Comparison of PV Module Technologies from Field Data at Different Locations

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Outline

• Approach
• Method to analyse outdoor data
• Results of technology comparison
• Conclusion
Approach

Comparison of outdoor data of:

- different PV module technologies
- different locations & climates
- different measurement setups
  - frequency of data recording (10 sec, 1, 5, 10, 15 min)
  - accuracies
  - MPP tracking, I-V curve
  - cleaning procedures of sensors and modules
  - periods of outdoor measurements
- different origin of STC parameters (nameplate $P_m$ and $I_{sc}$, indoor or outdoor measured values)

Increase comparability through

- Harmonised and easy to exchange data format
## Overview of Field Data

<table>
<thead>
<tr>
<th>Location</th>
<th>Technologies</th>
<th>Period of Measurements</th>
<th>Sampling rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cologne (TUV)</td>
<td>c-Si, a-Si/μc-Si, CIGS, CdTe</td>
<td>8/2011 – 7/2012</td>
<td>10 min</td>
</tr>
<tr>
<td>Denver (NREL)</td>
<td>c-Si, CIGS</td>
<td>08/2002 – 08/2003</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a-Si/a-Si</td>
<td>01/2004 – 12/2004</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c-Si, a-Si, aSi-aSi Ge, CIGS,</td>
<td>01/2011 – 12/2011</td>
<td>15 min</td>
</tr>
<tr>
<td></td>
<td>CdTe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadarache (INES)</td>
<td>c-Si, a-Si/a-Si/a-Si, CIGS, CdTe</td>
<td>06/2010 – 05/2012</td>
<td>5 min</td>
</tr>
<tr>
<td>Lugano (SUPSI)</td>
<td>c-Si</td>
<td>03/2011 – 08/2012</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a-Si/μc-Si, CIGS, CdTe</td>
<td>09/2011 – 08/2012</td>
<td>5 min</td>
</tr>
<tr>
<td>University of Agder</td>
<td>c-Si, a-Si/a-Si/a-Si, CIS</td>
<td>12/2010 – 12/2012</td>
<td>1 min</td>
</tr>
<tr>
<td>CREST (UK)</td>
<td>c-Si, a-Si, a-Si/a-Si/a-Si, CIGS</td>
<td>01/2010 – 12/2011</td>
<td>5 /10 min</td>
</tr>
<tr>
<td>Cyprus</td>
<td>a-Si/a-Si</td>
<td>07/2012 – 07/2013</td>
<td>10 sec</td>
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</table>
## Common Data Format

<table>
<thead>
<tr>
<th>Description</th>
<th>Formulas</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day type</td>
<td>clear/cloudy/very cloudy</td>
<td></td>
</tr>
<tr>
<td>( H_{\text{poa}} )</td>
<td>daily in-plane (plane of array) irradiation</td>
<td>( \int G_{\text{pyr}} , dt )</td>
</tr>
<tr>
<td>avg. ( T_{\text{bom}} )</td>
<td>daily avg. daylight (G&gt;0) back of mod. temp.</td>
<td>( \sum T_{\text{bom}} / n )</td>
</tr>
<tr>
<td>avg. ( T_{\text{amb}} )</td>
<td>daily avg. daylight (G&gt;0) air temp.</td>
<td>( \sum T_{\text{amb}} / n )</td>
</tr>
<tr>
<td>( T_{\text{bom,w}} )</td>
<td>daily avg. irr.-weighted module temp.</td>
<td>( \sum T_{\text{bom}} \cdot G_{\text{pyr}} / \sum G_{\text{pyr}} )</td>
</tr>
<tr>
<td>PR (Pm)</td>
<td>daily performance ratio of Pmax</td>
<td>(( \sum P_{\text{m}} / P_{\text{m, stc}} ) / (( \sum G_{\text{pyr}} / 1000 ))</td>
</tr>
<tr>
<td>PR (Isc)</td>
<td>daily performance ratio of Isc</td>
<td>(( \sum \text{Isc} / \text{Isc, stc} ) / (( \sum G_{\text{pyr}} / 1000 ))</td>
</tr>
<tr>
<td>PR(_{\text{filt}}) (Pm)</td>
<td>daily performance ratio of filtered Pmax</td>
<td>(( \sum P_{\text{m}} / P_{\text{m, stc}} ) / (( \sum G_{\text{pyr}} / 1000 ))</td>
</tr>
<tr>
<td>PR(_{\text{filt}}) (Isc)</td>
<td>daily performance ratio of filtered Isc</td>
<td>(( \sum \text{Isc} / \text{Isc, stc} ) / (( \sum G_{\text{pyr}} / 1000 ))</td>
</tr>
</tbody>
</table>
Meteorological Distributions

