COMPREHENSIVE EVALUATION OF IEC MEASUREMENT PROCEDURES FOR BIFACIAL SOLAR CELLS AND MODULES

Michael Rauer, Alexandra Schmid, Fan Guo, Frank Neuberger, Paul Gebhardt, Jochen Hohl-Ebinger
Fraunhofer Institute for Solar Energy Systems (ISE)
Heidenhofstraße 2, 79110 Freiburg, Germany

Corresponding author: Phone: +49(0)761/4588-5564, E-mail: michael.rauer@ise.fraunhofer.de

ABSTRACT: The IEC technical specification (TS) 60904-1-2 has been published recently in order to establish a standardized way of evaluating bifacial solar cells and modules. Two different methods for indoor measurements of the current-voltage characteristics of bifacial devices have been reported, which are based on simultaneous front and rear illumination (referred to as *bifacial method*) or on illumination at elevated irradiance levels from front only (referred to as *equivalent irradiance (G_E) method*). In this study, the measurement procedures and input parameters specified by the IEC TS for the bifacial and G_E methods are analysed in detail. This particularly applies to the bifaciality coefficients φ_{Isc} and φ_{Pmpp}, which are the ratios of rear to front I_{sc} and P_{mpp}, respectively, and are used for the calculation of the equivalent irradiance G_E. It is shown that the bifaciality coefficients have to be selected carefully to accurately determine the bifacial low-light performance with the G_E method. Evaluating the bifaciality coefficients as proposed by the IEC TS for nonlinear solar cells can lead to deviations between the bifacial and G_E methods of up to several percent in the parameters *BiFi*, $P_{mppBiFi10\%}$ and $P_{mppBiFi20\%}$ –standardized measures for the power gain of the bifacial device caused by additional rear irradiance. In addition, differences between bifacial and G_E methods can also arise for bifacial solar modules with partial rear shading. By comparing measurements with G_E and bifacial methods for these modules, it is shown that following the IEC procedure can lead to errors in *BiFi* of more than 18 % and in $P_{mppBiFi20\%}$ of more than 2 %. An alternative approach of evaluating bifaciality coefficients is therefore proposed in this study: By applying only the bifaciality coefficient φ_{Isc}, which is physically the most meaningful coefficient, and by evaluating φ_{Isc} at the actual front irradiance of the measurement, the agreement between the bifacial and G_E methods can be considerably improved. A criterion for the applicability of the G_E method using φ_{Isc} is derived by systematically varying the rear shading fraction of bifacial modules. It is thus shown that both methods can be applied in good agreement, if amendments to the IEC TS are made.

Keywords: Bifacial Solar Cells, Bifacial Solar Modules, Equivalent Irradiance (G_E) Method, Standardization, IV Measurement

1 INTRODUCTION

Today's market share of bifacial solar modules of 10 % is expected to triple over the next 10 years [1]. Although the share of solar cells fabricated in bifacial way is significantly higher [1], many bifacial solar cells are still assembled in monofacial solar modules, which means that these modules do not exploit the full potential of bifaciality. It is therefore essential to establish a standardized and robust way to compare bifacial with monofacial products and bifacial products among each other by making bifaciality quantifiable.

The IEC technical specification (TS) 60904-1-2 has been published recently for this purpose [2]. In the IEC TS, two different methods for indoor measurements of bifacial solar cells and modules have been introduced. The first method, which is referred to as *bifacial method* in this paper, is based on illuminating the device with an irradiance of 1000 W/m^2 from front and simultaneously with a reduced irradiance of 100 and 200 W/m^2, respectively, from the rear. The second method, which is referred to as *equivalent irradiance (G_E) method*, comprises front-side illumination only, but with irradiance higher than 1000 W/m^2 to account for the rear contribution.

Although the bifacial method represents realistic outdoor operation conditions more closely, it is more complicated to implement in laboratory measurement setups. Therefore, the G_E method was proposed as an alternative, which can be realized in most existing measurement setups. In the IEC TS, both methods are presented as consistent.

Several issues have been reported though, which can potentially lead to differences in results acquired with the two methods on solar cell and on module level [3-5]. Different photogeneration depth profiles resulting from illumination from both sides or from front only can be critical for bifacial solar devices with *e.g.* injection-dependent recombination [5]. Moreover, on module level, current mismatch between different cells under rear illumination or partial shading of the rear by the junction box, cables or module frames could lead to differences between the two methods [3, 4]. For manufacturers and investors, it is of utmost importance to know precisely which method to use for the characterization of their bifacial products. Already deviations of only 1.0 % – passed to yearly worldwide solar cell production– lead to additional budget uncertainties in the hundred million dollar range.

In this study, the measurement procedures and input parameters proposed for the bifacial and G_E methods by the IEC TS 60904-1-2 are analyzed in detail. This particularly applies to the bifaciality coefficients φ_{Isc} and φ_{Pmpp}, which are the ratios of rear to front I_{sc} and P_{mpp}, respectively, and are used for the calculation of the equivalent irradiance G_E. An advanced measurement setup at Fraunhofer ISE CalLab PV Modules is used for this purpose. The setups allows for the illumination of bifacial modules from either front side at elevated irradiance levels or both sides simultaneously. The setup has been optimized extensively to apply both measurement procedures with high accuracy and to detect differences between them precisely. Moreover, simulation models of bifacial devices have been elaborated to support experiments theoretically. We show that both bifacial and G_E methods can be applied in good accordance if amendments to the procedures proposed in the IEC TS are made.

2 MEASUREMENT METHODS FOR BIFACIAL SOLAR CELLS AND MODULES PROPOSED IN IEC TS 60904-1-2

The IEC technical specification (TS) 60904-1-2 covers indoor and outdoor measurement procedures of bifacial solar devices. In this study, we will focus on indoor measurements with solar simulators, which represent the majority of applications in test laboratories and in production lines. Two different methods have been proposed in the IEC TS and are outlined in the following. Both methods have in common that they need to be carried out in addition to conventional *I-V* measurements at standard testing conditions (STC) and are applied to quantify the bifacial performance of the bifacial device.

2.1 Both-Sided Illumination (*Bifacial Method*)

Using double-sided illumination best represents operation conditions in the field. In addition to *I-V* measurements at STC, further *I-V* measurements need to be performed. The bifacial device thereby needs to be illuminated with front irradiance G_{front} of 1000 W/m^2 and simultaneously with reduced rear irradiance G_{rear} in the range of 100 and 200 W/m^2, respectively.

2.2 Single-Sided Illumination (*Equivalent Irradiance (G_E) Method*)

Realizing double-sided illumination often involves constructional upgrades of the solar simulators by *e.g.* installation of rear light sources or mirror systems. Furthermore, some measurement systems for contacting bifacial solar cells require solid and opaque measurement chucks and do not allow to simultaneously illuminate the rear of the cells. The TS therefore proposes an alternative measurement procedure, which is based on single-sided illumination. This procedure is also known as *equivalent irradiance (G_E) method*.

