From bifacial PV cells to bifacial PV power plants – the chain of characterization and performance prediction

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Abstract

Bifacial PV technology raises new challenges for the characterization and modelling of solar cells and modules, as well as for the yield predictions of power plants, as the contribution of the rear side can significantly affect the performance of these types of device. Reliable measurements and simulations are essential for gaining the trust of investors in this new and powerfully emerging technology. This paper covers the entire field of bifacial device characterization, from the additional demands on the measurement of bifacial solar cells and modules, through the modelling of cell-to-module losses, to the simulation of bifacial gains at the system level. An overview of different measurement set-ups and procedures for bifacial solar cells and modules is given, and the way in which the major influences can be controlled in order to achieve highly precise measurements is explained. With regard to yield predictions, the paper discusses how the existing models need to be extended to consider the additional site- and mounting-related factors that influence the available rear irradiance. It is shown that a combination of raytracing and electrical modelling allows accurate yield predictions of bifacial PV systems. The advanced tools presented in this paper for modelling cell-to-module losses and yield prediction outline the possibility for optimizing module and system design, and thus for increasing expected gains.

Introduction

Bifacial PV technology is currently seeing a remarkable boom, in both publications and advertisements as well as in real installation figures; this is no wonder, as fairly small changes to solar cell and module technology can lead to potential improvements of 5% or 10% in system output – a huge step compared with other evolutions in PV technology. The shift from monofacial modules to bifacial concepts, however, requires changes in materials, processes and set-ups. Simply replacing the solar cells would miss the point: the components, production and use of modules also need to change in order to successfully account for bifacial properties. The common module set-up using white backsheets, large junction boxes and module labels on the rear needs to be adapted.

Component and material manufacturers have reacted by making available edge connectors, thin glasses or transparent foils. The changeover from monofacial modules to bifacial ones in terms of module manufacturing is already under way but still a long way off. What industry and customers lack are not manufacturing solutions, equipment or components, but rather the results of brainwork: regulations, characterization processes and scientific models. How should the module power be stated on the label, and how can the additional gain of a bifacial module be determined? How is this gain to be measured and how can laboratory results be transferred to outdoor performance?

The industrial realization of bifacial module concepts has certainly outpaced existing characterization standards, but any gaps will soon be closed with the updated IEC 60904 standards. Unfortunately, there are some other remaining issues to be addressed, and the future optimization of bifacial modules and systems will be even more difficult than the optimization of monofacial modules. Scientists and R&D specialists are facing new challenges resulting from the second active side of the solar cell.

Realistic yield predictions of bifacial PV systems require precise device characterizations, a profound understanding of cell, module and system behaviour, and numerical models in order to include this knowledge in reliable projections. This paper covers the full characterization and modelling chain, beginning with the determination of PV cell properties via PV module power prediction and PV module characterization, and concluding with the prediction of bifacial gains in PV systems.

“The precise measurement of the illuminated current–voltage (*I–V*) characteristics is of central importance for solar cell and module manufacturers.”

Accurate measurement of bifacial solar cells

The need for bifacial measurements is rather new, at both the cell and the module levels. A number of issues will be discussed at the cell level first; some of these issues will also show up again later at the module level.

The precise measurement of the illuminated current–voltage (*I–V*) characteristics is of central importance for solar cell and module manufacturers. While the procedure for the measurement of conventional monofacial solar devices is well defined in the standards [1], discussions regarding the measurement of bifacial devices are still ongoing. Comprehensive overviews of measurement procedures under discussion have been recently reported [2–5]. These procedures are based either on both-side illumination of the device or on just front-side illumination with increased irradiance. The applicability of the procedures depends on cost, throughput and accuracy requirements, and can be different in laboratory and production line environments.

Measurements with double-sided illumination

One measurement procedure – which is very close to operational conditions of the bifacial device – is based on illuminating the device with an irradiance of 1,000W/m^2 from the front, and a reduced irradiance in the range of 0 to over 200W/m^2 from the rear. The measurement of the *I–V* characteristics is performed for at least three different rear irradiances, and the measured power of the bifacial device is then interpolated to rear irradiances of 100 and 200W/m^2. In addition to the front and rear *I–V* parameters at standard test conditions (STC), these power values will also be given in the measurement report [2–5].

There are different possibilities for realizing double-sided illumination of bifacial solar cells. One option is the application of an additional light source for the rear illumination. It has been shown that the front and rear light sources can be synchronized successfully for flash applications [6]. The interaction of front and rear illumination by light transmission from one side to the other side is not critical [7].

As an alternative to set-ups with two different light sources, facilities with one light source and mirrors are in use [8–10]. Two mirrors are thereby employed to deflect the light of one solar simulator to the front and the rear of the bifacial device, which is mounted in parallel to the direction of the light source. Such a two-mirror set-up is used at Fraunhofer ISE CalLab PV Cells for the precise measurement and characterization of bifacial solar cells (see Fig. 1). It has the advantage that it can be used as a replaceable module in an established offline flasher set-up.

