NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PV Soiling Losses: Measurements, Modeling, and Mitigation Strategies

DuraMAT virtual seminar, July 11, 2022

Chris Deline & Matt Muller
with content from Kevin Anderson, Dirk Jordan, Kirsten Perry, Michael Deceglie & Robert White

Funded By:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Data through: PV Fleet Performance Data Initiative

OUTLINE

- PV soiling: background and general mitigation approaches
- State-of-the-art for extracting soiling information from PV data
- Data sharing
- Challenges with Bio-soiling

PV Soiling:
Background and State-of-the-art

What is PV soiling and why is it important?

- **PV soiling**: energy generation losses due soil blocking incoming irradiance from reaching the PV cells

- Energy losses vary:
  - Low, 1-2% in regions with regular rainfall such as the eastern USA or most of Europe
  - Moderate in semi-arid climates: S California, peak losses may exceed 15% but annual losses are still typically 5% or less.
  - High in regions like the Middle East where peak losses can reach 80% after dust storms and annual losses can be 20% or more.

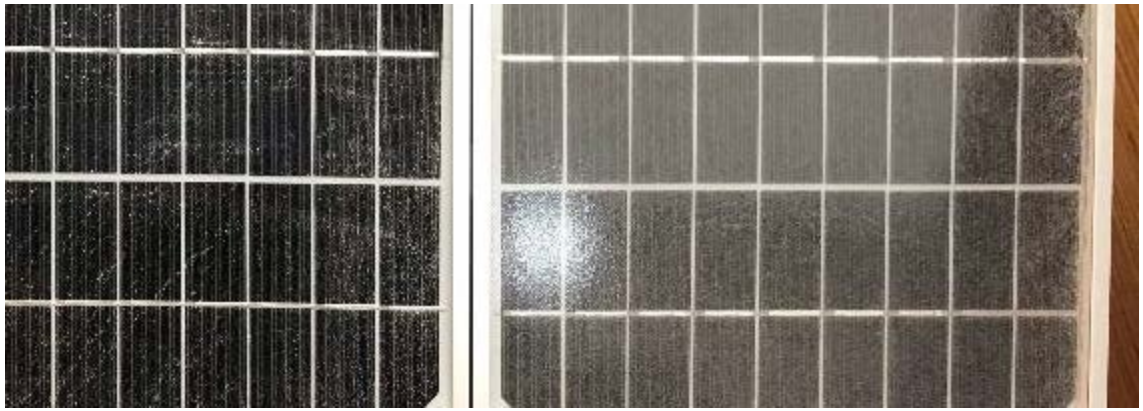
- Soiling losses are complex: varying by climate, season, localized pollution, land use, mounting configuration, and distances as short as a few kilometers

- GWs of PV are now being installed in high insolation dusty deserts resulting in billions of dollars of lost energy revenue

PV soiling mitigation and challenges

- Account for soiling losses and natural rainfall within models.
  - Modeling and supporting data for forecasting soiling losses are limited.
- Washing PV panels to remove soil
  - High Labor costs and water availability
  - It is difficult to predict when to clean
  - Robotic dry or wet brush cleaning (surface damage? reliability? Economics?)

- Anti-soiling coatings on the PV module surface
  - Applicability? effectiveness? Durability? economics?



Currently no soiling mitigation strategy has proven to be techno-economically applicable across the PV industry!

