Time evolution of PV soiling loss at test locations in different climates
Workshop on “Soiling Effect on PV Modules”
5 – 7 April 2016, Dubai, UAE

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Outline

- Introduction
- PV-KLIMA test locations
- Experimental approach for dust monitoring
- Results:
  - Soiling patterns for different climates
  - Impact of periodical cleaning for desert location
  - Angular transmission loss due to soiling
- Summary
Introduction – PV power loss due to soiling

- Dust deposition on PV modules is a complex phenomenon ⇒ Modelling requires better understanding of processes
- Dust accumulation on PV modules is very site-specific ⇒ Monitoring needed
- Economic operation of PV power plants requires periodical cleaning ⇒ O&M strategies to keep soiling loss below critical value

Photo: TÜV Rheinland Shanghai

Climatic impacts, dust concentration

Non-uniform soiling, glazing characteristics

Installation conditions

Surrounding environment, dust characteristics
PV-KLIMA Project (2012 – 2017)
Comparative energy yield testing of PV modules

Objective: Higher precision of energy yield prediction for various climates

Work programme:
- Comparative energy yield study of 15 PV modules (5 c-Si, 10 thin-film) in 5 climates
- PV module energy delivery: Impact of PV module characteristics, climatic impacts, soiling and degradation
- Provision of reference data sets for various climates
- Improvement of electrical models for PV devices

Partners: University of Oldenburg, Research Center Jülich

Funding: German Federal Ministry for Economic Affairs and Energy
PV-KLIMA Project
Test locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Country</th>
<th>Operation since</th>
<th>Köppen-Geiger climate classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ancona</td>
<td>Italy</td>
<td>01 Nov 2013</td>
<td>Cfa (mediterranean)</td>
</tr>
<tr>
<td>Tempe</td>
<td>Arizona/USA</td>
<td>15 Dec 2013</td>
<td>Bwh (hot desert)</td>
</tr>
<tr>
<td>Chennai</td>
<td>India</td>
<td>01 Feb 2014</td>
<td>Aw (tropical savanna, hot-humid/dry)</td>
</tr>
<tr>
<td>Cologne</td>
<td>Germany</td>
<td>01 Mar 2014</td>
<td>Cfb (temperate)</td>
</tr>
<tr>
<td>Thuwal</td>
<td>Saudi Arabia</td>
<td>11 Mar 2015</td>
<td>Bwh (hot desert, sandstorm impact)</td>
</tr>
</tbody>
</table>
### PV-KLIMA Project

#### Test Locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Tempe / Arizona</th>
<th>Chennai / Southeast India</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>TUV Rheinland PTL, LLC Tempe, AZ 85282</td>
<td>TUV Rheinland (India) Pvt. Ltd. Chennai 602117, India</td>
</tr>
<tr>
<td>Geographical position:</td>
<td>33.4°N / 111.9°W 358 m above sea level</td>
<td>13°N / 80°E 35 m above sea level</td>
</tr>
<tr>
<td>Inclination angle</td>
<td>33.5°</td>
<td>15°</td>
</tr>
<tr>
<td>Annual in-plane global</td>
<td>2360 kWh/m²</td>
<td>1860 kWh/m</td>
</tr>
<tr>
<td>solar irradiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average annual rainfall</td>
<td>219 mm</td>
<td>1597 mm</td>
</tr>
<tr>
<td>Surrounding environment</td>
<td>Industrial area, no vegetation</td>
<td>Rural environment, Farm land</td>
</tr>
</tbody>
</table>
# PV-KLIMA Project
## Test Locations

