Measuring PV System Soiling Losses

Bill Stueve
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www.atonometrics.com
About Atonometrics

- **Test & measurement** equipment for the PV industry
- A leader in **soiling measurement systems**
- Provided **500 soiling stations** worldwide on **100 sites**
- Founded in 2007 and based in Austin, Texas, USA
- **Patents:** 5 issued, 6 pending
Why Measure Soiling?

**Pre-construction site surveys:**
1. **Predict** future plant performance

**Operating PV plants:**
2. **Assess** actual performance
3. **Optimize** washing schedule Return on Investment
Basic Soiling Measurement Principle

Soiling Ratio = \( \frac{\text{Actual Output of Soiled PV}}{\text{Expected Output Based on Clean PV}} \)

Soiling Loss = \( SL = 1 - SR \)
Many Configurations – Cost / Accuracy

- Cell-Cell
- Module-Module
- Cell-Module

**Measurement Only**
- Manual Wash

**Isc Only**

**IV Curve and Pmax**

**Measurement**
- + Automatic Wash
Example: Cell-Module, with I-V, & Auto Wash

- **Clean Reference Cell**: Measure irradiance
- **Soiled Reference Module**: Sense soiling power loss
- **Daily Automatic Washing**

**Cell Wash System**
- (Reservoir, Pump, Level/Flow Sensors, Heaters)

**Measurement & Control Electronics**
- (Module IV Sweep, Cell Irradiance Measurement, Data Analysis, Wash Control)
Example: On Tracking Array
Example: Comparing Modules (Coatings, manufacturers, etc)
Data Output

• **Raw Data**
  – Current
  – Voltage
  – Power
  – IV Curves
  – Temperature (RTD)

• **Analyzed Data**
  – Soiling
  – Irradiance (from a calibrated device)
  – Temperature (Voc)
## Choices: Cell or Module?

<table>
<thead>
<tr>
<th></th>
<th>Cell</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Less rack space</td>
<td>• Captures true soiling effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• (Same glass, coatings, frames, wind, rain, etc.)</td>
</tr>
</tbody>
</table>
## Choices: Isc or Pmax?

| Isc (Short-Circuit Current) | • Simple to measure  
<table>
<thead>
<tr>
<th></th>
<th>• But not always proportional to output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pmax (Max Power)</td>
<td>• Tracks actual power output of modules in array</td>
</tr>
</tbody>
</table>
### Choices: Manual or Automated Washing?

<table>
<thead>
<tr>
<th></th>
<th>Manual</th>
<th>Automated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Lower <strong>up-front cost</strong></td>
<td>• Lower <strong>ongoing labor cost</strong></td>
</tr>
<tr>
<td></td>
<td>• <strong>Lower accuracy</strong> from weekly or fewer washings</td>
<td>• <strong>Better accuracy</strong> from daily washings</td>
</tr>
</tbody>
</table>
Uniform & Non-Uniform Soiling

• Uniform
  – Dust uniformly distributed across module

• Non-Uniform
  – Dust concentrated on specific parts of the module
  – Typically at module bottoms or edges
  – Rain, condensation, gravity, wind,...

Non-Uniform Soiling


Uniform vs. Non-Uniform – Effect on IV Curve

For non-uniform soiling: Isc may not track power loss

→ Pmax more accurate for non-uniform cases

Gostein¹, Littmann², Caron², Dunn¹, IEEE PVSC 2013
¹Atonometrics. ²First Solar.
Uniform vs. Non-Uniform – $I_{sc}$ vs. $P_{max}$

$I_{sc}$ loss can **over- or under-predict** soiling, based on non-uniformity

$\Rightarrow$ **$P_{max}$ measurement more accurate** for non-uniform cases

Gostein$^1$, Littmann$^2$, Caron$^2$, Dunn$^1$, IEEE PVSC 2013

$^1$Atonometrics. $^2$First Solar.
Incidence Angle Effect

Soiling loss can change by time of day

Soiling loss greater at high incidence angles
**Misalignment Artifact**

**Misalignment** (azimuth / tilt) causes measurement **artifact** – apparent changes by time of day.
Analysis: Soiling Ratio Metric

Soiling Ratio, measured once per minute:

\[ SR = \frac{\text{Measured Output}}{\text{Expected Output}} \]

\[ SR = \frac{P_{\text{soiled}}}{P_{\text{max},0}} \cdot \left(1 + \gamma \cdot (T_{\text{soiled}} - T_0)\right) \cdot \left(\frac{G}{G_0}\right) \]

Soiling Loss = SL = 1 - SR

Similar equation if using Isc instead of Pmax

Correct for temperature and irradiance

STC power rating

Temp. coef.

