RESULTS OF THE BIFACIAL PV CELLS AND PV MODULES POWER MEASUREMENT ROUND ROBIN ACTIVITY OF THE PV-ENERATE PROJECT

George Koutsourakis[1], Michael Rauer[2], Alexandra Schmid[2], Giovanni Bellenda[3], Tom R. Betts[4], James C. Blakesley[1], Martin Bliss[4], Johanna Bonilla[5], Karsten Bothe[6], Sebastian Dittmann[7], Juan Lopez-Garcia[8], Werner Herrmann[5], David Hinken[6], Robert Kenny[8], Ruben R. Molinero[3], Diego Pavanello[8], Stefan Riechelmann[9], Hendrik Sträter[9], Alberto Vegas[10], and Stefan Winter[9]

[1]National Physical Laboratory (NPL), Hampton Road, Teddington, Middlesex, TW11 0LW, United Kingdom
[2] Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, 79110 Freiburg, Germany
[3]University of Applied Sciences and Arts of Italian Switzerland (SUPSI), Via Pobiette 11, 6928 Manno, Switzerland
[4]Centre for Renewable Energy Systems Technology (CREST), Loughborough University, Loughborough, LE11 3GR, United Kingdom
[5]TÜV Rheinland Energy GmbH (TRE), 51105, Cologne, Germany
[6]Institute for Solar Energy Research GmbH (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany
[7]Anhalt University of Applied Sciences (HSA), Bernburger Str. 55, 06366 Köthen (Anhalt), Germany
[8]Joint Research Centre (JRC), Via E. Fermi, 2749, 21027 Ispra VA, Italy
[9]Physikalisch-Technische Bundesanstalt (PTB) Bundesallee 100, 38116 Braunschweig, Germany
[10]Instituto Nacional de Técnica Aeroespacial (INTA), ctra Ajalvir, Torrejón de Ardoz 28850, Madrid, Spain

ABSTRACT: Bifacial Photovoltaic (PV) technology is expected to acquire an increased market share of the solar PV industry in the future, due to the ability of bifacial PV modules to collect light from both the front and rear side, increasing the energy yield for a specific available area for a PV system. Accurate measurement procedures for bifacial products result in more accurate energy yield estimates, consequently improving the bankability of bifacial PV technology. This work aims to evaluate the procedures for the measurement of electrical power and bifacial parameters of bifacial solar devices, concerning to their applicability in calibration laboratories and production line environments. An intercomparison for bifacial PV cells and modules is carried out between nine different test laboratories across Europe, as part of the PV-Enerate project. The measurement procedures as described in IEC TS 60904-1-2:2019 are followed among the different test laboratories, to evaluate the applicability of these procedures. Three different types of bifacial PV cells and three different types of bifacial PV modules are measured. The intercomparison involves measurements with systems using both single and double-sided illumination conditions. The uncertainty budgets and systematic differences that these procedures result in between different laboratories are determined and discussed. Specific common mistakes are reported and improvements to the IEC TS 60904-1-2:2019 are proposed as a result of this intercomparison activity.
Keywords: Bifacial PV, Testing, PV modules

1 INTRODUCTION

Bifaciality of photovoltaic (PV) modules has demonstrated great potential to increase the output power of modules with relatively low additional cost [1]. Bifacial PV modules can potentially increase the energy yield of PV systems by 5 – 15 % compared to monofacial PV modules for the same available area. Establishing reliable and international standards that accurately determine the performance of bifacial PV products is crucial for bankability and further penetration of this technology into the market. Low uncertainties in the power rating of such products will result in low uncertainties in energy yield estimations of bifacial PV plants, reducing financial risks and increasing trust in bifacial PV technology. The latest technical specification IECTS 60904-1-2:2019 [2] describes the procedure for current-voltage characteristics measurements of bifacial photovoltaic devices.