<table>
<thead>
<tr>
<th></th>
<th>Cologne / Germany</th>
<th>Ancona / Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>TUV Rheinland Group 51101 Cologne, Germany</td>
<td>Loccioni 60030 Angeli di Rosora, Italy</td>
</tr>
<tr>
<td><strong>Geographical position:</strong></td>
<td>50.6°N / 7.0°E 53 m above sea level</td>
<td>13°N / 80°E 35 m above sea level</td>
</tr>
<tr>
<td><strong>Inclination angle</strong></td>
<td>35°</td>
<td>35°</td>
</tr>
<tr>
<td><strong>Annual in-plane global solar irradiation</strong></td>
<td>1195 kWh/m²</td>
<td>1556 kWh/m²</td>
</tr>
<tr>
<td><strong>Average annual rainfall</strong></td>
<td>774 mm</td>
<td>757 mm</td>
</tr>
<tr>
<td><strong>Surrounding environment</strong></td>
<td>Urban environment, Flat roof of 5 storey building</td>
<td>Hilly landscape with grassland and forest, agricultural use</td>
</tr>
</tbody>
</table>
### PV-KLIMA Project

**Test Locations**

<table>
<thead>
<tr>
<th>Location</th>
<th>Thuwal / Saudi-Arabia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>KAUST, NEO Thuwal 23955-6900, Saudi Arabia</td>
</tr>
<tr>
<td><strong>Geographical position:</strong></td>
<td>22.3°N / 39.1°O 3 m above sea level</td>
</tr>
<tr>
<td><strong>Inclination angle</strong></td>
<td>25°</td>
</tr>
<tr>
<td><strong>Annual in-plane global solar irradiation</strong></td>
<td>2386 kWh/m</td>
</tr>
<tr>
<td><strong>Average annual rainfall</strong></td>
<td>70 mm</td>
</tr>
<tr>
<td><strong>Surrounding environment</strong></td>
<td>University ground, coastal environment</td>
</tr>
</tbody>
</table>
Experimental Approach
Measurement of soiling rate

- Side-by-side irradiance measurement with two mini-modules
  - Standard PV glazing, center cell operated in short circuit (reference cell)

\[
G_{\text{EFF}} = \frac{I_{\text{SC,MEAS}}}{I_{\text{SC,STC}}} \times \frac{1}{1 + \alpha \times (T_{\text{MOD}} - 25^\circ \text{C})} \times 1000 \text{ W/m}^2
\]

- Dust accumulation = Transmission loss \( \Rightarrow \) Lower effective irradiance \( G_{\text{EFF}} \) reaching the cells

- Daily Soiling Loss Factor (SLF\(_D\)) = Ratio of daily insolation “soiled” / “clean” cell

\[
SLF_D = \frac{\sum G_{\text{EFF,Soiled}}}{\sum G_{\text{EFF,Clean}}}
\]

SLF\(_D\) = 1:
Both mini-modules are clean
Results

- Average SLF decrease in dry periods: -0.08% to -0.25%

Annual soiling loss
2014: -3.60%
2015: -1.24%
Results

- Significant variability in soiling pattern for 1\textsuperscript{st} and 2\textsuperscript{nd} year
  ⇔ Frequency of rainfall, dust accumulation rate

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</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>26</td>
<td>50.4</td>
<td>0.859</td>
<td>-1.8%</td>
</tr>
<tr>
<td>2015</td>
<td>55</td>
<td>78.6</td>
<td>0.937</td>
<td>-1.5%</td>
</tr>
</tbody>
</table>

- Effective cleaning by rain: SLF recovery >99%
- No permanent soiling observed during exposure
- No indication of sandstorm ⇔ Daily dust accumulation rate <2%
Results

- Average SLF decrease in dry periods: -0.12% to -0.39% per day

Annual soiling loss
2014: -2.3%
2015: -6.5%

Minimal SLF in dry season:
2014: 0.931
2015: 0.751

Max. daily SLF decrease:
2014: -1.61%
2015: -2.21%
Results
Soiling pattern for Ancona/Italy: Nov 2013 – Mar 2016