A temperature regulation unit and an isolating enclosure are used for the two-mirror set-up in order to stabilize the temperature of the solar cell to 25±0.5°C. The uniformity of the front and rear irradiances in the solar cell plane was measured to be better than classification A [11]. The crosstalk caused by light passing from one side to the other was minimized to below the detection limit by installing non-reflective, moveable apertures, which can be moved very close to the edges of the solar cell on all sides. A class A spectrum of the front and rear illumination was ensured by adapting the spectral filters in front of the flash lamp. Seven grating filters with transmittances in the range 10 to 40% are additionally available to reduce the irradiance onto the rear side of the solar cell in a spectrally neutral way [12]. In this way, a class A spectrum is maintained for irradiances below 1,000W/m^2 as well.

Up to now, it has not been clear which spectral distribution should be used for the rear illumination in measurements. When a bifacial device is operating in the field, the light reaching the rear side of the device is often not from direct sunlight, but from light which is reflected off the ground beneath the device. Since the ground reflectance can exhibit a significant spectral dependence, the spectral distribution of the rear illumination can differ significantly from the standard AM1.5g spectrum, which represents direct sunlight and is used for the illumination of the front side.

With a two-mirror set-up, both the standard spectrum and various spectral distributions can be implemented: spectrally neutral grating filters can be used for maintaining the standard spectrum, while other spectral distributions can be generated either by placing filters with distinct spectral dependence into the rear light path, or by replacing the rear mirror with reflectors having a defined reflectance.

To improve the measurement accuracy, it is important to consider the different front and rear spectral responsivities of the bifacial solar cell. This means that there are two different spectral mismatches for the front and rear sides, which is particularly critical if the front and rear spectral distributions differ. Further measurement errors can result from differences in the shading of the solar cell by the front and rear contact bars; this effect needs to be quantified and taken into account.

In conclusion, the two-mirror set-up developed at CalLab PV Cells fulfils the highest quality criteria (better than AAA classification) and enables the precise measurement of bifacial solar cells with double-sided illumination.

Measurements with single-sided illumination

The measurement procedure based on single-sided measurements has the advantage of requiring only minor changes to the available equipment. This procedure is also known as the *equivalent irradiance* (G_E) *method* [2–5]. An important point of this method – which needs special care – is the consideration of the additional current or power that would be generated by illumination of the rear side; therefore, in addition to measurements of front and rear *I–V* characteristics at STC under single-sided illumination, further front-side measurements at higher irradiances are performed. The bifaciality coefficients φ are calculated from the front and rear STC *I–V* parameters to quantify the differences in front and rear characteristics of the bifacial device. The rear irradiance is then weighted with these coefficients to determine the additional front irradiance that is required in order to yield similar conditions with front-side illumination only. At least three different hypothetical rear irradiances are measured, and the results interpolated to rear irradiances of 100 and 200W/m^2.

In practice, conventional set-ups can still be used for the application of the G_E method with single-sided illumination; however, as these measurements are performed at irradiances of up to 1,200W/m^2, the set-ups may need to be upgraded. Several equipment manufacturers have adapted their solar simulators to meet these requirements [2,13–16]. A potential issue for industrial inline measurements with high throughput could be the determination of front and rear I–V parameters at STC, which are needed for the calculation of the bifaciality coefficients of each cell. This requires either the solar cells to be flipped in between the measurements, or the use of a second solar simulator. A possible back-door solution could be to use the bifaciality φ of reference solar cells [3,5]; the applicability of this approach, however, needs to be carefully evaluated [6,7].

At CalLab PV Cells, the established and well-characterized steady-state solar simulator, which is customarily used for the calibrated measurement of conventional solar cells, is also used for measuring bifacial solar cells with single-sided illumination. A variety of measurement chucks with different reflectances and conductances are available for the mounting of the bifacial solar cells [17]. The simulator is operated at an increased lamp power to enable measurements to be taken at elevated irradiances.

Increasing the accuracy of measurements with single-sided illumination

Several correction procedures, such as the consideration of non-uniformity of irradiance or spectral mismatch correction, can be carried over from conventional measurements. However, there are also measurement uncertainties specific to bifacial solar cells; these need to be investigated carefully, and correction procedures need to be elaborated.

For the precise measurement of the fill factor of bifacial solar cells, it is important to consider the influence of the rear-contacting scheme [18]. Whereas conductive measurement chucks electrically contact the entire rear grid of the solar cells (busbars and fingers), non-conductive chucks contact only the busbars. Thus, differences in fill factor between the two measurement chucks occur: the higher the resistance of the metal fingers, the larger the difference [18]. Although this effect also arises for conventional monofacial solar cells, it is much more pronounced for bifacial solar cells. By measuring the finger resistance, this effect can be quantified and taken into account.

It is furthermore important to ensure 'true' single-sided measurements. This means that unwanted contributions to the measured current by the current generated from the side that is actually non-illuminated needs to be minimized [2–4]. In the case of bifacial solar cells mounted on a measurement chuck, the most critical contribution comes from light that is transmitted through the solar cell, reflected at the measurement chuck and re-entering the solar cell through its rear side. This contribution of current is directly proportional to the long-wavelength reflectance of the measurement chuck [17], which enables the determination of the 'true' single-sided short-circuit current [3,5]: by measuring the short-circuit current of the bifacial solar cell with chucks of different reflectances, the current can be extrapolated to zero reflectance.

A large set of bifacial solar cells of different technologies has been measured at CalLab PV Cells on two chucks with very different long-wavelength reflectances. The correction procedure mentioned above was carried out to determine the respective extrapolated currents for each solar cell. Fig. 2 shows the relative deviations from these extrapolated currents for the entire set of solar cells.

