



# Quantifying the Impact of Dust and Snow on PV Power Plants

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# Different types of soiling



Dust



Snow



Pollen



Agriculture



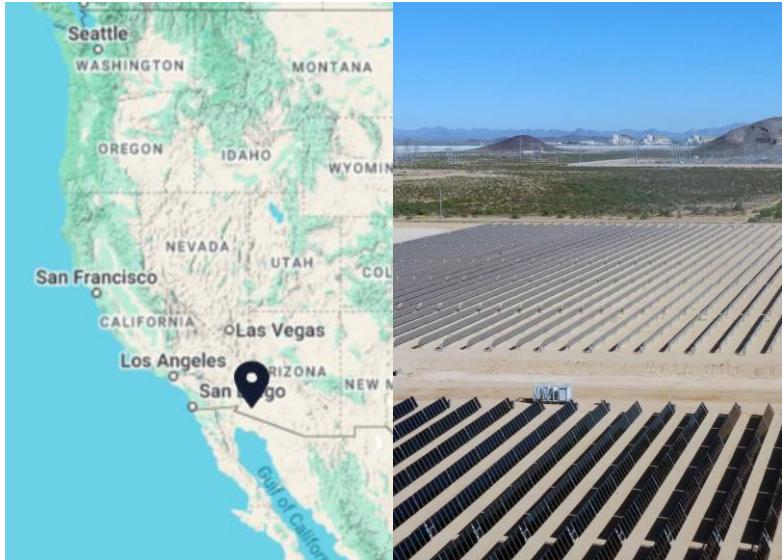
Birds

# Main Types of Dust Soiling Models



		Fixed rate models	Particle deposition models
General idea		<b>Soiling accumulates at a constant rate.</b>	<b>Soiling accumulates based on environmental conditions.</b>
Inputs		<ul style="list-style-type: none"><li>constant rate</li><li>rainfall</li></ul>	<ul style="list-style-type: none"><li>particle concentration (PM2.5, PM10, etc.)</li><li>wind, temperature, humidity ...</li><li>tilt angle</li></ul>
Parameters		<ul style="list-style-type: none"><li>rain cleaning threshold</li></ul>	<ul style="list-style-type: none"><li>rain cleaning threshold &amp; efficiency</li><li>dust deposition velocities</li><li>+ many more depending on model</li></ul>
Examples		Kimber model	Coello model / HSU, You, Bergin PVRADAR, ...

Let's look at an example:



New development project  
near Yuma, Arizona.

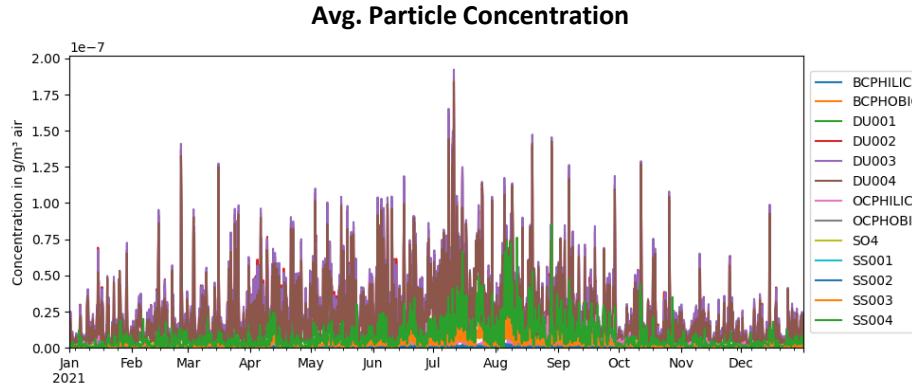
1. How to get average monthly soiling loss factors?
2. How to determine optimal cleaning frequency?

