New Developments in the Field of Primary Calibrations of Reference Solar Cells

29.10.2015
Overview

- Demand for high accuracy solar cell calibrations
- Standard Test Conditions
- DSR Method
- The new PTB setup: Advantages and disadvantages
- Validation by International Comparisons => WPVS
Economic Impact of Measurement Uncertainty for Photovoltaics

- Financial uncertainty = Global annual installation × Price × Uncertainty
- 2012: Financial uncertainty = 30 GW/year × 1.7 €/W × 1% = 500 M€/year

⇒ A measurement uncertainty of 1% leads to a financial uncertainty of 500 M€/year
⇒ High demand for high accuracy solar cell calibrations

Solar parks are financed from banks, who add the financial uncertainty arising from measurement uncertainty to the total amount to be financed. A low uncertainty leads to competitive advantage.
Economic Impact of Measurement Uncertainty for Photovoltaics

To achieve lower uncertainties, in addition more realistic standards are needed

⇒ Energy rating instead of Maximum Power for PV classification (EMRP-Project PhotoClass)
⇒ Energy rating approach needs much more parameters

- Temperature dependence
- Non-Linearity
- Angular dependency

\[\text{System prices for end customers in Euro/Watt}\]

\[\text{Prices in Euro/Watt}\]

\[\text{New PV installations}\]

\[\text{Yearly worldwide newly installed PV Power / GW}\]

Source of data: EPIA (European Photovoltaic Industry Association) and for 2015 according to IHS market research institute
Standard Test Conditions

- Reference solar spectrum AM1.5
- Irradiance $E_{STC} = 1000 \text{ W/m}^2$
- Cell-Temperature (25°C)
- Angular distribution important, but not defined

The calibration procedure must take into account these STC according to IEC 60904-3.
Metrological background

Reference solar spectrum AM1.5 according to IEC 60904-3:2008

Spectral responsivity of different solar cells

Photocurrent: \[ I = \int E_{\lambda,\text{Norm}}(\lambda) \cdot s(\lambda) \, d\lambda \]
Metrological background

Reference solar spectrum AM1.5 according to IEC 60904-3:2008

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Photocurrent: \[ I = \int E_{\lambda, \text{Norm}}(\lambda) \cdot s(\lambda) \, d\lambda \]
Comparison of integral and spectral measurements

<table>
<thead>
<tr>
<th>Integral Measurement</th>
<th>Spectral Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum cannot be interpolated</td>
<td>Spectral responsivity can be interpolated</td>
</tr>
<tr>
<td>Uncertainty due to the measurement of the spectrum, e.g. spectral straylight within the spectroradiometer</td>
<td>The AM1.5 spectrum of the standard can be used directly =&gt; No uncertainty component</td>
</tr>
<tr>
<td>High signal</td>
<td>Low signal</td>
</tr>
</tbody>
</table>

Photocurrent: \( I = \int E_{\lambda, \text{Norm}}(\lambda) \cdot s(\lambda) \, d\lambda \)
DSR-Method
Differential Spectral Responsivity

Bias radiation $E_b$

Modulated monochromatic radiation, measured with Ref.-PD

Solar cell

DC-Multimeter + Lock-In-Amplifier

$I_b + \Delta I_{sc}(\lambda, E_b)$

\[ \tilde{s}(E_b) = \frac{\Delta I(\lambda, E_b)}{\Delta E} \]

\[ \Delta E \ll E_b \rightarrow \frac{dI}{dE} \]
Result of DSR measurement

Absolute differential spectral responsivity
\( \tilde{s}(\lambda, I(E)) \) of polycrystalline Si solar cell

\[
\tilde{s}_{\text{abs}} \text{ in } \frac{\text{mA}}{\text{W/m}^2} 
\]

\[
\int E_{\text{AM1.5}}(\lambda) \tilde{s}(\lambda) \, d\lambda 
\]

\[
\tilde{s} \text{ in } \frac{\text{mA}}{\text{W/m}^2} 
\]

\[
E \text{ in W/m}^2 
\]

\[
\text{I in mA} 
\]

\[
\text{E in W/m}^2 
\]

\[
\text{I in mA} 
\]

\[
\text{Polycrystalline Si} 
\]

\[
S = \frac{I_{\text{STC}}}{\int_0^{I_{\text{STC}}} \frac{1}{\tilde{s}(I)} \, dI} 
\]

Polycrystalline Si
Calibration objects

Reference solar cells

Component solar cells for Space Application
Laboratory method instead of balloon flight

![Graph showing spectral responsivity of different solar cell types](image)
Calibration objects

Industry solar cells

![Image of solar cells](image_url)

Graph showing the spectral sensitivity of solar cells with varying intensities and wavelengths. The graph includes a legend indicating different intensities and wavelengths used in the calibration process.