Initially, the bifaciality coefficients $\varphi_{\mathrm{Isc,STC}}$ and $\varphi_{\mathrm{Pmpp,STC}}$ calculated from the ratios of rear to front short-circuit current and maximum power, respectively, need to be determined at STC:

$$\varphi_{\mathrm{Isc,STC}} = \frac{I_{\mathrm{scSTC,rear}}}{I_{\mathrm{scSTC,front}}}, \qquad \varphi_{\mathrm{Pmpp,STC}} = \frac{P_{\mathrm{mppSTC,rear}}}{P_{\mathrm{mppSTC,front}}}. \tag{1}$$

It is important that a non-reflective cover or measurement chuck is applied for the measurement to minimize contributions of transmitted and reabsorbed light [6, 7].

To account for the additional power that would be generated by rear side illumination, the front irradiance is increased to above 1000 W/m^2. This means that additional front side *I-V* measurements need to be performed with equivalent irradiance levels

$$G_E = 1000\ \mathrm{Wm^{-2}} + \varphi \cdot G_{\mathrm{rear}} \quad \text{with} \quad \varphi = \min(\varphi_{\mathrm{Isc,STC}}, \varphi_{\mathrm{Pmpp,STC}}). \tag{2}$$

φ thereby is equal to the minimum of $\varphi_{\mathrm{Isc,STC}}$ and $\varphi_{\mathrm{Pmpp,STC}}$ and serves as weight for the rear irradiance G_{rear}. In accordance with the *bifacial method*, G_{rear} values in the range of 100 and 200 W/m^2 should be used.

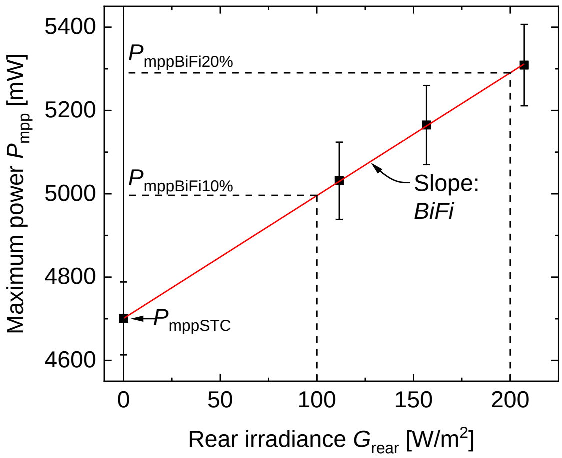

Figure 1: Evaluation of bifacial and G_E methods by plotting maximum power P_{mpp} as a function of rear irradiance G_{rear}, here shown for an exemplary bifacial solar cell. For the bifacial method, a constant front irradiance of 1000 W/m^2 and different rear irradiance levels should be used. For the G_E method, the rear irradiance is transferred to the front by using an equivalent irradiance higher than 1000 W/m^2 according to equation (2).

2.3 Standardized Evaluation

As different types of setups are applied for the measurements, the irradiance levels may vary slightly from facility to facility. To facilitate comparability, standardized parameters need to be determined. For this purpose, the maximum power P_{mpp} measured with the bifacial or G_E method is plotted as a function of the rear irradiance G_{rear}, together with the maximum power P_{mppSTC} measured at STC with front irradiance of 1000 W/m^2 and zero rear irradiance (Figure 1).

To evaluate the bifacial gain in a standardized way, a linear fit to P_{mpp} as a function of G_{rear} should be carried out. The slope of the linear fit is a measure for the power gain of the bifacial device caused by additional rear irradiance. It is referred to as the so-called *BiFi* parameter. Additionally, the interpolated maximum power values $P_{\mathrm{mppBiFi10\%}}$ and $P_{\mathrm{mppBiFi20\%}}$ at rear irradiance levels of 10 % and 20 % of $G_{\mathrm{front}} = 1000$ W/m^2, respectively, should be determined from the linear fit.

It is important to note that the G_E method has to be evaluated correctly, as the IEC TS in its present form is not concise in this aspect: The linear fit of P_{mpp} needs to be evaluated as a function of G_{rear} using equation (2) and not as a function of G_E. In the latter case, several difficulties arise: The slope of the linear fit needs to be divided by φ to derive *BiFi*. Additionally, the linear fit needs to be set to P_{mppSTC} at 1000 W/m^2 in an iterative way. A further detailed discussion on this issue can be found in [8].

2.4 Low-Light Performance

The bifacial and G_E methods can also be used to assess the low-light performance of bifacial solar cells and modules.

The IEC TS does not explicitly address measurements with the bifacial method under low-light conditions. Nevertheless, the obvious approach is to decrease the front irradiance to $G_{\mathrm{front}} < 1000\ \mathrm{W/m^2}$ and to adapt the simultaneous rear irradiance to $10\% \cdot G_{\mathrm{front}}$ and $20\ \% \cdot G_{\mathrm{front}}$.

For measurements with the G_{E} method under low-light conditions, the IEC TS proposes to adapt the calculation of G_{E} as follows:

$$G_{\mathrm{E}} = G_{\mathrm{front}} + \varphi \cdot G_{\mathrm{rear}}, \tag{3}$$

with $G_{\mathrm{front}} < 1000\ \mathrm{W/m^2}$ and G_{rear} equal to $10\% \cdot G_{\mathrm{front}}$ and $20\ \% \cdot G_{\mathrm{front}}$, respectively. The TS does not specify separate bifaciality coefficients φ for low-light conditions, so it can be assumed that φ should be evaluated at STC and, in particular, the minimum criterion $\varphi = \min(\varphi_{\mathrm{Isc,STC}}, \varphi_{\mathrm{Pmpp,STC}})$ should still be used.

3 AMENDMENTS TO IEC TS 60904-1-2 PROPOSED IN THIS WORK

As first amendment, we propose to use *generalized bifaciality coefficients* $\varphi_{\mathrm{Isc,G}}$ and $\varphi_{\mathrm{Pmpp,G}}$ to calculate the equivalent irradiance of the G_{E} method:

$$\varphi_{\mathrm{Isc,G}} = \frac{I_{\mathrm{sc,rear}}(G)}{I_{\mathrm{sc,front}}(G)}, \quad \varphi_{\mathrm{Pmpp,G}} = \frac{P_{\mathrm{mpp,rear}}(G)}{P_{\mathrm{mpp,front}}(G)}. \tag{4}$$

The front and rear short-circuit currents and maximum powers are thereby evaluated at the irradiance *G*, which can differ from STC.

