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Edition 1.0 2019-01

TECHNICAL SPECIFICATION

Photovoltaic devices –
Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices

IEC TS 60904-1-2:2019-01(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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PHOTOVOLTAIC DEVICES –

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FOREWORD

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Technical Specification are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 60904-1-2, which is a Technical Specification, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
82/1403/DTS	82/1508/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60904 series, published under the general title *Photovoltaic devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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PHOTOVOLTAIC DEVICES –

Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices

1 Scope

This part of IEC 60904 describes procedures for the measurement of the current-voltage (I-V) characteristics of bifacial photovoltaic devices in natural or simulated sunlight. It is applicable to single PV cells, sub-assemblies of such cells or entire PV modules.

The requirements for measurement of I-V characteristics of standard (monofacial) PV devices are covered by IEC 60904-1, whereas this document describes the additional requirements for the measurement of I-V characteristics of bifacial PV devices.

This document may be applicable to PV devices designed for use under concentrated irradiation if they are measured without the optics for concentration, and irradiated using direct normal irradiance and a mismatch correction with respect to a direct normal reference spectrum is performed.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60891, *Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics*

IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-2, *Photovoltaic devices – Part 2: Requirements for reference devices*

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

IEC 60904-4, *Photovoltaic devices – Part 4: Reference solar devices – Procedures for establishing calibration traceability*

IEC 60904-5, *Photovoltaic devices – Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method*

IEC 60904-7, *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*

IEC 60904-8, *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

IEC 60904-9, *Photovoltaic devices – Part 9: Solar simulator performance requirements*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

IEC TS 62446-3, *Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography*

IEC 62788-1-4, *Measurement procedures for materials used in photovoltaic modules – Part 1-4: Encapsulants – Measurement of optical transmittance and calculation of the solar-weighted photon transmittance, yellowness index, and UV cut-off wavelength*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 bifacial PV device

PV device, both surfaces of which (front and rear sides) are used for power generation

3.2 bifaciality

property expressing the ratio between the main characteristics of the rear side and the front side of a bifacial PV device quantified by specific bifaciality coefficients

Note 1 to entry: Unless otherwise specified, the bifacialities are typically referred to Standard Test Conditions STC. The main bifacialities are:

- Short-circuit current bifaciality: φ_{ISC}
- Open-circuit voltage bifaciality: φ_{VOC}
- Maximum power bifaciality: φ_{Pmax}.

3.3 rear irradiance driven power gain yield

BiFi

quantity which indicates the power gain, in addition to that obtained at STC conditions, per unit of rear irradiance

Note 1 to entry: It is expressed in W/(Wm^{-2}).

4 General considerations

The final performance of bifacial PV devices in a power plant depends not only on the spatial distribution of the irradiance incident onto the front surface, but additionally on that incident onto rear surface of the device, which is strongly affected by site-specific conditions, such as albedo, reflective surface size, the racking system, the device's elevation and its tilt angle. Due to these dependences and in order to obtain comparable measurement results, *I-V* characterisation is extended to quantify the bifaciality of the device and the rear irradiance driven power gain yield it can yield. Bifaciality is an intrinsic property of the device, unlike the site-specific conditions such as albedo. The measurement conditions for bifacial devices should strive to generate extra photocurrent proportional to their bifaciality. In general, this can be achieved with a test spectrum close to the reference spectrum such as provided by natural sunlight under suitable conditions or with a solar simulator whose irradiance level is adjustable. However, measurement conditions will never be perfect and will deviate from the reference conditions. This document sets limits on the permissible deviations for obtaining valid measurements. Smaller deviations are preferable, but may not be achievable in all cases. In any case, the deviations of the measurement conditions from the reference conditions shall be accounted for in the analysis of measurement uncertainty.

5 Apparatus

5.1 General

In addition to the apparatus requirements described in IEC 60904-1, one of the equipment sets described in 5.2, 5.3 and 5.4 and that described in 5.5 is necessary for the characterisation of bifacial devices.

