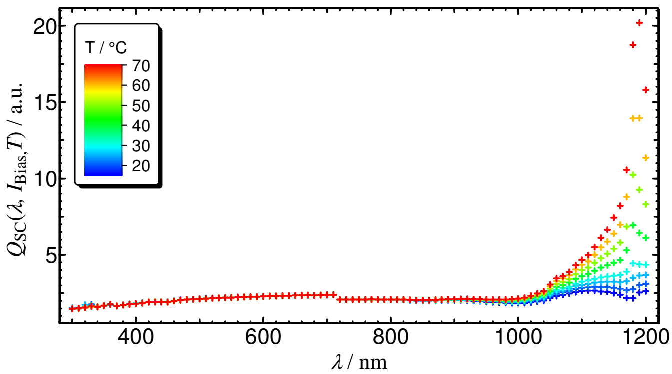
This good practice guide is a result of experiences gained within the EMRP Photoclass project consortium on temperature dependent measurements of photovoltaic devices using spectral and integral calibration procedures. The application of these kind of measurements aims at the IEC standard 61853-1 that describes irradiance and temperature performance measurements and power rating. The general measurement procedures are outlines and statements of the most significant measurement uncertainties are described.

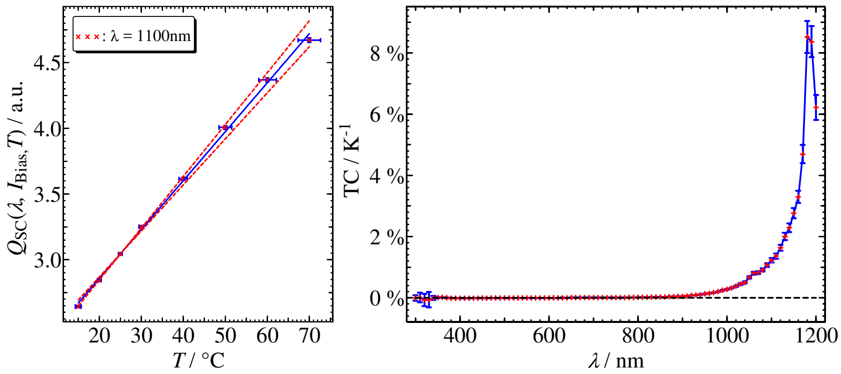
1. Differential spectral responsivity method

The determination of the temperature coefficient for the short circuit current at standard test conditions of a solar cell (SC) can be derived from temperature dependent measurements of the spectral responsivity $s_{\mathrm{STC}}(\lambda)$ using the differential spectral responsivity (DSR) method [1, 2]. Since a complete DSR calibration at several different temperatures can be very time consuming, such a measurement can be divided into a standard calibration of the spectral responsivity in order to determine $s_{\mathrm{STC}}(\lambda)$ and a temperature dependent measurement of the relative *differential* spectral responsivity $\tilde{s}(\lambda, T, I_{\mathrm{Bias}})$ by means of the measurement of the monitor corrected Lock-In signal of the solar cell at constant bias irradiance level E_{Bias} and at different temperature $Q_{SC}(\lambda, T, I_{\mathrm{Bias}})$.
According to IEC 60904-8:2014 7.5 [2] the spectral responsivity $s_{\mathrm{STC}}(\lambda)$ can be assumed to be equal to the differential spectral responsivity $\tilde{s}(\lambda, I_{\mathrm{Bias}})$, if I_{Bias} is approximately 30% - 40% of I_{STC}. Hence the temperature dependent measurements of the relative *differential* spectral responsivity are performed at $I_{\mathrm{Bias}} \approx 0.35 * I_{\mathrm{STC}}$. The measurement procedure would be as follows:

- Measurements of the monitor corrected Lock-In signal of the solar cell at constant bias irradiance level E_{Bias} at different temperature $Q_{SC}(\lambda, T, I_{\mathrm{Bias}})$ using the differential spectral responsivity method. Please note that the monitor principle is essential for this measurement, since lack of reproducibility is a major uncertainty contribution for such a *relative* measurement.

