19ENG01 Metro-PV

Metrology for emerging PV applications

**Deliverable D5a**

# Guidelines for PV module measurement uncertainty associated with IEC test procedures

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# Content



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# 1 Introduction

This technical report is a part of the joint research project 19ENG01 “Metrology for emerging PV applications” (Metro-PV) and has been developed under Work Package 2 “Determining the measurement uncertainties associated with IEC test procedures”. The content of this document is also available within wiki.pvmet.org as a living document and in the Open Access Repository oar.ptb.de of PTB.

The aim of this work was to gather existing knowledge on laboratory practices for uncertainty calculation associated with output power characterization and energy rating of PV modules.

This deliverable presents guidelines for calculating the measurement uncertainties related to the following IEC standards:

| | |
|---|---|
| IEC 60891: (2021) | Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics |
| IEC 60904-1: (2020) | Photovoltaic devices - Part 1: Measurement of photovoltaic current-voltage characteristics |
| IEC 61853-1: (2011) | Photovoltaic (PV) module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating |
| IEC 61853-2: (2016) | Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral responsivity, incidence angle and module operating temperature measurements |
| IEC 61853-3: (2018) | Photovoltaic (PV) module performance testing and energy rating - Part 3: Energy rating of PV modules |

**Table 1:** IEC standards for PV module performance measurements

# 2 Principles for PV measurement uncertainty assessment according to JCGM 100:2008

## 2.1 General

General principles for measurement uncertainty assessment are defined in the guidance document JCGM 100:2008 “Evaluation of measurement – Guide to the expression of uncertainty in measurement (GUM)” [1], which was prepared by the Joint Committee for Guides in Metrology (JCGM).

If a measurement variable $X$ has $X_i$ independent uncertainty sources, the **combined standard uncertainty $u_C$** is given by the formula

$$u_C = \sqrt{\sum_i (u_i)^2} \qquad (1)$$

where parameters $u_i$ are the standard uncertainties of uncertainty sources $X_i$, which are always related to 68% confidence level. This consideration allows to conclude that the true value of variable $X$ lies with 68% probability in the confidence interval

$$[measured\ value - u_C, measured\ value + u_C] \qquad (2)$$

For industrial applications, however, a higher confidence level of 95% is commonly used. This transition is accomplished by multiplication of $u_C$ with the coverage factor $k$ = 2. This results in the expanded combined measurement uncertainty

$$U = k \cdot u_C \qquad (3)$$

where $U$ is the Expanded measurement uncertainty, $u_C$ is the Combined standard uncertainty, and $k$ is the Coverage factor, $k$ = 2 for 95% confidence level.

Note: standard uncertainties ($k$ = 1) will be denoted by the (small) "$u$", whereas expanded uncertainties (normally $k$ = 2, but not necessarily) will be denoted by (large) "$U$".

## 2.2 Types of uncertainty sources

For a measurement variable *X*, two types of uncertainty sources can be distinguished:

Type A uncertainties $u_A$

These are determined by statistical analysis or a series of observations. The standard uncertainty $u_i$ of the uncertainty component $X_i$ is given by the standard uncertainty of the mean value.

Examples for type A uncertainties are:

- Reproducibility of I-V measurements, which have been taken at different test conditions (i.e. successive days) and with electrically disconnecting and removal of the PV module from the test area of the solar simulator.
- Repeatability of I-V measurements, which have been successively taken under the same test conditions without electrically disconnecting and removal of the PV module from the test area of the solar simulator.

Note 1: The standard uncertainties for type A uncertainties are normally determined from the standard deviation of a set of measurements. The standard deviation determined from small sample sizes (in practise everything below 30 samples) should be modified to a realistic value.

Note 2: If a single measurement is performed the (expected) standard deviation (determined from a separate set of measurements) should be used as standard uncertainty.

Note 3: If several measurements are made, the (arithmetic) average of these measurements should be reported as the measurement result. The uncertainty associated with this arithmetic average is either

a) in case the standard deviation has been determined from a separate set of measurements, the standard deviation divided by the square root of the number of measurements or
b) in case the standard deviation is determined/estimated from the same set of measurements that is used to calculate the arithmetic average, that standard deviation divided by the square root of the number of measurements minus 1.

Type B uncertainties $u_B$

These are based on estimations or assumptions according to the experience or best practice of the test laboratory. They may also include manufacturer specifications or calibration results of measurement equipment, such as reference cells (RC). In combination with type $u_B$ uncertainty, a probability shape must be considered to calculate the standard uncertainty $u_i$

- For a Gaussian distribution, the standard uncertainty $u_i$ is the provided or estimated expanded uncertainty $U_B$ divided by 2

  Note: Care should be taken that the Xi uncertainty is related to the expanded (combined) uncertainty ($k$ = 2).

- For rectangular shape, where all values in a Min-Max interval have (or are assumed to have) the same probability, the standard uncertainty $u_i$ is the provided or estimated uncertainty $u_B$ divided by $\sqrt{3}$

## 2.3 Spreadsheet for calculation of expanded measurement uncertainty

With this background, the working steps of measurement uncertainty analysis can be summarized as follows: a) Identification of uncertainty sources $u_A$ or $u_B$, b) calculation of standard uncertainties $u_i$ with consideration of probability shapes, c) calculation of the combined standard uncertainty $u_C$ and expanded uncertainty $U$.

The document JCGM 100:2008 provides a standardized calculation sheet for expanded measurement uncertainty, which is shown in Table 1.