5.2 Solar simulator with adjustable irradiance levels for single-side illumination

A solar simulator, as defined in IEC 60904-9, with adjustable irradiance level shall be used for the *I-V* characterisation of bifacial devices. Simulators shall be able to provide irradiance levels above 1 000 Wm^{-2} (typically up to 1 200 Wm^{-2}). The simulator's non-uniformity of irradiance shall be below 5 % and shall remain below this value at irradiance levels used for the characterisation of bifacial devices. The non-uniformity of irradiance, the spectral distribution and the temporal instabilities of irradiance shall be measured at the irradiance levels used for the characterisation of bifacial devices and those values used for corrections (such as spectral mismatch correction) and uncertainty evaluation.

For irradiances used above STC (>1 000 Wm^{-2}), the spatial uniformity, spectral distribution and temporal instability at 1 100 Wm^{-2} and 1 200 Wm^{-2} shall be measured.

5.3 Solar simulator with adjustable irradiance levels for double-side illumination

A solar simulator, as defined in IEC 60904-9, with the additional capability to simultaneously illuminate the bifacial device on both sides shall be used. Such simulators shall be able to provide irradiance at different levels on both sides. The non-uniformity of irradiance, the spectral distribution and the temporal instabilities of irradiance shall be measured on both sides when the test area is simultaneously illuminated on both sides. The non-uniformity of irradiance shall be below 5 % on both sides, at the irradiance levels used for the characterisation of bifacial devices and those values used for corrections (such as spectral mismatch correction) and uncertainty evaluation.

5.4 Natural sunlight

In addition to the general measurement requirements described in IEC 60904-1, at least 2 additional PV reference devices, as described in IEC 60904-2, are required to measure the irradiance level on the rear side and the rear-side irradiance non-uniformity. Their spectral responsivity should be as close as possible to the one of the device under test.

Care shall be taken to minimize the shadowing if placing sensors to measure the temperature of bifacial devices under natural sunlight or using double-side illumination. This needs to be considered in the measurement uncertainty analysis. Alternatively, contactless (IRT) or equivalent cell temperature calculation can be used as described in IEC TS 62446-3 and IEC 60904-5 respectively.

5.5 Non-irradiated background and background compensation

To measure the *I-V* characteristics of both front and rear surfaces of bifacial devices, the contribution from the light incident on the opposite side of the device under test shall be eliminated completely during the measurement by creating a non-irradiating background. The background is considered to be non-irradiating if the irradiance on the surface under test does not exceed 3 Wm^{-2}, at any point, on the non-exposed side of the device.

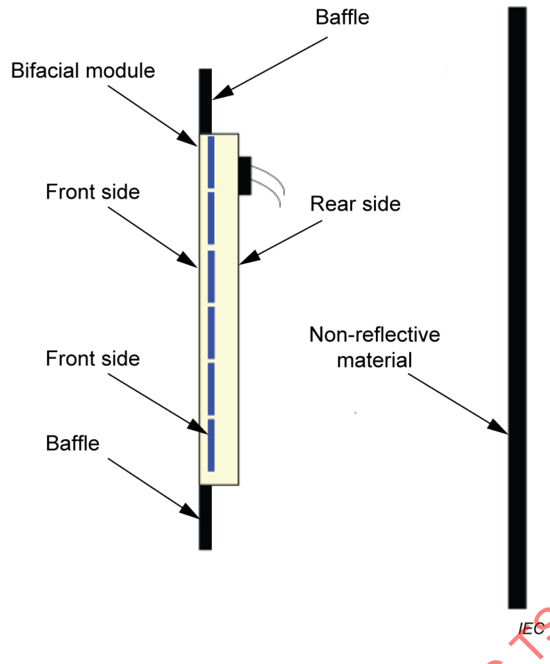


Figure 1 – Scheme of a bifacial PV module and the required non-irradiated background and aperture

In order to fulfil this requirement, in the case of PV modules, it is highly recommended to limit the size of the test area to that of the device under test using baffles as illustrated in Figure 1. Materials with minimized reflection in the wavelength range corresponding to the spectral responsivity of the test specimen, placed at a suitable distance from its non-exposed side, shall be used to reduce the irradiance level (non-reflective material).

To measure the irradiance on the non-exposed side, choose at least 5 points as shown in Figure 1, with symmetrical distribution, for instance, P1-P3-P5-P7-P9, P2-P4-P5-P6-P8 or P1-P2-P3-P7-P8-P9.

