Solar Cell Calibration at ISFH CalTeC
Measurement procedure and technical details

The ISFH CalTeC (Calibration and Test Center) is accredited according to ISO 17025 for the calibration of solar cells by the national accreditation body of the Federal Republic of Germany DAkkS (Deutsche Akkreditierungsstelle) under the registration number D-K-18657-01-00. The subjects of the accreditation are the measurements of the spectral responsivity (SR) and the determination of the characteristic parameters ($I_{sc}$, $V_{oc}$, FF and $\eta$) of the current voltage (IV) curve of solar cells measured under standard test conditions (STC) as defined in the IEC60904 standards. All parameters are reported with the accompanied uncertainty following from an approved measurement uncertainty analysis. In order to ensure traceability to SI-units all reference devices are calibrated at the national metrology institute of Germany, PTB (Physikalisch-Technische Bundesanstalt).

For SR measurements the ISFH CalTeC Solar Cell Laboratory is equipped with a grating monochromator based measurement setup allowing differential spectral response measurements at a large number of different wavelengths with a spectral bandwidth of about 10 nm. The monochromatic light field has an area of 160×160 mm². The setup comprises an array of halogen lamps allowing bias light intensities of up to 1100 W/m² (1.1 suns). To address non-linearities in the solar cells under test we always measure the differential spectral response over the whole wavelength range at a minimum of six bias light intensities $E$ between 5 W/m² and 1100 W/m² and calculate the relative spectral response for each wavelength by integration over $E$. Thus, approximate procedures which i.e. use a single monochromatic or a white bias ramp are avoided.

IV measurements are carried out using the light from an AAA solar simulator (WACOM WXS-156 S-L2) which comprises a two lamp system (halogen and xenon). The light field has an area of 160×160 mm². On a motorized x-axis a spectroradiometer and the measurement unit for the solar cell under test as well as for the WPVS reference solar cell are mounted. This allows a precise control of the intensity and spectrum of the solar simulator.

The calibration service of the ISFH CalTeC focuses on the measurement of wafer-based silicon solar cells from laboratory up to industrial formats. The procedure for a calibrated solar cell measurement consists of three tasks:

**Task 1: Area measurement**
The area of the solar cell under test is required for the calculation of the efficiency $\eta$. Thus, the first task is the measurement of the solar cell area. For this task a calibrated flatbed scanner is used.

**Task 2: Measurement of the spectral responsivity**
The second task determines the spectral responsivity (SR) which is required for the calculation of the spectral mismatch factor $f_{MM}$. The spectral mismatch correction compensates differences in the current generation between the target spectrum (usually AM1.5G) and the spectrum of the sun simulator used for the measurement of the current voltage curve of the solar cell under test.
In our SR measurement apparatus, the monochromatic light is generated by sending light coming either from a xenon or a halogen lamp through a grating monochromator. The wavelength of the monochromatic light can be adjusted between 280 nm and 1200 nm with a bandwidth of about 10 nm. The measurement wavelengths are controlled simultaneously using an array spectrometer. The light field in the test plane has an area of 160×160 mm².

The reported absolute spectral response \( s_{\text{STC}}(\lambda) \) of the solar cell under test has to correspond to an illumination intensity of \( E_{\text{STC}}=1000 \text{ W/m}^2 \). To determine \( s_{\text{STC}}(\lambda) \), we use the differential spectral responsivity procedure combined with a scaling-procedure using the measured short-circuit current from the IV-tester.

For the differential spectral responsivity procedure, chopped monochromatic light of low intensity is superimposed on white bias light of considerably higher intensity. A solar cell, illuminated with such light, provides a short-circuit current consisting of a constant and a pulsed part. The differential spectral response \( \tilde{s}_{\text{rel}}(\lambda,E) \) is the ratio of the pulsed part of the short-circuit current and the chopped illumination intensity at the bias light intensity \( E \). Differential spectral response measurements are carried out at a minimum of six bias light intensities between 5 W/m² and 1100 W/m². For each wavelength, the relative (non-differential) spectral responsivity \( s_{\text{STC,rel}}(\lambda) \) is calculated by integrating \( \tilde{s}_{\text{rel}}(\lambda,E) \) over \( E \) from 0 to \( E_{\text{STC}} \). In order to obtain the absolute spectral response \( s_{\text{STC}}(\lambda) \), the relative (non-differential) spectral responsivity \( s_{\text{STC,rel}}(\lambda) \) is scaled with a multiplication factor so that the
integral of the product of the scaled $s_{\text{STC,rel}}(\lambda)$ curve and the AM 1.5G reference spectrum matches the (spectral mismatch corrected) solar cell short circuit current measured under STC in task 3.

Note that for the determination of the spectral mismatch factor the relative spectral responsivity $s_{\text{STC,rel}}(\lambda)$ is sufficient and no scaling is required.

**Task 3: IV measurement**

The third task is the measurement of the current voltage (IV) curve under standard test conditions. For this procedure we developed an IV measurement system based on an AAA solar simulator (WACOM WXS-156 S-L2). On a motorized x-axis a spectroradiometer and a measurement unit for the solar cell under test as well as a reference cell are mounted and can be positioned below the sun simulator light field. In order to compensate for chucks of different height, the distance between the measurement unit and the solar simulator can be adjusted by a motorized z-axis. The spectrometer is used for a regular control of the sun simulator spectrum.