# Particle Concentration

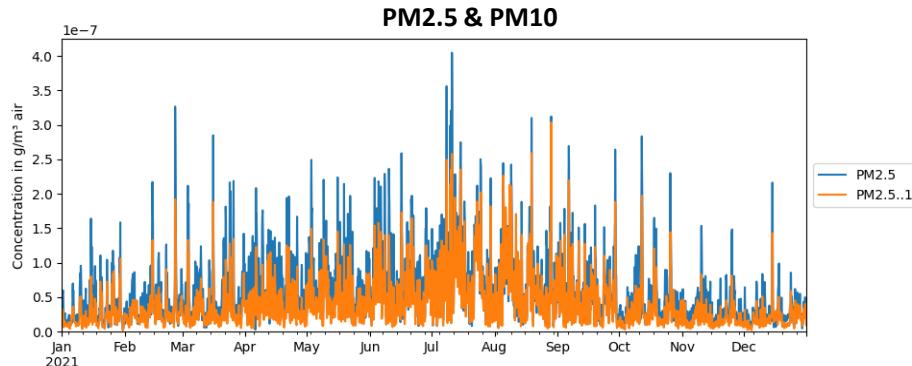


Physical Soiling model

Particle concentration



Energy & Cost



Modern-Era Retrospective analysis for Research and Applications (MERRA-2)

- MERRA2 offers concentration of a variety of particles
- Can be grouped by diameter to produce PM2.5 & PM10
- Other sources of soiling: snow, pollen, agriculture, industry ...