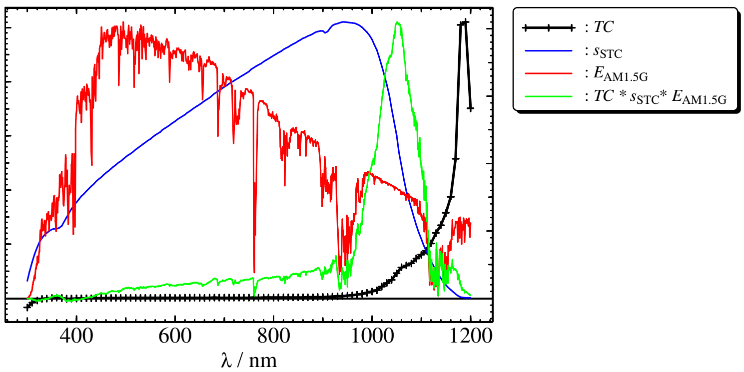


- Perform a linear regression of the temperature dependent differential response of the solar cell at every single wavelength. The slope corresponds to the spectral temperature coefficient. Express this function $TC(\lambda)$ in units of [1/K].



- Weighting the spectral temperature coefficient $TC(\lambda)$ with the spectral responsivity $s_{\mathrm{STC}}(\lambda)$ and the spectral irradiance of the AM1.5G spectrum $E_{\mathrm{AM1.5G}}(\lambda)$ gives the temperature coefficient of the short cicuit current under STC.

$$\alpha = \frac{\int TC(\lambda) \cdot s_{\mathrm{STC}}(\lambda) \cdot E_{\mathrm{AM1.5G}}(\lambda) \mathrm{d}\lambda}{\int s_{\mathrm{STC}}(\lambda) \cdot E_{\mathrm{AM1.5G}}(\lambda) \mathrm{d}\lambda}$$



The major uncertainty contributions are

- *Spectral responsivity:* The spectral responsivity of the DUT is needed for the calculation of α out of the spectral TC. Please note, that only the *relative* $s_{\mathrm{STC}}(\lambda)$ is needed. Hence all uncertainties related to the absolute value of $s_{\mathrm{STC}}(\lambda)$ can be neglected.
- *Over illumination of sample and reference:* The monochromatic light field should be larger than the active area of the solar cell. This includes encapsulation materials, since light transmission and reflection characteristics of encapsulation material might be temperature dependent.
- *Monitor principle:* Since the DUT is subsequently measured at different temperature, a drift of the monochromatic irradiance over that period should be corrected for. This can be realized by coupling a fraction of the monochromatic light onto a monitor detector (e.g. by using a beam splitter)
- *Reproducibility:* The reproducibility is a key uncertainty contribution. The non-uniformity of the monochromatic light field, the center wavelength of the monochromatic light and the bias irradiance level should be reproducible to a high degree for the temperature dependent measurements.
- *Temperature:* The DUT should be stabilized with respect to the set temperature. Deviation from the set temperature should be considered in the uncertainties. If the temperature sensor is in direct thermal contact to the DUT, additional uncertainties should be included (i.e. if there is a temperature gradient can be expected across the solar cell: backside cooling – temperature sensor – solar cell – encapsulant – front side heat load due to irradiation).
- *Uncertainty related to linear regression:* The uncertainties $U(T)$ and $U\left(Q_{SC}(\lambda, T, I_{\mathrm{Bias}})\right)$ should be used as weights for the linear regression for the determination of $TC(\lambda)$. The

uncertainty of $TC(\lambda)$ should be derived from the linear regression considering $U(T)$ and $U\big(Q_{SC}(\lambda, T, I_{\text{Bias}})\big)$.