In the case of PV bare cells, the use of non-reflective materials to manufacture cell holders may be insufficient to reach irradiance values below 3 Wm^{-2}. In that case, background compensation may be performed by extrapolating the short-circuit current as a function of the background irradiance.

6 Additional *I-V* characterisations for bifacial devices

6.1 General

The procedure for measurement of the *I-V* characteristics of standard (monofacial) PV devices is described in IEC 60904-1 and its provisions are also valid for the measurement of bifacial PV devices except where explicitly amended by this document. The procedure for the measurement of the *I-V* characteristics of a bifacial PV device is based on the same basic principles as in IEC 60904-1, but requires some additional considerations and also provides supplementary characteristics specific to bifacial devices.

The measurement conditions for I-V characteristics of bifacial devices require more attention than for monofacial devices as the measurement results for bifacial devices are more prone to effects due to the measurement conditions deviating from the reference conditions. For instance, the parasitic reflections from the rear side of the device under test can increase significantly the measurement uncertainty. The measurement results should be corrected for the deviations of the measurement conditions from the reference conditions wherever possible. The uncertainty of this correction and furthermore the uncertainty arising from corrections which are not possible or have not been made need to be considered in the uncertainty analysis.

The parameters calculated as described below shall adhere to the specified limitations, which define the permissible measurement conditions. The calculated parameters shall also be reported with the measurement results as indicated in Clause 0.

Proper selection of measurement conditions avoids or minimizes the magnitude of the correction that shall be applied to the measured characteristics. In any case, a detailed analysis of measurement uncertainties is required.

6.2 Determination of bifacialities

In order to determine the bifacialities of the test specimen, the main I-V characteristics of the front and the rear sides shall be measured at STC, as schematised in Figure 2 (with G = 1 000 Wm^{-2}). A non-irradiated background, as described in 5.5, shall be used in order to avoid the illumination of the non-exposed side.

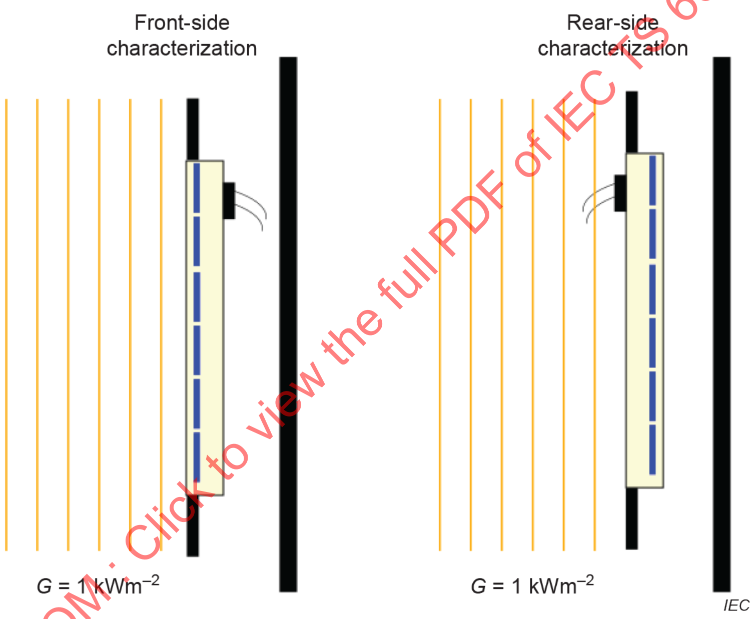


Figure 2 – Front- and rear-side characterization for bifaciality

In the case of PV modules, when the rear side of the device is being measured, the recommendations of the manufacturer about the handling of the cables shall be applied. If no specific recommendation has been made, each cable shall follow a path that minimizes the shadow on the cells.

Short-circuit current bifaciality, φ_{Isc}, is the ratio between the short-circuit current generated exclusively by the rear side of the bifacial device and the one generated by the front side. Both currents are measured at STC (1 000 Wm^{-2}, 25 °C, with the IEC 60904-3 reference solar spectral irradiance distribution AM1.5G):

$$\varphi_{\mathrm{Isc}} = \frac{I_{\mathrm{SCr}}}{I_{\mathrm{SCf}}} \qquad (1)$$

where

φ_{Isc} is the short-circuit current bifaciality. It is usually expressed as a percentage.