From a calibration laboratory point of view, deviations exceeding 0.1% are relevant for *I–V* measurements. At CalLab PV Cells, a non-reflective chuck with a long-wavelength reflectance of 4% is therefore used to reduce the contribution of transmitted light to values below $0.1\%_{\text{rel.}}$. For solar cell sorting environments, higher deviations can possibly be tolerated. To keep deviations below $0.3\%_{\text{rel.}}$ for the solar cells investigated in this study, chucks with long-wavelength reflectances below 17% need to be used (see Fig. 2). By carefully adapting the chuck to the necessary measurement accuracy, the contribution by the non-illuminated side can thus be minimized.

In conclusion, for the precise measurements of novel solar cell types, such as bifacial solar cells, special care must be taken to avoid systematic measurements errors. Detailed and comprehensive investigations are necessary in order to develop sound measurement procedures and set-ups. Both approaches currently under discussion for the measurement of bifacial solar cells – measurements with single-sided illumination using the G_E method and measurements with bifacial illumination – can be performed at ISE CalLab PV Cells with high accuracy.

From bifacial cell to module efficiency

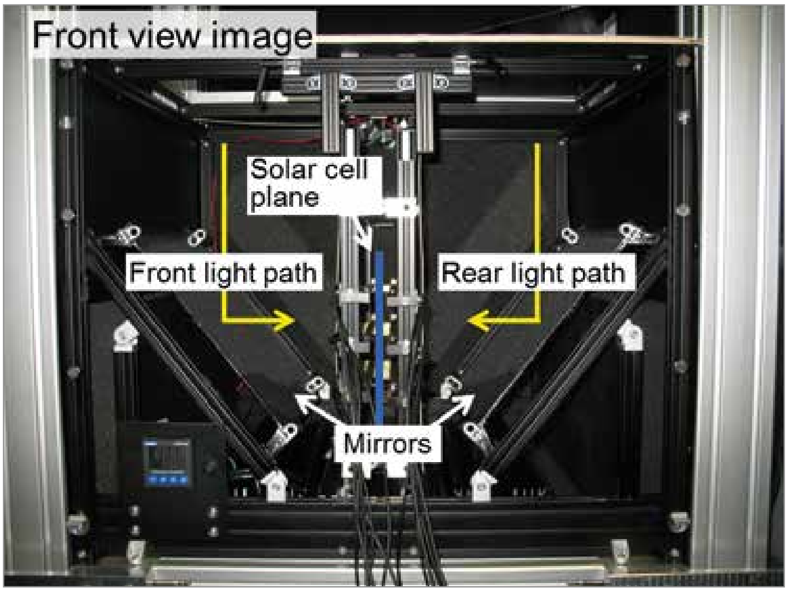
The cell-to-module (CTM) power ratio describes the ratio of the module power after module integration of the solar cells, to the sum of the power of the individual solar cells before integration. Optical and electrical gains and losses contribute to the CTM ratio [19,21]. This parameter is useful for assessing the losses caused by the integration of solar cells into modules. While the overall CTM ratio may be derived from a comparison of cell and module measurements, the roles of components and materials, as well as of new module concepts, can already be analysed and optimized with regard to power losses and efficiency in advance [22,24]. Of course, precise bifacial cell measurements as described above are a prerequisite for the successful completion of this task.

Introducing bifacial cells into PV modules means that existing models for CTM efficiency analysis or yield prediction [19] are no longer sufficient because of additional optical effects within the PV module, such as additional relevant internal reflections [20]. Conventional modules profit from backsheet reflection (Fig. 3, black) – i.e. light irradiating from the module front that reaches the cell front after internal reflections within the module. Bifacial modules feature three additional gains (Fig. 3, red), which also increase complexity in modelling [25]. In addition, gains resulting from a partial transparency and internal reflection occur in bifacial modules [25,26].

The power of bifacial cells naturally increases with additional irradiance from albedo reflection, but research also indicates that bifacial cells additionally profit from higher gains and internal reflection, as highlighted in Fig. 4 [25].

The additional light passing into the module and reaching the solar cell affects not only the optical CTM factors but also the electrical ones. The module current increases, and higher ohmic losses are a consequence. Alternatively, components (i.e. the cell interconnector ribbons) need to be adapted or new module topologies may be considered. Instead of serial cell-and-string interconnection,

Figure 1. Front-view image of the two-mirror set-up employed at ISE CalLab for measuring bifacial solar cells with double-sided illumination.



> “The characterization of complete bifacial PV modules is a must for any product entering the PV market.”

