

# Solar Cell Calibration at ISFH CalTeC

Measurement procedure and technical details (23a)



The ISFH solar cell calibration laboratory is part of the ISFH Calibration and Test Center ([CalTeC](#)). It is accredited 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 accreditation confirms that ISFH CalTeC fulfils the 'General requirements for the competence of testing and calibration laboratories' of the International Organization for Standardization as defined in the ISO/IEC 17025 standard. Moreover, the accreditation conforms that the solar cell calibration procedure is in accordance to the IEC60904 standards.

Specifically ISFH CalTeC is accredited for certified measurements of:

- The characteristic parameters of the current–voltage ( $I$ – $V$ ) curve (short-circuit current  $I_{sc}$ , open-circuit voltage  $V_{oc}$ , fill factor  $FF$  and power conversion efficiency  $\eta$ ).
- The spectral responsivity (SR).
- The temperature coefficients  $\alpha$  (for  $I_{sc}$ ),  $\beta$  (for  $V_{oc}$ ) and  $\delta$  (for  $P_{max}$ ).
- The area  $A$  of the solar cell or the aperture mask.

All these parameters are reported with the accompanied uncertainty following an approved measurement uncertainty analysis. In order to ensure traceability to SI units, all reference devices are calibrated at Physikalisch-Technische Bundesanstalt (PTB) – the National Metrology Institute of Germany or at DAkkS accredited calibration laboratories.

The ISFH CalTeC is listed in the “Solar cell efficiency tables” as a “[designated test center](#)” to confirm solar cell efficiency records. The efficiency tables, published in the international journal “[Progress in Photovoltaics](#)” (Wiley), list the currently highest independently confirmed efficiencies for solar cells and modules every six months.

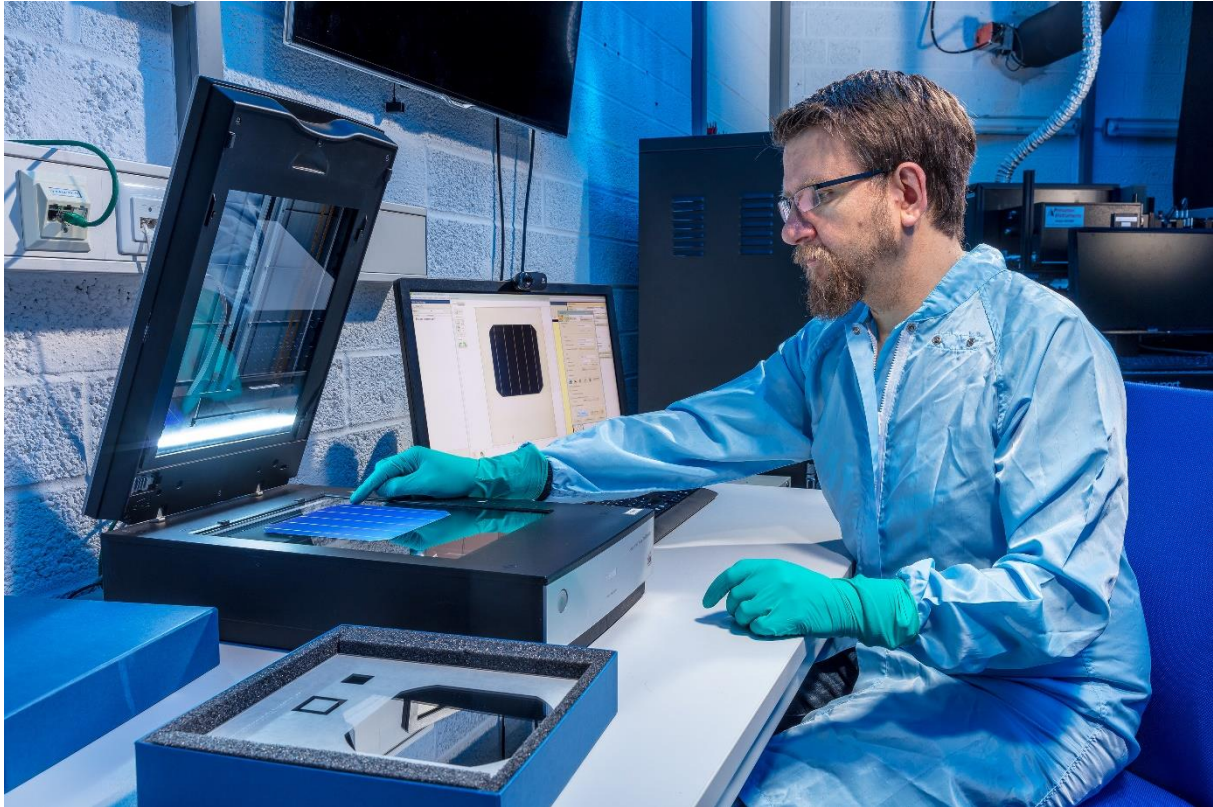
The calibration service of the ISFH CalTeC focuses on the measurement of wafer-based silicon solar cells from laboratory up to industrial formats up to M12. We can measure multibusbar (mBB) as well as busbarless (BB0) cells. The smallest bus bar distance, which we can contact, is 10 mm. This limit results from the width of the contact bar holders.