I_{SCr} is the short-circuit current when the device is illuminated only on the rear side, at STC.

I_{SCf} is the short-circuit current when the device is illuminated only on the front side, at STC.

Other bifacialities shall be reported and are calculated as described below:

$$\varphi_{Voc} = \frac{V_{OCr}}{V_{OCf}} \tag{2}$$

$$\varphi_{Pmax} = \frac{P_{maxr}}{P_{maxf}} \tag{3}$$

where

φ_{Voc} is the open-circuit voltage bifaciality. It is usually expressed as a percentage.

φ_{Pmax} is the maximum power bifaciality. It is usually expressed as a percentage.

V_{OCr} is the open-circuit voltage when the device is illuminated only on the rear side, at STC.

V_{OCf} is the open-circuit voltage when the device is illuminated only on the front side, at STC.

P_{maxr} is the maximum power when the device is illuminated only on the rear side, at STC.

P_{maxf} is the maximum power when the device is illuminated only on the front side, at STC.

The spectral mismatch correction shall be applied, according to IEC 60904-7, for the above mentioned calculations, unless it is known that the front and rear of the bifacial device have identical spectral responsivity.

It is recommended to measure the bifaciality on multiple samples and to provide its dispersion.

For indoor measurements with single-side illumination, care shall be taken to ensure that the same irradiance is applied on both sides of the device. Module framing might generate different geometries between the device and the light source, and with non-parallel irradiation this could lead to different irradiance levels between the two sides. When performing the measurements on both sides, care shall be taken to measure and correct for the irradiance level.

6.3 Determination of the rear irradiance driven power gain yield

6.3.1 General

The gain in power generation yielded by the rear irradiance on the bifacial device under test shall be determined as a function of the rear side irradiance level. To this end, outdoor or indoor measurement procedures shall be applied as described below.

The bifacial device under test shall be measured at STC, i.e. 1 000 Wm^{-2} ($G_r = 0$ Wm^{-2}), AM1.5G and 25 °C junction temperature. The front side irradiance shall be within ±10 % of the target irradiance and compensated to this target value (1 000 Wm^{-2}) according to IEC 60891. Note that this irradiance range is more restrictive than that of the IEC 60891, which allows for a larger compensation range (±30 %).

Additionally the P_{max} of the device under test shall be measured:

a) In the case of double sided illumination:
with G_f = 1 000 Wm^{-2} on the front side plus at least two different rear side irradiance levels G_r ;

b) In the case of single sided illumination:
with at least two different equivalent irradiance levels G_{E_i} on the front side according to formulae (6) and (7);

with, in both cases ($i = 1, 2, 3, ...$; for instance $0 \leq G_{r_1} < 100\ \mathrm{Wm}^{-2}$, $100\ \mathrm{Wm}^{-2} \leq G_{r_2} < 200\ \mathrm{Wm}^{-2}$ and $200\ \mathrm{Wm}^{-2} \leq G_{r_3} \ldots$).

The rear irradiance driven power gain yield, $BiFi$, is the slope derived from the linear fit of the P_{max} versus G_{r} data series (see the example in Figure 4 and Table 1). This linear least squares fit shall be forced to cross the P_{max} axis at P_{maxSTC} and its non-linearity shall be considered in the uncertainty estimation.

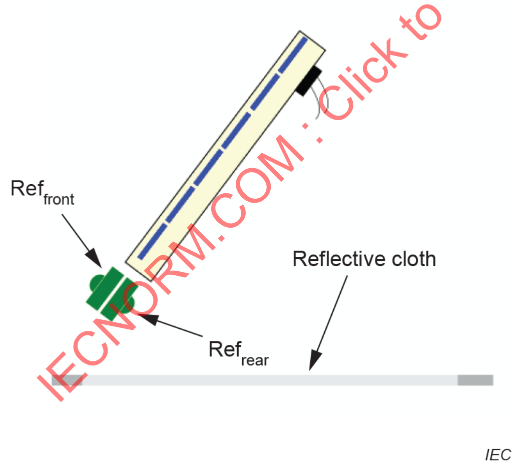
Besides $BiFi$, two specific P_{max} values shall be reported, $P_{\mathrm{maxBiFi100}}$ and $P_{\mathrm{maxBiFi200}}$, for $G_{r_1} = 100\ \mathrm{Wm}^{-2}$ and $G_{r_2} = 200\ \mathrm{Wm}^{-2}$ respectively. $P_{\mathrm{maxBiFi100}}$ and $P_{\mathrm{maxBiFi200}}$ shall be obtained by linear interpolation of the data series P_{max} versus G_{r} according to formulae (4) and (5).