# Historic Rain Patterns

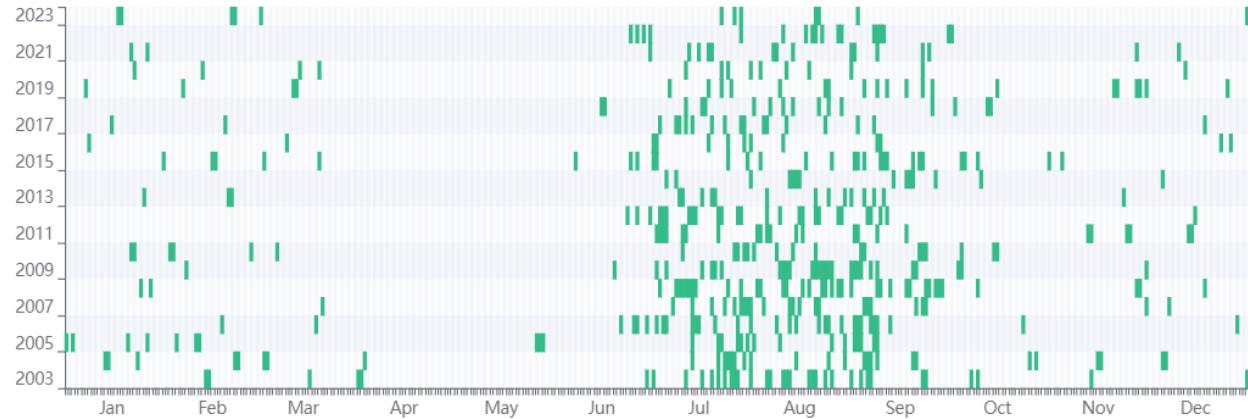


Heatmap showing all registered rain events for the past years

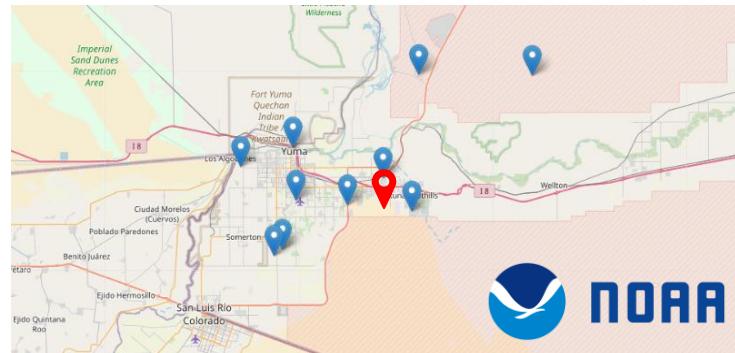
Physical Soiling model

Particle concentration

Rain



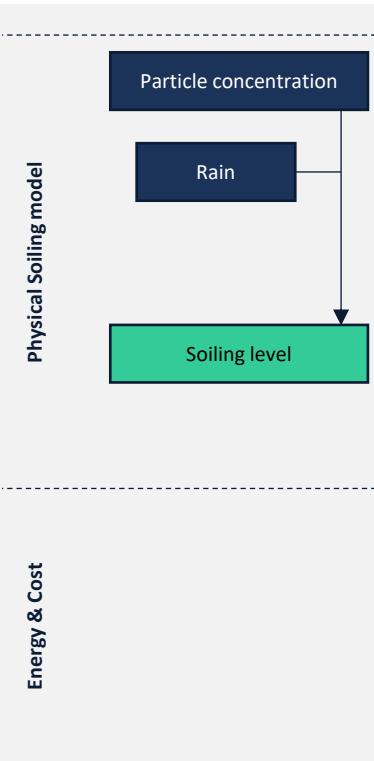
Energy & Cost



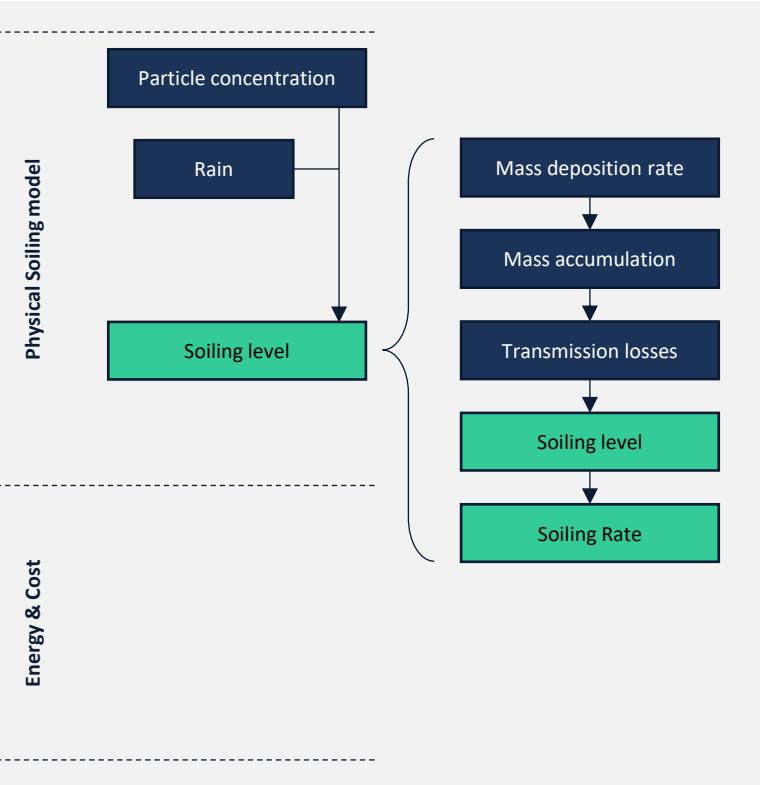
If available, always use data from nearby weather stations.

