responses, using the same reference solar cell for all the measurements leads to variations in the spectral mismatches between the tested solar cells and the reference cell. If no mismatch correction is carried out, this in turn can result in a broadening of the I_{sc} distribution.

In addition, the non-application of a monitor setup to correct the measurement for fluctuations in the lamp intensity of the sun simulator can also contribute to the random deviations [7].

These two aspects would occur for the measurement of monofacial and bifacial solar cells alike. There are also effects characteristic for bifacial solar cells, though, which lead to systematic deviations between the partners. These are discussed in more detail in section 4.1.

3.2 Open-circuit voltage deviations

Figure 2 shows that the deviations in V_{oc} among the different partners for reflective and non-reflective chucks are mostly within the uncertainty limits specified by partners 1 and 5 for the measurement of monofacial solar cells. The random variations in V_{oc} given by the widths of the distributions are thereby significantly smaller than the random variations in I_{sc}

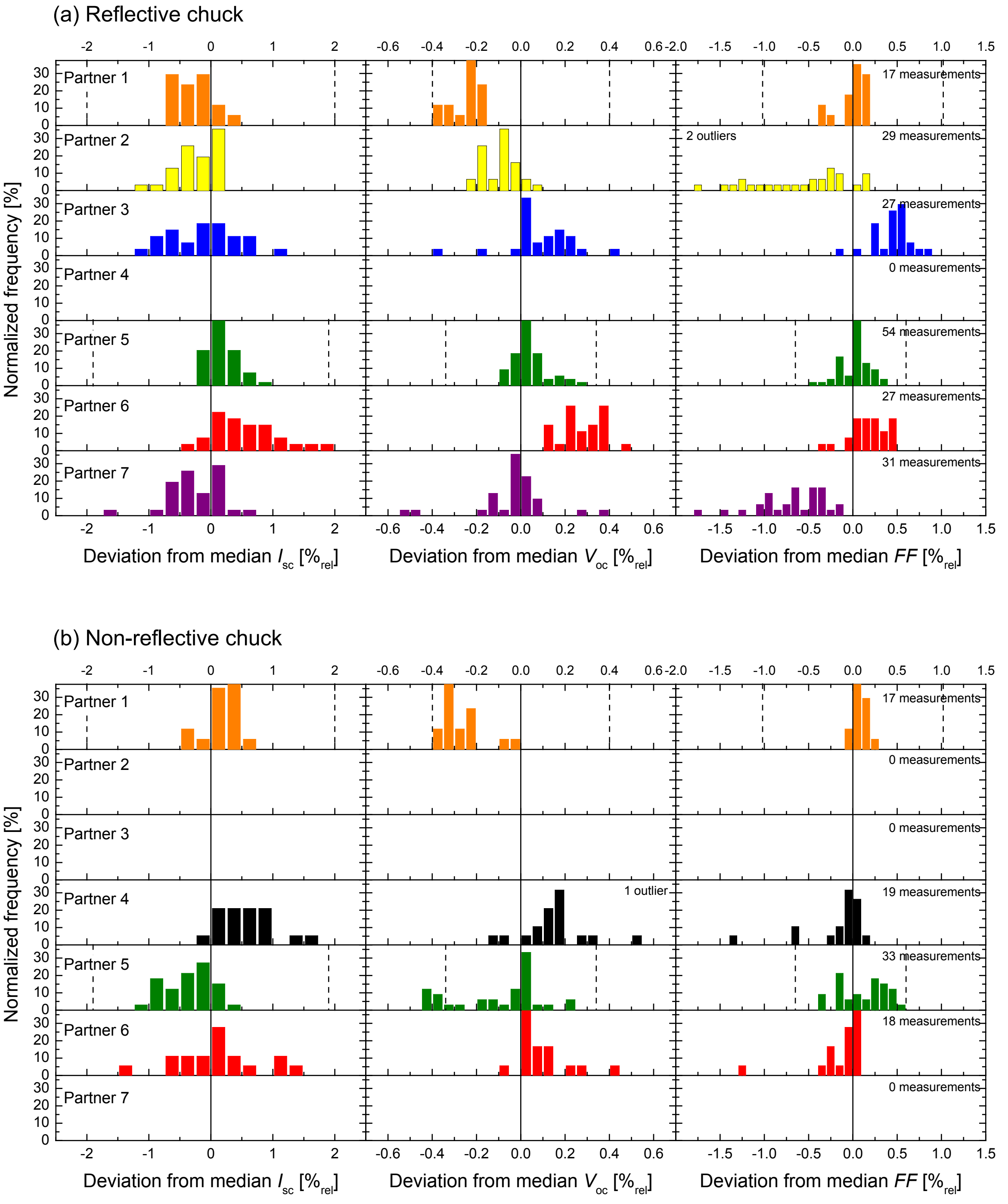


Figure 2: Relative deviation of the short-circuit current I_{sc}, the open-circuit voltage V_{oc} and the fill factor FF measured by each partner from the respective median value for measurements on (a) reflective chucks and (b) non-reflective chucks. Please note that not all the partners measured each solar cell; only solar cells measured by at least four different institutes were taken into account in the evaluation. The numbers in the upper right corners of the graphs indicate the amount of cells measured by the partners contributing to the evaluation. The dashed lines in the graphs of partners 1 and 5 demonstrate the respective expanded measurement uncertainties determined for monofacial solar cell measurements (coverage factor of 2). For the sake of clarity, outliers are not shown but indicated in the graphs.

discussed above, which has also been reported for earlier round robin evaluations [6]. Within the uncertainty limits, systematic deviations in V_{oc} among the partners occur. In relation to the widths of the respective distributions, the systematic deviations are larger for V_{oc} than for I_{sc} measurements.

It is well-known that the major uncertainty in the V_{oc} measurement comes from the control of the solar cell temperature. The small random variations in V_{oc} observed here show that the solar cell temperature is generally controlled accurately at the partners' setups, so that the V_{oc} determination is highly reproducible.