For so-called *linear* solar cells and modules [9], which feature a linear current-irradiance relation, $\varphi_{\mathrm{Isc,G}}$ is constant as a function of irradiance, as both $I_{\mathrm{sc,front}}$ and $I_{\mathrm{sc,rear}}$ are proportional to *G*. This also means that $\varphi_{\mathrm{Isc,G}}$ is equal to $\varphi_{\mathrm{Isc,STC}}$ as defined in equation (1) for all irradiance levels. For *nonlinear* solar devices, the proportionality of $I_{\mathrm{sc,front}}$ and $I_{\mathrm{sc,rear}}$ to *G* is not given any more and $\varphi_{\mathrm{Isc,G}}$ becomes a function of irradiance. That means that $\varphi_{\mathrm{Isc,STC}}$ evaluated at STC and $\varphi_{\mathrm{Isc,G}}$ at *e.g.* low-light conditions are different.

$\varphi_{\mathrm{Pmpp,G}}$ cannot be considered as constant for both linear and nonlinear solar devices, as the fill factor ratio – and for nonlinear devices also the short-circuit current ratio– depend significantly on irradiance.

As second amendment, we propose to omit the criterion $\min(\varphi_{\mathrm{Isc,STC}}, \varphi_{\mathrm{Pmpp,STC}})$ for the bifaciality coefficients proposed by the IEC TS. This minimum criterion has originally been introduced in the TS for solar modules with distorted rear *I-V* curves due to partial rear shading. We instead suggest to always apply the bifaciality coefficient $\varphi_{\mathrm{Isc,G}}$ of short-circuit current for the calculation of G_{E}. From a physical point of view, $\varphi_{\mathrm{Isc,G}}$ is more meaningful than $\varphi_{\mathrm{Pmpp,G}}$, as, at least for linear solar cells, the short-circuit current is proportional to irradiance and $\varphi_{\mathrm{Isc,G}}$ thus equal to the ratio of the rear to front proportionality constants. $\varphi_{\mathrm{Isc,G}}$ therefore provides a better weight for the rear irradiance G_{rear} in equations (2) and (3) than $\varphi_{\mathrm{Pmpp,G}}$.

To evaluate our amendment proposals and to give recommendations on how to calculate G_{E} in the most accurate way, we investigate the influence of our proposals on the consistency of the bifacial and G_{E} methods for two different applications: We analyse the low-light performance of linear and nonlinear bifacial solar cells in section 5 and evaluate bifacial solar modules with partial rear shading in section 6.

Table 1: Overview of the input data for the calculation of the equivalent irradiance according to IEC TS 60904-1-2 and as proposed in this work.

	IEC TS 60904-1-2	This work
Bifaciality coefficients	$\varphi_{\mathrm{Isc,STC}}$, $\varphi_{\mathrm{Pmpp,STC}}$ (equation (1))	$\varphi_{\mathrm{Isc,G}}$, $\varphi_{\mathrm{Pmpp,G}}$ (equation (4))
Application in G_{E} equation	$\min(\varphi_{\mathrm{Isc,STC}}, \varphi_{\mathrm{Pmpp,STC}})$	$\varphi_{\mathrm{Isc,G}}$

4 SETUPS FOR MEASUREMENT OF BIFACIAL SOLAR CELLS AND MODULES

For the *I-V* measurement of bifacial solar cells and modules, two different setups are available at CalLab PV Cells [5, 10] and at CalLab PV Modules [4, 11], respectively, to realize single- and double-sided illumination of the bifacial devices (see Figure 2).

The solar cell or module is placed vertically between two tilted mirrors, which deflect light of a xenon flash lamp to the front and rear side of the solar device. Several mesh filters are available to reduce the irradiance onto the rear side of the solar device without changing the spectral distribution. The setups have been optimized comprehensively to yield high accuracy in the measured *I-V* characteristics and to enable the precise comparison of the bifacial and the G_{E} method.

Further information on the setups and a detailed uncertainty evaluation can be found in [4, 5].

5 LOW-LIGHT PERFORMANCE OF LINEAR AND NONLINEAR BIFACIAL SOLAR CELLS

In the IEC TS 60904-1-2, the bifacial and the G_{E} methods are presented as consistent. There are several effects though, which could lead to differences between them. As first effect, we regard the low-light performance of bifacial solar devices.

We therefore investigate the consistency of the bifacial and the G_{E} methods at low irradiance levels for linear and nonlinear devices. We particularly compare the application of the bifaciality coefficients as input data for the calculation of G_{E} as it is proposed by the IEC TS with the application as proposed in this work. To be independent of additional differences between the methods specific to bifacial solar modules, this investigation has been carried out on solar cell level. We thereby assess the bifacial method to be the reference one as it resembles outdoor conditions best.

In a recent study, we have carried out a first evaluation of the low-light performance of bifacial solar cells by experiment and simulation [5]. We have used the setup of Figure 2 (a) to perform *I-V* measurements of nonlinear bifacial passivated emitter and rear (PERC) solar cells with silicon oxynitride/silicon nitride (SiO_xN_y/SiN_z) rear surface passivation [12] to compare the bifacial and the G_{E} methods. Due to the high positive

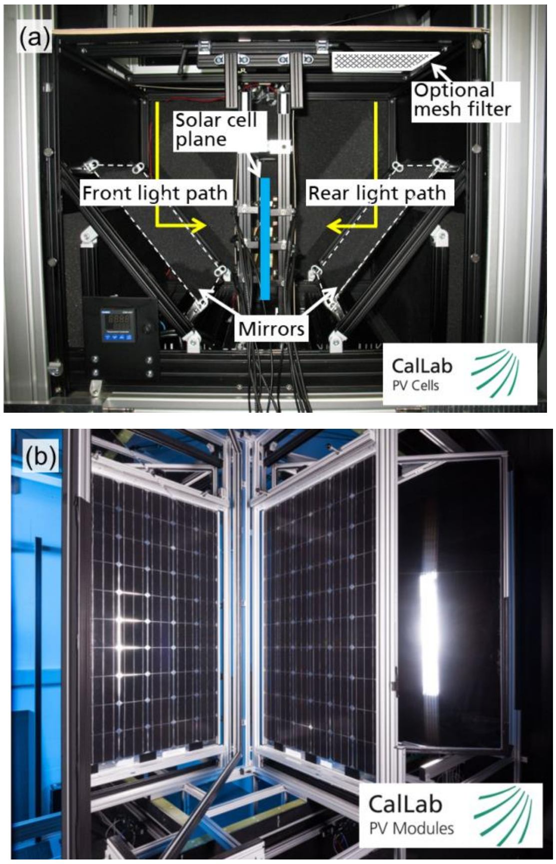

Figure 2: Pictures of two-mirror setups used in this study for the *I-V* measurement of (a) bifacial solar cells and (b) bifacial solar modules.

charge density of the SiO_xN_y/SiN_z layer stack [13], these solar cells exhibit a strong injection-dependency of the rear passivation resulting from inversion layer shunting [14]. This leads to a nonlinear current-irradiance relation which particularly affects the solar cell characteristics at low irradiance levels. We have additionally set up a PC1D model of the nonlinear PERC solar cell [5, 10] to support the experimental investigation. The simulation model was thereby chosen to represent a worst case scenario with strongly nonlinear characteristics [5].