PV

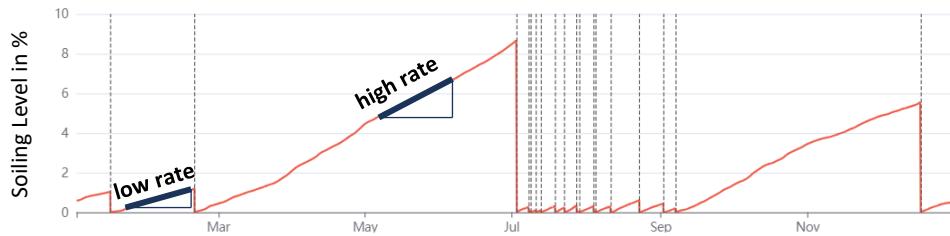
# Soiling Level & Rain Cleaning



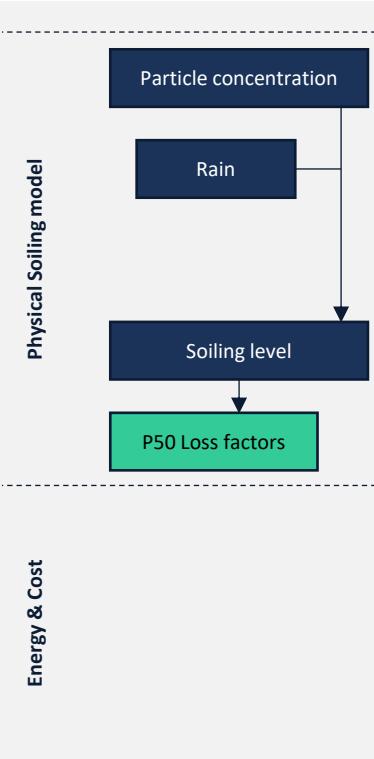
# Soiling Accumulation



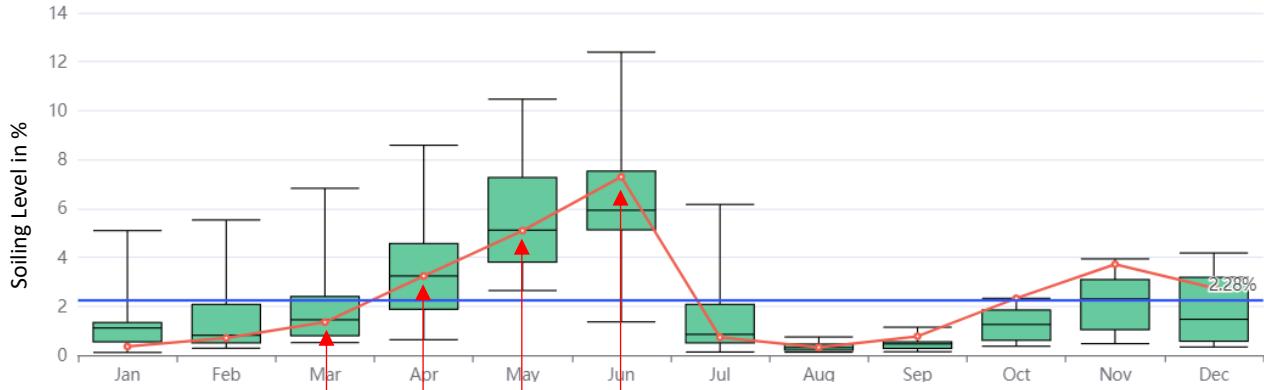
- Particles deposit on the (front) surface of PV modules
- Particles accumulate on the glass surface
- Particles shade part of the incoming irradiation



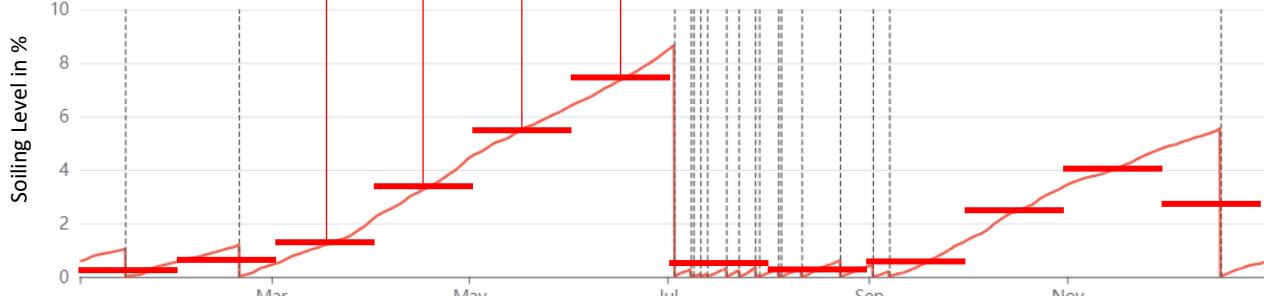
# P50 Soiling Loss Factors



Boxplot showing average monthly soiling levels of past years



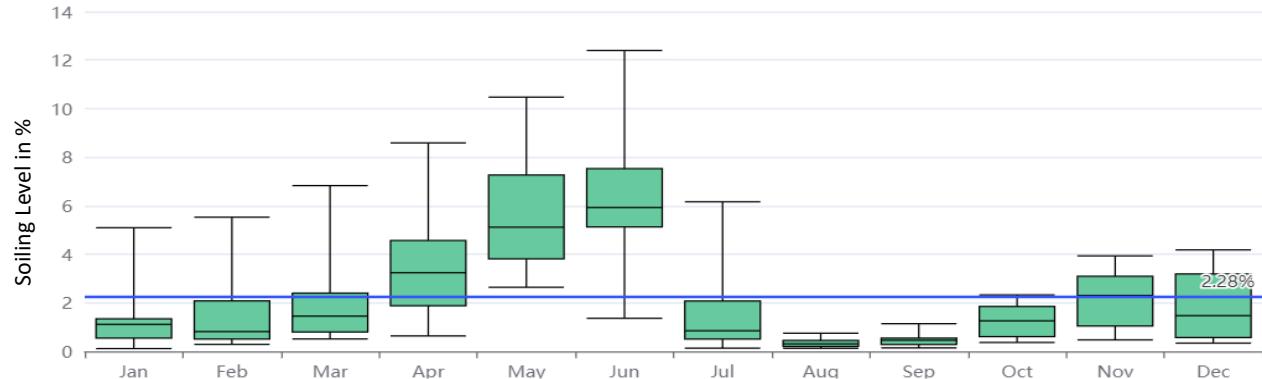
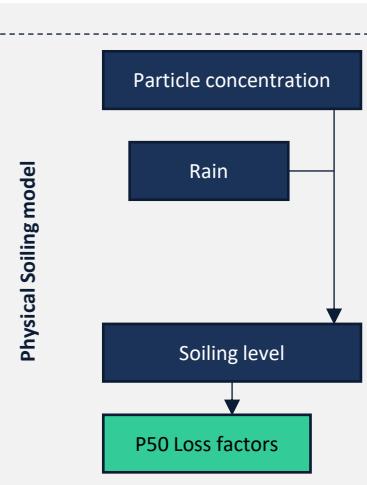
Soiling profile for 2017