The larger systematic differences in V_{oc}, however, indicate that the absolute temperature may vary among the different partners due to different positioning of the temperature sensor (*e.g.* directly on the solar cell or indirectly on the measurement chuck). This has also been reported in earlier round robin evaluations [6, 7]. Figure 2 shows that this issue occurs for reflective and non-reflective measurement chucks alike.

For partner 5, the deviations from the median V_{oc} exceed the respective measurement uncertainty for measurements on non-reflective chucks. Provided that the medians approximate the respective real values adequately, this implies that the uncertainty budget for non-reflective chuck measurements needs to be adapted.

In section 4.2, the differences in temperature control on reflective and on non-reflective chucks are investigated in more detail.

3.3 Fill factor deviations

For most partners, the deviations in *FF* are within the uncertainty limits of monofacial solar cell measurements for both reflective and non-reflective chucks. Only the fill factor values measured by partners 2 and 7 exceed these limits and are broadly distributed towards smaller values. It was found that the *FF* deviations of partner 2 thereby correlate with the series resistances of the metal grids of the tested solar cells, *i.e.* the higher the grid series resistance, the higher the *FF* deviation from the respective median. This suggests that a systematic error is the cause for the measurement deviations of partner 2. No equivalent correlations were found for the measurements of partner 7. Further investigations on this issue are still pending.

Apart from the measurement results of partners 2 and 7, no significant differences in the systematic and random *FF* variations were found between measurements on reflective and on non-reflective chucks.

In section 4.3, reasons for the systematic deviations are investigated and discussed in more detail.

4 SYSTEMATIC DEVIATIONS SPECIFIC TO THE MEASUREMENT OF BIFACIAL SOLAR CELLS

In order to investigate the systematic deviations further, the differences in IV parameters between reflective and non-reflective chuck measurements were examined as observed directly by the different partners. This allows for a higher precision in the assessment of deviations between the two chuck types, since the variations measured by one partner are generally smaller than the variations among the different partners [7, 8].