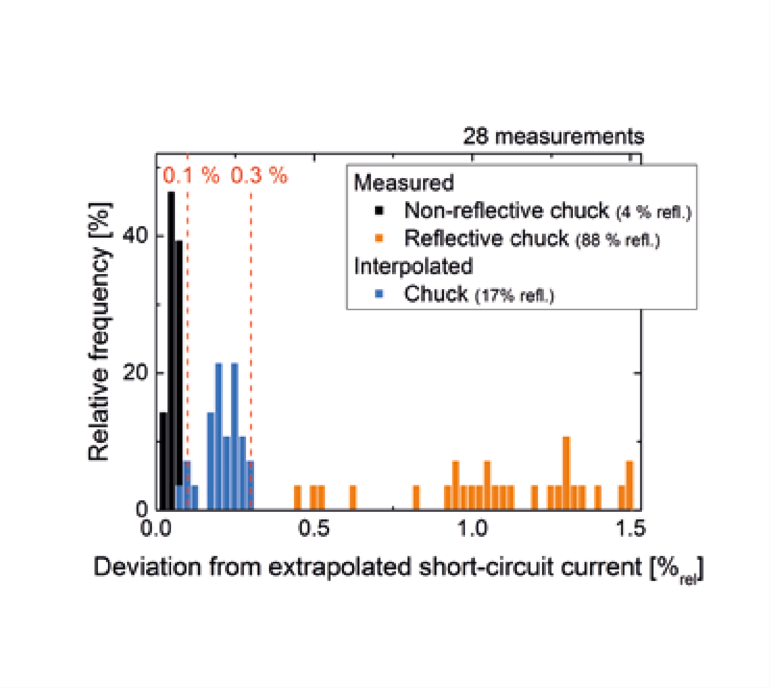
parallel circuits or networks might be used. In addition, a shifting of concepts away from ribbon-based interconnection of squared cells towards round-wire interconnection, half cells or shingling with bifacial cells will impact all types of CTM losses [27,28]. The possibilities are numerous, but the evaluation of all the concepts is difficult.

The different CTM factors influence each other and render the optimization of modules and components a non-trivial task. A holistic and flexible approach is necessary, and new models are required in order to successfully optimize bifacial modules. Fraunhofer ISE presented such an approach [19,22], and is currently extending and implementing models for bifacial solar cells into ‘SmartCalc.CTM’ – a software package to support CTM analyses and module optimization [22,29]. This tool allows virtual prototyping as well as supporting iterative development processes for several different module, cell and interconnection concepts. Adding the possibility to also optimize bifacial cells now supports the PV industry and allows the optimization of bifacial modules, given the increasing market share of bifacial cells.

Accurate measurement of bifacial PV modules

Following cell characterization and module design optimization, the characterization of complete bifacial PV modules is a must for any product entering the PV market. Here, similar challenges to those associated with cell measurements discussed above will be encountered, and, accordingly, various methods are currently under discussion for this very purpose.

Figure 2. Relative deviation from ‘true’ single-sided short-circuit current resulting from light that is transmitted through the solar cell, reflected at the measurement chuck and re-entering the solar cell through its rear side. A large set of bifacial solar cells was measured on measurement chucks with different reflectances for this purpose.



Since the existing standards for the *I*–*V* measurement of PV devices neither consider gains arising from rear irradiation, nor define the measurement conditions for the rear side of the module, it is often not clear how the nominal power of a particular commercial module is determined. The labelled values often refer to front-side measurement under STC, while the irradiance condition on the rear side is not specified. Depending on whether the rear side was covered or open to incident stray light, or measured with a proprietary (i.e. non-standardized) reflector behind the module, the resulting measured power can vary by several per cent. Many datasheets state values for the boost in bifacial power: these are mostly extrapolated from front-side STC values, assuming a linear power boost, or they are determined by more advanced calculations. Values for rear-side efficiency or bifaciality are usually not mentioned, despite this information being needed to estimate bifacial gains for the specific installation conditions. In any case, the comparability and meaningfulness of datasheet values is not very satisfactory.

Set-ups for double-sided illumination

The easiest way to obtain additional rear irradiance in the *I*–*V* measurement of bifacial modules is to place a reflective material behind the module. The light transmitted through the module and stray light incident on the reflector will be reflected onto the rear side of the module. The resulting quality of the rear irradiance is highly dependent on the material properties of the reflector (specularity and spectral distribution) and the distance between module and reflector, as well as on the module transmission. With this method, the achievable light intensity and homogeneity is limited and influenced by the module under test.

An alternative method is to place a second light source behind the module; this way, the rear intensity is tuneable independently of front-side intensity, and the light quality can be well defined. Homogeneity and spectral match are only determined by the light source and are not influenced by module properties. Some companies are already offering sun simulators with double-sided illumination. With the exception of table flashers, sun simulators for modules typically have a very large footprint: the fact that for this kind of set-up the footprint is doubled for bifacial illumination, along with the additional costs, might discourage module manufacturers from upgrading their sun simulators.

Another option for creating a defined rear irradiance is to split up the light from the sun simulator and direct it simultaneously onto both sides of the module by using mirrors. A schematic of this set-up is shown in Fig. 5.

At CalLab PV Modules, a mirror set-up has been developed, enabling bifacial illumination of full-size modules of up to 1m × 2m, with an irradiation quality of better than AAA. Two mirrors at a 45° angle to the lamp direct the light of the solar simulator simultaneously onto both sides of the module, as described above for bifacial PV cells. The mirrors are constructed from a silver-coated reflector sheet, with a reflectance of over 95% in the wavelength range from 300 to 1,200nm, so that the reflected spectrum remains of A+ quality. The reflector sheets are attached to glass panes in order to achieve a smooth surface for maintaining homogeneity of irradiance. The lamp power can be adjusted between 100 and 1,000W/m^2, and by inserting attenuation filters the rear intensity can be reduced. The attenuation filters used for this work are made of woven wire mesh, a material which demonstrates spectrally neutral transmission and good spatial homogeneity on large areas, as reported in Santamaria et al. [12]. The currently available transmissions are 20, 35 and 55%. With this variable light intensity and variable front-to-rear intensity, typical irradiation conditions for different installation geometries (e.g. south, east–west) can be simulated.