The sheet also contains so-called sensitivity factors $c_i$, which are unity if all uncertainty contributions $u_i$ are expressed in the same units. Conversion of uncertainty contributions into other units will require the calculation of specific sensitivity factors, which can be a complex task.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Expanded Measurement Uncertainty** | | | | | | | | |
| (Version 1.0) | | | | | | | | |
| **Measurement variable name:** | | | | | | | | |
| **Xi uncertainty unit:** | | | | | | | | |
| **Expanded uncertainty:** | 0,00 | | | | | | | |
| | Type A: Statistical analysis of a series of observations | | | G = Gaussian | | | | |
| | Type B: Estimations or assumptions (best practice) | | | R = Rectangular | | | | |
| **Source of Uncertainty Xi** | **Type (Enter A or B)** | **Xi Uncertainty** | **Unit** | **Probability Shape (Enter G or R)** | **Division Factor** | **Standard Uncertainty u (Xi)** | **Sensitivity Coefficient Ci** | **Uncertainty Contribution ui** |
| | | | | | | | | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | 1 | |
| | | | | | | | | |
| | | | | **Combined standard uncertainty, $u_c$ =** $\sqrt{\sum_i (u_i)^2}$ | | | | 0,000 |
| | | | | **Coverage factor k (level of confidence = 95%)** | | | | 2 |
| | | | | **Expanded uncertainty U = $u_c$ * k** | | | | **0,00** |

***Table 2:*** *Standardized calculation table for expanded measurement uncertainty according to JCGM 100:2008 [1]*

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# 3 Uncertainly analysis for measurement of PV module I-V characteristic in accordance with IEC 60904-1

In view of PV module output power characterization in accordance with IEC 60904-1 [2], the uncertainty analysis is typically performed for the following variables, resulting from I-V curve measurement:

- Short circuit current ($I_{sc}$)
- Open circuit voltage ($V_{oc}$)
- Maximum output power ($P_{max}$)
- Fill factor (FF)

For each variable the calculation tables for expanded measurement uncertainty need to be developed independently.

It must be noted that out of the four variables, only three are independent. Therefore, depending on the order of determination, the uncertainty of the fourth variable has to be determined considering the correlation between the other three. For example, if FF uncertainty is to be determined based on equation

$$\mathrm{FF} = \frac{P_{MAX}}{I_{sc} \cdot V_{OC}}$$

there will be considerable correlation between the uncertainties of the three other variables. For FF parameter, care must be taken that a double count of uncertainty contributions is excluded.

Figure 1 shows how major uncertainty sources affect the shape of the PV module I-V curve. The I-V curve measurement depends on the ambient test conditions, which are given by the PV module temperature and the irradiance setting of the solar simulator. The uncertainty analysis of these test conditions is performed separately and the resulting expanded combined uncertainties are used as input for further uncertainty calculation of parameters $P_{max}$, $I_{sc}$ and $V_{oc}$.

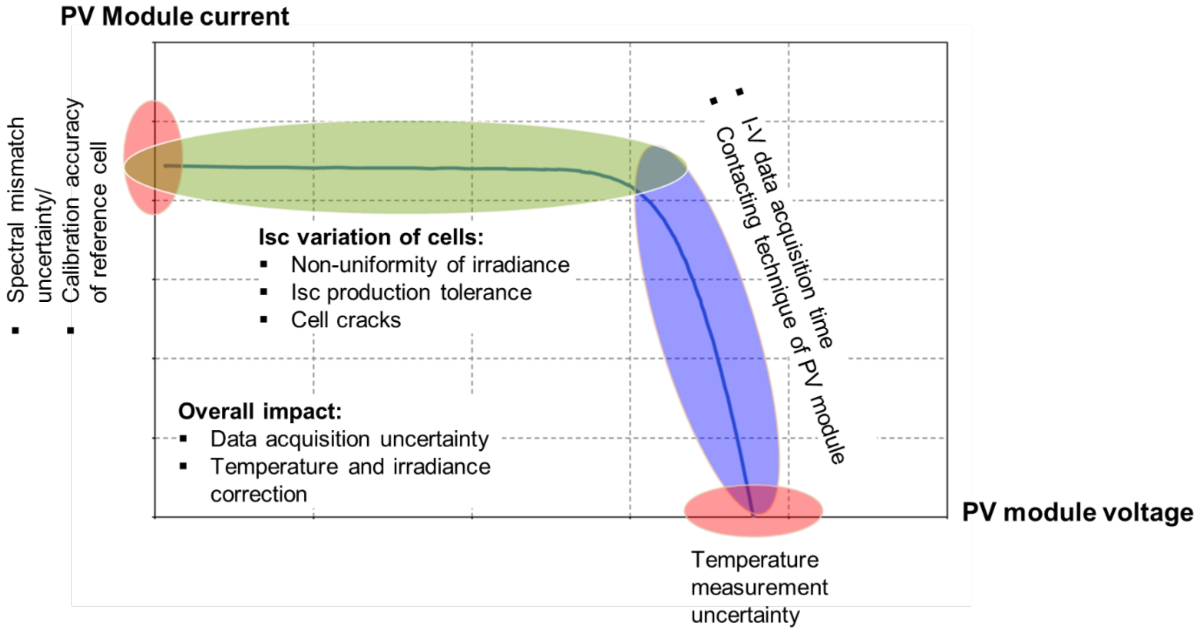


***Figure 1:** Impact of uncertainty sources on I-V measurement of PV modules*

## 3.1 Uncertainty related to irradiance measurement

| Source of Uncertainty Xi | Type (Enter A or B) | Xi Uncertainty | Unit | Probability Shape (Enter G or R) | Division Factor | Standard Uncertainty u (Xi) | Sensitivity Coefficient Ci | Uncertainty Contribution ui | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| Calibration accuracy of reference cell (REF) | B | 0.50 | % | G | 2.000 | 0.250 | 1 | 0.250 | 1) |
| Uncertainty related to drift of calibration covering last 3 periods | B | 0.20 | % | R | 1.732 | 0.115 | 1 | 0.115 | 2) |
| Uncertainty related to REF shunt resistor UC | B | 0.10 | % | G | 2.000 | 0.050 | 1 | 0.050 | 3) |
| Uncertainty related to REF zero offset | B | 0.10 | % | R | 1.732 | 0.058 | 1 | 0.058 | 4) |
| Uncertainty related to REF transimpedance amplifier | B | | % | G | 2.000 | | 1 | | 5) |
| Uncertainty related to REF temperature uncertainty | B | 0.01 | % | R | 1.732 | 0.006 | 1 | 0.006 | 6) |
| Uncertainty related to DAQ voltage measurement | B | 0.20 | % | G | 2.000 | 0.100 | 1 | 0.100 | 7) |
| | | | | | | | | 0.303 | |
| Uncertainty related to spectral mismatch (REF - DUT) | B | 0.50 | % | R | 1.732 | 0.289 | 1 | 0.289 | 8) |
| Uncertainty related to spectral mismatch uncertainty | B | 0.00 | % | R | 1.732 | 0.000 | 1 | 0.000 | 9) |
| Uncertainty related to temporal instability of irradiance | B | 0.00 | % | R | 1.732 | 0.000 | 1 | 0.000 | 10) |
| Uncertainty related to misalignment (REF - DUT) | B | 0.10 | % | R | 1.732 | 0.058 | 1 | 0.058 | 11) |
| Uncertainty related to angular mismatch (REF - DUT) | B | 0.10 | % | R | 1.732 | 0.058 | 1 | 0.058 | 12) |
| Uncertainty related to (REF - DUT) difference in distance to lamp | B | 0.10 | % | R | 1.732 | 0.058 | 1 | 0.058 | 13) |
| Uncertainty related to RC positioning | B | 0.20 | % | R | 1.732 | 0.115 | 1 | 0.115 | 14) |
| | | | | | | | | 0.327 | |
| | | | | Combined standard uncertainty, $u_c = \sqrt{\sum_i (u_i)^2}$ | | | | 0.445 | |
| | | | | Coverage factor k (level of confidence = 95%) | | | | 2 | |
| | | | | Expanded uncertainty $U = u_c * k$ | | | | 0.89 | |