[1] Metzdorf et al. "*Calibration of solar cells. 1: The differential spectral responsivity method*", Applied Optics Vol. **26** No. 9, 1987
[2] IEC 60904-8:2014, Measurement of spectral response of a photovoltaic (PV) device (2014)

2. Steady-state solar simulators and natural sunlight

The temperature dependence measurement of the three main electrical parameters I_{SC}, V_{OC}, P_{MAX} under steady-state irradiance conditions is performed by varying the temperature of the PV device while keeping the total irradiance level constant [2]. The latter has to be measured by a calibrated reference cell (RC) kept at 25 °C, because the resulting temperature coefficients (TCOs) of the device under test (DUT) refer to the irradiance level at which they have been measured.

When steady-state solar simulators or natural sunlight are used as light source, the heating component of the radiation can be used to naturally warm up the PV device by keeping it constantly exposed to light.

The usual procedure for measuring the temperature coefficients α (for I_{SC}), β (for V_{OC}) and δ (for P_{MAX}) for large devices (from large-area cells to module size) is as follows:

- The PV device has to be prepared by cooling it down to a temperature below the lower limit of the range of interest.
- When the device is ready and temperature uniformity reached, it is connected to a setup suitable for I-V curve acquisition according to IEC 60904-1 [3] and exposed to steady-state artificial or natural sunlight.
- While the PV device is warming up due to incoming irradiance, a series of I-V curves are acquired in the same way as STC I-V curves would be recorded. Consecutive I-V curves are acquired at least every 5 °C for a total temperature range of at least 30K. The temperature of the DUT and of the RC is recorded together with the irradiance value and the I-V curve.
- Once the whole temperature range of interest is spanned and the I-V curve sequence is terminated, the three parameters I_{SC}, V_{OC} and P_{MAX} are extracted from each I-V curve and the functions $I_{SC}(T)$, $V_{OC}(T)$, $P_{MAX}(T)$ are fit with a least-square linear fit [2]:

$$Y(T) = m_{abs} \times T + Y_0 \qquad \text{Eq. (1)}$$

where m_{abs} represents the absolute TCO, T is the measured DUT temperature and Y_0 is the value of the parameter at 0 °C. The relative TCO is then calculated as [2]:

$$m_{rel} = \frac{m_{abs}}{Y(25\,°\text{C})} \times 100 \qquad \text{Eq. (2)}$$

where Y(25 °C) is the value of the parameter Y at 25 °C as calculated from Eq. (1) and m_{rel} is given in units of [%/°C] or [%/K].

When the DUT is a reference cell, a procedure similar in principle to the just-described one is applied, but usually with the addition of a temperature-controlled stage to be able to precisely control the temperature of the DUT through the range of interest. This allows variation of the method. Whereas above the DUT temperature is never in a steady-state condition, here such steady-state conditions can be adjusted. It allows further to measure the TCO with increasing temperatures or decreasing temperatures. For RCs only $I_{SC}(T)$ is measured instead of the full I-V curve dependence on T.

As the TCO measurement is ultimately a relative measurement, many components that would enter the UC budget for a standard measurement at STC are cancelled out. Therefore, the following issues can be considered major measurement uncertainty contributions for relative TCO measurements:

- *DUT temperature*: the major component of the UC budget comes from the reading of the DUT temperature. First of all, the value measured together with (and therefore associated to) the I-V curve shall always be used, with a UC component (minor compared to what follows) related to the measuring instrument to be included. However, the most significant contributions to the DUT temperature UC are due mainly to the distance between the point at which the temperature is read by the Pt100 sensor and the actual position of the DUT junction, to the delay between the reading of the temperature and the sweep of the I-V curve and to the non-uniformity of the temperature in the DUT;
- *RC temperature*: even if actively controlled in temperature, the RC temperature contributes to the overall UC budget due to sequential reading with respect to the I-V curve sweep and to the UC related to the measuring instrument.
- *Uncertainty related to linear fit*: the standard error for the Y estimate from the linear-square fit is used as UC component for the computational part of the TCO determination.
- *Uncertainty related to spectral mismatch:* the change in the spectral responsivity with temperature and consequently spectral mismatch for certain materials (e.g. c-Si) can be a significant contribution. For natural sunlight this contribution can be neglected in first order. For solar simulators it depends crucially on the match of their spectral irradiance to the reference spectrum in the wavelength range where the spectral responsivity of the DUT is most sensitive to temperature changes. The full uncertainty can only be calculated if the SR as function of temperature is available for the DUT. In absence of this information, such data for typical devices similar to the DUT can be used to estimate the UC contribution.

[2] IEC, *IEC 60891 Photovoltaic devices – Procedures for temperature and irradiance corrections to measured IV characteristics.*, International Electrotechnical Commission, 2009

[3] IEC, *IEC 60904-1 Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*, International Electrotechnical Commission, 2006

3. *Flash solar simulators*

The measurement of the temperature coefficients by using a flash solar simulator is similar to the previous method. However, as the irradiance produced by the light source is not enough to warm up the DUT, an additional heating system is necessary in order to vary the DUT temperature over the range of interest. Suitable means are an insulated temperature-controlled cabinet with a transparent window or a shutter door, capable of containing the module and producing a quasi-steady and uniform temperature on it. According IEC 60891(2009) [2] the temperature uniformity of the DUT has to be within ±2 °C and has to be verified for large devices by the mean of a minimum of 4 temperature measurements positioned as described in the standard. The average temperature is used as reference value.
The procedure to measure DUT TCOs is as follows:

- The PV device is mounted on a setup suitable for I-V curve acquisition according to IEC 60904-1 [3] and brought to the lowest temperature of the range of interest. If a temperature-controlled box is used, the RC is mounted on the outside, to be kept at 25 °C. Also, a calibration of the transmittance of the transparent door of the box has to be always carried out at the beginning of the TCO measurements.
- When the device is ready and its temperature deemed stable, at least three I-V curves are acquired.
- The DUT temperature is then varied by the chosen method. Additional I-V curves are acquired at least every 5 °C for a total temperature range of at least 30 °C. The temperature of the DUT and of the RC is recorded together with the irradiance value and the I-V curve.
- Once the whole temperature range of interest is spanned and the I-V curve sequence is terminated, the three parameters I_{SC}, V_{OC} and P_{MAX} are extracted from each I-V curve and the functions $I_{SC}(T)$, $V_{OC}(T)$, $P_{MAX}(T)$ are fit with a least-square linear fit [2] according to Eq. (1). The relative TCO is then calculated according to Eq. 2 [2].

The following issues can be considered major measurement uncertainty contributions for measurements at flash solar simulators:

- *DUT temperature*: the major component of the UC budget comes from the reading of the DUT temperature. First of all, the value measured together with (and therefore associated to) the I-V curve shall always be used, with a UC component (minor compared to what follows) related to the measuring instrument to be included. However, the most significant contributions to the DUT temperature UC are due mainly to the distance between the point at which the temperature is read by the Pt100 sensor and the actual position of the DUT junction and to the delay between the reading of the temperature and the sweep of the I-V curve. In the case of flash solar simulators, though, the non-uniformity of the DUT temperature is not influenced by the simulated sunlight. If the procedure achieves a good temperature uniformity of the DUT, this will be a minor component of the overall UC.
- *RC temperature*: even if actively controlled in temperature, the RC temperature contributes to the overall UC budget due to sequential reading with respect to the I-V curve sweep and to the UC related to the measuring instrument.
- *Uncertainty related to linear fit*: the standard error for the Y estimate from the linear-square fit is used as UC component for the computational part of the TCO determination.
- *Uncertainty related to spectral mismatch:* as for TCO measurements under steady-state simulated sunlight.