Values for intensity (I) and wavelength (λ) are given in the legend:
- I = 27.4 mA (30)
- I = 191.6 mA (32)
- I = 1010.1 mA (34)
- I = 2887.4 mA (35)
- I = 4481.8 mA (36)
- I(λ, 1000 W/m²) (37)

The x-axis represents the wavelength (λ) in nm, while the y-axes show the absolute differences in spectral sensitivity (Δs) and relative uncertainty (k=2) in mA/W/m².
Validation of the DSR method for non Si responsivities

- Comparison of component solar cells with “extraterrestrial” calibration by ESA
- The results agree within 0.4% and 0.6%.

Realisation und maintainance of the „World Photovoltaic Scale“
EURAMET supplementary comparison S.5

- Started in 2013, Draft A this year
- Star-like order: Participant -> PTB -> Participant
- Calibration of $I_{sc}$ under STC
- Participants
  - PTB (Coordinator)
  - VNIIOFI
  - KRISS
  - A*STAR
  - ITRI
  - NIM
- Asked for participation in the next round: NIST
How to measure the Differential Spectral Responsivity

- **Xenon or quartz halogen lamp based system** (DSR, SCF)
  (or laser-driven xenon lamps or supercontinuum systems)

  + Easy to use
    - Low Power (100 µW) with subsequent problems
      - Uniformity
      - Large bandwidth
      - Bad Signal-To-Noise especially at high bias levels
      - Rel. & abs. measurement needed
      - Size of the solar cells is limited

S. Winter, T. Wittchen, J. Metzdorf in Proc. 16th EU PVSEC, (Glasgow 2000)
The new Laser-DSR setup

- Tunable laser substitutes lamps
  - Power increases up to a factor 100 – 10000
    + Good uniformity
    + Low bandwidth possible
    + No interpolation between relative and absolute measurement

Modelocked Ti:Sapphire laser

Optical parametric Oscillator (OPO), SHG, THG, FHG

Pulsed with 80 MHz

680 nm – 1080 nm

190 nm – 4000 nm

Pulse-to-CW converter

Bandpass limitation (monochromator)

Many further improvements in detail
Design of the new Facility

Electronic
x,y,z-Table
Φ-θ-Goniometer
Biasradiator
Compact Array Spectroradiometer
Scientist
Pulse-to-CW Convertor (Fiber)
Chopper
PhD-Student
Climate Chamber
Optics (Lenses, Apertures, Monitor photodiode)
Monochromator
Lasersystem (Ti:Saphir Laser, OPO, SHG, THG, FHG)
Laser-DSR- Facility: From Design to Realisation
Measurement results: Radiation power

- Factor 100-10,000 higher optical power than with the old facility
- Spectral range 200-1600nm

![Graph showing radiation power vs. wavelength and photon energy.]

- GW: switch of monochromator grating
  - DSR Xenon lamp, incident on solar cell, measured with Si-PD
  - DSR FEL-lamp, incident on solar cell, measured with thermocolumn
  - LDSR, incident on solar cell, measured with powermeter
  - LDSR, direct laser output, measured with powermeter
Conclusion

- DSR method is well suited for the primary calibration of different types of solar cells
- The method is validated for many different stable single junction solar cells
- PTB develops the next-generation of the DSR facility: LASER-DSR
- The high power improves the signal to noise ratio and enables higher resolution and better uniformity
- It is a multipurpose spectral comparison facility.

\[ s = s(\lambda, E, f_{\text{Chopper}}, T, x, y, z, \varphi, \theta) \]
Conclusion

Thank you for your attention

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“Towards an energy-based parameter for photovoltaic classification”
The new Laser-DSR setup

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  - 190 nm – 4000 nm

- Pulse-to-CW converter

- Absolute spectral responsivity

- Bias lamps with dichroic mirrors for absolute calibration

- Bandpass limitation (monochromator)
Why do we need a monochromator behind the laser?

- Laser peak:
  - FWHM = 9.5 nm
- Behind monochromator:
  - FWHM = 2.8 nm
The new Laser-DSR setup

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Pulsed with 80 MHz

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Pulse-to-CW Converter

Absolute spectral responsivity

Bias lamps with dichroic mirrors for absolute calibration

Monitor photodiode
Pulse to cw converter

Fiber bundle with 100 multimode fibers, each with an individual length

\[ L_0 = l_0 \]
\[ L_1 = l_0 + 2.5 \text{ cm} \]
\[ L_2 = l_0 + 5.0 \text{ cm} \]
\[ L_3 = l_0 + 7.5 \text{ cm} \]
...  
\[ L_{99} = l_0 + 247.5 \text{ cm} \]

\[ t_0 = t_0 \]
\[ t_1 = t_0 + 0.125 \text{ ns} \]
\[ t_2 = t_0 + 0.250 \text{ ns} \]
\[ t_3 = t_0 + 0.375 \text{ ns} \]
...  
\[ t_{99} = t_0 + 12.375 \text{ ns} \]

And after 12.5 ns the next pulse from the laser appears.
Pulse to cw converter

Fiber 1

Fiber 1, 33 and 66

Fiber 1, 25, 50 and 75

Fiber 1 and Fiber 50
Pulse to cw converter

All 100 fibers