**Table 3:** Calculation spreadsheet for irradiance measurement uncertainty

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Table 3 shows the listing of uncertainty sources for irradiance setting of a solar simulator, which is typically used for calibration or performance measurement of PV modules.

The values given in the yellow fields for uncertainty sources are example data. It is the task of the test laboratory to calculate values from measurement series or from the test geometry. Also estimates for best practice can be used. The review of the uncertainty analysis by technical auditors is part of laboratory accreditation in accordance with ISO/IEC 17025.

Remarks:

| | |
|---|---|
| 1) | Refer to calibration report of accredited test institute |
| 2) | Historical data of reference cell calibration |
| 3) | Refer to data sheet, no entry if transimpedance amplifier is used |
| 4) | Current impact from voltage drop caused by shunt resistor, refer to I-V curve of reference cell, no entry if transimpedance amplifier is used |
| 5) | Refer to data sheet of instrument, no entry if shunt resistor is used |
| 6) | Refer to reference cell data sheet . The temperature accuracy of sensor depends on the sensor type (i.e. Pt100 or thermocouple) and the temperature set value (i.e. 15°C to 75°C). The ). The “Uncertainty related to REF temperature uncertainty” is given by (temperature accuracy of the sensor) x (temperature coefficient of cell). |
| 7) | Manufacturers' data sheet and verification by annual calibration |
| 8) | Best practice: a) use estimate acc. to lab experience for REF - DUT combinations and irradiance levels, b) set zero if SMM correction is performed. |
| 9) | Best practice: a) Set zero if UC related to SMM is estimated, b) use lab experience if SMM correction is performed<br><br>Note: Care should be taken that the entry in lines 8) or 9) are connected. One of the cells is zero and the other has a value |
| 10) | Only applicable for non-simultaneous measurement of irradiance (REF), DUT current and DUT voltage |
| 11) | Text experience and best practice of laboratory |
| 12) | Depends on view angles of REF and DUT related to the optical axis. Impact increases with rising diffuse irradiance in the test area. |
| 13) | Glass thickness or frame design may lead to a shift of the cell to lamp distance. Uncertainty to be calculated according to quadratic distance law. |
| 14) | Irradiance at RC position must correspond to average irradiance in the module area. Uncertainty contribution to this non-uniformity can be reduced if non-uniformity correction is applied. The residual uncertainty is then the reproducability of the non-uniformity i.e. the uncertainty of the non-uniformity correction factor. |

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## 3.2 Uncertainty related to temperature measurement

| Source of Uncertainty Xi | Type (Enter A or B) | Xi Uncertainty | Unit | Probability Shape (Enter G or R) | Division Factor | Standard Uncertainty u (Xi) | Sensitivity Coefficient Ci | Uncertainty Contribution ui | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| Accuracy of surface temperature sensor | B | | degC | G | 2,000 | | 1 | | 1) |
| Device temperature | 25 | | degC | | | | 1 | | 2) |
| Uncertainty related to DAQ temperature measurement | | | degC | R | 1,732 | | 1 | | 3) |
| Uncertainty related to thermal contact of sensor to PV module | | | degC | R | 1,732 | | 1 | | 4) |
| | | | | | | | | | |
| Accuracy of IR sensing head including electronics | B | 1 | degC | G | 2,000 | 0,500 | 1 | 0,500 | 5) |
| | | | | | | | | | |
| Temperature non-uniformity in the PV module area | B | 1,00 | degC | R | 1,732 | 0,577 | 1 | 0,577 | 6) |
| Temperature difference between junction and PV module rear | B | 0,50 | degC | R | 1,732 | 0,289 | 1 | 0,289 | 7) |
| Temperature drift during a measurement series (i.e. G-T matrix) | B | 0,50 | degC | R | 1,732 | 0,289 | 1 | 0,289 | 8) |
| | | | | | | | | | |
| | | | | Combined standard uncertainty, $u_c$ = | | | $\sqrt{\sum_i (u_i)^2}$ | 0,866 | |
| | | | | Coverage factor k (level of confidence = 95%) | | | | 2 | |
| | | | | Expanded uncertainty U = $u_c$ * k | | | | 1,73 | |

**Table 4:** Calculation spreadsheet for PV module temperature measurement uncertainty

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Table 4 shows the listing of uncertainty sources for measurement of PV module operating temperature. The values given in the yellow fields for uncertainty sources are example data. It is the task of the test laboratory to calculate values from measurement series or to give estimates based on best practice. The review of the uncertainty analysis by technical auditors is part of laboratory accreditation in accordance with ISO/IEC 17025.

