Spectral Responsivity of WPVS Reference Cells under Varied Temperatures and its Influence on Performance Measurements beyond STC

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Abstract — The authors present the results of a study which investigates the temperature dependence of the spectral responsivity of WPVS reference cells and its influence on measurement uncertainties for performance measurements beyond standard test conditions (STC). Five crystalline unfiltered reference cells from three different manufacturers were spectrally characterized at different temperatures. The authors calculated the temperature coefficient of the reference cells at different wavelengths and temperature ranges and showed significant deviations from the temperature coefficient of the calibration certificate. However, it is shown that the tested commercial reference cells have a non-linear behavior for a temperature range of 25 to 60°C and therefore they cannot be used for measurements at high temperatures e.g. outdoor applications or temperature coefficient measurements. The report demonstrates how this affects performance measurements above 25°C.

Index Terms — reference cells, temperature coefficients, performance measurements

I. INTRODUCTION

WPVS (World PhotoVoltaic Scale) reference cells are used in indoor or outdoor measurements to detect the total irradiance and to correct a current-voltage (I-V) curve to the standard reference value of total irradiance, i.e. 1000 W/m² for terrestrial applications.

Reference cells are calibrated at 25°C and to the standard spectrum AM1.5g. The calibration certificate often provides a temperature coefficient of the short circuit current (Isc) determined in a limited temperature range (e.g. 20-30°C). Moreover, those reference cells could be also used for outdoor module characterization as well as for temperature coefficient (TC) measurements, with cell temperature up to 65°C or higher.

However, the TC of the short circuit current of PV modules is a critical parameter because it is used for temperature correction in e.g. production lines or laboratories. Measurement campaigns among different institutes show deviations of up to ±80% in Isc temperature coefficient measurements [1]. However, we could observe measurement artefacts and differences up to 30-60% in the TC of the short circuit current α(Isc) and up to 3% in the TC of the power γ(Pm) of the device under test (DUT), if the reference cell is operating above 40°C.

To investigate the temperature behavior of the different WPVS reference cells and its influence on performance measurements at temperatures above 25°C, the experiment is divided into the following three steps.

A. Spectral responsivity at different temperatures

The SR is measured on a filtered light source with 28 narrow band-pass filters from 360 to 1200nm. The SR measurements were taken for all cells in a temperature range from 25 to 60°C with 5°C steps.

II. SUPPORTING EXPERIMENTS

For this study, five crystalline unfiltered reference cells from three different manufacturers were spectrally characterized at different temperatures. The reference cells are encapsulated in a WPVS design [3] and all meet the requirements of IEC 60904-2. Table I shows an overview of the tested reference cells.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Manufacturer</th>
<th>Cal. value [mV/(kW/m²)]</th>
<th>α(Isc) [ppm/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. cell 1</td>
<td>Manufacturer A</td>
<td>122.73</td>
<td>465</td>
</tr>
<tr>
<td>Ref. cell 2</td>
<td>Manufacturer A</td>
<td>123.98</td>
<td>469</td>
</tr>
<tr>
<td>Ref. cell 3</td>
<td>Manufacturer B</td>
<td>126.84</td>
<td>540</td>
</tr>
<tr>
<td>Ref. cell 4</td>
<td>Manufacturer B</td>
<td>126.04</td>
<td>540</td>
</tr>
<tr>
<td>Ref. cell 5</td>
<td>Manufacturer C</td>
<td>141.10</td>
<td>450</td>
</tr>
</tbody>
</table>

It is well-known how the temperature affects directly the bandgap of semiconductors: as a result, the spectral responsivity (SR) of PV cells varies with temperature, as has already been reported in the literature (see for example Müllejans et al. [2]). This work presents the results of a study which investigates the influence of the temperature dependence of the spectral responsivity of WPVS reference cells on measurement uncertainties for performance measurements at high temperatures.
B. Calculation of temperature coefficient \( \alpha(\text{Isc}) \) in different wavelength and temperature regions

The Isc of the reference cells and its temperature coefficient \( \alpha(\text{Isc}) \) were calculated from the following equation:

\[
\text{Isc} = A \int_{a}^{b} \text{SR}_{\text{Ref.-cell}}(\lambda) \cdot E_s(\lambda) \cdot d\lambda
\]