$$P_{\mathrm{maxBiFi100}} = P_{\mathrm{maxSTC}} + BiFi \cdot 100 \quad (4)$$

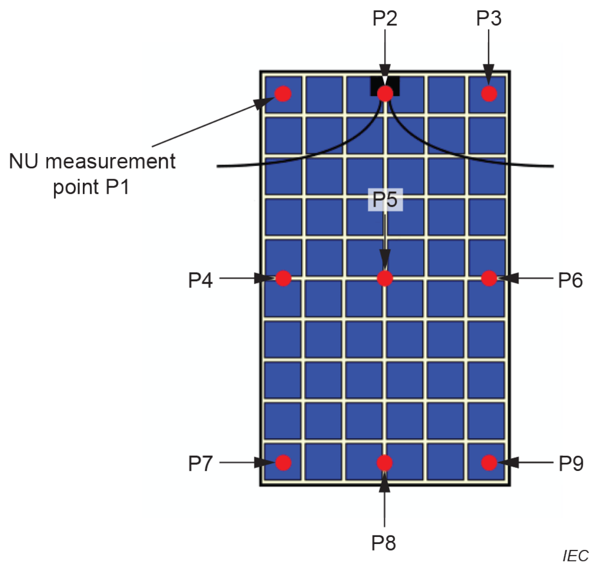
$$P_{\mathrm{maxBiFi200}} = P_{\mathrm{maxSTC}} + BiFi \cdot 200 \quad (5)$$

6.3.2 Outdoor rear irradiance driven power gain yield measurement

In order to perform outdoor measurement of the rear irradiance driven power gain yield, the non-uniformity of irradiance on the rear side shall be below 10 %. In order to measure the non-uniformity of irradiance on the rear side, besides the reference device used for the irradiance measurement on the rear side, another reference device shall be used to measure the non-uniformity of irradiance on the rear side on at least 5 points, before and after the *I-V* characterization. Choose at least 5 points as shown in Figure 3b), with symmetrical distribution, for instance, P1-P3-P5-P7-P9, P2-P4-P5-P6-P8 or P1-P2-P3-P7-P8-P9. Figure 3a) shows a schematic representation of an outdoor measurement setup. Multiple reference devices can also be used for non-uniformity measurement. The measurements should be corrected for the mean value of the irradiance on the backside. The reference devices are described in IEC 60904-2.



a) Two reference devices, as described in IEC 60904-2, are used to measure the irradiance on the front and the rear sides of the device under test during outdoor measurements



b) Proposed points to measure the non-uniformity (NU) of irradiance outdoor

The manufacturer's recommendations about the handling of the cables, when available, shall be applied.

Figure 3 – Outdoor measurement

In order to improve the uniformity of irradiance on the rear side, it is recommended to elevate the device under test to higher positions, e.g. to a distance of 0,5 m to 1,0 m between the bottom edge of the device and the ground. A matt, reflective cloth can also be used to increase the reflection uniformity of the surface behind the device.

6.3.3 Indoor rear irradiance driven power gain yield measurement with single-side illumination

In order to perform indoor measurement of the rear irradiance driven power gain yield, a solar simulator with adjustable irradiance levels for single-side illumination, as described in 5.2 can be used. To this end, a non-irradiated background is required as described in 5.5.