In this work the procedures described in the IEC TS 60904-1-2:2019 are applied by different laboratories both for bifacial PV cells and for modules. A round robin activity has been organised, involving different test laboratories across Europe, measuring specific bifacial PV cell and module samples and following the procedures described in IEC TS 60904-1-2:2019. This activity will evaluate the efficiency, practicality, accuracy and clarity of these procedures, and will look into any potential systematic deviations and other issues in measurements of bifacial PV devices. All participating laboratories are acquiring measurements using single-sided illumination systems, with one of the participants using additionally a double-sided illumination, both for cells and modules. Previous work has looked into the features and differences between single-sided (equivalent irradiance - G_E method) and double sided systems and it has been reported that the two methods are consistent with each other [3]–[5].

The purpose of this round robin activity has been to potentially help to develop improved bifacial PV device measurement procedures, highlight common issues and ambiguities and increase the clarity of specifications. In this work the measurement methodologies used are summarised, the overall measurement deviations for the samples across the participants are reported and common pitfalls and crucial calculation procedures are highlighted. The participating laboratories for the bifacial PV cell and PV module round robin are presented in Table 1. The round robin activities are organised by the National Physical Laboratory (NPL) and Fraunhofer Institute for Solar Energy Systems (ISE) as part of the EMPIR PV-Enerate project. The bifacial round robin activities for both cells and modules are still ongoing and further measurements and uncertainty analyses are currently being conducted.

Table 1. Participating laboratories in the bifacial cell and module round robin activity

Module round robin activity	Fraunhofer ISE
	University of Applied Sciences and Arts of Italian Switzerland (SUPSI)
	European Solar Test Installation, Joint Research Centre (JRC)
	TÜV Rheinland Energy GmbH(TRE)
	Physikalisch-Technische Bundesanstalt (PTB)
Cell round robin activity	Fraunhofer ISE
	Institute for Solar Energy Research in Hamelin (ISFH)
	Anhalt University

2 SAMPLES AND METHODS

2.1 Samples

Three different types of bifacial cells and three different types of bifacial PV modules were selected for this study. One type of monofacial samples is included in both cases, for reference purposes. Basic information and nominal rating values of the samples used in this activity are presented in Table 2. Including both bifacial PV modules and cells for this activity will provide insights for the specific measurement challenges in each case.

Table 2. Selected nominal values for PV cells and modules used in the round robin activity of this work.

	Module type	Cells	Pmax (W)	Cell type	Busbars
1	Bifacial framed	72	390	Bifacial PERC	5
2	Bifacial frameless	60	300	Bifacial nPERT	5
3	Bifacial framed	60	280	Bifacial PERC	3
4	Monofacial framed	60	280	Monofacial nPERC	5

Twenty hours of light soaking has been applied to all samples, both cells and modules for Light-Induced Degradation (LID) stabilisation. Two samples per type of cell or module are measured by each partner lab, while one monofacial PV module is measured for reference purposes. Type 1 modules were not possible to be measured with the available double sided system, due to the large size of the modules and the limitations of that system at the time of measurements. All measurements and procedures are conducted according to IEC TS 60904-1-2:2019 for double-sided, or single-sided measurements, depending on the facilities of each partner laboratory. No degradation of any of the modules or cells was observed through measurements or electroluminescence (EL) imaging during the round robin activity.

2.2 Methods

In order to define the bifaciality parameters of a PV device, the main I-V characteristics of the front and the rear sides have to be measured at standard testing conditions (STC). The short-circuit current bifaciality coefficient φ_{Isc} is the ratio between the short-circuit current (I_{SC}) at STC generated exclusively by the rear side of the bifacial device and the I_{SC} generated only by the front side:

$$\varphi_{I_{SC}} = \frac{I_{SCr}}{I_{SCf}} \quad (1)$$

$\varphi_{I_{SC}}$ is usually expressed as a percentage, I_{SCr} is the short circuit current generated when the device is illuminated only on the rear side and I_{SCf} is the short circuit current generated when the device is illuminated only on the front side. A spectral mismatch correction for both sides should be applied according to IEC 60904-7 [6]. Bifaciality coefficients for open-circuit voltage V_{OC} and maximum power P_{max} can also be calculated:

$$\varphi_{V_{OC}} = \frac{V_{OCr}}{V_{OCf}} \quad (2)$$

$$\varphi_{Pmax} = \frac{P_{maxr}}{P_{maxf}} \quad (3)$$

where $\varphi_{V_{OC}}$ is the open-circuit voltage bifaciality coefficient and φ_{Pmax} is the maximum power bifaciality coefficient. For measurements of bifacial PV devices with single-sided illumination systems, a solar simulator with adjustable irradiance levels is required for the I-V characterisation. P_{max} of the device is measured at equivalent irradiance levels corresponding to 1000 Wm^{-2} front side, plus the equivalent amount of front side irradiance corresponding to the rear side irradiance level G_{R_i}. The total equivalent irradiance levels on the front side G_{E_i} are determined as functions of the bifaciality coefficient φ:

$$G_{E_i} = 1000\ Wm^{-2} + \varphi \cdot G_{R_i} \quad (4)$$

$$\varphi = Min\ (\varphi_{Isc}, \varphi_{Pmax}) \quad (5)$$

It has to be noted that as the IEC TS 60904-1-2:2019 describes, the φ value used to calculate the G_{E_i} values is the minimum between φ_{Isc} and φ_{Pmax}.

To calculate the *BiFi* parameter, which expresses the bifacial power generation gain for each unit of rear irradiance, P_{max} of the device under test needs to be measured for at least two different equivalent irradiance levels, G_{E_i} (i=0,1,2,…). A third point is P_{maxf} at STC, which already has been measured . *BiFi* is then defined as the linear fit's slope of the P_{max} (i) versus G_{R_i} data series, with the linear least-squares fit forced to cross the P_{max} axis at P_{maxf} (STC). Since the resulting fit curve is a straight line, any non-linearities have to be considered in the uncertainty budget.

In practice, to apply the G_E method, the target values rear irradiance levels of G_{R1}= 100 Wm^{-2} and G_{R2} = 200 Wm^{-2}, respectively, are used to calculate G_{E_i} using equation (4). The G_{E_i} irradiance levels are then set by the solar simulator and measurements on the front side of the module are acquired. Although the measurements are acquired using G_{E_i} irradiance levels, the G_{R_i} values need to be used to calculate the linear fit's slope of the P_{max} (i) versus G_{R_i} data series.

A schematic of the single-sided illumination configuration for bifacial device measurements is presented in **Figure 1**. Extra care has to be taken to ensure the rear side irradiance is lower than 3 W/m^2 during measurements, calculated by averaging measurements at 5 points at the rear side of the PV module. This can be achieved by choosing the appropriate non-reflective material for the background and correctly setting the distance between the background and the rear side of the module, as described in detail in [5].

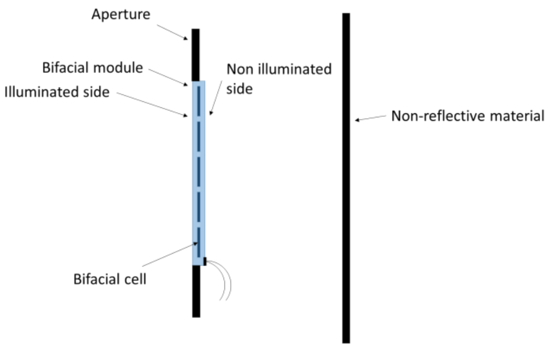

Figure 1: Schematic of bifacial PV module and the required non-reflective background and aperture.

