Seasonal Trends of Soiling on Photovoltaic Systems

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Soiling stations: common way to quantify soiling. Consist of two reference cells (or modules).

$$\text{daily Soiling Ratio} = \frac{I_{sc\text{-Soiled}}}{I_{sc\text{-Control}}}$$

(Avg. of 12PM and 1PM data, only POA irradiance > 500 W/m²)

$$\text{daily SRatio} = 1 \text{ at clean conditions, }$$
$$\text{daily SRatio} < 1 \text{ in soiling conditions.}$$
Particulate matter (i.e. concentration of particles suspended in air) has the best correlation with Sratio for long time periods (> 6 months) in the USA [1].

Parameters with the highest coefficient of determination when related to soiling ratios and soiling rates.

The identification of seasonal patterns is essential to determine the most adequate cleaning schedule.
Introduction: Aim

• Providing an instrument to quantify the seasonal soiling.

• Investigating, with a systematic approach, the seasonal soiling occurring at 15 different sites over a 12-month period.

• Analyzing the causes of seasonal soiling.
Introduction: Definition of seasonal soiling

Colwell [2], using the term “contingency,” defined seasonality as the degree to which time and states statistically dependent on each other.

Our aim is identifying how much soiling can vary in one year (“variability”) and which factors are driving these changes.

“Seasonality Index” (SI): parameter introduced in 1981 to describe the degree of variability in monthly rainfall through one year [3].

<table>
<thead>
<tr>
<th>SI</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.2</td>
<td>Very equable</td>
</tr>
<tr>
<td>≥ 0.2 and &lt; 0.4</td>
<td>Equable, but with a definite wetter season</td>
</tr>
<tr>
<td>≥ 0.4 and &lt; 0.6</td>
<td>Rather seasonal with a short drier season</td>
</tr>
<tr>
<td>≥ 0.6 and &lt; 0.8</td>
<td>Seasonal</td>
</tr>
<tr>
<td>≥ 0.8 and &lt; 1.0</td>
<td>Markedly seasonal, with a longer drier season</td>
</tr>
<tr>
<td>≥ 1.0 and &lt; 1.2</td>
<td>Most rain in 3 months or less</td>
</tr>
<tr>
<td>≥ 1.2</td>
<td>Extreme, almost all rain in 1–2 months</td>
</tr>
</tbody>
</table>

"Seasonality Index" has been adapted to describe the variability of soiling across a 12-month period and renamed as "Soiling Variability Index" (SVI).

\[
SVI\text{(site)} = \frac{\sum_{m=1}^{12} |S_m(m) - (S_{m\_sum}/12)|}{S_{m\_sum}}
\]

With the monthly soiling metric \((S_m)\) being:

\[
S_m(m) = \sum_{d=1}^{n_d} (1 - \text{dailySRatio}(d))
\]

\(S_m\) is 0 if no soiling occurred; otherwise, it is always greater than 0.
Quantifying the seasonal soiling: Soiling Variability Index.

As for the **Seasonality Index**, 

- the **Soiling Variability Index** varies
  - from 0 (**no variability**: same soiling occurring any month)
  - to 1.83 (**max variability**: all soiling accumulated in 1 month)

- No correction has been made to balance the different number of days among the various months.

*ideal cases*
Soiling Variability Index: Results

Soiling Variability Index can be used to determine high soiling seasons occurring within a 12-month period.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>$R^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max monthly $S_m$</td>
<td>Max $S_m$ registered in one month</td>
<td>73</td>
</tr>
<tr>
<td>Max 3-month $S_m$</td>
<td>Max $S_m$ when three consecutive months are considered</td>
<td>82</td>
</tr>
<tr>
<td>Max 6-month $S_m$</td>
<td>Max $S_m$ when six consecutive months are considered</td>
<td>37</td>
</tr>
</tbody>
</table>
### Soiling Variability Index: Classification

The analyzed datasets fall into five categories:

<table>
<thead>
<tr>
<th>SVI</th>
<th>Class</th>
<th>Soiling profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.2</td>
<td>Seasonal variability in soiling not present or negligible.</td>
<td>Losses are equally distributed during the year: about 50% of the losses recorded in 6 months.</td>
</tr>
<tr>
<td>≥ 0.2 and &lt; 0.4</td>
<td>Limited seasonal soiling.</td>
<td>0% to 70% of their soiling losses occurring in 6 months.</td>
</tr>
<tr>
<td>≥ 0.4 and &lt; 0.6</td>
<td>Non-negligible impact of seasonal soiling.</td>
<td>70% to 80% of the total losses occur in 6 months.</td>
</tr>
<tr>
<td>≥ 0.6 and &lt; 0.8</td>
<td>High variability in soiling.</td>
<td>Most of the losses occur in 3 to 4 months and 85% to 90% of soiling is experienced in 6 months.</td>
</tr>
<tr>
<td>≥ 1.0</td>
<td>Extreme variability.</td>
<td>Almost all the losses (&gt; 95%) occur in 6 months.</td>
</tr>
</tbody>
</table>
Soiling Variability Index vs. Soiling Ratio

Site A: SRatio > 0.99, SVI = 0.77.
Site C: SRatio = 0.97, SVI = 0.40.
Site P: SRatio = 0.99, SVI = 0.42.

Both the SVI and the annualized SRatio must be considered.
Seasonality is generally determined using multi-year datasets.

Lacking such long soiling datasets, the prediction of seasonal soiling relies on identifying its correlation with other more widely available parameters.

The investigation here is limited to PM$_{10}$ data.
Causes of seasonal soiling: Particulate Matter

- **R² of 0.39** if the monthly accumulated daily losses compared against the accumulated daily PM₁₀ concentrations.

- **R² of 0.47** if monthly data are replaced with data accumulated in three consecutive months.

- **R² of 0.63** if data occurring for dry periods longer than 90 days are removed.
Causes of seasonal soiling: Particulate Matter

Lower $R^2$ between SRatio and PM$_{10}$ compared to our previous study:

- the variability of other parameters (e.g. rainfall) is more relevant for short than for longer time periods [4,5].

- daily PM10 registered by the EPA monitoring stations are discontinue and require an appropriate data process.

- the EPA monitoring stations might not be able, in some cases, to register the local seasonal PM10 trend of a site.


Causes of seasonal soiling: Particulate Matter

Soiling Station in Colorado (green mark)
Orange marks: PM10 stations
Yellow marks: PM2.5 stations
Green circle: 50-km radius around the site
Yellow circle: 20-km radius around Denver

Source: 39.75685 & -104.62025. Google Earth, 12/30/16. 01/19/17.
Initial results of an investigation on seasonal PV soiling, using data from 15 stations in the USA.

- **Seasonal variability index** (SVI) introduced to quantify the seasonal behavior of soiling over a 12-month period.
- SVI used to **classify the sites** depending on the number of months in which most of the soiling losses occurred.
- SVI cannot distinguish high or low soiling sites.
- Correlations among monthly soiling and pollution data have **lower accuracy** that those reported for longer-term data. Results **enhanced if three month periods** are considered.
Thank you!

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More on NREL soiling project on the thursday 10.30-12.00 Poster Session:
Lin Simpson, NREL Efforts to Address Soiling on PV Modules (e-poster)
Micheal Deceglie, Quantifying Year-to-Year Variations in Solar Panel Soiling from PV Energy-Production Data (K39)
Leonardo Micheli, A Unified Global Investigation on the Spectral Effects of Soiling Losses of PV Glass Substrates: Preliminary Results (K52)
Matthew Muller, A Method to Extract Soiling Loss Data From Soiling Stations with Imperfect Cleaning Schedules (L4)
Monte Carlo computation: the uncertainty can be particularly significant for low soiling ratio sites.

- Considered a 5% uncertainty on dailySRatio.
- Each dataset is regenerated 1,000 times.
- A new SVI is calculated.
- Randomly generated daily.

The uncertainty on SVI tends to increase with the soiling ratios, ranging from values of 1% to 42%.
The identification of seasonal patterns is essential to determine the most adequate cleaning schedule.