The equivalent irradiance levels are determined as functions of the bifaciality coefficient φ according to formulae (6) and (7):

$$G_{\mathrm{E_i}} = 1\,000\,Wm^{-2} + \varphi \cdot G_{\mathrm{r_i}} \tag{6}$$

$$\varphi = Min(\varphi_{\mathrm{Isc}}, \varphi_{\mathrm{Pmax}}) \tag{7}$$

where φ is the minimum value between the I_{sc} and the P_{max} bifaciality coefficients φ_{Isc} and φ_{Pmax}.

Example: A device with bifaciality of $\varphi = 80\,\%$, shall be irradiated, on the front side at $G_{\mathrm{E_2}} = 1\,160\ \mathrm{Wm^{-2}}$ to provide the equivalence of $G_{\mathrm{r_2}} = 200\ \mathrm{Wm^{-2}}$.

The same approach may be applied to assess the low-light behaviour of bifacial PV devices, e.g. for a measurement at $200\ \mathrm{Wm^{-2}}$ on the front side of a device with 80 % of bifaciality, $P_{\mathrm{maxBiFi200\text{-}LIC}}$ shall be measured at $G_{\mathrm{r-LIC}} = 40\ \mathrm{Wm^{-2}}$ or $G_{\mathrm{E-LIC}} = 232\ \mathrm{Wm^{-2}}$ where the subscript LIC refers to Low Irradiance Characteristics.

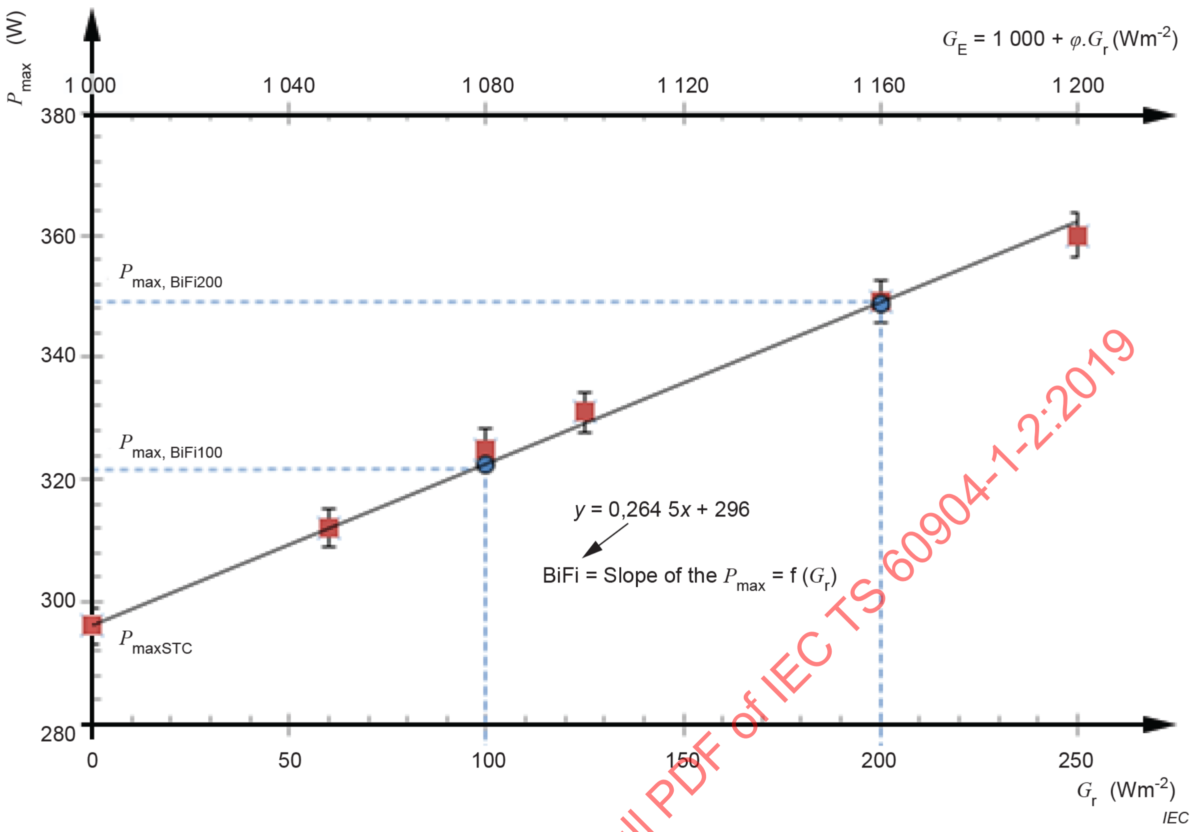


Figure 4 – Examples of P_{max} as a function of irradiance level on the rear side G_r (for outdoor or double-side illumination) or its 1-side equivalent irradiance G_f for a device of bifaciality φ = 80 %