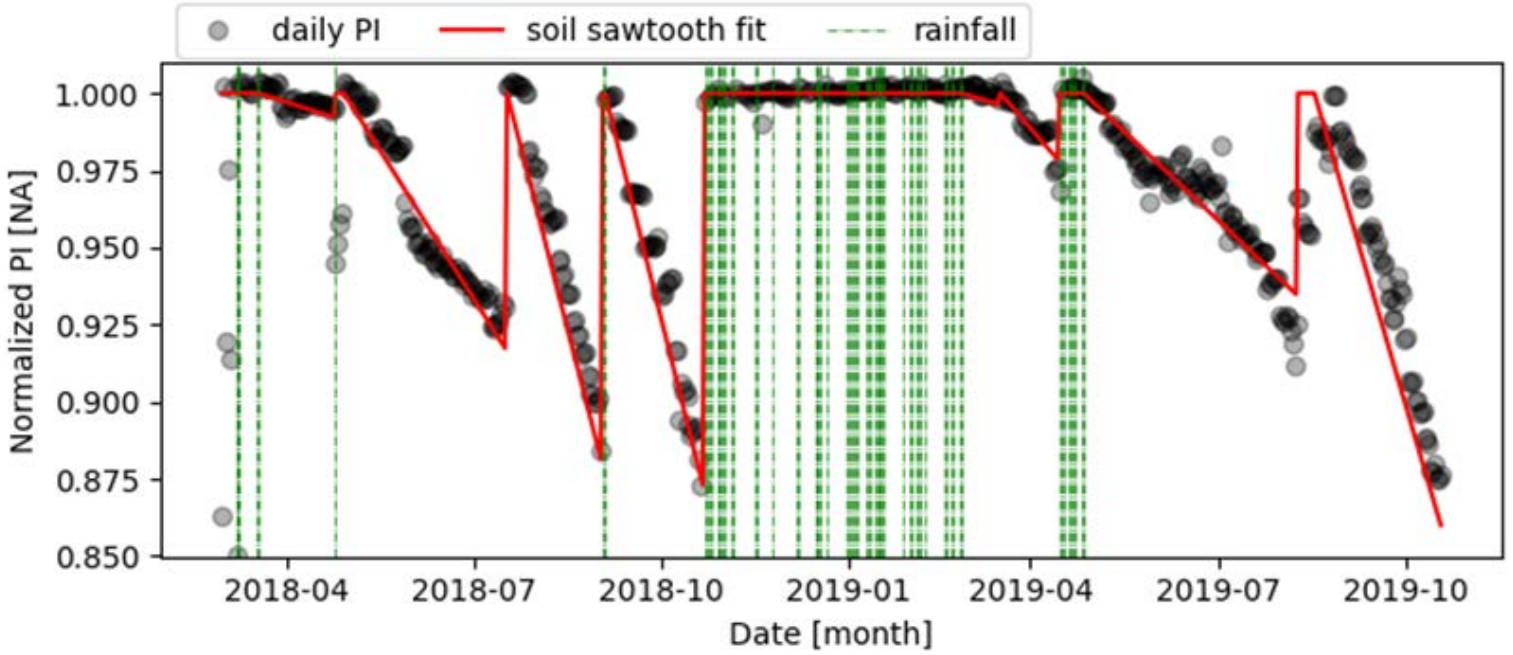
Addressing the PV soiling challenge

- Improving mitigation:
  - Industry is continually working to improve effectiveness and cost of robotic or other cleaning methods
  - Ongoing development of anti-soiling coatings, durability standards, and efficacy test development
- Improving knowledge about where and when mitigation will be needed
  - Development of soiling loss models based on environmental or other relevant parameters.
  - Increased data collection through improved soiling measurement equipment and lower cost equipment
  - Development of models that allow accurate extraction of soiling loss information from wide scale existing PV time series data

Extracting soiling information from PV data: State-of-the-art

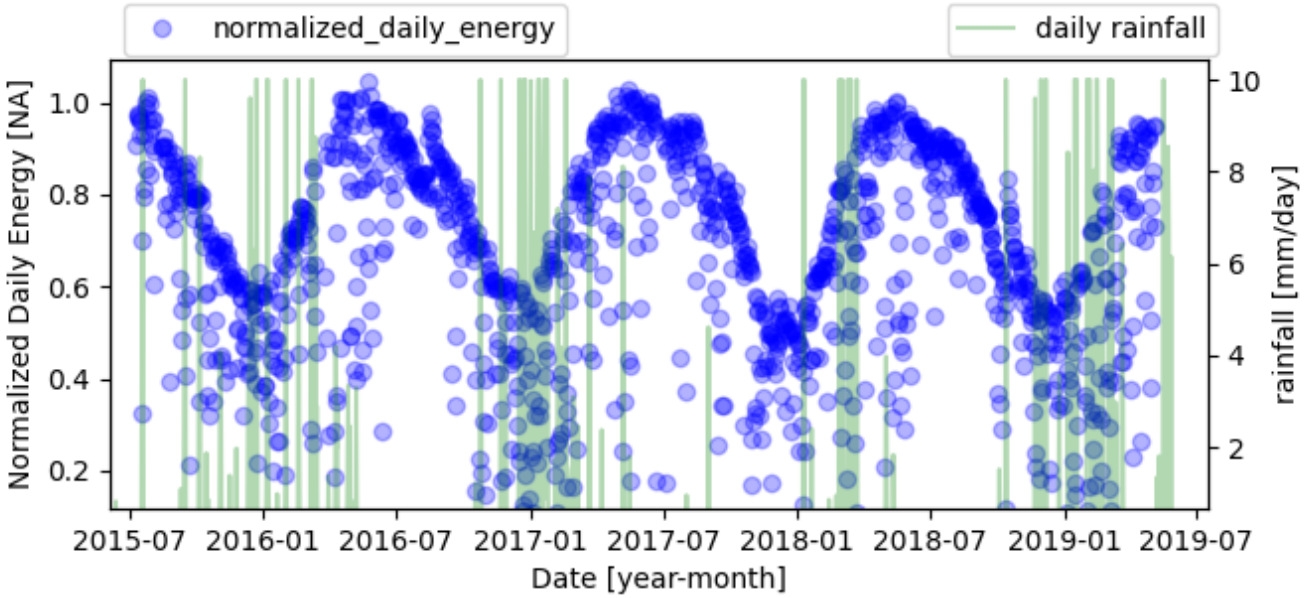
PV Soiling Characteristic Assumption

- Normalized daily PV performance index (PI) should be 1 if no soiling
- In non-rainy periods soiling will generally cause a linear reduction in the PI
- The rate of linear decline is dependent of amount of dust in the air, PV orientation, wind and other environmental factors
- Rainfall causes cleaning or an upward shift in the PI
- These assumptions together result in the assumption that soiling follows a sawtooth pattern as given by the red fit to the black data.