Where \( A \) is the cell area and \( \text{SR}_{\text{Ref.-cell}}(\lambda) \) is the SR of the tested reference cell in the following configurations: with two different spectra \( E_s(\lambda) \) (Xe-lamp and the standard AM1.5g); between the wavelength limits \( (a \) and \( b) 300-1200 \text{ nm}, 300-900 \text{ nm} \) and \( 900-1200 \text{ nm}; \) and for two different temperature ranges \( 25-35^\circ\text{C} \) and \( 40-60^\circ\text{C}. \)

C. Performance measurement of a c-Si module at different temperatures with the current values given by point B

To verify the influence of the calibration value of the reference cell and its TC, I-V curves of a standard c-Si module are measured with a class AAA pulsed solar simulator at different temperatures. The module is mounted in a thermal chamber where the temperature can be stabilized at any temperature between 15 and 75\(^\circ\text{C}\). For this study I-V curves were taken every 5\(^\circ\text{C}\) between 25 and 60\(^\circ\text{C}\). The obtained Isc from paragraph ii and the one provided by the calibration certificate were used as calibration values of the reference cells. The reference cell and the device under test have equivalent temperatures during the test. To exclude the influence of the temperature behavior of the reference cell, the measurement was repeated with the reference cell stabilized at 25\(^\circ\text{C}\).

III. RESULTS AND DISCUSSION

A. Spectral responsivity at different temperatures

Fig. 1 shows the SR between 25 and 60\(^\circ\text{C}\) of one of the tested reference cells as well as the standard spectrum AM1.5g [4] and the spectrum of the pulsed solar simulator used (Xe source). Due to the decrease of the bandgap with increasing temperature, the deviations from the value at 25\(^\circ\text{C}\) increase with higher wavelengths and higher temperatures.

Fig. 1. SR at different temperatures of reference cell 01, AM1.5g spectrum according to IEC 60904-3 (purple) and spectrum of the used pulsed solar simulator with xenon lamps (blue).

Fig. 2 shows the change of the measured SR with temperature for specific wavelengths. The differences for wavelengths \( \leq 900 \text{ nm} \) are less than \( \pm 1\% \) for all tested reference cells. Instead for wavelengths \( > 900 \text{ nm} \) the differences are between 10 to 35\%. For one cell a difference of up to 60\% could be observed for the measurement at 1172 nm, as shown in Fig. 2.

Fig. 2. Change of SR with temperature for specific wavelengths between 900 and 1172 nm of ref. cell 2. SR is normalized to the value at 25\(^\circ\text{C}\).

B. Calculation of temperature coefficient \( \alpha(\text{Isc}) \) in different wavelength and temperature regions

The box plot diagrams in Fig. 3 show the calculated TC for the short-circuit current of the tested reference cells in two temperature regions (25-35\(^\circ\text{C}, 40-60^\circ\text{C}\)) and three different wavelength bands (300-1200 nm, 300-900 nm, 900-1200 nm) compared to the one provided by the calibration certificate. The TCs were calculated with the Isc obtained with (a) the standard spectrum AM1.5g and (b) the spectrum of the pulsed solar simulator with Xe lamp (class AAA).

Both calculated TCs from the SR data show deviation from the certificate in the specified temperature and wavelength.
ranges. The calculations show lower TC values for temperature < 40°C and wavelengths < 900 nm and higher values with increasing temperature and wavelengths. Moreover, TCs calculated with the flasher spectrum show 50% higher values for higher temperature as the one calculated with AM1.5g.

![Box plot of temperature coefficient α(Isc) of the five tested reference cells for two selective temperature regions and selective wavelengths determined with (a) standard spectrum AM1.5g and (b) spectrum of pulsed solar simulator with Xe lamps (class AAA) in comparison to the calibration certificate.](image1)

Fig. 3. Box plot of temperature coefficient α(Isc) of the five tested reference cells for two selective temperature regions and selective wavelengths determined with (a) standard spectrum AM1.5g and (b) spectrum of pulsed solar simulator with Xe lamps (class AAA) in comparison to the calibration certificate.

![Normalized Isc of the reference cell 1. The blue squares are the Isc obtained with the temperature coefficient of the calibration certificate; the red squares are the calculation from SR with the standard spectrum AM1.5 and the green triangles are the calculation from SR with the flasher spectrum.](image2)

Fig. 4. Normalized Isc of the reference cell 1. The blue squares are the Isc obtained with the temperature coefficient of the calibration certificate; the red squares are the calculation from SR with the standard spectrum AM1.5 and the green triangles are the calculation from SR with the flasher spectrum.