4.1 Chuck reflectance

The differences ΔI_{sc} in the short-circuit current from reflective to non-reflective chuck measurements as detected by partners 1, 5 and 6 are shown in Figure 3. ΔI_{sc} could thereby only be determined for the partners that carried out measurements on both reflective and non-reflective chucks.

A significant offset between the ΔI_{sc} distribution of partner 1 and the distributions of partners 5 or 6 can be seen. Although the average ΔI_{sc} values of partners 5 and 6 agree, the widths of the respective distributions differ.

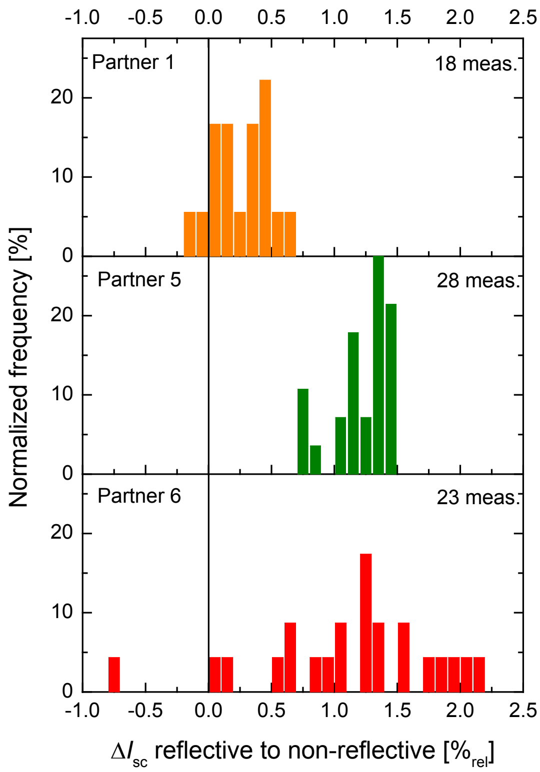


Figure 3: Relative difference ΔI_{sc} between the short-circuit currents measured on reflective and non-reflective chucks by the different partners. The difference could only be determined for the partners that carried out measurements on both reflective and non-reflective chucks.

In order to investigate the offset in ΔI_{sc} further, the reflectances of the measurement chucks used by the partners were measured, as shown in Figure 4. It can be observed that (i) the reflectances corresponding to one chuck type vary significantly among the partners, and (ii) the differences in reflectance between reflective and non-reflective chucks vary as well. Partner 1 intentionally uses a non-reflective chuck with slightly higher reflectance. The focus of the chuck design is to enable the accurate thermal control of the tested solar cells.

Differences in chuck reflectance lead to different contributions of the transmitted and reflected light to the respective short-circuit current. Thus, the larger the difference in the chuck reflectance between reflective and non-reflective chuck, the larger the short-circuit current difference ΔI_{sc}.

It becomes obvious that the classification into reflective and non-reflective chucks actually has to be differentiated further as there are no *typical* measurement chucks. The chuck reflectance is an important parameter for the measurement of bifacial solar cells because it can significantly affect the measured I_{sc} values. For standardization of the IV measurements, it is therefore important to either define an admissible reflectance range for reflective and non-reflective measurement chucks or to explicitly specify the chuck reflectance in the measurement report.

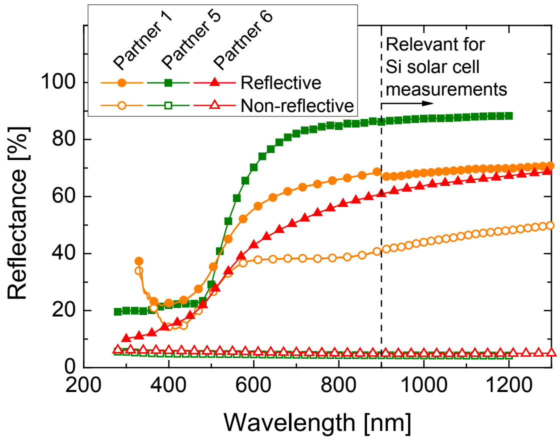


Figure 4: Reflectance of the measurement chucks applied by partners 1, 5 and 6. Full symbols represent measurements on reflective chucks, empty symbols on non-reflective chucks.

