Impact of Spectral Irradiance on Energy Yield of PV Modules Measured in Different Climates

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# Agenda

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Introduction

PV module performance characteristics and environmental factors influence the energy yield: **How big is the impact of spectral effects?**

- Commercial available PV modules have different spectral response (SR)
- Real outdoor spectrum for PV module characterization differs from AM1.5 spectrum used in the lab (IEC 60904-3)
- Reliable spectral irradiance data for different locations are not available
- Impact of spectral irradiance on energy yield prediction is unclear
Introduction

- TÜV Rheinland is operating **five test sites** in different climates
- **15 PV module types** under test (3x CdTe, 4x CIGS, 3x a-Si, 5x c-Si)
- **One year spectral irradiance data of four test sites available**

New test-site: Thuwal (Saudi-Arabia)
Introduction

- Results for optimal mounting conditions – test sites tilted and facing south
  - Measurements in plane of array
  - 300 nm – 1600 nm
  - 1 min data recording interval
  - Identical setup at 5 test locations
  - Calibration by TÜV Rheinland in intervals of one year
Spectral Response Measurements

- Spectral response measurement according to IEC 60904-8
- Monochromatic light beam on 5 x 5 cm² from 280 – 1700 nm
- Non-destructive on PV module level
- Down to 1nm step-size also for multi-junction PV devices

Spectral Response Measurements

- Commercial available PV modules show different spectral response (SR) also variation within one module type

- Some CIGS samples work till 1300nm → shall be covered by spectral irradiance measurements

- Differences for c-Si mainly caused by cell quality and front glass type

- CdTe and a-Si most sensitive for spectral shifts

Normalized spectral response signal of the tested sample types
Spectral Response Measurements

Cut-out of an electroluminescence image (50 x 90 cm²) of a CIGS thin-film PV module with inhomogeneous deposition and the resulting spectral response curves measured.

- Absolute and relative spectral response signal can vary within one module.
- Inhomogeneous gas deposition during processing can lead to different spectral mismatch factors and to an increase of $P_{\text{Max}}$ measurement uncertainty of up to 1.7.
Outdoor Spectral Irradiance Measurements

Analysis with average photon energy factor (APE):

\[
APE = \frac{\int_{a}^{b} E_i(\lambda) d\lambda}{q_e \int_{a}^{b} \Phi_i(\lambda) d\lambda}
\]

- Blue shift in summer
- Red shift in winter
- Great daily spread

APE values calculated out of one year spectral irradiance data measured in Tempe

\[1.65\text{eV} = \text{AM1.5}\]
Outdoor Spectral Irradiance Measurements

Factors influencing spectral irradiance:
Clouds, AirMass (AM), Mounting Direction, Location, Aerosols

APE depending on daytime for clear sky days in winter (17.01.14) and summer (26.07.14), test-site: Tempe

APE depending on Angle of Incidence (AoI) and AirMass (AM) for clear sky days in Tempe
Outdoor Spectral Irradiance Measurements

- Annual average spectral irradiance near AM1.5, influence of clouds high for Cologne and Chennai

- Seasonal and daily shifts compensate for single-junction devices over the year and play a minor energetic role

- Measuring uncertainty unknown, e.g.: different angular response of spectroradiometer input optics and module under test

- Long-term data needed to estimate differences between years
Impact on Performance and Energy Yield

Spectral Mismatch Factor according to IEC 60904-7:

\[
\text{MMF} = \frac{\int E_{\text{Simulator}}(\lambda) \cdot SR_{\text{Sample}}(\lambda) d\lambda}{\int E_{\text{AM1.5}}(\lambda) \cdot SR_{\text{Reference}}(\lambda) d\lambda} \cdot \frac{\int E_{\text{AM1.5}}(\lambda) \cdot SR_{\text{Sample}}(\lambda) d\lambda}{\int E_{\text{Simulator}}(\lambda) \cdot SR_{\text{Reference}}(\lambda) d\lambda}
\]

Spectral effects can be corrected to STC for I-V curve data to track PV module stability more precisely.