Table 1 – Maximum peak power, P_{max}, measured at different rear irradiances, G_r, (double-side with G_f = 1 000) or alternatively equivalent front irradiances, G_E, and the rear irradiance driven power gain yield, *BiFi*, derived from the slope of the linear fit on $P_{max}(G_r)$. Also calculated values $P_{max,BiFi100}$ and $P_{max,BiFi200}$.

φ	G_r Wm^{-2}	G_f Wm^{-2}	P_{max} W	$P_{max,BiFi}$ W	*BiFi* W/(Wm^{-2})
80 %	0	1 000	296		0,2645
	60	1 048	312		
	100	1 080	325	322,45	
	125	1 100	331		
	200	1 160	349	348,9	
	250	1 200	360		

6.3.4 Indoor rear irradiance driven power gain yield measurement with double-side illumination

Double-side illumination, as described in 5.3, can alternatively be applied to determine the rear irradiance driven power gain yield.

Reflections between the two light sources may add irradiance non-uniformity. This may generate significant offsets between single-side and double-side measurement methods results. In this case, double-side illumination results shall be corrected. Using black masking around the module is recommended to avoid unwanted reflections in double-side measurements.

7 I-V characterisation of bifacial PV devices in practice

7.1 General

Two cases are to be considered for the I-V characteristics measurement of bifacial devices. In the first case, the bifaciality coefficients of the test specimen are not known. This is usually the case for newly developed or modified devices and PV test and calibration laboratories perform the measurements. The second case corresponds usually to PV production environments, where reference devices of the same technology as the devices to be tested are available.

The determination of the bifaciality coefficients and the measurement of the rear irradiance driven power gain yield of the reference devices are to be performed in PV laboratories whereas these characteristics are used to assess the PV production output. The main differences are described below.

7.2 I-V measurement of reference bifacial PV devices

In order to assess reference bifacial devices, in addition to the measurements described in IEC 60904-1 and the requirements of IEC 60904-2 and IEC 60904-4, the bifaciality coefficients and the rear irradiance driven power gain yield shall be determined according to the procedures described in this document.

Determination of the following parameters is required:

– Spectral responsivity (or Quantum Efficiency) of the front side, measured according to IEC 60904-8.

– Spectral responsivity (or Quantum Efficiency) of the rear side, measured according to IEC 60904-8.

– I_{sc}, V_{oc} and P_{max} as functions of irradiance level on the rear side G_r or its 1-side equivalent irradiance G_E, e.g. $0 \leq G_{r1} < 100\ \text{Wm}^{-2}$, $100\ \text{Wm}^{-2} \leq G_{r2} < 200\ \text{Wm}^{-2}$ and $200\ \text{Wm}^{-2} \leq G_{r3}$.

When measuring the spectral responsivities, care shall be taken to minimize the contribution of the non-exposed side, particularly when bare cells are assessed.

Determination of the following parameters is highly recommended but is not obligatory:

– Transmittances of the Device Under Test, T_{DUT}, and the one of its encapsulant, T_{Enc}, as a function of wavelength according to IEC 62788-1-4 (see Figure 5).

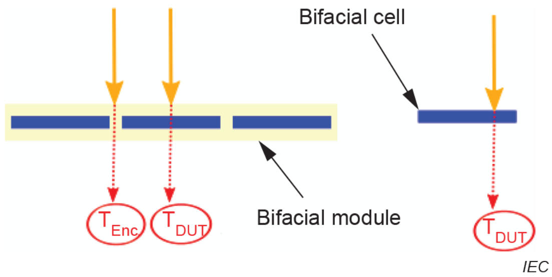


Figure 5 – Transmittances of the device (T_{DUT}) and its encapsulant (T_{ENC})