After calculating *BiFi*, there are two additional parameters that should be reported: $P_{maxBiFi10}$ and $P_{maxBiFi20}$, which represent the power of the device for front irradiance of 1000 W/m^2 plus rear irradiance levels of G_{R1} = 100 Wm^{-2} and G_{R2} = 200 Wm^{-2} respectively. It should be highlighted that $P_{maxBiFi10}$ and $P_{maxBiFi20}$ must be obtained by linear interpolation of the data series $P_{max}(i)$ versus G_{R_i}, even in the case that measurements have been acquired for the G_{R_i} points of 100 Wm^{-2} and 200 Wm^{-2}

$$P_{maxBiFi10} = P_{max,front} + BiFi \cdot 100\,Wm^{-2} \quad (6)$$

$$P_{maxBiFi20} = P_{max,front} + BiFi \cdot 200\,Wm^{-2} \quad (7)$$

The I-V characteristics of bifacial PV devices can also be determined from measurements with double-sided illumination systems, which potentially offer a closer representation of actual operating conditions of bifacial devices. The front side irradiance is set to 1000 Wm^{-2} and, similarly to the G_E method, at least two different rear irradiance levels are applied, 0 Wm^{-2} ≤ G_{R1} ≤ 100 Wm^{-2}, 100 Wm^{-2} ≤ G_{R2} ≤ 200 Wm^{-2}, with a third point being the STC measurement (G_{R0} = 0 Wm^{-2}). The *BiFi* parameter is once again calculated by the linear fit's slope of the P_{max} (i) versus G_{R_i} data series, with the linear least-squares fit forced to cross the P_{max} axis at P_{maxf}. In this case, the G_{R_i} points have been measured directly.

Although systems exist that utilise two different light sources (front and rear) and can potentially offer equal accuracy as conventional systems, such systems can result in more complicated setups, additional requirements for calibration, measurements of multiple parameters (non-uniformity, spectrum, angular response) and potentially higher cost of equipment. A common approach suitable for calibration laboratories is using a double-mirror system as shown in the schematic of **Figure 2**. In such a system, a single solar simulator is used as a light source. A double mirror system is utilised to provide illumination to both sides of the bifacial sample, which is placed between the mirrors appropriately so that the incident irradiance on both sides of the sample is perpendicular to the sample's surface. Appropriate absorption filters are used to set the right amount of rear irradiance. This configuration allows double sided measurements of bifacial samples with a single flash from the solar simulator. Nevertheless, such a configuration is not easily applicable to production lines.

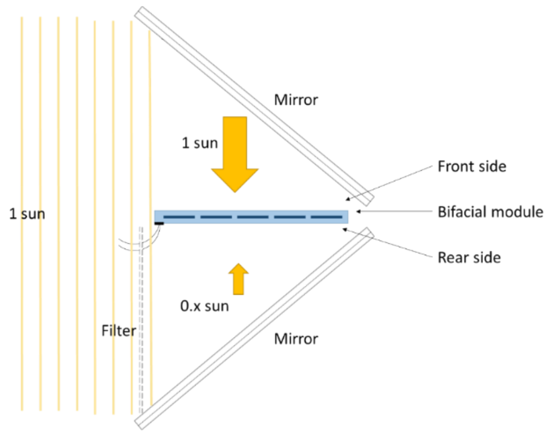

Figure 2. Schematic of a double mirror system approach for testing of bifacial cells or modules.

3 BIFACIAL PV CELL RESULTS

Measurements for bifacial PV cells were acquired by three different partners which have different systems. Measured parameters are presented in Figure 3. In some cases, the uncertainty values of the measurements have not been given by the participants or have been given incompletely. Cells 5 and 6 were not measured by partner 1.

Although the number of participants has been small (and uncertainty estimations are not yet available for all participants), it can be observed for almost all instances that differences fall within the calculated uncertainties which are common uncertainty values for this kind of measurement. Larger deviations can be observed for P_{max} compared to I_{SC} and V_{OC}. This can be potentially attributed to contacting differences between different partners, which will induce slightly different series resistance values.

The measurements of the bifacial parameters are presented in ***Figure 4***. The value of φ is calculated by equation (5). All participants applied the G_E method (equivalent irradiance) for measuring the *BiFi* parameter, while one of the partners additionally used a double illumination system for measuring these parameters based on the method described in the previous section. For φ there is a difference for Cell 1, while the rest of the measurements are more consistent. There are significant differences between all partners for the *BiFi* parameter, while there is a negligible difference between the single-sided and double-sided systems for the same partner. These differences could affect the calculated values of

$P_{maxBiFi10}$ and $P_{maxBiFi20}$, which depend on the *BiFi* parameter.