Basically, we can also measure IBC solar cells with both contact polarities on the solar cell rear side. However, since these cells require a contact layout that is exactly matched to the metallization of the cell, we are not as flexible here, but will gladly try to find a solution with and for you.

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.



*Fig. 1: Solar cell and aperture area measurement system based on a high-resolution flatbed scanner calibrated with an area reference standard.*

### 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 from either 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  $170 \times 170 \text{ mm}^2$ .



*Fig. 2: Differential spectral response (DSR) measurement setup.*

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  $s_{\text{STC,rel}}(\lambda)$ , 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  $5 \text{ W/m}^2$  and  $1100 \text{ W/m}^2$  (Bothe, Hinken, Min, & Schinke, 2018). 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 have two IV measurement systems. The first system is used for solar cells up to M6 and is based on an A+AA+ two lamp (xenon and halogen) WACOM WXS-156 S-L2 solar simulator. The second system utilizes a wavelabs LED solar simulator with 27 different LED colors and allows measurement of solar cells up to M12.



Fig. 3: Setup for the measurement of the current voltage characteristic of solar cell up to M6 using a Wacom two lamp solar simulator.

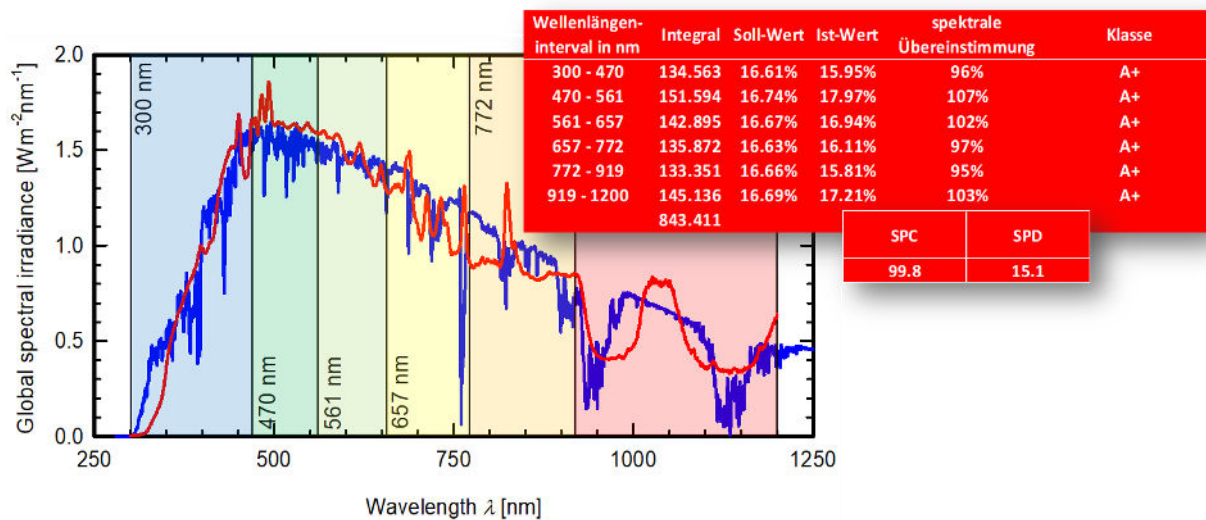


Fig. 4: Spectrum and classification of the Wacom solar simulator used in the setup for solar cells up to M6.



Fig. 5: Setup for the measurement of the current voltage characteristic of solar cell up to M12 using a LED solar simulator from wavelabs with 27 different LED colors.