# P50 Soiling Loss Factors



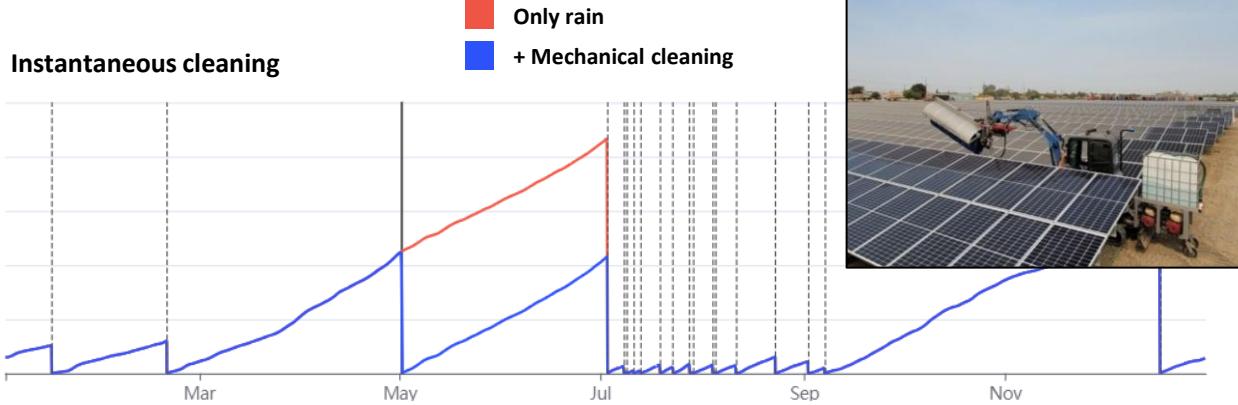
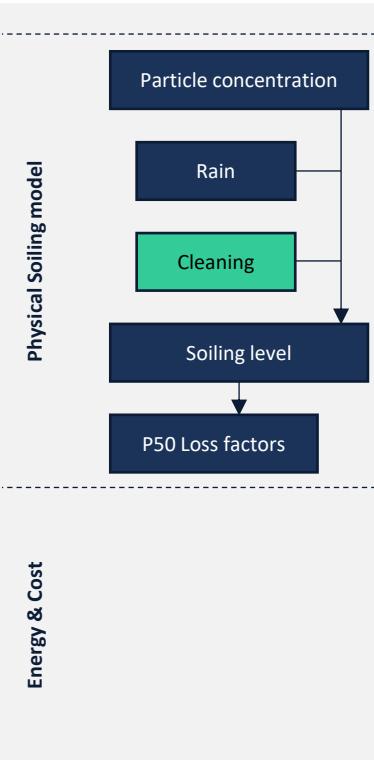
Boxplot showing average monthly soiling levels of past years