4.2 Temperature control

In section 3.2, systematic differences in the V_{oc} distributions among the different partners have been identified. These deviations can most likely be attributed to differences in the solar cell temperature control.

It has yet to be investigated if the temperature control is different for the two chuck types. Figure 5 shows the differences in V_{oc} between reflective and non-reflective chuck measurements for partners 1, 5 and 6. All ΔV_{oc} distributions are systematically shifted to positive voltages, *i.e.* V_{oc} is measured higher on reflective chucks. This shift is thereby more pronounced for partners 5 and 6, who also exhibit broader distributions.

We have considered the implications of physical origins for the V_{oc} differences: assuming similar measurement conditions, the only physical reason for the measurement of different V_{oc} values on reflective chucks is the increased injection resulting from an increased chuck reflectance. To assess the relevance of the increased injection, we calculated the corresponding V_{oc} increase using the ideal diode equation. We calculated values well below 0.1 $\%_{rel}$, which shows that this effect is negligible. Measurable differences in V_{oc} on reflective and non-reflective chucks are therefore measurement-related and are attributed to inaccuracy in temperature control. The comparison of the V_{oc} values measured with the two different chuck types thus provides a good measure to check consistency in temperature control.

Reflective chucks exhibit good thermal conductance. For these chucks, there is an adequate thermal contact between the solar cells under test and the chuck. For non-reflective chucks, though, the insulating layer generally covering the surface is of poor thermal conductance. The temperature adjustment is therefore more critical for non-reflective chucks [9]. Underestimating the heating of the solar cell under test during measurement on non-reflective chucks results in the determination of too small V_{oc} values and thus to $\Delta V_{oc} > 0$. This can be seen for the measurements of partners 5 and 6. Partner 1 applies a non-reflective measurement chuck which is optimized for improved thermal contact to the tested solar cells. Figure 5 shows that this leads to a smaller difference in V_{oc} between the two chuck types.

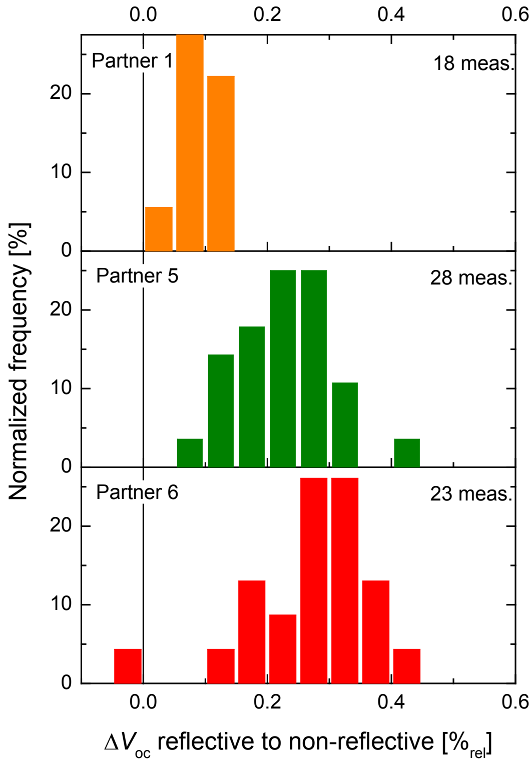


Figure 5: Relative difference ΔV_{oc} between the open-circuit voltages measured on reflective and non-reflective chucks by partners 1, 5 and 6.

In conclusion, the temperature of bifacial solar cells has to be adjusted carefully to standard testing conditions. This round robin showed that there are not only general differences in the temperature control among the different partners, but also between the different chucks used by the individual partners.

4.3 Influence of chuck conductivity

Figure 6 shows the differences in fill factor ΔFF between reflective and non-reflective chuck measurements as observed by partners 1, 5 and 6. A systematic shift to positive ΔFF values can be seen for all three partners, *i.e.* the fill factors are measured higher on reflective as compared with non-reflective chucks.