Remarks:

| | |
|---|---|
| 1) | • No entry if IR sensor is used<br>• Pt100 class A: 0.15°C+0.002*$T_{mod}$<br>• Pt100 class B: 0.3°C+0.005*$T_{mod}$ |
| 2) | Reference temperature for calculation of sensor uncertainty |
| 3) | No entry if IR sensor is used, refer to DAQ data sheet |
| 4) | No entry if IR sensor is used, best practice of test laboratory |
| 5) | No entry if surface temperature sensor is used, refer to sensor/instrument data sheet |
| 6) | Estimate according to test experience of laboratory |
| 7) | Estimate according to test experience of laboratory |
| 8) | Estimate according to test experience of laboratory |

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## 3.3 Uncertainty analysis for maximum output power ($P_{MAX}$)

| Source of Uncertainty Xi | | Type (Enter A or B) | Xi Uncertainty | Unit | Probability Shape (Enter G or R) | Division Factor | Standard Uncertainty u (Xi) | Sensitivity Coefficient Ci | Uncertainty Contribution ui | |
|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty related to irradiance setting | | A | 0,92 | % | G | 2,000 | 0,460 | 1 | 0,460 | 1) |
| Uncertainty related to temperature measurement | | A | 0,78 | % | G | 2,000 | 0,389 | 1 | 0,389 | |
| Temperature uncertainty [K] | 1,73 | | | | | | | | | 2) |
| Temperature coefficient Pmax @1000 W/m² [%/K] | 0,45 | | | | | | | | | 3) |
| Uncertainty related to data acquisition (DAQ) | | B | 0,28 | % | G | 2,000 | 0,141 | 1 | 0,141 | |
| Voltage measurement [%] | 0,2 | | | | | | | | | 4) |
| Current measurementm [%] | 0,2 | | | | | | | | | 5) |
| Uncertainty related to I-V repeatability | | A | 0,10 | % | G | 2,000 | 0,050 | 1 | 0,050 | 6) |
| Uncertainty related to I-V reproducibility | | A | 0,50 | % | G | 2,000 | 0,250 | 1 | 0,250 | 7) |
| Uncertainty related to Pmax determination on I-V curve | | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 8) |
| Uncertainty related to I-V correction | | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 9) |
| Uncertainty related to hysteresis effects | | B | 0,50 | % | R | 1,732 | 0,289 | 1 | 0,289 | 10) |
| Uncertainty related to irradiance non-uniformity in the module area | | B | 0,20 | % | R | 1,732 | 0,115 | 1 | 0,115 | 11) |
| Uncertainty related to incomplete electrical stabilization | | B | 0,50 | % | R | 1,732 | 0,289 | 1 | 0,289 | 12) |
| | | | | | | | | | | |
| | | | | | Combined standard uncertainty, $u_c = \sqrt{\sum_i (u_i)^2}$ | | | | 0,797 | |
| | | | | | Coverage factor k (level of confidence = 95%) | | | | 2 | |
| | | | | | Expanded uncertainty $U = u_c * k$ | | | | 1,59 | |

**Table 5:** Calculation spreadsheet for PV module for maximum output power (PMAX)uncertainty

Table 5 shows the listing of uncertainty sources for maximum output power determination of a PV module with single junction solar cells. The values given in the yellow fields for uncertainty sources are example data. It is the task of the test laboratory to calculate values from measurement series or to give estimates based on best practice. The review of the uncertainty analysis by technical auditors is part of laboratory accreditation in accordance with ISO/IEC 17025.

Remarks:

| | |
|---|---|
| 1) | Value transferred from spreadsheet “irradiance measurement uncertainty” |
| 2) | Value transferred from spreadsheet “temperature measurement uncertainty” |
| 3) | Refer to lab measurement or PV module data sheet |
| 4) | Refer to manufacturers' data sheet and verification by annual calibration |
| 5) | Refer to data sheet, verification by annual calibration |
| 6) | Xi shall be determined from a minimum 10 successive I-V measurements under the same test conditions (either forward or reverse voltage sweeps) and without electrical disconnection |
| 7) | Xi shall be determined from the spread of a time-series of $P_{max}$ measurements of a reference PV module, covering the ranges of ambient conditions in the lab and instrumentation practices from operators that are qualified for this measurement |
| 8) | Xi is the difference between the reported $P_{max}$ value by the I-V data acquisition system and the Pmax value resulting from quadratic regression of I-V data points around the maximum power point. This uncertainty source is relevant for a low resolution of I-V data points. |
| 9) | Refer to lab test experience based on error propagation studies for an assumed spread of PV module I-V correction parameters (see section 4) |
| 10) | Lab experience: Analysis of I-V curves recorded for forward and reverse voltage sweeps as a function of I-V data acquisition time, b) Estimate provided by the developer of the test method to compensate transient effects |
| 11) | Refer to lab test experience |
| 12) | Depending on the PV technology |

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## 4 Uncertainly analysis for temperature and irradiance correction of measured I-V characteristics in accordance with IEC 60891

The standard IEC 60891 [3] offers 4 different procedures for temperature and irradiance correction of measured *I-V* characteristics. Most commonly, the two algebraic correction procedures (procedures 1 and 2) are used in test laboratories. The determination of the PV module specific $I$-$V$ correction parameters is described in sections 5, 6 and 7 of the standard IEC 60891.

For algebraic procedures, the translation equations for current and voltage are expressed as a function of a set of *I-V* correction parameters, the PV module temperature (*T*) and the in-plane irradiance (*G*). The translation equations of an *I-V* data point are expressed as a function of the test conditions (index 1), the target conditions (index 2) and the PV module *I-V* correction parameters.

$$I_2 = f(T_1, G_1, T_2, G_2, \text{IV correction parameters})$$
$$V_2 = f(T_1, G_1, T_2, G_2, \text{IV correction parameters}, I_2)$$

The mean square error of a corrected *I-V* data point ($I_2$,$V_2$) on the current-voltage characteristic can be calculated according to the error propagation law on the mean errors of the directly measured quantities $\Delta I_1$, $\Delta V_1$, $\Delta T_1$, $\Delta G_1$and the uncertainties of the module specific *I-V* correction parameters.

$$\Delta I_2(T_1, G_1, \cdots) = \pm\sqrt{\left(\frac{\partial I_2}{\partial T_1}\Delta T_1\right)^2 + \left(\frac{\partial I_2}{\partial G}\Delta G_1\right)^2 + \cdots}$$

$$\Delta V_2(T_1, G_1, \cdots) = \pm\sqrt{\left(\frac{\partial V_2}{\partial T_1}\Delta T_1\right)^2 + \left(\frac{\partial V_2}{\partial G}\Delta G\right)^2 + \cdots}$$

The relative translation errors are given by $\Delta I_2/I_2$ and $\Delta V_2/V_2$.