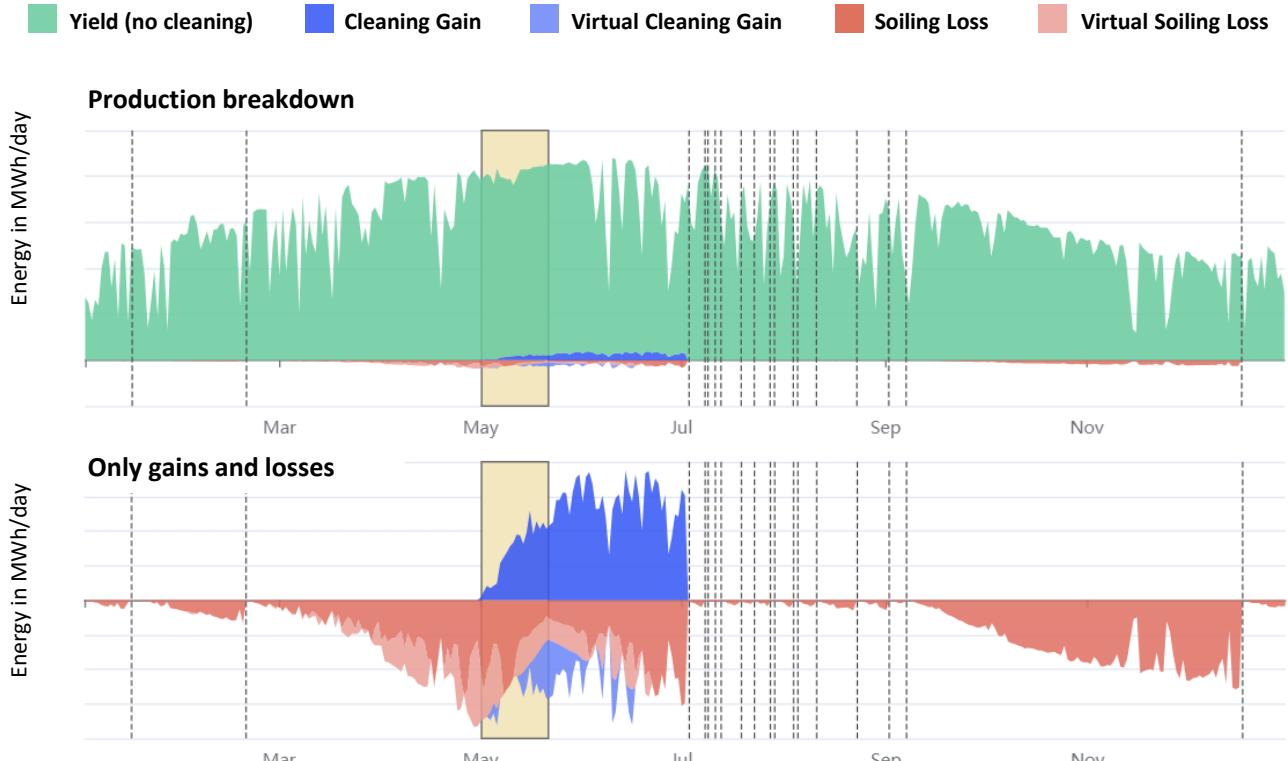
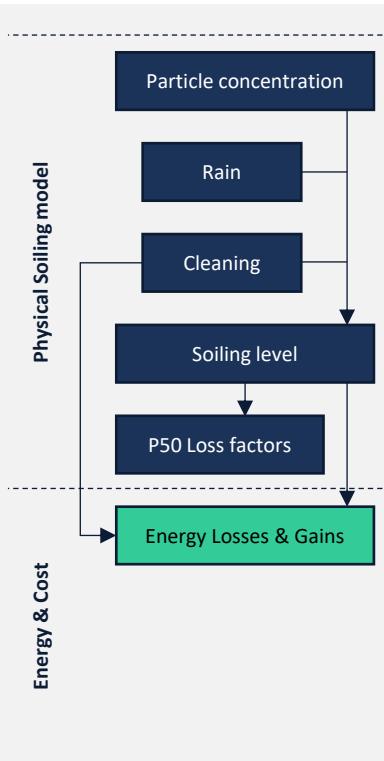
P50, P90 & P99 Monthly Soiling Loss Factors

Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P50	1.111	0.8147	1.448	3.239	5.112	5.925	0.8483	0.3075	0.4555	1.257	2.302	1.467
P90	2.381	3.285	4.508	6.616	8.566	8.881	2.578	0.5601	0.6738	2.052	3.717	3.419
P99	5.091	5.526	6.824	8.586	10.47	12.39	6.16	0.744	1.139	2.324	3.934	4.177

# Mechanical cleaning



# Energy Losses & Gains



# Modelling of Cleaning Alternatives



Manual Cleaning



Fully-autonomous robot



Tractor + Brush (dry / wet)