Daily irradiation sums

Energetic distribution of daily irradiation

Daily average $T_{amb} \ (G>0)$

Average daily ambient temperature $[°C]$
Daily Performance Ratios of Pm

\[
PR(Pm) = \frac{\sum Pm}{\sum Pm_{stc}} / \frac{\sum G_{pyr}}{1000}
\]

(a-Si) vs. (c-Si) average T_bom [°C]

Average T_bom (°C)
Daily Performance Ratios of Pm

Folded Data* (January-December)

*stability is verified separately!
Daily Performance Ratios of $P_m$

$$PR (P_m) = \frac{\sum P_m}{P_{m, stc}}/\left(\frac{\sum G_{pyr}}{1000}\right)$$

**Impact factors:**

Meas. accuracies / technical effects
- Irradiance measurement
- $P_{m, stc}$
- Thermal effects
- Spectral effects
- Staebler-Wronsky effect (a-Si)

- **c-Si:** mainly affected by thermal effects
- **a-Si:** thermal effects are hidden by spectral and Staebler-Wronsky effect
Daily Performance Ratios of $I_{SC}$

$$PR (lsc) = \frac{\sum I_{sc}/I_{sc, stc}}{\sum G_{pyr}/1000}$$

Impact factors:
Meas. accuracies/technical effects
- Irradiance measurement
- $I_{sc, stc}$
- Spectral effects
- Thermal effects (neglectable)

- **c-Si**: almost not affected by spectral effects
- **a-Si**: affected by spectral effects
Normalization of PR(Pm) with PR(Isc) self reference approach

Impact factors:
Meas. accuracies / technical effects
- Irradiance measurement
- \( P_{m, stc} \)
- Spectral effects
- Staebler-Wronsky effect (a-Si)
- Thermal effects

\[ \text{PR(Isc)} = 1 \]

\[ \text{PR(Pm)} \]

\[ \text{norm. PR(Pm)} \]
Normalized Performance Ratios of $P_m$

**PR ($P_m$)**

**Norm. PR ($P_m$)**

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**c-Si**

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**a-Si**

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Normalized Performance Ratios of Pm

\[ \text{Norm. PR (Pm)} = \text{Norm.} \left( \frac{\sum P_m}{P_{m, stc}} \right) / \left( \frac{\sum G}{1000} \right) \]
Temperature Behaviour

Outdoor temperature coefficient of $P_m$ can be determined.

$\rightarrow$ Slope of graph: $TC \text{ c-Si} > TC \text{ a-Si}$
Low Irradiance Behaviour

- Thermal effects dominant for high irradiation days
- Low irradiance behaviour can be analysed by low irradiation days.
Conclusions

- Plots easy to be calculated from measured $G_{tilt}$, $T_{amb}$, $T_{bom}$ and I-V data
- No exchange of raw data required: Aggregated data are exchanged and compared from different sources.
- Plots allow easy comparison of technology and location with respect to:
  - Low irradiance behaviour
  - Temperature behaviour
  - Spectral effects (to be implemented)
  - Degradation/Recovery effects over the year
- Problems of correct determination of $P_{max}$, $I_{sc}$ and malfunction of sensors can be identified.
Acknowledgements

We like to acknowledge the following colleagues & labs for their data delivery and fruitful discussions:

• INES, & CEA, Cadarache, France
• EURAC, Bolzano, Italy
• UiA, University of Agder, Norway
• NREL, Denver, CO, USA
• CREST, University of Loughborough, UK
• UCY, University of Cyprus, Cyprus
Thank You for Your Attention!
Module energy yield data from test fields in different climates

G. Friesen
SUPSI, Switzerland
OBJECTIVES

1. Assess and harmonize measurement procedures, quality control and uncertainty calculations for outdoor module energy yield data.

2. Collect and give access to high quality module outdoor data from different climatic zones for the validation of module performance models and energy rating (DRAFT IEC61853 – part3).

3. Show technological dependent behavior in different climates.
APPROACH

1. Start from the work done in the old Task3.1 (Data Format with daily aggregates)
2. Collect needs from other partners
3. Complete e.g. with high resolution meteo data. spectral data, better module inputs
4. Find new contributors
5. Harmonize measurement procedures
6. Add error bars on measured data
7. Add Spectrum
8. Add Degradation
OUTPUT

- **Report**: “Long-term Photovoltaic Module Outdoor Energy Yield Measurements – existing approaches and equipment”
  
  (first draft: 12/2014; final draft: 06/2015)

- **Data**: “High quality data sets”
  
  (first draft: 04/2016; final draft: 10/2016)

- Conference and /or journal paper
## Participants

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<tr>
<th>Institution</th>
<th>PM/Year</th>
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<tr>
<td>TüV</td>
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<td>CAT (Australia)</td>
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<td>TorVergata</td>
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