We have shown that the bifacial and G_E methods are consistent down to front irradiance levels G_{front} = 200 W/m^2 for these solar cells if the generalized coefficient $\varphi_{Isc,Gfront}$ evaluated at the respective lower G_{front} is used for the calculation of G_E – a procedure in contradiction to the IEC TS. In the present study, we intend to evaluate the applicability of the bifaciality coefficients in more detail.

5.1 Simulation Approach

We have carried out further PC1D simulations of the nonlinear PERC solar cell. In addition, we have modified the simulation model to also simulate a *linear* bifacial PERC solar cell with linear current-irradiance relation. We have replaced the SiO_xN_y/SiN_z rear surface passivation by an aluminium oxide/silicon nitride (Al_2O_3/SiN_x) layer stack in the model, which exhibits a high density of negative charges [15]. Figure 3 shows simulated generalized bifaciality coefficients for both

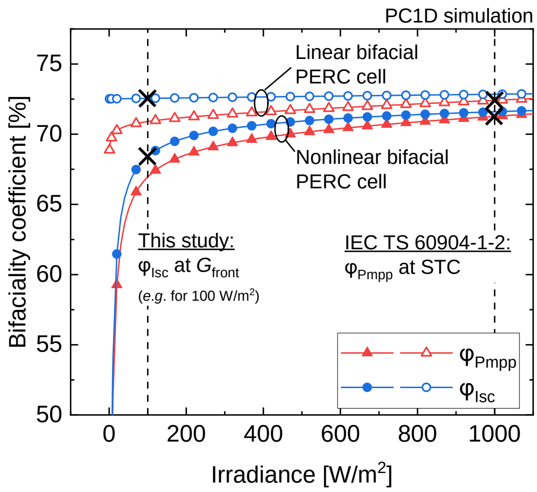

Figure 3: PC1D-simulated generalized bifaciality coefficients $\varphi_{Isc,G}$ and $\varphi_{Pmpp,G}$ for a linear (open symbols) and a nonlinear bifacial PERC solar cell (closed symbols). According to the IEC technical specification (TS) 60904-1-2, φ_{Pmpp} should be evaluated at STC for the calculation of the equivalent irradiance. In this study, we propose to use φ_{Isc} evaluated at G_{front} instead. The black crosses mark the coefficients which shall be used as input for the G_E calculation of the linear and the nonlinear cell.

linear and nonlinear PERC cells as a function of irradiance.

The linear PERC cell exhibits a constant short-circuit current bifaciality coefficient $\varphi_{Isc,G}$ but the power coefficient $\varphi_{Pmpp,G}$ is slightly dependent on irradiance, particularly at low-light conditions. For all irradiance levels, $\varphi_{Pmpp,G}$ is lower than $\varphi_{Isc,G}$, which means that $\varphi_{Pmpp,G}$ meets the minimum criterion specified by the IEC TS.

For the nonlinear PERC cell, both coefficients $\varphi_{Isc,G}$ and $\varphi_{Pmpp,G}$ are dependent on irradiance and, in particular, decline strongly in low-light conditions. This can be attributed to the increased impact of inversion layer shunting at the rear, which results in decreasing $I_{sc,rear}$ and $P_{mpp,rear}$ values. For the nonlinear solar cell as well, $\varphi_{Pmpp,G}$ meets the minimum criterion of the IEC TS for all irradiance levels.

As discussed in section 3, the bifaciality coefficient φ used as input for the calculation of G_E can be evaluated either according to the IEC TS or according to the amendment proposals of this study. The IEC TS proposes to apply values evaluated at STC, *i.e.* at 1000 W/m^2, and to furthermore use the criterion $\min(\varphi_{Isc,STC}, \varphi_{Pmpp,STC})$. This means that $\varphi_{Pmpp,STC}$ should be used for both the linear and the nonlinear simulated PERC solar cell. It is evident from Figure 3 that the generalized bifaciality coefficients in low-light conditions differ significantly from these values, especially for the nonlinear solar cell. In this study, we have therefore proposed to apply the generalized bifaciality coefficient $\varphi_{Isc,Gfront}$ evaluated at the respective lower irradiance G_{front}. The different approaches for the evaluation of the bifaciality coefficients of the IEC TS and of this study can therefore lead to very different input data for the calculation of G_E in low-light conditions.

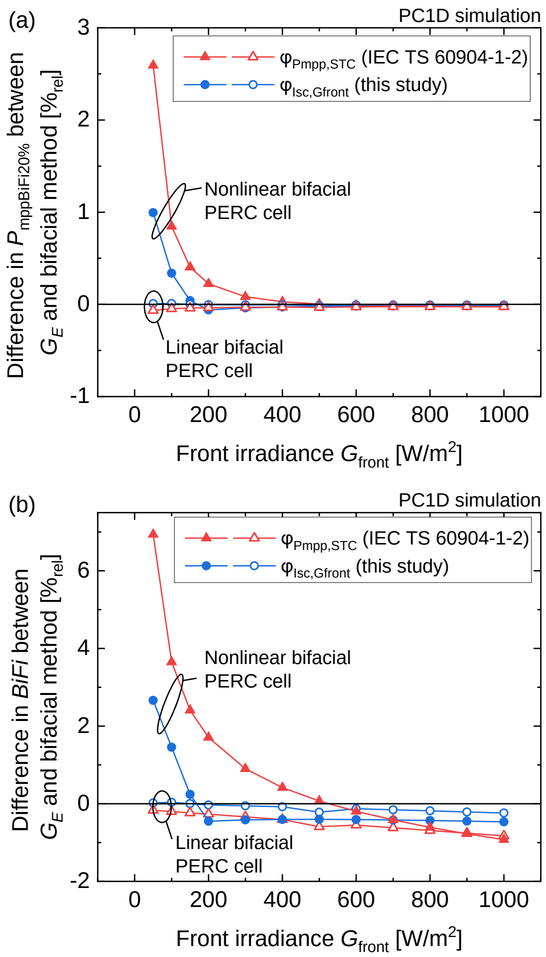

Figure 4: PC1D-simulated difference in the parameters (a) $P_{\text{mppBiFi20\%}}$ and (b) *BiFi* between the G_{E} and the bifacial methods as a function of front irradiance for the two different approaches of φ evaluation: the IEC TS approach (red triangles) and the approach proposed in this study (blue circles).