With this information the relative error of translated maximum output power $P_{MAX} = I_{MP} \cdot V_{MP}$ is

$$\frac{\Delta P_{MAX}}{P_{MAX}} = \pm\sqrt{\left(\frac{\Delta I_{MP}}{I_{MP}}\right)^2 + \left(\frac{\Delta V_{MP}}{V_{MP}}\right)^2}$$

**Correction procedure 1**

$$I_2 = I_1 + I_{SC1} \times \left(\frac{G_2}{G_1} - 1\right) + \alpha \times (T_2 - T_1) \quad (1)$$

$$V_2 = V_1 - R_S \times (I_2 - I_1) - \kappa \times I_2 \times (T_2 - T_1) + \beta \times (T_2 - T_1) \quad (2)$$

where:

- $I_1$, $V_1$, $T_1$ and $G_1$ are the measured current, voltage, module temperature and irradiance, respectively;
- $I_2$ and $V_2$ are the corresponding pair of current and voltage values of the to target conditions corrected *I-V* curve;
- $T_2$ and $G_2$ are the target module temperature and irradiance respectively;
- $I_{SC1}$ is the measured short-circuit current that may result from interpolation or extrapolation of I-V data points in the short-circuit range;
- $R_S$ is the internal series resistance;

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- $\alpha$ and $\beta$ are respectively the absolute short-circuit current and open-circuit voltage temperature coefficients at the target irradiance for correction;
- $\kappa$ is the curve correction factor.

The uncertainty of *I-V* translation is composed of the partial derivatives, which are listed in Table 6.

| **Uncertainty contributions** | **Translation uncertainty $\Delta I_2$** | **Translation uncertainty $\Delta V_2$** | **Remarks** |
|---|---|---|---|
| Irradiance measurement | $\frac{\partial I_2}{\partial G_1}\Delta G_1$ | $\frac{\partial V_2}{\partial G_1}\Delta G_1$ | $\Delta G_1$ is the measurement uncertainty resulting from section 3.1 |
| Temperature measurement | $\frac{\partial I_2}{\partial T_1}\Delta T_1$ | $\frac{\partial V_2}{\partial T_1}\Delta T_1$ | $\Delta T_1$ is the measurement uncertainty resulting from section 3.2 |
| $I_{sc}$ temperature coefficient | $\frac{\partial I_2}{\partial \alpha}\Delta \alpha$ | | The uncertainty of $\alpha$ is highly dependent on the spectral irradiance of the light source, with which $\alpha$ has been measured. A reasonable estimate is $\Delta\alpha = 0.5 \cdot \alpha$ |
| Current measurement | $\frac{\partial I_2}{\partial I_1}\Delta I_1$ | | $\Delta I_1$ is the measurement uncertainty of short circuit current, which considers all uncertainties except uncertainty related to G1 (data acquisition, potential interpolation or extrapolation, etc.) |
| $V_{oc}$ temperature coefficient | | $\frac{\partial V_2}{\partial \beta}\Delta \beta$ | A reasonable estimate is $\Delta\beta = 0.1 \cdot \beta$ |
| Translated current | | $\frac{\partial V_2}{\partial I_2}\Delta I_2$ | $\Delta I_2$to be calculated first |
| Internal series resistance | | $\frac{\partial V_2}{\partial R_S}\Delta R_S$ | A reasonable estimate is $\Delta R_S = 0.5\ m\Omega \cdot N_S/N_P$<br>Where<br>$N_S$ : No. of serially connected cells<br>$N_P$: No. of parallel connected cell strings |
| Curve correction factor | | $\frac{\partial V_2}{\partial \kappa}\Delta \kappa$ | A reasonable estimate is $\Delta\kappa = 0.5 \cdot \kappa$ |

**Table 6:** Calculation of IEC 60891 *I-V* translation uncertainty (procedure 1)

Note:

The translated short circuit current and open circuit voltage do not directly result from the translation formulas. Both must be interpolated or extrapolated from the translated I-V curve. Corresponding uncertainties must be additionally considered in $\Delta I_{SC,2}$ and $\Delta V_{OC,2}$.

### Correction procedure 2

The equations are as follows:

$$I_2 = \frac{G_2}{G_1} \times I_1 \times \frac{\left(1 + a_{\text{rel}} \times (T_2 - 25\ °C)\right)}{\left(1 + a_{\text{rel}} \times (T_1 - 25\ °C)\right)} \quad (13)$$

$$\begin{aligned} V_2 = V_1 - R'_{S1} \times (I_2 - I_1) \\ - \kappa' \times I_2 \times (T_2 - T_1) + V_{\text{OC,STC}} \\ \times \left\{\beta_{\text{rel}} \times [f(G_2) \times (T_2 - 25\ °C) - f(G_1) \times (T_1 - 25\ °C)] + \frac{1}{f(G_2)} \right. \\ \left. - \frac{1}{f(G_1)}\right\} \end{aligned} \quad (2)$$

$$R'_{S1} = R'_S + \kappa' \times (T_1 - 25\ °C) \quad (3)$$

$$V_{OC,STC} = \frac{V_{OC1} \times f(G_1)}{1 + \beta_{rel} \times (T_1 - 25\ °C) \times f^2(G_1)} \quad (4)$$

$$f(G) = \frac{V_{OC,STC}}{V_{OC}(G)} = B_2 \times ln^2\left(\frac{1\,000\ W/m^2}{G}\right) + B_1 \times ln\left(\frac{1\,000\ W/m^2}{G}\right) + 1 \quad (5)$$

where:

- $V_{OC,STC}$ is the open-circuit voltage at STC. It can be calculated from Eq.(*4*);
- $\alpha_{rel}$ is the relative short-circuit temperature coefficient;
- $\beta_{rel}$ is the relative open-circuit voltage temperature coefficient;
- $R'_S$ is the internal series resistance determined at 25 °C;
- $R'_{S1}$ is the internal series resistance at measured temperature $T_1$, it can be calculated from Eq.(3);
- $\kappa'$ is the temperature coefficient of the internal series resistance $R'_S$;
- $B_1$ is the irradiance linear correction factor for $V_{OC}$ that is related to the diode thermal voltage of the *p-n* junction and the number of cells $N_S$ serially connected in the DUT;
- $B_2$ is the irradiance correction factor for $V_{OC}$, which accounts for non-linearity of $V_{OC}$ with irradiance.