At the moment, most module producers and labs only have the possibility of taking measurements under single-sided irradiance. It has not so far been proved that measurements under single-sided and bifacial irradiance produce the same results, and so these approaches will be compared, on the basis of measurements of different commercial bifacial modules, in the following sections.

I–V measurement under single-sided illumination

For a basic characterization of bifacial modules, it is necessary to measure each side separately at STC, with the other side being protected from incident stray light. For all single-sided measurements in this work, the rear side of the module was covered by a black curtain. The spectrally weighted reflection of the material is 4.3% and is fairly constant over the relevant wavelength range between 300 and 1,200nm. Along the long edges of the module, a mask prevents light from passing by the module, so that the incident light on the rear cover is limited solely to the light transmitted through the module and to that passing by the short edges of the module. In this way the electrical module parameters of each side are determined with maximum precision. With these results, the bifaciality φ of current and power, which is defined as the ratio of the rear-side value to the front-side value, can be calculated. The single-sided STC parameters are also the basis for yield simulations of bifacial PV systems [30].

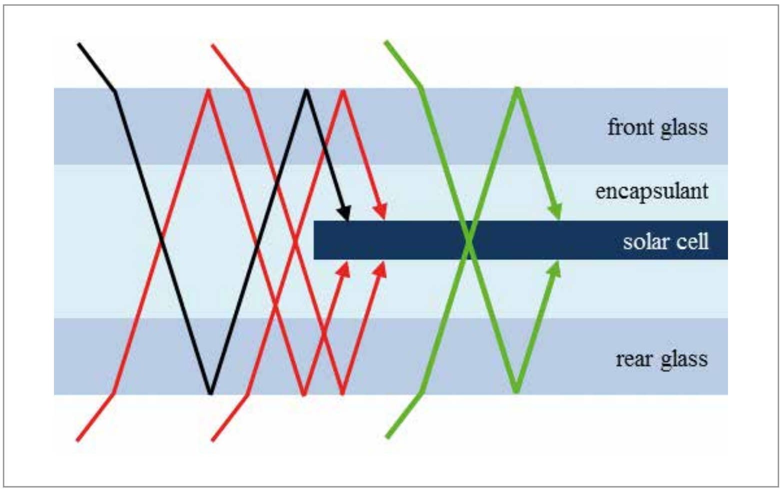


Figure 3. Schematic of cover reflection gains in modules with bifacial cells and transparent rear cover.

Single-sided vs. bifacial measurement

When comparing the front-side measurement under elevated irradiance (the G_E method) with the measurement under real bifacial irradiance, the question is: to what extent does the light-incident side influence the results? As shown in Schmid et al. [31], the role of the light-incident side for short-circuit current I_{sc} and open-circuit voltage V_{oc} can be described by the bifaciality φ for I_{sc}, while the fill factor *FF* is determined by different influences.

In the comparison of single-sided and bifacial measurements of commercial modules, it is important to also consider the shape of the *I–V* curves. Most bifacial modules have distorted rear *I–V* curves, as a result of partial shading by the junction box, cabling, frame or label, or because of cell sorting according to front-side current only. An example of typical *I–V* curves is shown in Fig. 6. Since in the G_E method a module *I–V* curve is measured only under elevated front irradiance, the distortion of the rear *I–V* curve will not be detected, as can be observed in Fig. 6. While the *I–V* curve of the G_E measurement is as smooth as that of the front-side STC measurement, the *I–V* curve for the bifacial measurement is affected by the partial shading of the rear side of the module. Depending on the rear intensity and the severity of the distortion, this can lead to a deviation between measured power and *FF* for G_E and bifacial measurements.

Fig. 7 shows measured *FF*s for different illumination conditions for a typical module. FF_{FRONT} and FF_{REAR} refer to single-sided irradiance in 100W/m^2 steps between 100 and 1,000W/m^2. FF_{BIFA} refers to symmetrical irradiance for the front and rear sides. Additionally, the *FF*s for the G_E and the bifacial measurement, corresponding to 1,000W/m^2 front and 200W/m^2 rear intensities, are shown. The *x* axis is scaled to I_{sc} instead of irradiance, in order to enable a comparison to be made of the *FF* at the same current level.

In the case of measurements under single-sided illumination on the front and rear sides, a higher *FF* for the rear-side illumination was found. This higher *FF* is not just related to the fact that the lower rear