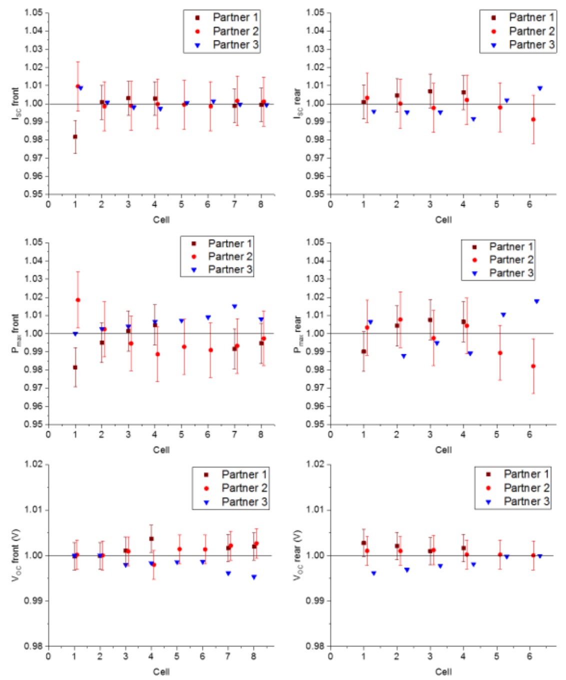

Figure 3. I_{SC}, P_{max} and V_{OC} for the front and rear side of the bifacial PV cell samples, measured by different partners. Values are normalised by average value. Cells 7 and 8 are monofacial cells.

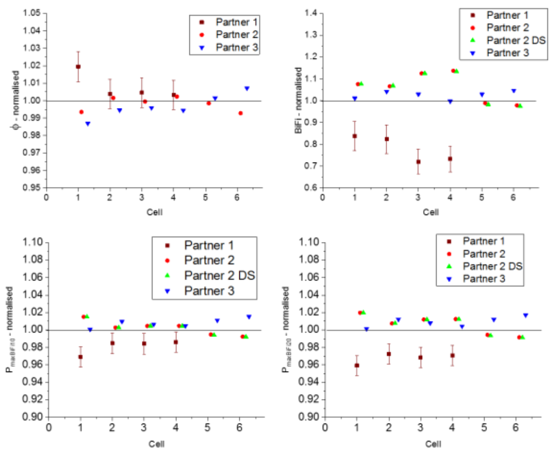

Figure 4. Bifacial parameters of the bifacial PV cell samples, measured by different partners. Values are normalised by average value. The measurements with a double-sided system are marked as "DS".

To understand the source of difference for the *BiFi* parameters, the G_E methods calculations are considered for one of the cell samples (cell 3). The methodology is presented in Figure 5. Measurements of P_{max} at different equivalent irradiance levels for the different assumed rear irradiance levels have been performed, as described in the previous section. As can be observed in Figure 5, different partners have used different G_R values, while partner 2 has used 4 points for acquiring the linear fit, both for the single-sided and the double-sided measurements. As described before, the *BiFi* parameter is the linear fit's slope of the $P_{max}(i)$ versus G_{R_i} data series, with the linear least-squares fit forced to cross the P_{max} axis at P_{max}(STC). Based on the measured values for each partner, the derived slope values of the linear fit can be observed in Figure 5. Measurements of partner 1 at irradiance levels higher than 1000 W/m^2 produced slightly different values than partners 2 and 3, leading to a significantly different slope value. This demonstrates that for measuring the *BiFi* parameter, it is essential that the accuracy of the measurement system at higher irradiances needs to be maintained (non-uniformity features, spectral profile stability). In addition, using G_R values close to or higher than 200 W/m^2 will help to have a broader data basis for determining the slope when uncertainties are considered. However, measurements at $G_R \geq 200$ Wm^{-2} or higher could have higher uncertainties for some systems. Non-linearity effects are considered negligible for the cells and irradiance ranges under investigation.