5.2 Standardized Evaluation in Low-light Conditions

We have simulated the *I-V* parameters of the linear and nonlinear bifacial PERC solar cells using the bifacial and the G_{E} methods. For the G_{E} method, we have applied the two different approaches for evaluation of the bifaciality coefficient φ: Using $\varphi_{\text{Pmpp,STC}}$ evaluated at STC according to the IEC TS and $\varphi_{\text{Isc,Gfront}}$ evaluated at G_{front} as proposed in this study. We have then determined the standardized parameters *BiFi*, $P_{\text{mppBiFi10\%}}$ and $P_{\text{mppBiFi20\%}}$ as described in section 2.3.

Figure 4 (a) shows the difference in $P_{\text{mppBiFi20\%}}$ between the G_{E} and bifacial methods for the two approaches. For the linear bifacial solar cell, both approaches yield good agreement between the methods with deviations below 0.1 $\%_{\text{rel}}$. For the nonlinear solar cell, however, the G_{E} method overestimates $P_{\text{mppBiFi20\%}}$ in the low-irradiance range. The overestimation is thereby much more pronounced for the approach of the IEC TS. For the approach proposed in this study, the deviation is below 0.1 $\%_{\text{rel}}$ for irradiance levels down to 150 W/m^2.

Figure 4 (b) shows the difference in *BiFi* between the G_{E} and the bifacial methods for the two approaches. Applying $\varphi_{\text{Pmpp,STC}}$ according to the IEC TS leads to significant differences in *BiFi* of several percent for the nonlinear bifacial solar cell, especially at low irradiance levels. Using $\varphi_{\text{Isc,Gfront}}$ as proposed in this study results in improved accordance between the two methods for irradiance levels down to 150 W/m^2. Please note that the offsets in *BiFi* for higher irradiance levels are caused by different curvatures of the $P_{\text{mpp}}(G_{\text{rear}})$ relations for G_{E} and bifacial methods: Whereas the P_{mpp} curve of the G_{E} method is a straight line, the P_{mpp} curve of the bifacial method exhibits a positive curvature. The different curvatures can be attributed to different *FF* versus G_{rear} relations of the bifacial and G_{E} methods. This issue will be investigated further in future work.

In conclusion, this evaluation shows that the application of the generalized bifaciality coefficient $\varphi_{\text{Isc,Gfront}}$ evaluated at G_{front} leads to better agreement between the G_{E} and bifacial methods than with the coefficients proposed by IEC TS 60904-1-2. We therefore recommend to use $\varphi_{\text{Isc,Gfront}}$ to calculate the equivalent irradiance in low-light conditions in order to quantify the bifacial gain of bifacial solar devices more accurately.

6 BIFACIAL SOLAR MODULES WITH PARTIAL REAR SHADING

For bifacial modules, further effects have been reported that can lead to differences between the bifacial and the G_{E} method [3, 4]. As second effect, we therefore investigate the impact of partial rear shading on the agreement between the two methods in more detail in this section.

6.1 Effect of Partial Rear Shading on Difference Between Bifacial and G_{E} Method

Two different bifacial solar modules, both consisting of 60 linear solar cells in three sub-strings, have been measured with the setup shown in Figure 2 (b). Module A has been optimized for bifacial application, module B exhibits partial rear shading by the junction box and the module frame. The setup allows for the measurement with single- and double-sided illumination, so that bifacial and G_{E} methods can both be applied and compared with high accuracy. To reduce measurement errors by hysteresis of the forward and reverse *I-V* curve, segmented measurements with multiple flashes have been performed.

Influence of partial rear shading on I-V curves

Figure 5 shows the *I-V* curves of modules A and B measured from front and rear at STC and for the bifacial and the G_{E} methods for a rear irradiance of 200 W/m^2 according to the IEC TS.

Module A shows no conspicuous features in its *I-V* curves and both bifaciality coefficients $\varphi_{\text{Isc,STC}}$ and $\varphi_{\text{Pmpp,STC}}$ are approximately equal. According to the minimum criterion of the IEC TS, $\varphi_{\text{Isc,STC}}$ is used for the calculation of the equivalent irradiance. It can be seen that the bifacial and G_{E} methods agree well with deviations in P_{mpp} of less than 0.2 $\%_{\text{rel}}$. As the approach of the IEC TS and the approach proposed in this work coincide, good accordance between the two measurement methods is achieved for both approaches.

The *I-V* curves of module B exhibit kinks, which are caused by partial rear shading leading to bypassing of strings by the bypass diodes. P_{mpp} under rear side

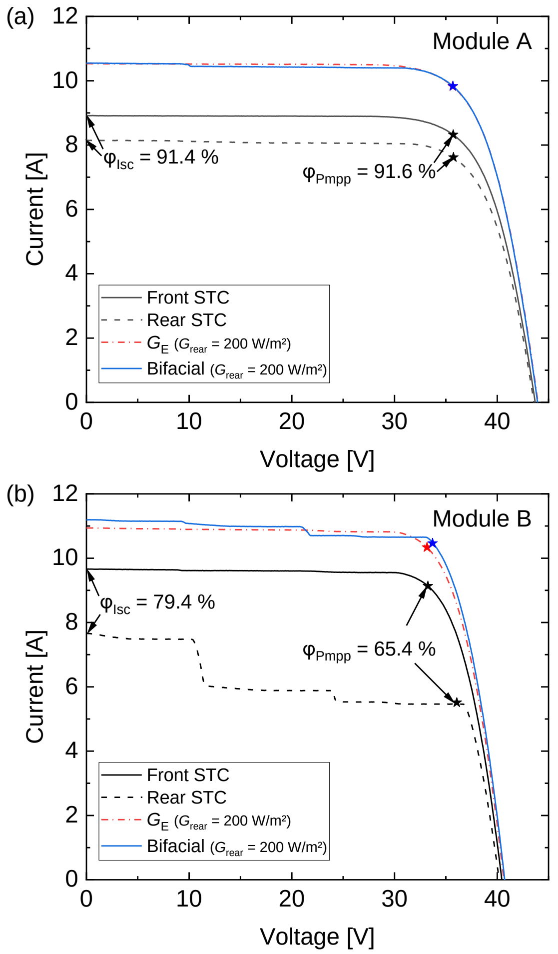

Figure 5: *I-V* curves measured under STC from front and rear and with the equivalent irradiance and the bifacial methods of two different bifacial solar modules. Solid and dashed black lines show front and rear measurements at STC, respectively. Solid blue lines represent measurements with the bifacial method for $G_{rear} = 200$ W/m^2. Dot-and-dashed red lines show measurements with the G_E method for $G_{rear} = 200$ W/m^2 according to IEC TS 60904-1-2. Stars indicate maximum power points.