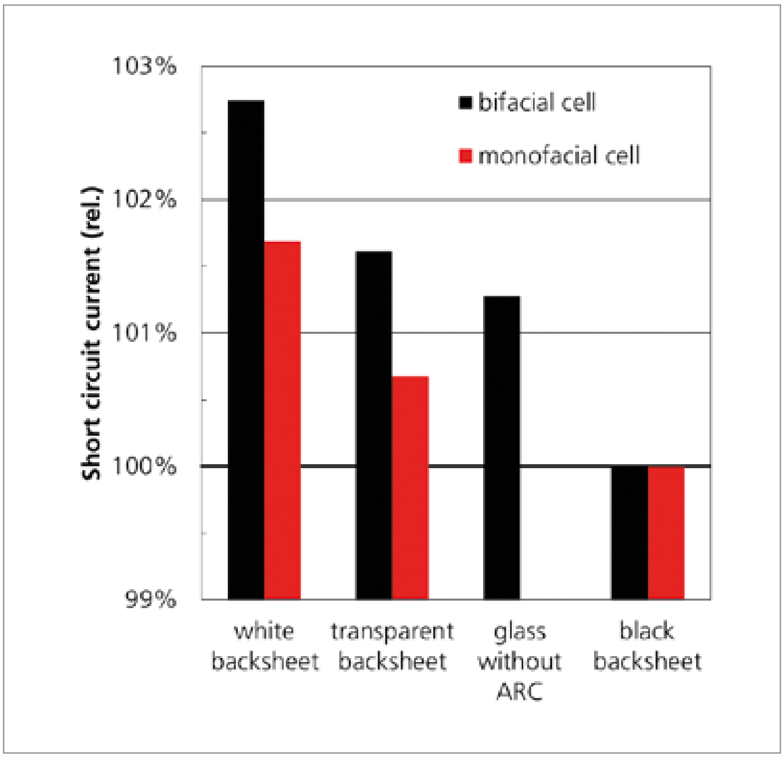


Figure 4. Short-circuit current gain of monofacial and bifacial solar cells (different manufacturers) in four-cell modules with different rear-cover materials and 2mm cell spacing. (Front-side irradiance only, mask used, normalized to I_{sc} measured with a black backsheet.)

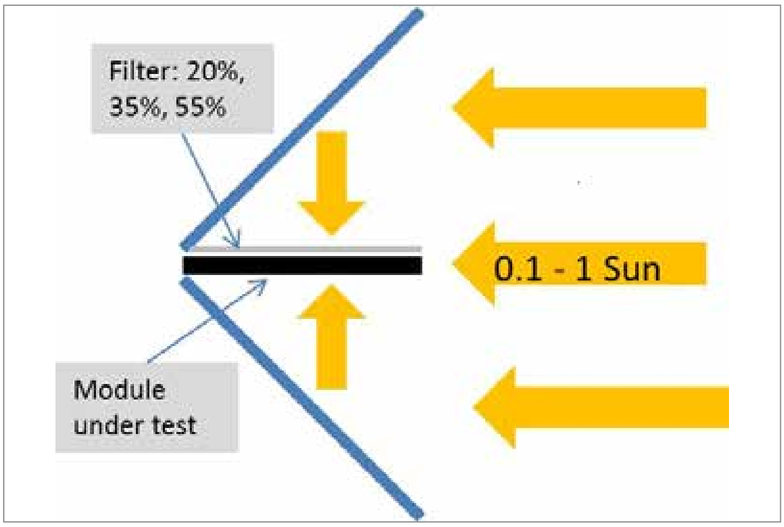


Figure 5. Schematic of a possible bifacial measurement set-up: two mirrors at a 45° angle to the lamp simultaneously direct the light onto both sides of the module

current leads to a smaller series resistance loss. Even when comparing the front and rear fill factors for the same current level, as shown in the graph in Fig. 7, the rear fill factor is significantly higher. The mean difference in *FF* between front and rear illumination was found to be 0.3% for commercial modules at the same current level. This affects the *FF* in the bifacial measurement as opposed to the reduction in *FF* due to partial shading mentioned earlier. As can be seen in the graph, the *FF* under bifacial irradiance is typically found to be higher than in the measurement under G_E.

> "The well-known algorithms for the calculation of irradiance at the front side of a module are not adequate for bifacial applications."

The deviation of measured P_{MPP} was calculated for all bifacial modules measured with the bifacial set-up and with the G_E method. With irradiance conditions of 1,000W/m^2 on the front side and 200W/m^2 on the rear side, the mean deviation was 0.5%, ranging from a minimum deviation of 0.24% to a maximum of 0.9%. The difference is strongly influenced by the distortion of the rear *I–V* curve. As these effects can only be determined by true bifacial measurements, it is recommended not to count on G_E measurements alone when reliable results are needed.

Bifacial PV power plants

Finally, all the knowledge gathered about bifacial PV cells and modules is utilized when a bifacial PV power plant's performance is to be predicted or assessed. Again, there are some differences compared with the well-established procedures for monofacial PV systems.

The additional energy delivered by bifacial PV modules is commonly (but not accurately) called *bifacial gain (BG)*. Compared with solar cell development steps which just increase STC power per area, the yield gain produced by the rear-side contribution of bifacial PV modules is no longer a pure module property. The *BG* depends heavily on the amount and distribution of the irradiation reaching the rear module surface. Moreover, in contrast to the front side of the module, the availability of rear-surface irradiance depends on a greater number of system-related factors, such as:

- Mounting geometry (module height, module tilt angle, row-to-row distances)
- Ground albedo and its homogeneity
- Mounting structure (which also influences the homogeneity of rear-side irradiance)

As the amount of irradiation available to the rear side of a bifacial module is strongly influenced by system properties, the final bifacial gain too is essentially regarded as a system property. In a first step, the irradiance gain from the rear surface of the module may be expressed as optical bifacial gain:

$$BG_{OPT} = G_{REAR} / G_{FRONT}$$

Unfortunately, the rear side of a bifacial PV module is less efficient than the front side. Typical ratios of rear-side to front-side efficiency (called *bifaciality* φ) range from 60 to 95%. Consequently, the rear-side electricity production of any module will not be directly proportional to the optical gain, but will instead be reduced by the bifaciality factor, which leads to the bifacial gain of the module:

$$BG_{MOD} = \varphi\, G_{REAR} / G_{FRONT}$$

Finally, the additional electricity production may differ from BG_{MOD}, as the system response is not completely linear (especially if clipping effects from inverter or grid power limitations come into play). This final BG_{SYS} value may only be derived from two simulation runs – one with bifacial modules and one with monofacial modules with identical properties:

$$BG_{SYS} = E_{REAR} / E_{FRONT} = (E_{BIFA} - E_{MONO}) / E_{MONO}$$

These steps are detailed in the next two sections, while some typical results for *BG* will be given in a subsequent section.