Typical PV time series data

- Below is a typical time series of normalized daily energy from a PV system
  - Sinusoidal behavior from seasonal variation in irradiance
  - Noise per variable cloud cover, temperature, soiling, shading, spectral changes, inverter issues….
  - In green is daily rainfall capped a 10mm for readability
  - How does one extract soiling from this signal?

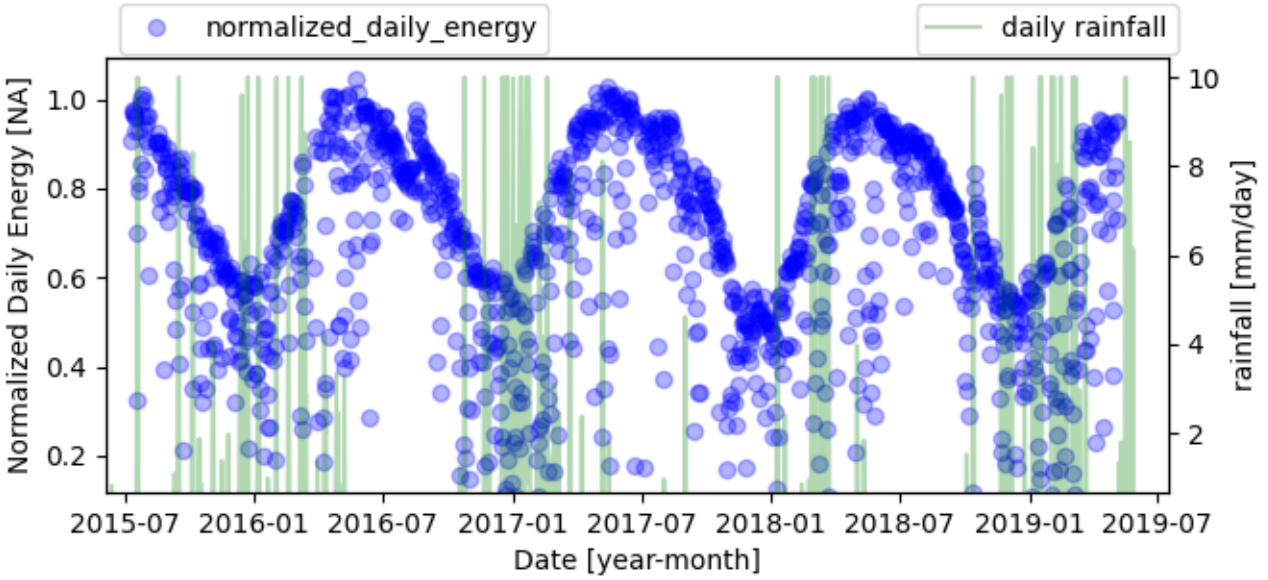


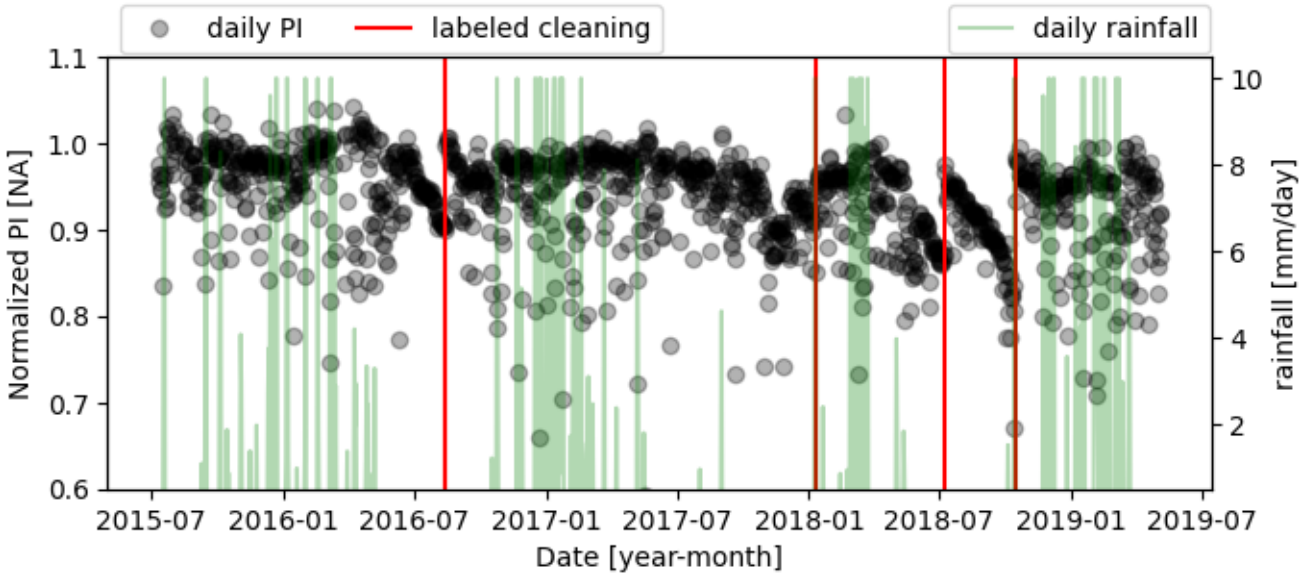
Generate a daily performance index

PI=measured/modeled PV performance

The model primarily accounts for irradiance and temperature variation but other factors can be included if when data is available.