A physical reason for the measurement of different fill factors with the two chuck types is the different injection conditions leading to different series resistance losses. Using Quokka simulations of a typical industrial bifacial Si solar cell [10], this effect was estimated to be below 0.1 $\%_{rel}$, though, and thus to be negligible.

A measurement-related reason for $\Delta FF > 0$ is the difference in the rear contacting scheme of the two chuck types. Whereas reflective chucks contact the entire rear metal grid of the solar cells, non-reflective chucks contact only the rear busbars. Therefore, the lateral resistance of the rear metal finger grid contributes to the series resistance of the tested solar cells for non-reflective but not for reflective chuck

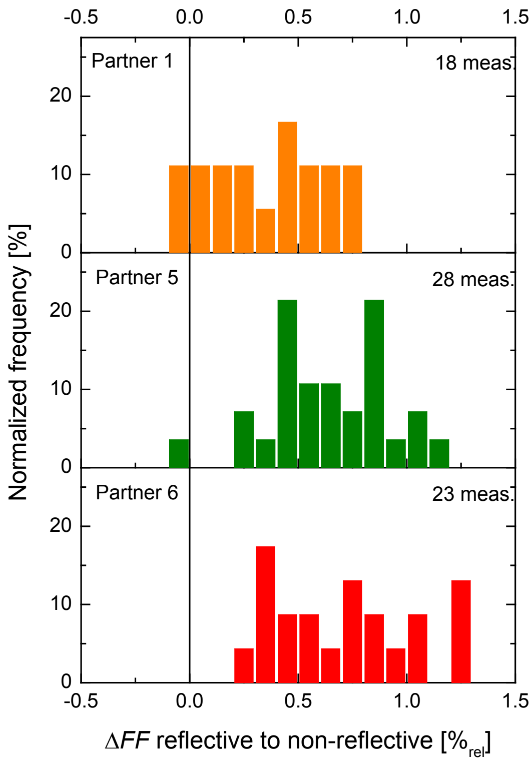


Figure 6: Relative difference ΔFF between the fill factors measured on reflective and non-reflective chucks by partners 1, 5 and 6.

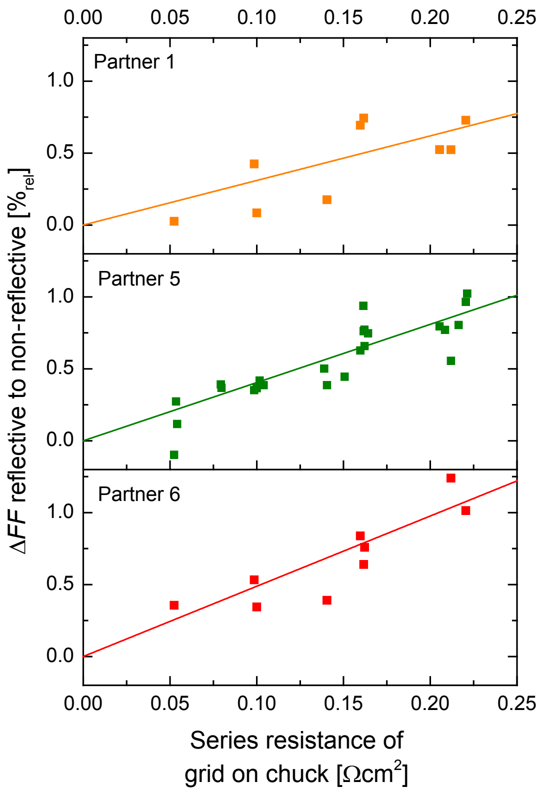


Figure 7: Relative difference ΔFF between the fill factors measured on reflective and non-reflective chucks as a function of series resistance of the metal grid contacting the chucks. The lines are guides to the eyes.

measurements. To evaluate this effect, the series resistance of the front and rear metal grid was determined for each solar cell of this round robin by measuring the respective average busbar-to-busbar resistances. The fill factor differences ΔFF between reflective and non-reflective chucks were then correlated with the series resistances of the grids contacting the chucks during the measurements, *i.e.* ΔFF corresponding to front side measurements of a specific solar cell was related to the grid resistance of its rear side and *vice versa*. Figure 7 shows that there is a clear correlation between ΔFF and the grid series resistance for all three partners.