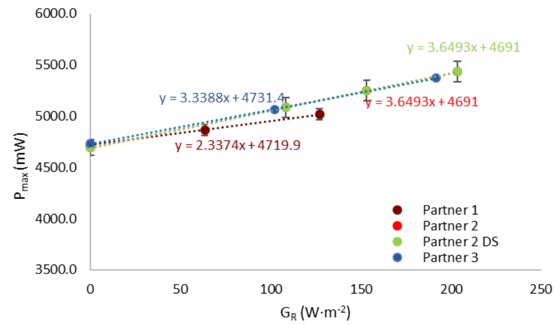

Figure 5. Calculation of the *BiFi* parameter of a bifacial PV cell for all partners, using the linear fit's slope of the P_{max} versus G_R.

An additional consideration that has to be taken into account in measurements of bifacial PV cells is the irradiance of the background (rear-side irradiance) when applying the G_E method. Since the PV cells are placed on a temperature-controlled chuck during tests in a calibration laboratory, measurements of the background are practically impossible with the PV cell in place and the rear-side irradiance is estimated by considering the reflectivity of the chuck that the cell rests upon. One would need to measure the transmission of the cell and the reflectivity of the chuck. Alternatively, one needs to use an open rear and local contacting which makes the cooling of the cell difficult, thus, flashers can be used only in this case. As a result of this round-robin activity for bifacial PV cells, it is highlighted that better specifications for defining the background (rear side) irradiance for the G_E method are required for bifacial PV cells, such as potential requirements for the spectral reflectivity of the testing platform.

4 BIFACIAL PV MODULES RESULTS

Measurements of the bifacial PV modules were acquired by five different partners. Uncertainties for measured values have been provided by three partners, but not for all parameter values. One of the partners additionally used a double-sided illumination system (double mirror system) for testing, although Modules 1 and 2 were not measured by the double-sided system, due to having a larger size than the system's capability. Measured electrical parameters for all samples and partners are presented in Figure 6. All values are normalised by the median, for easier comparison. In almost all cases the observed deviations for each measured value are within the uncertainties provided by the partners. Modules 3 and 4 are heterojunction cell type, modules with high bifaciality factor and a small difference in spectral response between the front and rear side, which is potentially why lower deviation can be observed for the rear side I_{SC} and P_{max} values for these modules, compared to the other two types of modules. These small deviations also affect the calculation of φ.

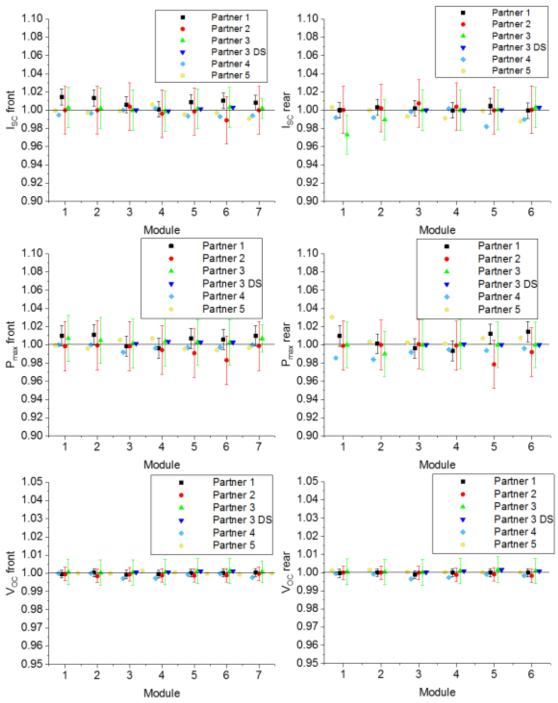

Figure 6. I_{SC}, P_{max} and V_{OC} for the front and rear side of the bifacial PV cell samples, measured by different partners. Values are normalised by the median value. Module 7 is monofacial. The measurements with a double-sided system are marked as "DS".