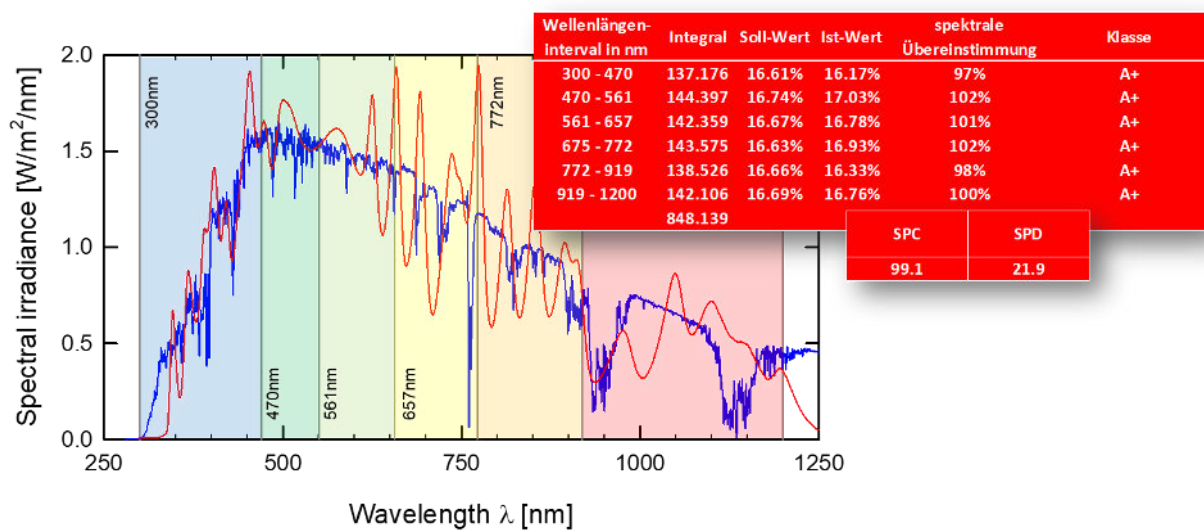


Fig. 6: Spectrum and classification of the wavelabs led solar simulator used in the setup for solar cells up to M12.

In both systems a spectroradiometer, the measurement unit for the solar cell under test as well as a reference cell are mounted on a motorized x-axis to position them below the sun simulator light field. To compensate for height differences between different contacting units, the distance between the measuring unit and the sun simulator can be adjusted via a motorized z-axis. The spectrometer is used for a regular control of the sun simulator spectrum as well as for an individual spectral mismatch correction for every measurement.

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  $I_{sc,WPVS,STC}$  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 ( $f_{MM}$ ) and light field inhomogeneity ( $f_{hom}$ ). The spectral mismatch  $f_{MM}$  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  $f_{hom}$  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  $I_{sc,WPVS,corr} = I_{sc,WPVS,STC} / f_{MM} / f_{hom}$ .

In the third step, we compensate for shading. To do so we determine the shading free short-circuit current  $I_{sc,0}$  by one of two available approaches. Either we contact the solar cells at the outer edges of the busbars with Kelvin probes or we measure with a varying number of contact bars. The first approach is used as long as the potential at the centre of the busbar is below 200 mV under short-circuit conditions or moderate reverse voltage (up to -1.0 V). We can then apply a reverse voltage to extract the whole light generated current. In case of lowly conductive busbars or solar cells without busbars, we measure the short-circuit current as a function of the number of contact bars used.  $I_{sc,0}$  follows from extrapolation to zero bars as shown in Fig. 5. Afterwards contact bars are mounted and the light intensity of the solar simulator is increased until  $I_{sc,0}$  is reproduced.