The second graph demonstrates that the PI can still be noisy and present challenges to extracting soiling.

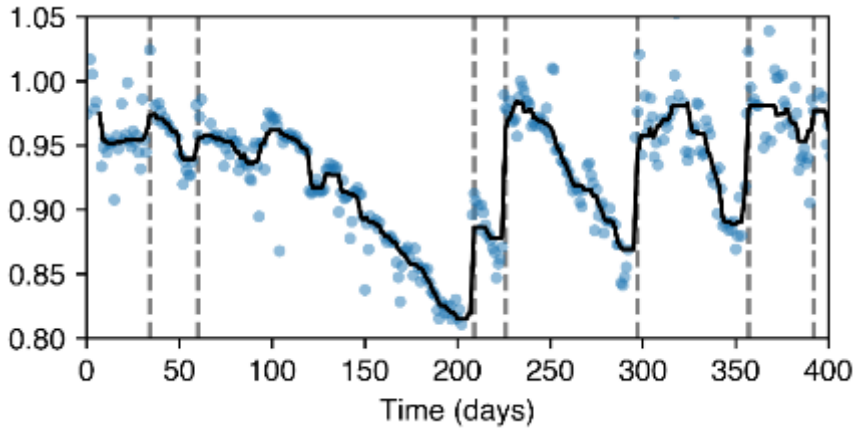




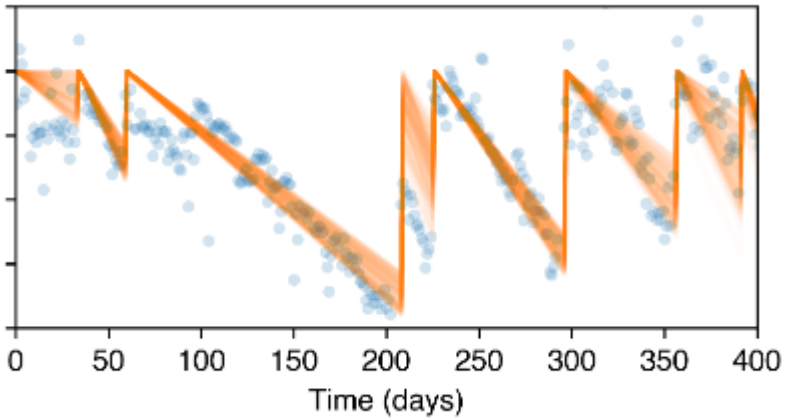
Stochastic rate and recovery (SRR) method

- Segment the PI data into soiling intervals
  - Smooth the data per a 13-day rolling median
  - Cleanings are positive shifts in the rolling median > $Q3 + \alpha(Q3-Q1)$ Q1 and Q3 are the 1st and 3rd quartiles and Q3-Q1 is the interquartile range or IQR
- Fit each interval using the Theil Sen method
- Reject intervals with positive slopes
- Repeat the fit process 1000s of times per the Monte Carlo method
- Provides statistics on soiling rates observed and irradiance-weighted soiling losses

Solid black is 13-day rolling median, Dashed lines are cleaning events segmenting the soiling intervals