The measurements of the bifacial parameters are presented in **Figure** *7*. All participants applied the G_E method (equivalent irradiance) for measuring the *BiFi* parameter, while partner 3 additionally used a double-sided illumination system. The deviations for φ are in most cases within the uncertainty budgets provided by some of the partners. While there are apparent differences in the measurement of the *BiFi* parameter, they fall within the uncertainty budgets. This is also expected considering that the deviations of *BiFi* do not affect the $P_{maxBiFi10}$ and $P_{maxBiFi20}$ parameters, which present the same deviations as the P_{max} values. There is a negligible difference between the single-sided and double-sided systems for the partner that has used both systems.

A summary of the deviation (one standard deviation range) for each parameter, for each sample across all partners is presented in Table 3. Deviations for the front side are consistently lower than for the rear side, which can be attributed to measurement system differences at each lab (such as mounting configurations), the level of background rear-side irradiance or spectral mismatches. Nevertheless, deviations are consistently lower than 1% for P_{max} and $P_{max,rear}$, demonstrating that the standard procedure for bifacial modules can consistently produce reliable results across different testing labs. The highest deviations for all parameters are observed for *BiFi*, without however causing significant deviations in the values of $P_{maxBiFi10}$ and $P_{maxBiFi20}$. This highlights that higher deviations can be expected and the uncertainty budget for *BiFi* should always be considered.

The calculation of the *BiFi* parameter for Module 3 is presented in Figure 8. The calculation of *BiFi* by linear fitting using measurements both with the G_E method and the double-sided illumination method is included in the same graph. The equations of the best linear fit for the datasets are also presented in the graph for all data series. The methodology for modules is much more consistent, while the results for the double-sided system are consistent with the G_E method results. It is important to highlight that the G_R values need to be used for the *BiFi* calculations and not the G_E values. This is not always straightforward to apply, since for the G_E method, the G_R values are not measured values, while the G_E is set and measured. This was the most common point of confusion during the round robin activity.

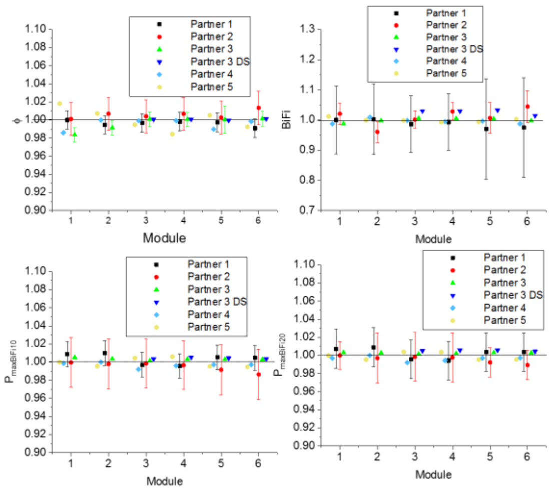

Figure 7, Bifacial parameters of the bifacial PV modules, measured by different partners. Values are normalised by the median value. The measurements with a double-sided system are marked as "DS".

The double-sided illumination method of partner 3 provided a wider range of G_R to calculate the *BiFi* parameter, acquiring consistent results with the equivalent single-sided system of the same partner and the results from the rest of the partners. More testing between single-sided and double-sided systems should be realised in order to validate that the G_E method is equivalent to the measurements with a double-sided system, for a broader range of bifacial samples, of all sizes and technologies. Potential differences may exist due to non-linearity effects of rear side performance of some bifacial PV module types, especially for technologies with significant differences in processing for the front and rear side of cells. In addition, small differences may occur due to partial rear shading of bifacial modules by junction boxes, cables or the frame.

Table 3. Deviations (one standard deviation) between all round robin participants for all parameters of bifacial PV modules measured and calculated in this activity.