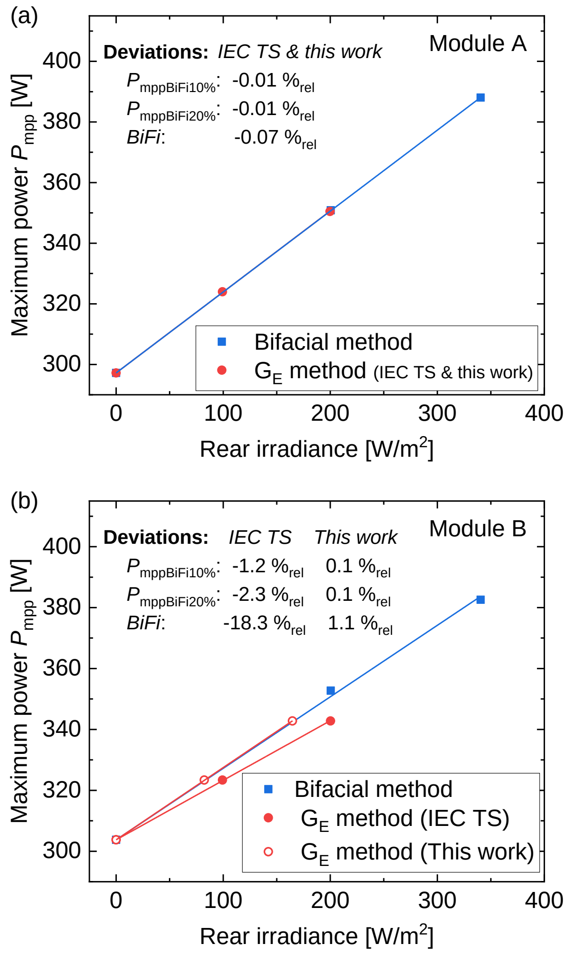

Figure 6: Measured maximum power P_{mpp} for different rear irradiance levels with both-sided illumination (blue squares) or with front-side illumination only using the G_E method (orange circles) for the two bifacial solar modules of Figure 5. The deviations in the standardized parameters $P_{mppBiFi10\%}$, $P_{mppBiFi20\%}$ and *BiFi* between the G_E and bifacial methods are given in the tables in the figures.

illumination at STC is thus significantly reduced by the kinks. This leads to a reduced bifaciality coefficient $\varphi_{Pmpp,STC}$, which is more than 10 $\%_{abs}$ lower than $\varphi_{Isc,STC}$. According to the IEC TS, $\varphi_{Pmpp,STC}$ shall be used as the smaller of both coefficients for calculating G_E. Figure 5 (b) shows that the *I-V* curves of the bifacial and G_E methods measured this way vary significantly and the difference in P_{mpp} between both methods amounts up to 2.9 $\%_{rel}$. Although kinks also appear in the *I-V* curves measured with the bifacial method, the impact on the power of the module is small: Under both-sided illumination with front side irradiance of 1000 W/m^2 and rear side irradiance in the range of 100 to 200 W/m^2, the maximum power point of the *I-V* curve is hardly affected by the kinks because of the low rear contribution. The G_E method is affected stronger though as the kinks measured in the rear characteristics at STC are more pronounced and have a significant impact on the bifaciality coefficients. As a consequence, the equivalent irradiance is systematically underestimated and the *I-V* curve of the G_E method shifted systematically toward lower current values relative to the curve of the bifacial method.

These measurements show that partial rear shading strongly affects the input parameters for the G_E method according to the IEC TS. The proposal of this study is to omit the minimum criterion and to apply $\varphi_{Isc,STC}$, independent of the occurrence of kinks. This is investigated further in the following.

Standardized Evaluation

The *I-V* parameters of the two modules have been measured with the bifacial and the G_E methods at additional rear irradiance levels. The measured P_{mpp} values have been plotted as a function of rear irradiance G_{rear} (see Figure 6) in order to evaluate the standardized bifacial parameters. The G_E method is thereby analysed for the approach of the IEC TS and for the approach proposed in this work.

It can be seen that the bifacial and G_E methods agree well for module A with deviations in $P_{mppBiFi20\%}$ of less than 0.1 $\%_{rel}$. As the approach of the IEC TS and the approach proposed in this work coincide, good

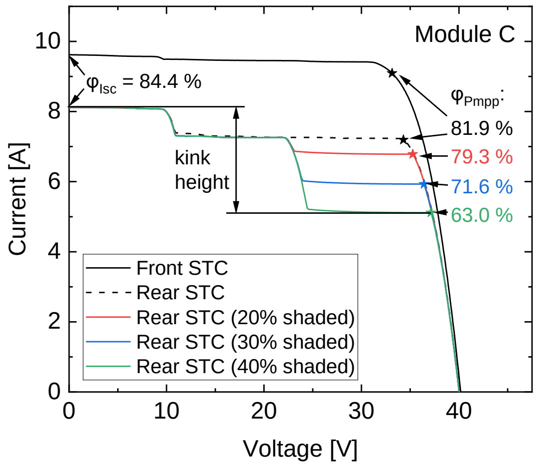

Figure 7 Front and rear *I*-*V* curves of module C at STC for different amount of rear shading. Stars indicate maximum power points. The relative difference between $I_{sc,rear}$ and $I_{mpp,rear}$ is referred to as kink height.

accordance between the two measurement methods is achieved for both approaches.

For module B, there is a significant difference of 2.3 $\%_{rel}$ in $P_{mppBiFi20\%}$ and of 18.3 $\%_{rel}$ in *BiFi* between the bifacial and G_E methods for the approach of the IEC TS: By using $\varphi_{Pmpp,STC}$, the equivalent irradiance levels are strongly underestimated and the resulting P_{mpp} values are measured too low. By applying $\varphi_{Isc,STC}$ instead of $\varphi_{Pmpp,STC}$, as proposed in this work, G_E and P_{mpp} significantly increase. Figure 6 (b) shows that the agreement between bifacial and G_E methods could be considerably improved to deviations of 0.1 $\%_{rel}$ in $P_{mppBiFi20\%}$ and 1.1 $\%_{rel}$ in *BiFi*.

6.2 Systematic Rear Shading

To investigate the impact of partial rear shading in more detail, a systematic variation of the shading and the rear irradiance was performed.

For two further modules with a bifaciality $\varphi_{Isc,STC}$ of 84 % (module C) and 56 % (module D), respectively, artificial rear side shading was applied. The amount of shading was systematically varied by covering about 20 %, 30 % and 40 % of the area of one cell with a black, opaque carton. Both modules showed typical built-in shading by the frames and the junction boxes of approximately 15 %. For the additional artificial shading, an unshaded solar cell in a string already affected by built-in shading was chosen in order to not affect the I_{sc} of the modules. The resulting *I*-*V* curves at standard testing conditions of module C are shown in Figure 7.

The shading fraction can also be expressed as difference of $I_{sc,rear}$ and $I_{mpp,rear}$ of the rear *I*-*V* curve. This parameter is a quantitative measure for the “height” of the kinks in the rear *I*-*V* curves and is easier to determine and to implement in the evaluation. We therefore define the *kink height* as follows:

$$\frac{I_{scSTC,rear} - I_{mppSTC,rear}}{I_{scSTC,rear}}. \qquad (5)$$

The corresponding kink heights for the modules C and D are summarized in Table 2. With increasing rear shading fraction the differences between $I_{mpp,rear}$ and $I_{sc,rear}$ and thus the kink heights increase.