The uncertainty of $I$-$V$ translation is composed of the partial derivatives which are listed in Table 7.

| **Uncertainty contributions** | **Translation uncertainty** $\Delta I_2$ | **Translation uncertainty** $\Delta V_2$ | **Translation uncertainty** $\Delta V_{OC,2}$ | **Remarks** |
|---|---|---|---|---|
| Irradiance measurement | $\frac{\partial I_2}{\partial G_1}\Delta G_1$ | $\frac{\partial V_2}{\partial G_1}\Delta G_1$ | $\frac{\partial V_2}{\partial G_1}\Delta G_1$ | $\Delta G_1$ is the measurement uncertainty resulting from section 3.1 |
| Temperature measurement | $\frac{\partial I_2}{\partial T_1}\Delta T_1$ | $\frac{\partial V_2}{\partial T_1}\Delta T_1$ | $\frac{\partial V_2}{\partial T_1}\Delta T_1$ | $\Delta T_1$ is the measurement uncertainty resulting from section 3.2 |
| Isc temperature coefficient | $\frac{\partial I_2}{\partial \alpha}\Delta \alpha_{rel}$ | | | The uncertainty of $\alpha$ is highly dependent on the spectral irradiance of the light source, with which α has been measured. A reasonable estimate is $\Delta\alpha_{rel} = 0.5 \cdot \alpha_{rel}$ |
| Voc temperature coefficient | | $\frac{\partial V_2}{\partial \beta}\Delta \beta_{rel}$ | $\frac{\partial V_2}{\partial \beta}\Delta \beta_{rel}$ | A reasonable estimate is $\Delta\beta_{rel} = 0.1 \cdot \beta_{rel}$ |
| Translated current | | $\frac{\partial V_2}{\partial I_2}\Delta I_2$ | | $\Delta I_2$to be calculated first |
| Internal series resistance | | $\frac{\partial V_2}{\partial R_S}\Delta R'_S$ | | The internal series resistance is subject to production tolerance. If not measured, reasonable estimates are<br>$R'_S = 5\ m\Omega \cdot N_S/N_P$<br>$\Delta R'_S = 0.5\ m\Omega \cdot N_S/N_P$<br>where<br>$N_S$ : No. of serially connected cells<br>$N_P$: No. of parallel connected cell strings |
| Curve correction factor | | $\frac{\partial V_2}{\partial \kappa}\Delta \kappa'$ | | A reasonable estimate is $\Delta\kappa' = 0.5 \cdot \Delta\kappa'$ |
| Irradiance linear correction factor for $V_{OC}$ | | $\frac{\partial V_2}{\partial B_1}\Delta B_1$ | $\frac{\partial V_2}{\partial B_1}\Delta B_1$ | A reasonable estimate is $\Delta B_1 = 0.1 \cdot B_1$ |
| Irradiance non-linear correction factor for $V_{OC}$ | | $\frac{\partial V_2}{\partial B_2}\Delta B_2$ | $\frac{\partial V_2}{\partial B_2}\Delta B_2$ | A reasonable estimate is $\Delta B_2 = 0.5 \cdot B_2$ |

**Table 7:** Calculation of IEC 60891 $I$-$V$ translation uncertainty (procedure 2)

Note:

The translated short circuit current does not directly result from the translation formulas. It must be interpolated or extrapolated from the translated $I$-$V$ curve. The corresponding uncertainty must be additionally considered in $\Delta I_{SC,2}$.

For procedure 1 the translated $V_{\mathrm{oc}}$ does not result directly from the formula and must be interpolated or extrapolated. The associated uncertainty depends on how far the $I$-$V$ curve was measured in the negative current range (beyond $V_{\mathrm{OC}}$). In case of extrapolation, a quadratic extrapolation is recommended where the $I$-$V$ data points should cover a range of at least 2 V.

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# 5 Uncertainly analysis for G-T matrix measurement in accordance with IEC 61853-1

The *G-T* matrix measurement in accordance with IEC 61853-1 [4] determines the electrical performance of a PV module under variable module temperature ($T$) and irradiance ($G$). As shown in Table 8 the characterization is composed of $I$-$V$ measurements at 22 test conditions.

| | PV module temperature (*T*) | | | |
|---|---|---|---|---|
| **Irradiance ($G$)** | 15°C | 25°C | 50°C | 75°C |
| 100 W/m² | • | • | N/A | N/A |
| 200 W/m² | • | • | N/A | N/A |
| 400 W/m² | • | • | • | N/A |
| 600 W/m² | • | • | • | • |
| 800 W/m² | • | • | • | • |
| 1000 W/m² | • | • (STC) | • | • |
| 1100 W/m² | N/A | • | • | • |

**Table 8:** Test conditions for *G-T* matrix measurement

(*G-T*) matrixes of PV module performance parameters ($P_{max}$, $I_{sc}$ and $V_{oc}$) are resulting from $I$-$V$ measurements for each test condition and measurement uncertainties result from the procedures described in section 3.