Estimation of optical gain and module gain

The well-known algorithms for the calculation of irradiance at the front side of a module are not adequate for bifacial applications; Fraunhofer ISE has therefore developed appropriate methods and tools on the basis of 'Radiance', a backward raytracing software package. Radiance, developed at the Lawrence Berkeley Labs, USA, is a powerful lighting simulation software; it has been in use within the daylighting research and application community for several decades, and offers excellent flexibility in the description of surface properties and structural geometry. The Radiance calculation scheme uses absolute properties of radiance and irradiance in suitable physical units of W/m^2sr or W/m^2. Models of the natural sun and sky light sources are provided via the gendaylit tool, which creates a complete sky radiance distribution for any reasonable pair of global and diffuse horizontal irradiance parameters G_{HOR} and D_{HOR} given as input values. Radiance can both render images and provide numerical values of local irradiance as 'seen' by virtual irradiance sensors. A comparison with monitoring data from real bifacial PV plants ensures the accuracy of the simulation results. A model validation in particular was presented in Reise et al. [30].

Other approaches use the radiosity method, which is well known from computer graphics rendering. Based on a radiative energy balance between many neighbouring surface elements, this method is much faster than raytracing, although not as accurate, and requires a larger number of test cases for validation. Both the raytracing and radiosity methods may be used to calculate look-up tables, representing the relationship between *BG* and a small number of geometry parameters, such as tilt angle, row distance and height above ground.

In the case in question, a raytracing model considers all details of the PV module mounting geometry (module type, fixed or varying module tilt angle, row-to-row distance, components of the mounting structure). For a realistic estimation of bifacial gains, the calculations are typically carried out for a module in the centre of a large homogeneous generator section.

Using the raytracing tool, the calculation of the irradiation levels is performed for each time step of the meteorological input data and for both sides (front and rear) of each of the 60 or 72 solar cells within a module. These individual irradiance values are then aggregated to front- and rear-side module irradiance values. From these values, the optical bifacial gain BG_{OPT} and the module bifacial gain BG_{MOD} may be calculated. At the same time, an effective irradiation on the module is known:

$$G_{EFF} = G_{FRONT} + \varphi\, G_{REAR}$$

Finally, G_{EFF} serves as the input to the calculation of PV power generation and all related losses using 'Zenit', Fraunhofer ISE's own modelling tool for PV power plants. In fact, using G_{EFF} here is quite similar to the G_E concept explained above for PV module characterization.

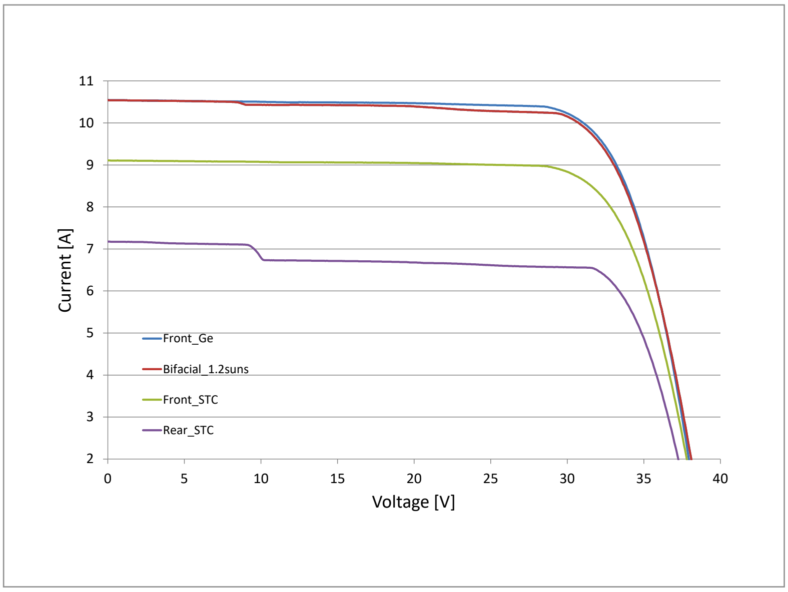
Estimation of system level gain

In this calculation, as in a standard yield estimation, both module-related and BOS-related losses are addressed. The most important losses are:

- Reflection losses due to non-normal incidence of irradiation.
- Efficiency losses (or gains) due to the deviation from STC.
- Conduction losses on both DC and AC (low and medium voltage) sides.
- Inverter losses (device efficiency and, if applicable, power limitations).
- Transformer losses (when feeding into the medium- or high-voltage grid).

System-level bifacial gains are then determined from two separate model runs, using time series of G_{FRONT} or G_{EFF} as input. This appears to be a somewhat incorrect comparison, as no-one would operate a bifacial module with a covered rear surface. However, from a modelling point of view, the output of a monofacial module is simply

Figure 6. *I–V* curves of a typical commercial module under front-side irradiance and under rear-side irradiance (STC conditions), compared with bifacial and G_E irradiance corresponding to a rear irradiance of 200W.