Thermopile pyranometer and CdTe spectral response with respect to the AM1.5G standard spectrum and annual average spectrum of Tempe.

STC correction of top-limiting a-Si/a-Si PV module data.
Impact on Performance and Energy Yield

**MMF of PV module using annual average spectral data describes photo current gains (= energy yield gains) caused by spectrum:**

<table>
<thead>
<tr>
<th>Sample type</th>
<th>MMF Cologne</th>
<th>MMF Ancona</th>
<th>MMF Chennai</th>
<th>MMF Tempe</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si 1</td>
<td>1,3%</td>
<td>0,5%</td>
<td>1,6%</td>
<td>-0,8%</td>
</tr>
<tr>
<td>c-Si 2</td>
<td>1,3%</td>
<td>0,5%</td>
<td>1,6%</td>
<td>-0,8%</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>CIGS 4</td>
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<td>0,7%</td>
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<td>-0,1%</td>
</tr>
<tr>
<td>CdTe 1</td>
<td>2,3%</td>
<td>0,9%</td>
<td>5,3%</td>
<td>1,1%</td>
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<tr>
<td>CdTe 2</td>
<td>2,3%</td>
<td>0,9%</td>
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</tbody>
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Impact on Performance and Energy Yield

How big is the influence of spectral effects relative to others?

Module performance ratio (MPR) shows how well the PV modules perform in operation compared to STC efficiency:

$$ MPR = \frac{\left( \sum_{1\text{Year}} P_{MAX} \right) / P_{STC}}{\left( \sum_{1\text{Year}} G_{POA} \right) / 1000\text{Wm}^{-2}} $$

STC: 1000 W/m², 25°C, AM1.5
Impact on Performance and Energy Yield

Loss mechanisms $\Delta MPR$ for operation of PV modules in different climates:

Results of laboratory measurements and measured meteorological data:

$$ MPR_{\text{Calculated}} = 100\% - \Delta MPR_{\text{TEMP}} \pm \Delta MPR_{\text{LIRR}} - \Delta MPR_{\text{SOIL}} \pm \Delta MPR_{\text{MMF}} - \Delta MPR_{\text{AOI}} \pm \Delta MPR_{\text{Meta}} $$

- $\Delta MPR_{\text{TEMP}}$: Deviation of average irradiance weighted module temperature to STC (25°C) x $P_{\text{MAX}}$ temperature coefficient
- $\Delta MPR_{\text{LIRR}}$: Sample $\eta_{\text{rel.}}(G) \times$ irradiance profile of the test site
- $\Delta MPR_{\text{MMF}}$: MMF of $SR_{\text{Sample}}$ and annual average spectral irradiance
- $\Delta MPR_{\text{SOIL}}$: Ratio between a clean and a soiled reference cell
- $\Delta MPR_{\text{AOI}}$: Deviation of angular response curves between reference and test sample
- $\Delta MPR_{\text{Meta}}$: Metastable impacts on electrical output power. *Can’t be calculated!*
Impact on Performance and Energy Yield

- Highest avg. module temperature in Chennai 42.4°C → $\Delta MPR_{\text{TEMP}}$: -5.3% to -9.6%
- Low irradiance behavior most pronounced in Cologne → $\Delta MPR_{\text{LIRR}}$: +1.1% and losses of -3.6%
- Spectral impact $\Delta MPR_{\text{MMF}}$ mostly positive and high for CdTe technologies with a spectral gain of up to 5.3% (Chennai)
- Max. $\Delta MPR_{\text{SOIL}}$ observed in Tempe → -3.7% soiling loss per year
- $\Delta MPR_{\text{AOI}}$ comparable for all test sites < -1.3%
Conclusions

- Great seasonal and daily spectral irradiance shifts almost compensate for energy weighted one year data
- Spectral effects are most important for CdTe (+5.3 % gain in photo current in Chennai)
- Impact of spectral irradiance on energy yield plays a minor role for c-Si (max. +1.6 % in Chennai), for CIGS it depends on the manufacturer
- **Outlook:** Further results and evaluation of 1 year data from Thuwal

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Thank you for your attention!