It must be noted that the contributions from uncertainty sources may change with varying module temperature and irradiance, resulting in specific uncertainty tables for parameters $P_{max}$, $I_{sc}$ and $V$oc. On the other hand, some contributions from uncertainty sources are highly correlated for all G-T matrix elements (i.e. Irradiance uncertainty from the reference). The following points must be considered individually for each G-T matrix element for the uncertainty analysis:

- **Irradiance non-uniformity:** The irradiance non-uniformity in the test area of a solar simulator usually changes with the lamp power or by using attenuator masks. A contribution to measurement uncertainty arises from the fact that the average irradiance in the module area may deviate from the irradiance measured at the location of the reference cell. Compensation may be required by adjusting the scaling factor of the reference cell.
- **Uncertainty related to irradiance setting:** High precision reference cells of “Word PV Scale (WPVS) design” are not designed for operation in high ambient temperature environment. To avoid degradation, the reference cell is preferably held constantly at 25°C. This can be achieved either by placing it outside the temperature chamber (in which the test module is installed) or by active cooling (e.g. Peltier element). In the first case an uncertainty contribution arises from the transfer of calibration to the new position outside the test chamber.
- **Temperature measurement uncertainty:** Infrared temperature sensors, which are typically used for PMAX measurement under STC, may not be suitable for operation in a high temperature environment. An uncertainty contribution results from the use of contact sensors such as Pt100 or thermocouples. In case of incomplete thermal stabilization, the measured temperature will not correspond to the module junction temperature and this difference between measured temperature and junction temperature constitutes an uncertainty contribution.
- **Temperature non-uniformity:** If a temperature chamber is used, depending on the air circulation conditions, uncertainty contributions can result from a higher temperature non-uniformity in the PV module area compared to STC measurements. Uncertainties related to temperature non-uniformity will also arise when heating is achieved by continuous light exposure (i.e. steady-state solar simulator).
- **Spectral mismatch uncertainty:** Spectral responsivity of the PV module under test changes with operating temperature. Furthermore, if a temperature chamber is used, the spectral transmittance

of the glass cover at the light entrance side will have an impact on the spectral irradiance reaching the PV module. Both effects are combined within spectral mismatch uncertainty.

# 6 Uncertainly analysis for angular response measurement in accordance with IEC 61853-2

| Source of Uncertainty Xi | Type (Enter A or B) | Xi Uncertainty | Unit | Probability Shape (Enter G or R) | Division Factor | Standard Uncertainty u (Xi) | Sensitivity Coefficient Ci | Uncertainty Contribution ui | |
|---|---|---|---|---|---|---|---|---|---|
| Uncertainty related to measurement noise | A | 0,10 | % | G | 2,000 | 0,050 | 1 | 0,050 | 1) |
| Uncertainty related to DUT amplifier calibration | B | 0,00 | % | R | 1,732 | 0,000 | 1 | 0,000 | 2) |
| Uncertainty related to amplifier non-linearity | B | 0,09 | % | R | 1,732 | 0,052 | 1 | 0,052 | 3) |
| Uncertainty related to positioning | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 4) |
| Uncertainty related to reference plane | B | 0,02 | % | R | 1,732 | 0,012 | 1 | 0,012 | 5) |
| Uncertainty related to polarisation | B | 0,04 | % | R | 1,732 | 0,023 | 1 | 0,023 | 6) |
| Uncertainty related to incident angle | B | 0,51 | % | R | 1,732 | 0,294 | 1 | 0,294 | 7) |
| Uncertainty related to non-linearity of DUT | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 8) |
| Uncertainty related to temperature deviation of DUT | B | 0,01 | % | R | 1,732 | 0,006 | 1 | 0,006 | 9) |
| Uncertainty related to interreflections (specular) | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 10) |
| Uncertainty related to spectral mismatch of solar simulator | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 11) |
| Uncertainty related to reproducability | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 12) |
| Uncertainty related to background / straylight | B | 0,10 | % | R | 1,732 | 0,058 | 1 | 0,058 | 13) |
| Uncertainty related to non-uniformity | B | 0,11 | % | R | 1,732 | 0,064 | 1 | 0,064 | 14) |
| Uncertainty related to underillumination | B | 0,00 | % | G | 2,000 | 0,000 | 1 | 0,000 | 15) |
| | | | | Combined standard uncertainty, $u_c = \sqrt{\sum_i (u_i)^2}$ | | | | 0,342 | |
| | | | | Coverage factor k (level of confidence = 95%) | | | | 2 | |
| | | | | **Expanded uncertainty $U = u_c * k$** | | | | **0,68** | |

**Table 9:** Calculation spreadsheet for angular response uncertainty. As several uncertainty sources are dependent on the rotation angle setting of the test apparatus, MU tables have to be provided for each setting. The given values are example data for 40° rotation angle.

Table 9 shows the listing of uncertainty sources for angular response measurement of a solar cell and a PV module in accordance with IEC 61853-2 [5]. For modules, the standard defines various measurement methods with simulated sunlight, all of which have in common that the IAM measurement relates to a single cell in the connection circuit.

The values given in the yellow fields for uncertainty sources are example data. It is the task of the test laboratory to calculate these values from measurement series or to give estimates based on best practice. The review of the uncertainty analysis by technical auditors is part of laboratory accreditation in accordance with ISO/IEC 17025.

Remarks:

| | |
|---|---|
| 1) | Perform repetitive measurements for each angle and determine the standard uncertainty. |
| 2) | Sources for the measurement uncertainties $u$_R ($\theta$) could be Temperature coefficients of *R*, calibration of *R*, Unknown calibration values of *R* (AutoRange). |
| 3) | Sources for the measurement uncertainties $u$_(*R*,NL) ($\theta$) are non-linearities of the measurement electronics. For AOI measurements the current output of the DUT changes by a factor of 10 (Cos(85°)≈0.09). If the measurement electronics such as amplifier and multimeters show a non-linearity in the measurement range of interest, these deviations must be considered as measurement uncertainty. |
| 4) | The centre of the DUT must be placed exactly in the centre of rotation, if divergent light sources are used. In case of a misalignment, systematic measurement deviations dependent on $\theta$ can occur. Consequently, the alignment accuracy must be considered as measurement uncertainty. The measurement uncertainty can be derived from a sensitivity analysis, i.e. by measurements with well-defined misalignments and evaluation of the systematic measurement deviation. |
| 5) | The surface, i.e. the reference plane of the DUT must be placed exactly in the centre of rotation, if divergent light sources are used. In case of a misalignment, systematic measurement deviations dependent on $\theta$ can occur. Consequently, the alignment accuracy must be considered as measurement uncertainty. The measurement uncertainty can be derived from a sensitivity analysis, i.e. by measurements with well-defined misalignments and evaluation of the systematic measurement deviation." |
| 6) | Partly polarized light leads to measurement deviations relative to the unpolarised reference conditions. The uncertainty should be proportional to the overall magnitude of the polarization effect, i.e. the uncertainty should become negligible, if the DUT does not show any polarization effect. The estimated magnitude of the polarization effect should be treated as uncertainty, if no correction is applied. |
| 7) | An extended light source with an aperture A, leads to an angular distribution of the incoming light between $\theta-\Delta\theta$ and $\theta+\Delta\theta$ on the extended DUT with a dimension L at a distance z. Additionally, there is an alignment uncertainty resulting in an angle offset $\theta$_0. Consequently, this leads to a measurement deviation, that can be derived from a measured AOI dependence. This should be treated as measurement uncertainty. |
| 8) | The DUT could be non-linear with respect to irradiance. This linearity can be of different magnitude dependent on irradiance level. If the AOI testing conditions (i.e. low irradiance) differ significantly in irradiance from the target conditions of the DUT (i.e. STC), the effect on non-linearity should be treated as measurement uncertainty." |
| 9) | There are different uncertainty sources for the temperature measurement: Accuracy of temperature sensor, Calibration of temperature sensor, Possible temperature offsets (i.e. due |