25 ºC

Clean Device Irradiance

1000 W/m²
Irradiance Stability – Need Sophisticated Data Analysis

Data filtering needed during times with fast-moving clouds
Analysis: Filtered Daily Average

**Daily Irradiance-Weighted Average Soiling Ratio:**

$$\langle SR \rangle_d = \frac{\sum SR \cdot G}{\sum G} \quad \text{Correct for time-of-day variation}$$

Filter points prior to average, to remove **outliers**

$$Soiling\ Loss = SL = 1 - SR$$
Analysis: Filtered Daily Average

[Graph showing Soiling Ratio with Time of day variation and Clouds indicated]

[Graph showing Irradiance (W/m²) with peaks on June 10 and June 12]

[Graph showing Rain with a significant amount on June 11]
Typical Data Features

- Soiling Accumulation: ~1%/week
- Cleaning from Rain
- Partial Clean
Incidence Angle & Alignment Effects

- Tilt alignment artifact
- Azimuthal alignment artifact
- Soiling loss angular dependence

Gostein\textsuperscript{1}, Caron\textsuperscript{2}, Littmann\textsuperscript{2}, IEEE PVSC, 2014
\textsuperscript{1}Atonometrics. \textsuperscript{2}First Solar
Long-Term Data Example – c-Si in U.S. Southwest

Fig. 2. Measured daily average values of the $SR^{ise}$ and $SR^{pmax}$ metrics (top) along with daily rainfall (bottom, y-axis limited to 10 mm) over a 24-month period. The four lettered arrows (a, b, c, d) indicate the days shown in the module photographs in Fig. 1.

Gostein$^1$, Stueve$^1$, Chan$^2$, 44th IEEE PVSC, 2017
$^1$Atonometrics. $^2$E-On Climate & Renewables
Soiling Method Comparisons – Utility Scale Focus

<table>
<thead>
<tr>
<th>System Type</th>
<th>Measured Parameter</th>
<th>Soiling Ratio Measurement Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Configuration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell-Module</td>
<td>Power</td>
<td>1-2%</td>
</tr>
<tr>
<td>Module-Module</td>
<td>Power</td>
<td>1-2%</td>
</tr>
<tr>
<td>Cell-Module</td>
<td>Current</td>
<td>3-5%</td>
</tr>
<tr>
<td>Module-Module</td>
<td>Current</td>
<td>3-5%</td>
</tr>
<tr>
<td>Cell-Cell</td>
<td>Current</td>
<td>4-7%</td>
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</tbody>
</table>
Power Plant Correlation – 5 CdTe Plants Worldwide

Fig. 3. Time-series plots of daily soiling ratio (thick line) and normalized weekly PPI (thin line) for the five PV power plants from April 2013 through April 2014. Bars show rainfall in mm (right axes).

Gostein¹, Caron², Littmann², IEEE PVSC, 2014

¹Atonometrics. ²First Solar
Soiling Method Correlations – PV vs. Pyranometers

Fig. 1. Monitoring Station with SR20 (Left), LP02-1 (center), LP02-2 (right), self-cleaning reference cell (foreground), and reference module (back right)
Soiling Method Correlations – PV vs. Pyranometers

Fig. 2. Measured daily average values of the soiling ratios for the POA PV module and thermopile pyranometer and daily rainfall.

Waters¹, Tirumalai¹, Gostein², Stueve² IEEE PVSC, 2017
¹Recurrent Energy, ²Atonometrics
Soiling measurements provide insight into plant performance

Compare “soiled” reference to “clean” reference
  – Note that modules/cells may soil differently

Wash the clean reference routinely

Non-uniform soiling affects Isc & Pmax differently
  – Measure both Isc & Pmax to get most complete information

Soiling loss measurement varies by time of day
  – Perform daily average, filtering out cloud movements