- No variation in annual soiling pattern ±1% SLF variation

Annual soiling loss
- 2014: -0.1%
- 2015: -0.1%

Minimal SLF in dry season:
- 2014: 0.988
- 2015: 0.997

Max. daily SLF decrease:
- 2014: -0.45%
- 2015: -0.40%
Results

- Average daily SLF decrease: = -0.22% to -0.67%
Results

- **Sandstorm** ⇒ Max. daily percent decrease SLF = -7.7%

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Results

Dust accumulation characteristic

- Sandstorm Impact \(\Delta\)SLF < -2.5%
- Site specific dust accumulation
- Wind

Average = -0.47%
Standard deviation = 0.59%

Daily percent change of SLF

Frequency
Results

- PV installations in desert climate require periodical cleaning of PV modules to optimize the energy yield

Soiling loss in 20 weeks period:
-1.4%
Results
Impact of angle of incidence (AoI)

- Dust accumulation on the PV module cover glass changes its angular response
  - Soiling loss factor is not constant during the day but is “W” shaped
Results
Impact of angle of incidence (AoI)

- Soiling loss due to AoI effects is significant in desert climate
- Tempe: 25% of annual soiling loss is caused by angular transmission loss in the AoI range >20°
### Summary 1/3
Measuring results

<table>
<thead>
<tr>
<th></th>
<th>Average annual rainfall(^1)</th>
<th>Annual transmission loss due to soiling</th>
<th>Average daily SLF decrease in dry periods</th>
<th>Max. daily SLF decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tempe / Arizona</td>
<td>219 mm</td>
<td>2013: -3.6% 2014: -1.2%</td>
<td>-0.1% to 0.3%</td>
<td>-1.8%</td>
</tr>
<tr>
<td>Chennai / India</td>
<td>1597 mm</td>
<td>2013: -2.3% 2014: -6.5%</td>
<td>-0.1% to 0.4%</td>
<td>-2.2%</td>
</tr>
<tr>
<td>Ancona / Italy</td>
<td>757 mm</td>
<td>Approx. -0.1%</td>
<td>N/A</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Cologne / Germany</td>
<td>774 mm</td>
<td>Approx. -0.1%</td>
<td>N/A</td>
<td>-1.1%</td>
</tr>
<tr>
<td>Thuwal / Saudi-Arabia</td>
<td>70 mm</td>
<td>N/A</td>
<td>-0.2% to 0.7%</td>
<td>-7.7%</td>
</tr>
</tbody>
</table>

\(^1\) [http://de.climate-data.org](http://de.climate-data.org)
Summary 2/3
Principle effects

- **Self-cleaning effect:**

  Rainfall leads to nearly full recovery of PV module performance in case of dry dust.

  Permanent soiling can occur if humidity condensate sticks dust to the surface.

- **Soiling pattern:**

  Daily soiling loss factor (SLF$_D$) is a suitable parameter to describe the time-evolution of soiling loss $\Rightarrow$ Variation of dust accumulation rate

  Site specific soiling can be described by the frequency distribution of daily percent change of soiling loss factor.

  Modelling of PV electricity generation in desert climates requires dust monitoring over a representative period of time $\Rightarrow$ automated dust monitoring devices needed
Impact of soiling for various climates

- **Hot-dry climate:**
  - **Tempe:** Moderate dust settlement between rainfall events leads to annual performance loss <4%.
  - **Thuwal:** Considerable dust settlement and occasional rainfall events lead to substantial annual soiling loss. Economic operation of a PV power plant requires periodical cleaning.

- **Hot-humid/dry climate:**
  - **Chennai:** Considerable dust settlement during 3-months dry season leads to substantial soiling loss. Cleaning during dry season must be considered to improve the profitability of a PV power plant.

- **Temperate and Mediterranean climate:**
  - **Ancona, Cologne:** No measureable performance loss due to frequent rainfall.
Acknowledgements

The kind assistance of the following cooperation partners in operation and maintenance of the PV-KLIMA test sites is gratefully acknowledged.