This demonstrates that the rear contacting scheme significantly affects the measured *FF* for bifacial solar cells. This effect also occurs in the measurement of conventional monofacial solar cells, however to a much lesser degree. Since conventional solar cells feature a full-area rear metal contact, the series resistance due to lateral current flow to the rear contacting unit is typically one order of magnitude smaller (0.02 to 0.03 Ωcm^2 [11]). Therefore, the influence of the contacting scheme associated with the chuck type on the measured *FF* is significantly smaller.

Although all partners measure higher fill factors with reflective as compared with non-reflective chucks for the solar cells of this round robin, the *extent* how much higher the *FF* is measured is different for partner 1 and partners 5 and 6, *i.e.* there is an offset in the ΔFF distributions between these partners. This can partially be explained by the differences in the control of the solar cell temperature, which has been discussed in the previous section. Underestimating the temperature on non-reflective chucks leads to the measurement of too small fill factors and a slight overrating of ΔFF. Further contributions to ΔFF differences possibly result from differences in placement and distance of current and voltage pins among the partners. Since the contact pin geometry affects reflective and non-reflective chucks differently (front contact for reflective chucks, both front and rear contacts for non-reflective chucks), different contact pin geometries of the partners could result in differences in ΔFF.

In conclusion, it has been shown that the contacting scheme is more critical for the measurement of bifacial as compared to the measurement of monofacial solar cells due to the high series resistance of the metal grids. For standardization of the IV measurements, it is therefore crucial to explicitly specify the contacting scheme used for the measurements.

5 SUMMARY

A round robin among seven different research institute partners in Europe has been carried out to investigate the application of monofacial IV measurement conditions to bifacial silicon solar cells. Twenty-seven solar cells of five different fabrication techniques were used for the measurements. The measurement chucks applied by the partners were divided into two categories: (i) reflective and conductive chucks and (ii) non-reflective and non-conductive chucks.

It has been shown that, for both chuck configurations, the deviations in the short-circuit currents, open-circuit voltages and fill factors measured for the bifacial solar cells among the different partners are mostly within the uncertainty limits commonly reported for monofacial solar cell measurements. Within these limits, systematic differences in the IV parameters among the partners larger than random variations were found for measurements on both chuck types. The measurements which exceeded the uncertainty limits were examined further and possible causes for these discrepancies were discussed.

In order to investigate the systematic deviations among the partners in more detail, the differences in the IV parameters between reflective/conductive and non-reflective/non-conductive chuck measurements as observed directly by the different institutes were examined. It was thus demonstrated that there are several effects, which play a minor role in the measurement of monofacial solar cells, but are strongly relevant for bifacial solar cell measurements.

The comparison of the chuck reflectances has shown that the reflectances differ significantly for both reflective/conductive and non-reflective/non-conductive chucks among the partners. It is demonstrated that this has a significant effect on the measured short-circuit current of bifacial solar cells.

Significant differences in the open-circuit voltages among the different partners were observed, which is likely caused by the temperature control of the solar cells. In addition to differences in the positioning of the temperature sensor among the partners, which is expected to affect both types of measurement chucks alike, the heating of the bifacial solar cells on non-reflective/non-conductive chucks seems to result in an additional underestimation of V_{oc} on these chucks for some partners.

The contacting scheme, which differs for the two measurement chuck types (contact to entire rear grid for reflective/conductive chucks, contact to the busbars only for non-reflective/non-conductive chucks), significantly affects the measured fill factor due to the different contribution of the rear metal grid. Although this effect also occurs for monofacial solar cells, it is significantly more pronounced for bifacial solar cells due the higher series resistance of the rear contact grid compared to a conventional full-area rear contact.

For standardization of bifacial solar cell measurements, it is therefore important to either define admissible ranges for the chuck reflectance and to specify the contacting scheme in the standard or to explicitly state these parameters in the measurement report.

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