Table 2: Influence of additional rear shading on the kink height, which is defined as the relative difference between $I_{sc,rear}$ and $I_{mpp,rear}$ measured at STC.

Shading fraction $[\%_{abs}]$	Kink height $[\%_{rel}]$ Module C	Module D
None	11.4	5.1
20	16.4	12.5
30	27.0	22.9
40	37.0	33.6

For the different shading configurations, the *I*-*V* curves of the modules were measured with the bifacial and the G_E methods using $\varphi_{Pmpp,STC}$ according to the minimum criterion of the IEC TS and $\varphi_{Isc,STC}$ as proposed in this study.

The impact of shading on the measured P_{mpp} values for the different methods is shown in Figure 8. The P_{mpp} values determined from the G_E method of the IEC TS strongly decrease with increasing shading fraction, because $\varphi_{Pmpp,STC}$ –and thus the equivalent irradiance– is directly reduced by the rear kinks. In contrast, shading does not influence $\varphi_{Isc,STC}$. The P_{mpp} values measured with the G_E method as proposed in this study are constant and independent of rear shading.

Rear shading also affects the bifacial method. To show this more clearly, the rear irradiance range was extended beyond the requirements of IEC TS to irradiance levels up to 600 W/m^2. The resulting maximum power P_{mpp} was compared with the nonshaded measurement. Figure 8 shows that for minor rear shading or low rear irradiance, the contribution by rear kinks is superimposed by the much stronger front contribution and the mpp of the measurement with the bifacial method is not affected by the kinks. P_{mpp} of shaded and nonshaded measurements are thus similar. For larger shading fractions or rear irradiance levels, P_{mpp} of the bifacial method is increasingly reduced by the kinks. For these measurement conditions, the curves of P_{mpp} as functions of G_{rear} –as it is used for the standardized evaluation discussed in section 2.3– are not linear any more.

The standardized parameters for each shading scenario were evaluated for the bifacial method and compared with the G_E methods using $\varphi_{Pmpp,STC}$ according to the minimum criterion of the IEC TS and $\varphi_{Isc,STC}$ as proposed in this study. For the evaluation, a rear irradiance range of 0 to 200 W/m^2 has thereby been applied. In Figure 9 the deviations between the two different G_E approaches and the bifacial method are shown.

The parameter $P_{mppBiFi20\%}$ determined with the IEC TS approach shows deviations up to 3.8 % (module C) and 1.8 % (module D) from the bifacial method. The deviations particularly increase with increasing kink heights. The $P_{mppBiFi20\%}$ values of the G_E method using $\varphi_{Isc,STC}$ agree much better with the bifacial method, with deviations within 0.5 % (module C) and 0.2 % (module D). For the shading fractions and rear irradiance levels used for the evaluation here, the maximum power points of the bifacial method are not yet reduced by kinks.

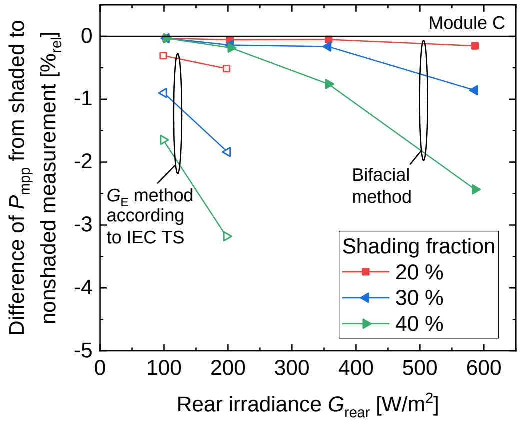

Figure 8 Deviation in P_{mpp} between shaded to nonshaded measurement for different rear irradiance levels measured with bifacial method (full symbols) and G_E method according to the IEC TS (open symbols). Measurements with the G_E method as proposed in this study are not shown as P_{mpp} is not affected by rear shading.

The deviations in *BiFi* between the bifacial method and the G_E method according to the IEC TS increase as well with increasing kink heights and reach values of up to 26 % (module C) and 19 % (module D). This G_E approach thus does not adequately reproduce the bifacial method for modules with significant rear shading. The results of the G_E method using $\varphi_{Isc,STC}$ agree much better with the bifacial method, with deviations within 3.5 % (module C) and 2.5 % (module D).

The results show that the G_E method using $\varphi_{Isc,STC}$ is in good agreement with the bifacial method if the maximum power point of the latter is not affected by the shading. In the following, a criterion is proposed which can be used to estimate the range of applicability of the G_E method proposed in this study.

6.3 Applicability of G_E Method Using $\varphi_{Isc,STC}$

For *I-V* curves without kinks, the difference in I_{sc} and I_{mpp} measured from the front at STC is similar to those measured with the G_E and bifacial methods, and usually is in the range of 5 to 7 %. Partial shading has a low influence on P_{mpp} of the two methods if $\varphi_{Isc,STC}$ is used and the kink height does not exceed this difference, so that I_{mpp} is not reduced further.

In the bifacial method, the contribution of the rear side is superimposed by the usually much larger contribution of the front illumination. In order to assess the effective rear contribution, it needs to be weighted by the ratio of rear to front irradiance of the measurement and by the bifaciality. The contribution of rear kinks can be weighted similarly. If the weighted height of rear kinks exceeds the kink height of the front side, rear shading will affect the mpp of the bifacial method and the P_{mpp} will be reduced. In this case the G_E method using $\varphi_{Isc,STC}$, which is not influenced by rear side shading, will overestimate the bifacial P_{mpp}. The criterion for the applicability of the G_E method using $\varphi_{Isc,STC}$ can thus be expressed as:

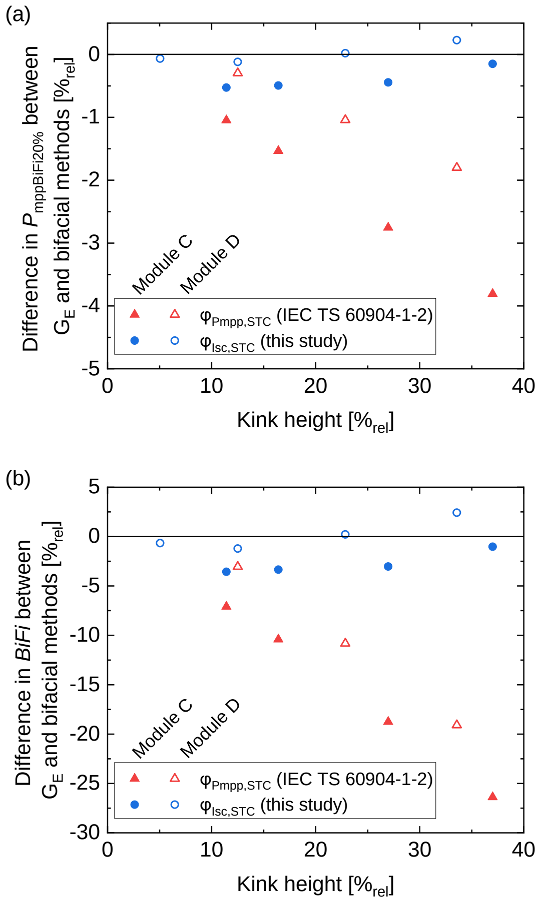

Figure 9: Deviation in (a) $P_{mppBiFi20\%}$ and (b) *BiFi* between G_E and bifacial methods as a function of the kink heights in the rear *I-V* curves, which is quantified by the difference between $I_{mpp,rear}$ and $I_{sc,rear}$, for modules C and D. Red triangles represent the φ evaluation of IEC TS 60904-1-2, blue circles the evaluation proposed in this study.

$$\frac{I_{scSTC,front} - I_{mppSTC,front}}{I_{scSTC,front}} \geq \varphi_{Isc,STC} \cdot \frac{G_{rear}}{G_{front}} \cdot \frac{I_{scSTC,rear} - I_{mppSTC,rear}}{I_{scSTC,rear}}. \tag{6}$$

If this inequality is true, the G_E method using $\varphi_{Isc,STC}$ can be applied in accordance with the bifacial method. Kinks in the rear *I-V* curves are thus more serious for modules with higher bifaciality due to the enhanced contribution of the rear side.

Based on the front and rear *I-V* curves measured at STC, this criterion allows deciding if the G_E method proposed in this study gives reliable results for the bifacial gain. The criterion can be either used to assess which rear irradiance range can be used for a given kink height or which rear kink height is tolerable for a given irradiance range to still have good agreement between the bifacial and the G_E methods. Attention should be paid if the irradiance levels or kink heights exceed the criterion. If the rear kinks influence the mpp of the bifacial method, the linearity of P_{mpp} vs. G_{rear} is not given any more and *BiFi* will be dependent on the evaluated irradiance range.

Deviations between the bifacial and G_E methods then need to be expected.

It is important to note that, to the authors' knowledge, the criterion should be met for all realistic cases of partial rear shading from junction boxes, cables and frames for the measurement conditions of the IEC TS. This means that the G_E method using $\varphi_{Isc,STC}$ should give reliable results for all bifacial modules commercially available. Partial rear shading may be more critical for measurements of bifacial modules intended for vertical east-west installation, which exhibit similar front and rear irradiance levels. These are not yet covered by the measurement conditions of the IEC TS, though.

For rear irradiance levels up to 200 W/m^2, kink heights of maximally 32.4 $\%_{rel}$ for module C and 55.2 $\%_{rel}$ for module D would be tolerable according to the criterion. All shading scenarios investigated in this study have yielded lower kink heights and good agreement between bifacial and G_E methods have been shown. For higher shading fractions, deviations between methods can be expected, which need to be investigated in future work.

7 SUMMARY

In this study, the consistency of the bifacial method and the equivalent irradiance (G_E) method, which have been recently proposed in the IEC technical specification (TS) 60904-1-2 for characterisation of bifacial solar devices, is evaluated in detail. This particularly applies to the bifaciality coefficients φ_{Isc} and φ_{Pmpp}, which are the ratios of rear to front I_{sc} and P_{mpp}, respectively, and are used as input parameters for the calculation of G_E.

The IEC TS specifies to evaluate the bifaciality coefficients at standard testing conditions (STC), *i.e.* at an irradiance level of 1000 W/m^2, and to particularly apply the minimum of φ_{Isc} and φ_{Pmpp}. In this study, two amendments to the evaluation of the bifaciality coefficients are proposed: It is suggested to omit the minimum criterion and to only use φ_{Isc}, which is physically the more meaningful coefficient. Additionally, it is proposed to evaluate φ_{Isc} at the irradiance of the actual measurement, which can differ from STC. The agreement of the G_E method of the IEC TS and of this study with the bifacial method is assessed by investigating the low-light performance of bifacial solar cells and partial rear shading of bifacial solar modules.

It is shown that the bifaciality coefficients of bifacial solar cells with nonlinear current-irradiance relation can depend significantly on irradiance in low-light conditions. Evaluating φ_{Pmpp} at 1000 W/m^2, as proposed by the TS for the calculation of G_E, can lead to deviations between the bifacial and G_E methods of up to several percent in the parameters *BiFi*, $P_{mppBiFi10\%}$ and $P_{mppBiFi20\%}$ which are measures for the power gain by additional rear irradiance. By applying φ_{Isc} evaluated at the respective lower irradiance as proposed in this study, the agreement between the measurement procedures can be significantly improved not only for nonlinear but also for linear bifacial solar cells.

For bifacial solar modules, current mismatch and partial rear shading can lead to deformation and kinks in the rear *I-V* curves, which reduce the maximum power point under rear illumination and lead to a difference between φ_{Isc} and φ_{Pmpp}. It is shown that the difference can range up to more than 10 $\%_{abs}$ for modules not optimized for bifacial applications. Whereas rear kinks thus strongly affect the input parameters for the G_E method according to the IEC TS, the impact on the bifacial method is significantly less strong: The maximum power point (mpp) of the *I-V* curve measured with both-sided illumination is often not affected by the kinks as the rear contribution is superimposed by the much stronger front contribution. It is shown that following the IEC procedure for these modules can lead to errors in *BiFi* of more than 18 % and to errors in $P_{mppBiFi20\%}$ of more than 2 % by comparing measurements with G_E and bifacial methods. The agreement of the results can be considerably improved to 1.0 % and 0.1 %, respectively if φ_{Isc} is used for the determination of G_E as proposed in this study.

The applicability of the G_E method proposed in this study has been investigated by systematically varying the rear shading of two bifacial modules. It is shown that good agreement to the bifacial method is achieved as long as the contribution of the rear shading does not affect the mpp of the bifacial method. This is the case for extensive rear shading or high rear irradiance levels. A criterion has been introduced to assess the applicability of the G_E method on the front and rear *I-V* curves measured at STC. For the irradiance conditions specified by the IEC TS, all typical module designs should meet the criterion and the G_E method using $\varphi_{Isc,STC}$ is applicable. Deviations may occur for solar modules intended for vertical east-west installation, which are not yet covered by the IEC TS though.

In conclusion, recommendations on how to apply IEC TS 60904-1-2 for the precise measurement of bifacial solar devices are given. It is shown that both bifacial and G_E methods can be applied in good accordance if several amendments to the procedure proposed in the TS are made.

8 ACKNOWLEDGEMENTS

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme within the project "PV-Enerate" (number 16ENG02).

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