C. Performance measurement of a c-Si module at different temperatures with the current values given by point B

Fig. 5 shows the Isc of a c-Si module obtained from I-V curve measurements at different temperatures by using (a) the calibration value of the reference cell corrected with the TC provided by the calibration certificate (Table I), (b) calibration value obtained from SR data with the flasher spectrum and (c) the reference cell stabilized at 25°C during the entire measurement.

In case (a) we see a slight decrease of the measured irradiance with higher temperature. The Isc of the DUT decreases as well slightly with higher temperature. The determined TC of Isc is 725 ppm/K. In case (b) if the calibration value from SR data is used or rather in case (c) if the reference cell is stabilized at 25°C the irradiance is stable over the entire temperature range and thus no measurement artefacts could be observed. The determined TC is 575 ppm/K. The resulting TC of the short circuit current is for case (a) 26% higher in comparison to case (b) and (c).

Table II summarized the temperature coefficient measurements with all tested reference cells. It is clearly visible that all tested reference cells are showing the same difference of about 27% between the measurement where the reference cell is operating at temperature between 25 - 60°C and measurements where the reference is operating at 25°C or rather the SR data is used. Only ref. cell 02 shows a higher deviation of 67%. However, the TCs of the open circuit voltage and the module power are less affected. Differences of ±2% and ±3% (with an outlier of 9%) for β(Voc) and γ(Pm) respectively.
Fig. 5. Results of I-V measurements at different temperatures. The purple dots represent the irradiance measured by the reference cell using the calibration value corrected with TC provided by calibration certificate, case (a), and the red squares are the corresponding Isc of the DUT. The green triangles are the irradiance by using the calibration value obtained from SR data, case (b), or rather if the reference is stabilized at 25°C, case (c). The yellow dots and the blue squares are the corresponding Isc values of the DUT for case (b) and (c) respectively. The Isc of the DUT is normalized to the value at 25°C.

### TABLE II
RESULTS OF TC MEASUREMENTS OF A C-Si MODULE WITH THE FIVE TESTED REFERENCE CELLS.

<table>
<thead>
<tr>
<th>Cell</th>
<th>α [ppm/K]</th>
<th>β [ppm/K]</th>
<th>γ [ppm/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. cell 1</td>
<td>725</td>
<td>-3210</td>
<td>-4392</td>
</tr>
<tr>
<td>Ref. cell 2</td>
<td>965</td>
<td>-3184</td>
<td>-4053</td>
</tr>
<tr>
<td>Ref. cell 3</td>
<td>740</td>
<td>-3221</td>
<td>-4324</td>
</tr>
<tr>
<td>Ref. cell 4</td>
<td>726</td>
<td>-3205</td>
<td>-4275</td>
</tr>
<tr>
<td>Ref. cell 5</td>
<td>704</td>
<td>-3206</td>
<td>-4335</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ref. cell at 25°C / from SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell</td>
</tr>
<tr>
<td>Ref. cell 1</td>
</tr>
<tr>
<td>Ref. cell 2</td>
</tr>
<tr>
<td>Ref. cell 3</td>
</tr>
<tr>
<td>Ref. cell 4</td>
</tr>
<tr>
<td>Ref. cell 5</td>
</tr>
</tbody>
</table>

### IV. CONCLUSIONS

The results show that the calibration values or rather the temperature coefficients of the five tested reference cells for different wavelengths and temperatures differ from the one provided by the calibration certificate. Furthermore, if a pulsed solar simulator with Xe lamps (e.g. class AAA) is used the calculated TC of the reference cells for temperatures above 40°C is 50% higher than the calculation with a standard spectrum AM1.5g. This could mostly be explained due to the Xe peaks in the wavelength range 900 to 1200nm and the spectral mismatch to the standard spectrum.

Performance measurements at different temperatures have shown that the short-circuit current and thus the temperature coefficient of the device under test is highly overestimated if the reference cell is operating above 25°C and a standard temperature coefficient is used. TC measurements where the reference cell is operating at temperature between 25 - 60°C and measurements where the reference is operating at 25°C or rather the SR data is used, show differences of up to 27% in α(Isc). The TC of the Voc and Pm are less affected.

Moreover, the results show that the tested commercial reference cells are non-linear for a temperature range of 25 to 60°C. Therefore, they cannot be used for measurements at high temperatures e.g. outdoor applications or temperature coefficient measurements without knowing the exact temperature behavior of the cell.

However, the authors recommend performance measurements behind STC such as TC measurements with reference cells stabilized at 25°C only.

### REFERENCES