Monte Carlo of possible soiling profiles

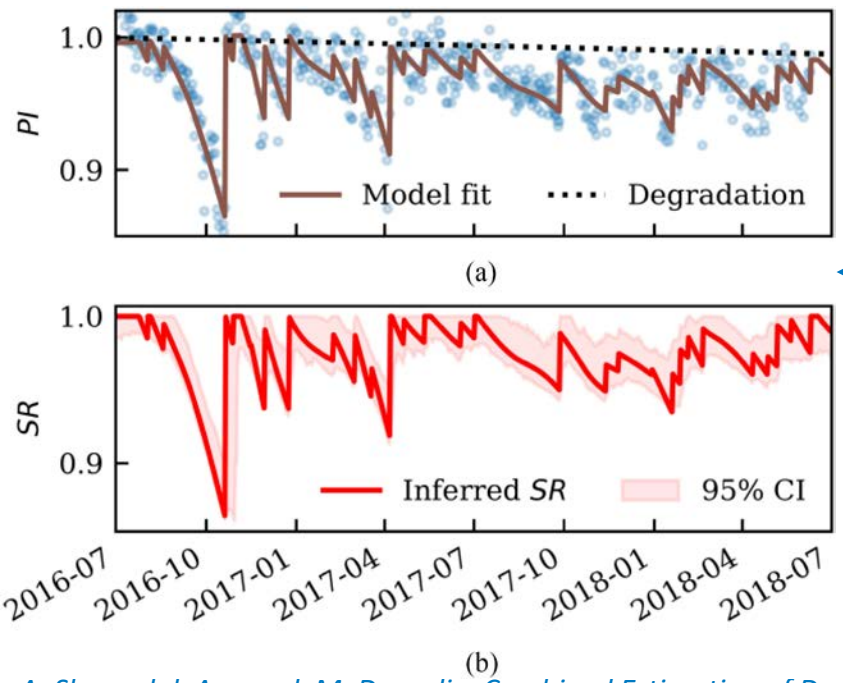


M. Deceglie, L. Micheli, M. Muller, "Quantifying soiling loss directly from PV yield," IEEE Journal of Photovoltaics, vol. 8. 2018.

Combined Degradation and Soiling (CODS)

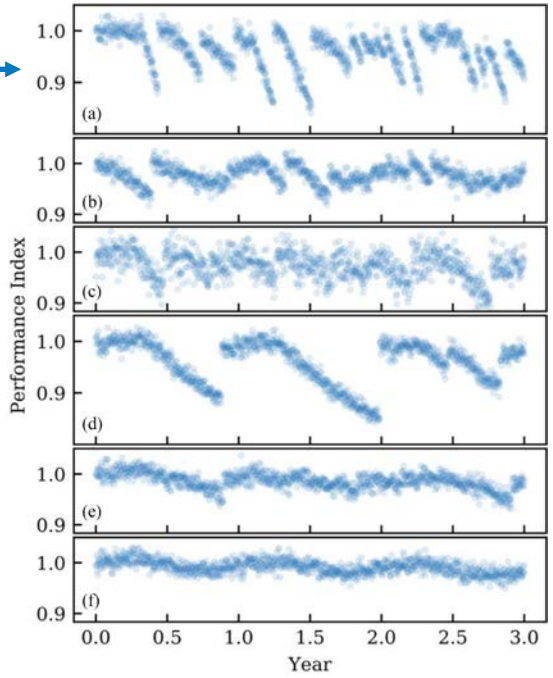
- It is assumed that the multi-year PI data can be decomposed into four components which have a multiplicative effect on the PI
  - 1) Soiling trend, 2) Seasonal trend, 3) Degradation trend, and 4) noise

1. Segment the PI data into soiling intervals per significant positive shifts per the SRR approach with a 9-day rolling median of the PI
2. Use a Kalman filter for estimating the soiling trends (allows slow changes in soiling rate)
3. Estimate the seasonal component by decomposing the time series per the LOESS model
4. Apply the Year-on-Year degradation method
5. Iterate per steps 1-4, convergence per RMSE minimization (estimated and measured PI)