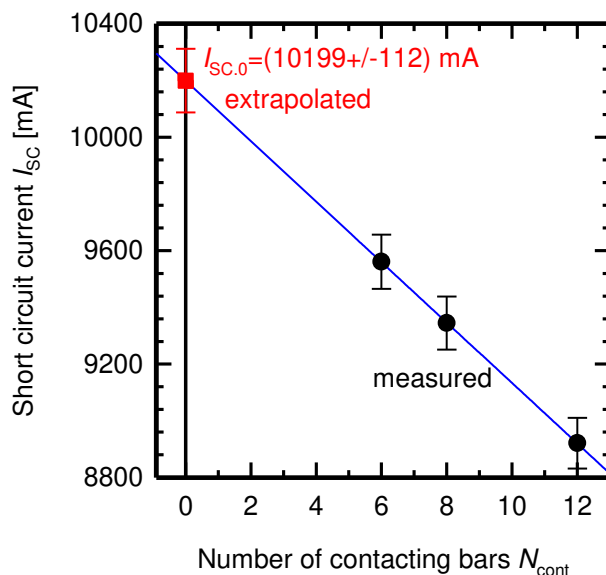
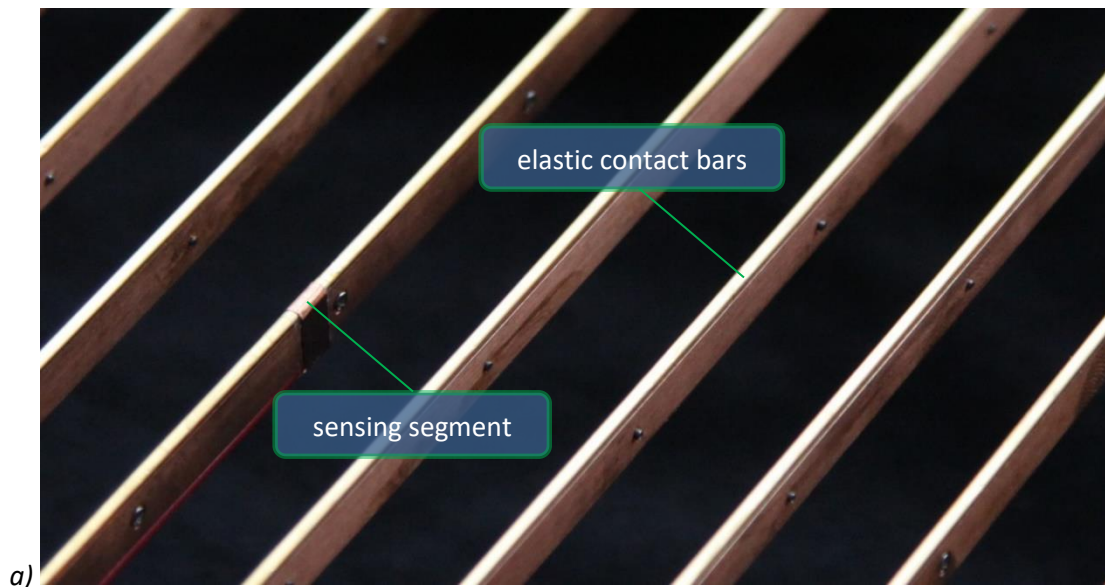


Fig. 7. Short circuit current as a function of the number of contacting bars. Measured values are shown as black circles. The shadow-free short circuit current  $I_{sc,0}$ , shown as red square, results from extrapolation to zero contact bars.



Cells are contacted with *elastic contact bars* made from gold plated metallic foil wrapped around an elastic core. Voltage sensing is carried out with a sensing segment, which is a small region isolated from the current-carrying part and is pressed directly on the busbar. Busbarless cells are also contacted with the elastic contact bars shown in Fig. 8. However, voltage sensing is performed by placing a wire at a position at one-fifth of the distance of two current-carrying contacts.



*Fig. 8: Elastic contact bars used contacting multibusbar and busbarless solar cells during IV measurement.*

In a fourth step the solar cell under test is positioned below the solar simulator light field and the 25.0°C-equivalent open circuit voltage is determined by applying the  $V_{oc}$ - $t$ -method (Emery, et al., 1996). This method is required since the temperature of the solar cell under test may deviate from the temperature measured 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  $V_{oc}$ - $t$ -method the temperature of the solar cell under test is adjusted in the dark to 25.0°C measured at the solar cell rear. In order to avoid any damage on the back of the solar cell as well, the PT-1000 temperature sensor is installed in a thinned out area of the measuring block. After stable temperature conditions have been reached, the light of the solar simulator need to switched on as fast as possible. In case of the Wacom solar simulator a high-speed shutter is opened while the LED solar simulator can be switched on and of fast enough. In both cases the open-circuit voltage is measured as function of time simultaneously. The maximum  $V_{oc,max}$  of the resulting  $V_{oc}$ - $t$ -curve is the best approximated value for  $V_{oc}$  at 25.0°C under illumination.

In the fifth step the solar cell under test remains illuminated. 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 (Luque & Hegedus, 2003) and Paviet-Salomon (Paviet-Salomon, et al., 2017). 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  $d = 0.1$ .
- 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 DSR/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.

On request, we carry out customer-specific temperature and illumination treatments. This service is charged on a time and material basis.

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## References

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