![Fig. 3: Setup for the measurement of the current voltage characteristic.](image)

The measurement of the current voltage curve is divided in five steps.

In the first step the WPVS reference solar cell is positioned below the solar simulator light field and its intensity is adjusted in order to reproduce the short circuit current $I_{\text{SC,WPVS,STC}}$ of the reference cell determined during calibration at PTB. Afterwards the spectrometer is positioned below the light field and the corresponding spectrum is measured.

In the second step we compensate for spectral mismatch ($f_{\text{MM}}$) and light field inhomogeneity ($f_{\text{hom}}$). The spectral mismatch $f_{\text{MM}}$ is calculated according to the IEC60904-7 standard on the basis of the
spectral response data determined in task 2 and the measured solar simulator spectra. The light field inhomogeneity correction $f_{\text{hom}}$ is calculated from xy-data obtained by scanning the light-field with a light sensor and by knowing the exact positions of the WPVS reference solar cell and the solar cell under test. The WPVS reference solar cell is positioned below the solar simulator again and the light intensity is set to $I_{\text{sc,WPVS}} = I_{\text{sc,WPVS,STC}} / f_{\text{M/M}} / f_{\text{hom}}$.

In the third step the solar cell under test is mounted and electrically contacted with kelvin probes to avoid any shading. The solar cell under test is positioned below the solar simulator and the short circuit current $I_{\text{sc,probes}}$ is measured. Afterwards contact bars are mounted and the short circuit current is increased such the current $I_{\text{sc,probes}}$ measured with probes is reproduced. The contact bars used for the measurement of the entire IV curve contact the busbars over its full length via spring-loaded contact probes. Based on the detailed analysis by Kruse [1] the probes are arranged in five equally distributed triples (current/sense/current), as shown in Fig. 4.

Fig. 4: Contact bars with spring-loaded probes arranged in five triples.

In a fourth step the solar cell under test is positioned below the solar simulator light field again and the 25.0°C equivalent open circuit voltage is determined by applying the $V_{\text{oc}}$-$t$-method [2]. This method is required since the temperature of the solar cell under test may deviate from the temperature measured with a tactile sensor at the solar cells rear. A tactile measurement from the front runs the risk of scratching the sensitive solar cell front surface. As preparation for the $V_{\text{oc}}$-$t$-method the temperature of the solar cell under test is adjusted in the dark to 25.0°C measured at the solar cell rear using a tactile PT-1000 temperature sensor. Afterwards the solar simulator high speed shutter is opened and the open circuit voltage is measured as function of time. The maximum of the resulting curve $V_{\text{oc,max}}$ is the best approximated value for $V_{\text{oc}}$ at 25.0°C under illumination.
In the fifth step the shutter of the IV tester remains opened, thus illuminating the solar cell under test continuously. As preparation for the IV curve measurement, the temperature of the measurement chuck is adjusted until the continuously measured $V_{oc}$ equals $V_{oc,max}$. Finally, the current voltage curve is measured using a four-quadrant current voltage source. From the resulting curve the characteristic parameters such as the short circuit current ($I_{sc}$), the open circuit voltage ($V_{oc}$), the fill factor ($FF$), the energy conversion efficiency ($\eta$) and the maximum output power ($P_{mpp}$) are determined.

Our parameter extraction procedure is based on the publications of Luque [3] and Paviet-Salomon [4]. First the parameters are pre-evaluated from the data: $I_{sc,d}$ is the current data with voltage closest to zero, $V_{oc,d}$ is the voltage data with current closest to zero, $P_{mpp,d}$ is the data with highest power and $V_{mpp,d}$ is the voltage data of highest power. These parameters allow defining data ranges for the different interpolation routines:

- $I_{sc}$ follows from a linear interpolation within the data which satisfies the constraints
  1. $(1 - a) \cdot I_{sc,d} < I < (1 + a) \cdot I_{sc,d}$ with $a = 0.04$ and
  2. $-b \cdot V_{oc,d} < V < b \cdot V_{oc,d}$ with $b = 0.2$.

- $V_{oc}$ is determined by fitting a second order polynom in the data range
  1. $-c \cdot I_{sc,d} < I < c \cdot I_{sc,d}$ with $c = 0.3$ and
  2. $(1 - d) \cdot V_{oc,d} < V < (1 + d) \cdot V_{oc,d}$ with $b = 0.1$.

- The maximum power point is determined by fitting a fifth order polynom in the data range defined by
  1. $P > P_{mpp,d} \cdot e$ with $e$ being 0.9 and
  2. $V > V_{mpp,d} \cdot f$ with $f$ being 0.9.

**Additional information**

A calibration certificate is issued for the SR measurement and for the IV measurement. All parameters are reported with the accompanied uncertainty.

Please note that calibrated measurements will only be performed if standard testing conditions as defined in the IEC 60904 standards can be ensured through the whole measurement procedure. The temporal stability of the solar cells lies in the responsibility of the customer.

**Prices**

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<th>Number of cells</th>
<th>Price in € per cell (SR and IV)</th>
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All prices are net prices not including any taxes/customs. Packaging and transport costs are not included in the price.

**Contact**

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References