Synthetic data used in developing CODS

CODS applied to field data

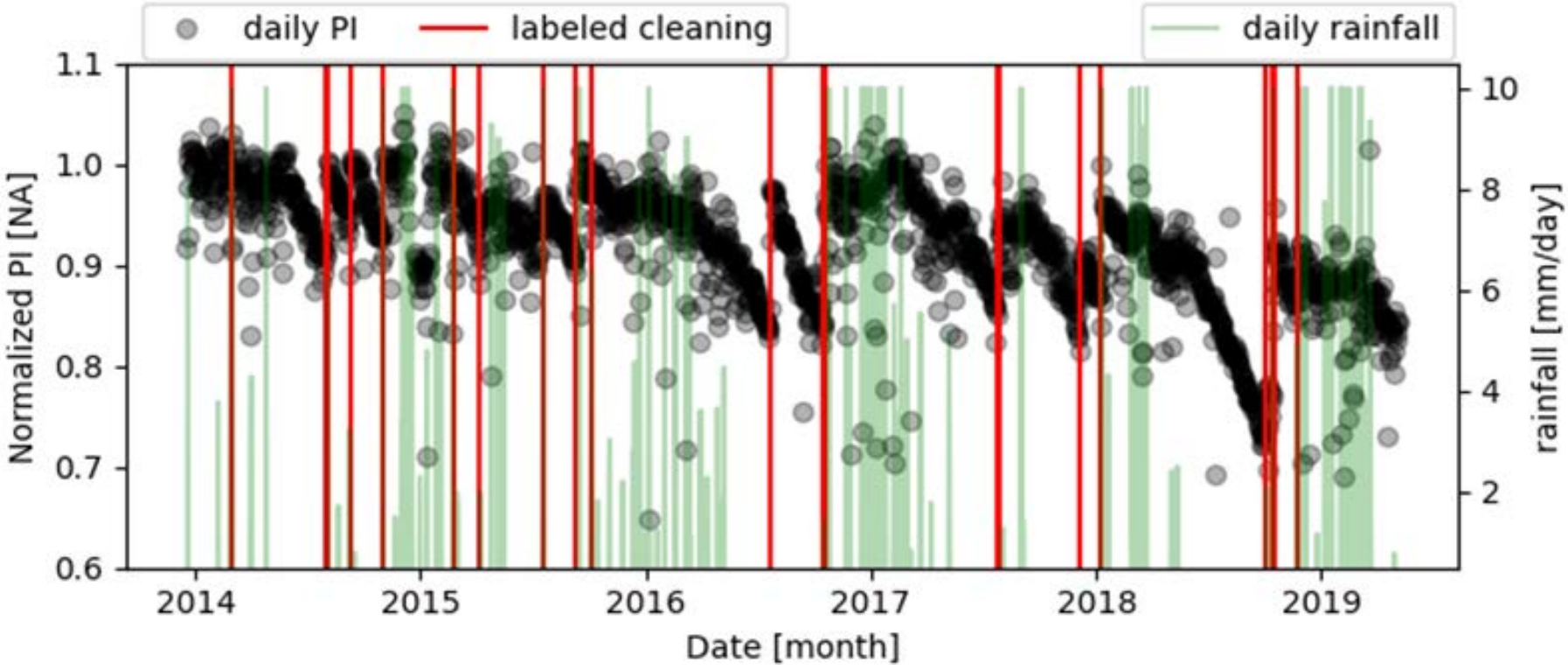


A. Skomedal, Asmund, M. Deceglie, Combined Estimation of Degradation and Soiling Losses in Photovoltaic Systems, IEEE J. of Photovoltaics 2020.

Data Sharing

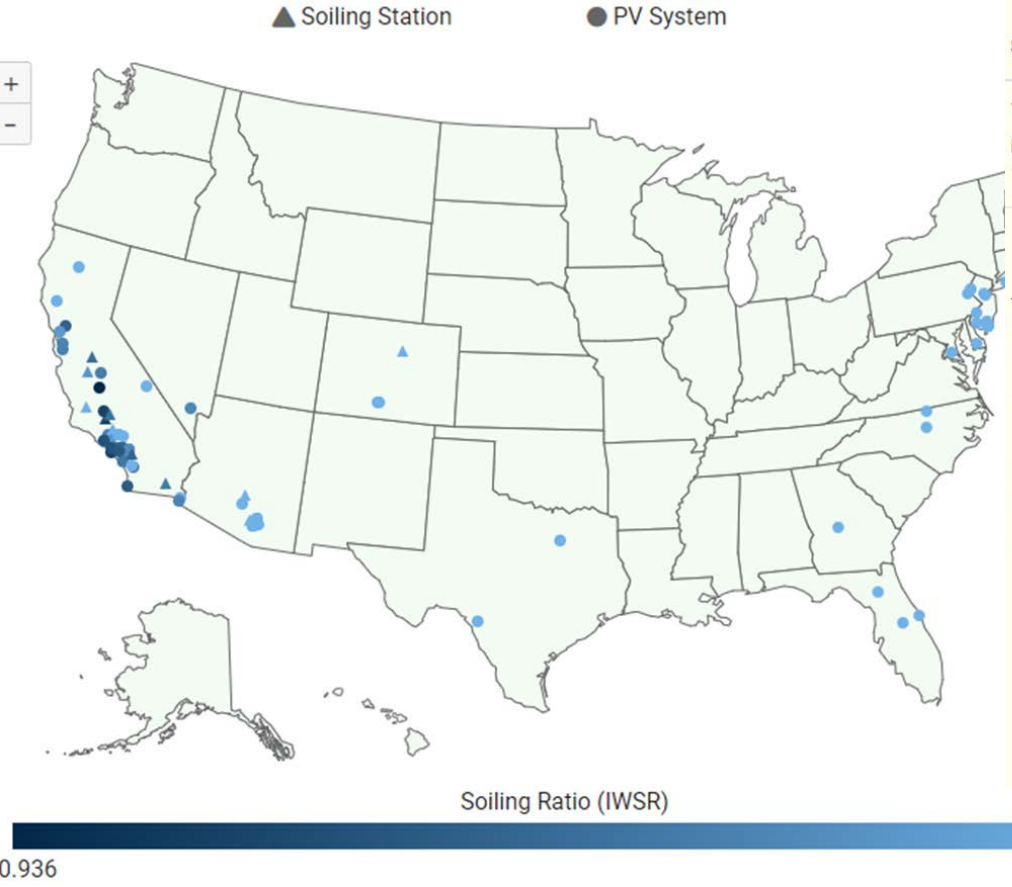
Data for improving soiling extraction models

- 22 systems from NREL PV fleets were identified for soiling trends and 3 expert analysts labeled the data sets for cleanings per an agreed rubric.
- The labeled data sets are being shared on the DuraMAT data hub
- More advanced synthetic data sets are currently underdevelopment as well and will be shared.