	Module 1	Module2	Module 3	Module 4	Module 5	Module 6	Module 7
$I_{SC,front}$	0.67%	0.61%	0.25%	0.31%	0.49%	0.71%	0.61%
$V_{OC,front}$	0.04%	0.07%	0.13%	0.12%	0.09%	0.09%	0.10%
$P_{max,front}$	0.46%	0.52%	0.41%	0.47%	0.54%	0.75%	0.51%
$I_{SC,rear}$	1.10%	0.56%	0.42%	0.40%	0.72%	0.61%	
$V_{OC,rear}$	0.07%	0.07%	0.14%	0.13%	0.11%	0.10%	
$P_{max,rear}$	1.50%	0.74%	0.35%	0.31%	1.07%	0.74%	
φ	1.24%	0.63%	0.30%	0.68%	0.48%	0.74%	
BiFi	1.33%	1.72%	1.33%	1.58%	1.85%	2.22%	
$P_{maxBiFi10}$	0.39%	0.50%	0.42%	0.44%	0.51%	0.64%	
$P_{maxBiFi20}$	0.35%	0.48%	0.45%	0.44%	0.49%	0.54%	
FF	0.34%	0.22%	0.43%	0.30%	0.32%	0.31%	0.32%
FF_{rear}	1.35%	0.30%	0.55%	0.59%	1.17%	1.03%	

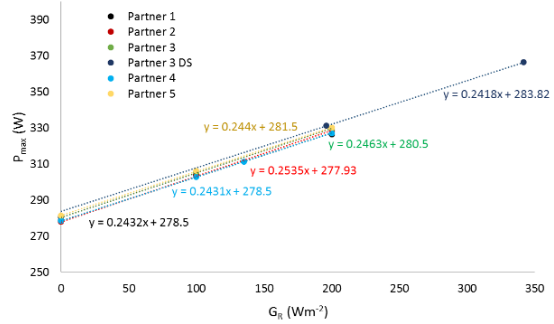

Figure 8. Calculation of the BiFi parameter of a bifacial PV module for all partners, using the linear fit's slope of the P_{max} versus G_R.

6 CONCLUSIONS

A round robin activity for power measurements of bifacial PV cells and modules has been conducted and the results have been presented in this work. The measurement procedures as described in IEC TS 60904-1-2:2019 were followed among the different test laboratories. The activity involved measurements with systems using both single and double-sided illumination conditions.

Measurements of bifacial PV cells at different partners have demonstrated that while consistent results are acquired, further improvements on the technical specifications are possible regarding bifacial PV cells. A better procedure for determining the rear-side background irradiance when applying the G_E method for bifacial PV cells can help towards decreasing uncertainties. No specific differences between the double-sided illumination measurements and the G_E method were observed in this work.

Measurements of bifacial PV modules based on the standard procedures produced consistent results between different partners, with deviations for most measured and calculated parameters being within the common uncertainty budgets provided by some of the partners. Results have demonstrated that observed deviations occurred mostly for the rear side of PV modules that feature differences in the spectral response of front and rear side, or have a much larger size than usual. This demonstrates that the spectral response of both sides of a bifacial PV module has to be considered in spectral mismatch calculations.

The most common point of confusion during the round robin activity was how to correctly apply the G_E method when using single-sided illumination systems. In some cases G_E was incorrectly used instead of G_R versus the P_{max} values in order to calculate *BiFi* as the slope of a linear fit. Care has to be taken to always use the target G_R values versus P_{max} (*i*), even if the G_E irradiance is what is set and measured. This is more straightforward to apply for double-sided illumination systems where G_R is measured, nevertheless the calculations have to be applied in the same way for all systems. Moreover, *BiFi*, $P_{maxBiFi10}$ and $P_{maxBiFi20}$ parameters make no sense if they have been calculated from G_E The method provides consistent results, as it has been demonstrated in this work, with no noticeable differences between single-sided and double-sided illumination systems. Additional comparisons between single-sided and double-sided illumination systems and between different test laboratories should be performed, to ensure that the two methods produce consistent results, for all bifacial PV module products.

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