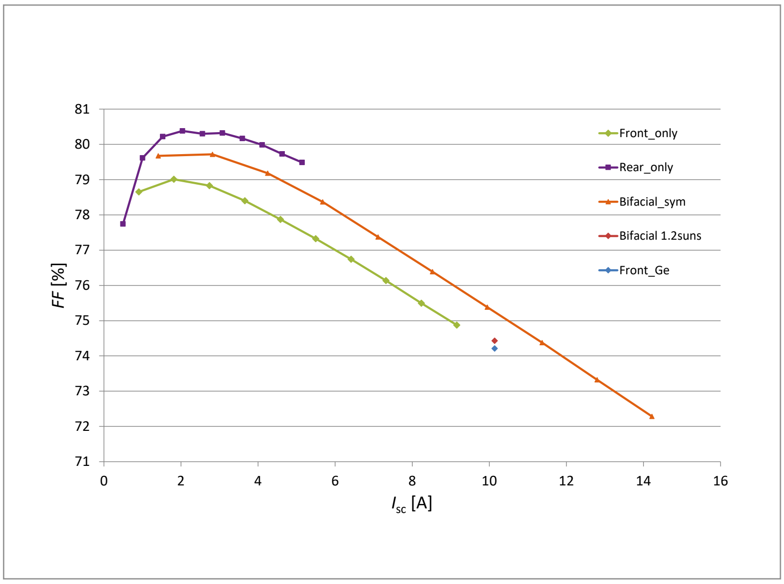


Figure 7. *FFs* measured for front-side, rear-side and bifacial irradiance, with respect to I_{sc}. Additionally the *FFs* for the G_E and bifacial measurements with 200W rear intensity are shown.

related to that of a bifacial one featuring the same front-side STC power. A number of important effects, such as increased module operating temperature, or the results of a more-or-less correct inverter sizing are clearly reproduced when applying the G_E or G_{EFF} method to a standard yield-prediction model.

Representative results

With commercial bifacial PV projects, the module mounting will probably follow, and somehow adapt, traditional installation schemes. However, when seeking optimized yields, some design contradictions may occur:

- For rooftop systems, increased module height (for higher rear-surface irradiance) will also increase wind loads, demanding more stable and expensive mounting structures.
- For many systems, increased row-to-row distance will increase not only optical gains, but also all costs related to the area requirements.
- Artificially increased albedo (for both ground-mounted and rooftop systems) will also increase maintenance (cleaning) efforts.

Since 2009, Fraunhofer ISE has been extending its yield-prediction service to bifacial PV systems. A number of studies have been prepared since then, covering single commercial projects as well as parameter studies for bifacial PV systems. Table 1 presents a number of representative results for BG_{MOD}, as extracted from a number of studies for sites in Central Europe.

Type	Height [m]	Tilt angle [°]	Albedo	GCR	BGMOD [%]	Notes
Ground mounted	0.7m	30	0.20	0.43	5	(1)
Ground mounted	1.0m	30	0.20	0.40	8	(2)
Ground mounted	0.5m	30	0.20	0.40	9	(3)
Ground mounted vertically	0.0m	90	0.20	0.00	9	(4)
Ground mounted vertically	0.0m	90	0.20	0.20	–17	(5)
Rooftop	0.1m	20	0.40	0.40	6	(6)
Rooftop	0.3m	20	0.40	0.40	11	(6)
Rooftop	0.3m	20	0.60	0.40	16	(6)

Notes: (1) three modules stacked in landscape mode; (2) one module in landscape mode, calculated w/o mounting structure; (3) two modules stacked in portrait mode; (4) single row, gain vs. 30° south monofacial; (5) multiple rows, gain vs. 30° south monofacial; (6) calculated w/o mounting structure.

Table 1. Predicted yield values for typical large-scale bifacial PV system configurations (GCR = ground cover ratio = module area/ground area).

Ground-mounted systems in a traditional geometric configuration on grass or similar natural surfaces deliver bifacial gains between 5 and 9%. The *BG* depends mainly on row-to-row distance, but also, less importantly, on mounting height. For dense PV systems, bifacial gains may at least compensate for the mutual shading that occurs between module rows.

Bifacial modules mounted vertically should yield module bifacial gains close to the bifaciality factor (*BF*), since both module surfaces receive the same amount of irradiation. However, from a commercial point of view, the output of vertical bifacial systems will be comparable to that of monofacial systems in a standard layout (e.g. 30° tilted towards the south). Single rows then demonstrate a gain of around 9%, while multiple rows lead to a loss of some 17% for a specific configuration.

Bifacial PV systems installed on flat roofs may yield gains in the range 6 to 16%. In contrast, here the *BG* depends primarily on the (typically low) mounting height, and, to a lesser extent, on the row-to-row distance. Rooftop systems have the option to substantially increase albedo and *BG* by using bright roofing membranes.

Conclusions

All in all, with larger commercial systems, realistic bifacial gains are expected to range from 5 to 15%. Ground-mounted systems on natural (non-desert) surfaces will probably stay below 10%, while rooftop systems offer the potential for higher gains through the use of highly reflecting roofing materials.

> "With larger commercial systems, realistic bifacial gains are expected to range from 5 to 15%."

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