NREL PV Fleet Soiling Map

https://www.nrel.gov/pv/soiling.html



Selected Location

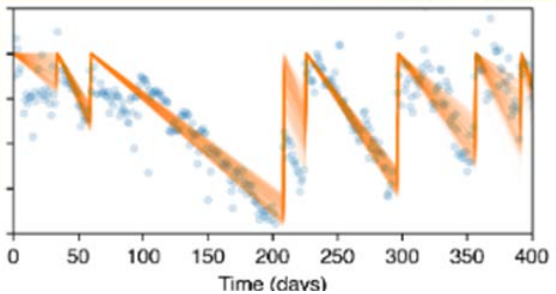
Site	Measurement type	IWSR	IWSR lower	IWSR upper	Months in data set	Tilt	County	State	Mounti
7135_ac_power_inv_14807	PV System	0.936	0.934	0.938	67.5	0	Kings County	CA	Fixed

Annual Soiling Ratios

Year	IWSR	IWSR lower	IWSR upper
2012	0.957	0.939	0.975
2013	0.941	0.936	0.947
2014	0.905	0.901	0.909
2015	0.954	0.951	0.957
2016	0.919	0.915	0.924
2017	0.943	0.938	0.948
2018	1	1	1

Monthly Soiling Rates

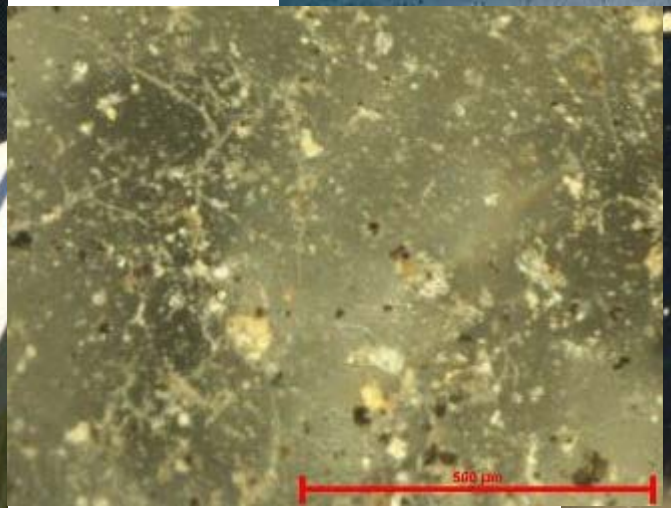
Month	Soiling rate	Soiling rate lower	Soiling rate upper	Interva count
Jan	-0.003	-0.0033	-0.0027	1
Feb		Insufficient data		
Mar	-0.0014	-0.0028	-0.0007	3
Apr	-0.0022	-0.0044	-0.0009	6
May	-0.0024	-0.0047	-0.001	6
Jun	-0.0024	-0.0044	-0.0013	7
Jul	-0.0026	-0.0046	-0.0015	7
			-0.0015	7
			-0.0029	8
			-0.0033	8
			-0.0012	5
			-0.0022	3

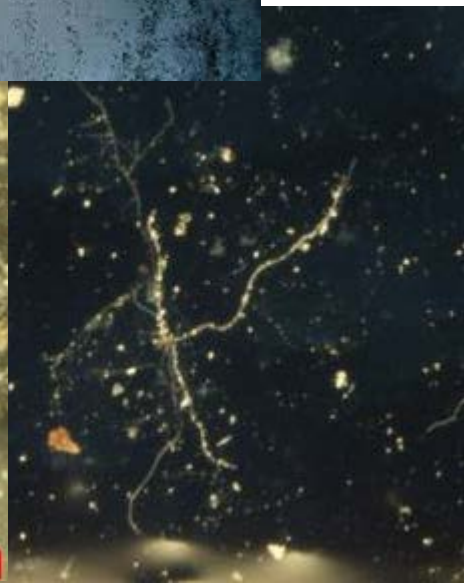


BioSoiling

Bio-Soiling Challenge

- Assumption of sawtooth soiling is violated when sticky/well adhered/cemented substances don't readily clean off per rainfall
- Bio-Soiling such as filamentous fungi (types of mold) or certain pollens are examples of this problem
- PV Fleets partners have been encountering this problem at select locations in the SE

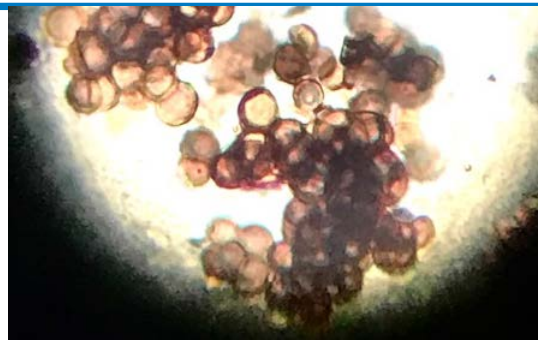




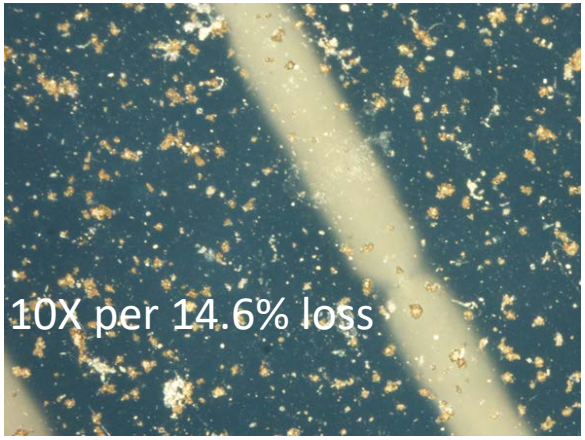
Black Mold on PV System in S.E. U.S.