| | |
|---|---|
| | to thermal gradient between temperature Sensor and pn-junction), Temperature non-uniformity of DUT. |
| 10) | Dependent on the measurement facility there could be inter-reflections leading to a falsification of the measurement signal. The effect can be dependent on the angle $\theta$. The magnitude of this effect and hence the estimated measurement uncertainty can be derived from: Measurements, Estimations from reflectivity coefficients of facility components, Ray tracing simulation- |
| 11) | The relative light transmission of a PV device can generally be assumed to be wavelength dependent, since absorption and reflectivity coefficients are generally wavelength dependent. If the light spectral irradiance differs significantly from the reference spectrum (i.e. halogen lamp vs AM1.5), the spectral relative light transmission is weighted differently leading to different measurement results. In this case an appropriate measurement uncertainty must be considered. |
| 12) | The reproducibility is an estimated uncertainty that covers possible unknown systematic effects/deviations. If a measurement is repeated several times under identical conditions and if the deviation between these measurements extend the deviations that can be expected from the measurement noise or other quantified uncertainties, then these deviations should be quantified and treated as an additional measurement uncertainty. The kind of distribution for that uncertainty should be chosen according to the observed distribution of that reproducibility. The reproducibility could be angle dependent and/or angle independent. Instability of monitor principle is a source of this uncertainty |
| 13) | Contributions to the measurement signal that do not originate from the direct illumination |
| 14) | Non-uniformity of irradiance changes within rotation volume of PV device. This effect is generally not measured (high effort). It can be modelled, and the estimated impact should be treated as measurement uncertainty. |

Since the relative light transmission is a current measurement normalized to normal incidence, correlations of the measurement uncertainties between $I$sc ($\theta$) and $I$sc (0°) must be taken into account. Systematic effects could cancel out i.e. could be enhanced.

The highest contribution is given by the uncertainty related to incident angle ΔΘ. For assumed ΔΘ=0.5° the related uncertainty at Θ=80° is

$$\Delta IAM = \left[\left(\frac{\cos(80.5°)}{\cos(80°)} - 1\right), \left(\frac{\cos(79.5°)}{\cos(80°)} - 1\right)\right] = [-4.44, +4.19]$$

As previously mentioned, the IAM uncertainty is dependent on the incident angle Θ. Therefore, the calculation spreadsheet must be filled for all Θ settings: 0°, 10°, 20°, 30°, 40°, 50°, 60°, 65°, 70°, 75° and 80°. As an example, Figure 2 shows the IAM (Θ) curve with associated measurement uncertainties ΔIAM (Θ).

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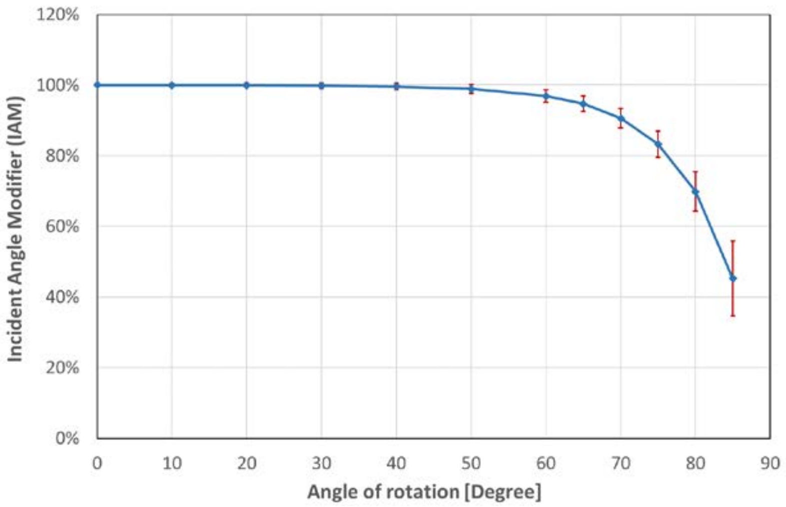


**Figure 2:** Incident Angle Modifier curve IAM (Θ) and associated measurement uncertainties

Based on the IAM measurements, the angular response curve of a PV module is described by a single parameter ($a_r$) which is derived from the IAM model defined in IEC 61853-2 [4]. With reference to Figure 2 the uncertainty of the $a_r$ parameter will result from the upper and lower IAM range limits. In this example the evaluation yields $a_r$ = 0.168 ±0.008.

# 7 Summary

Within the joint research project 19ENG01 "Metrology for emerging PV applications" (Metro-PV), the development of calculation tables for measurement uncertainties associated with the power rating and energy rating of PV modules in accordance with IEC 61853 has been analysed.

The results can be used for future discussions in standardization working group IEC TC82 WG2 to implement uncertainty aspects in the IEC standards for PV modules.

# 8 References


[1] Joint Committee for Guides in Metrology (JCGM), „JCGM 100, Evaluation of measurement – Guide to the expression of uncertainty in measurement (GUM)", 2008

[2] IEC 60904-1:2020 "Photovoltaic devices - Part 1: Measurement of photovoltaic current-voltage characteristics"

[3] IEC 60891:2021 "Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics"

[4] IEC 61853-1:2011 "Photovoltaic (PV) module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating"

[5] IEC 61853-2:2016 "Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral responsivity, incidence angle and module operating temperature measurements"