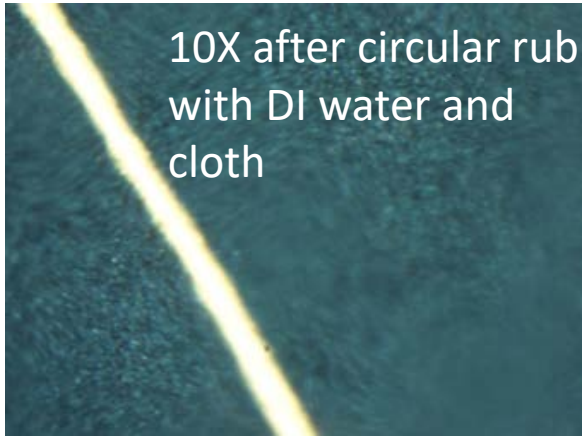
- PVfleets partner reached out to NREL due to unexpected performance losses
  - Regular rainfall
  - No nearby factories or expected high pollution sources
  - 4 years old
- O&M staff finding black residue when you wipe a module
- Suspected black mold, contracted with experts in microbiology
- Contracted with a cleaning crew fall of 2021

NREL examination BioSoiled modules



- 5 modules to NREL (1 control 2 prior to wash, 2 after the wash)
- "after the wash" were outdoors 2 months prior to shipping
- At NREL 1"after wash" module was lightly wiped down
- Measured I-V curves on all modules
  - Control module within nameplate
    the following are Pmax reductions as compared to the control
  - 13.4% and 14.6% reduction for the unwashed modules
  - 6.1% reduction for the untouched "after wash" module, 4.2% reduction for the module that was wiped down
- We sprayed the 14.6% module with hose water and remeasured at 12.9% losses
- We then applied soft bristle brush and hose water now found 8.1% losses





Summary

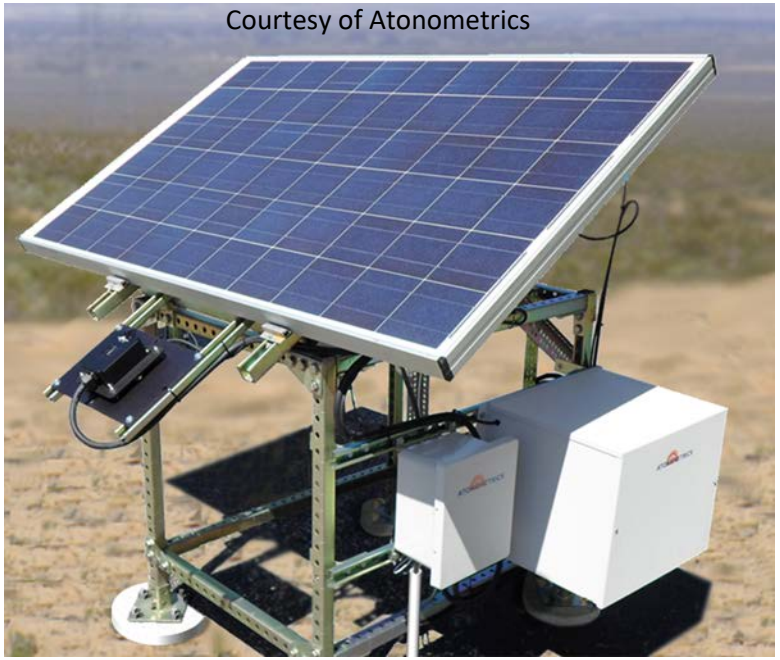
- PV Soiling is a complex problem that adds substantial cost to the industry
- No soiling mitigation strategy has proven to be techno-economically applicable across the PV industry
- Work is ongoing from various sides of the problem but more funding is needed to continue making progress
- BioSoiling is presenting substantial losses in locations that are typically expected to have low to no soiling losses

Backup Slides

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL/PR-5K00-83486

Typical PV Soiling Measurement


Courtesy of Atonometrics

- The typical soiling measurement equipment consists of a regularly cleaned PV device and a second PV device that is allowed to naturally soil
- Variations include matching PV cells, a cell versus a full-sized module and matching modules
- Operation and Maintenance (O&M) varies
  - Manual cleaning at various frequencies
  - Automatic water cleaning with infrequent filling of water tank
  - Automatic cover/uncover of the clean device
  - Automatic brush cleaning of the clean device