Semi autonomous robot



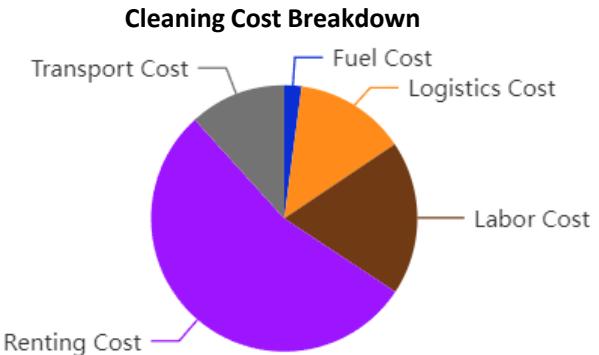
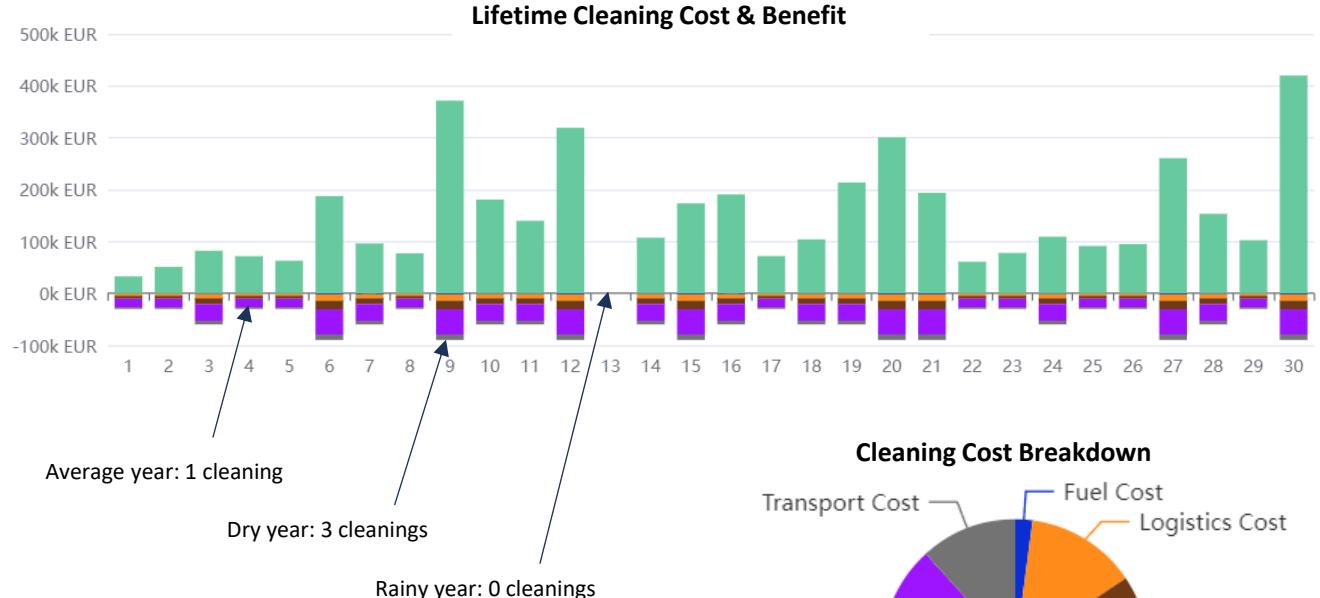
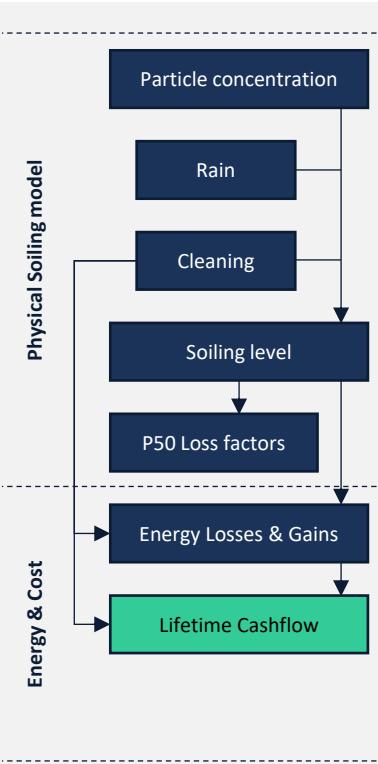
## Technical parameters

- Cleaning speed
- Water & Fuel consumption
- Personnel needed
- Component lifetimes
- ...

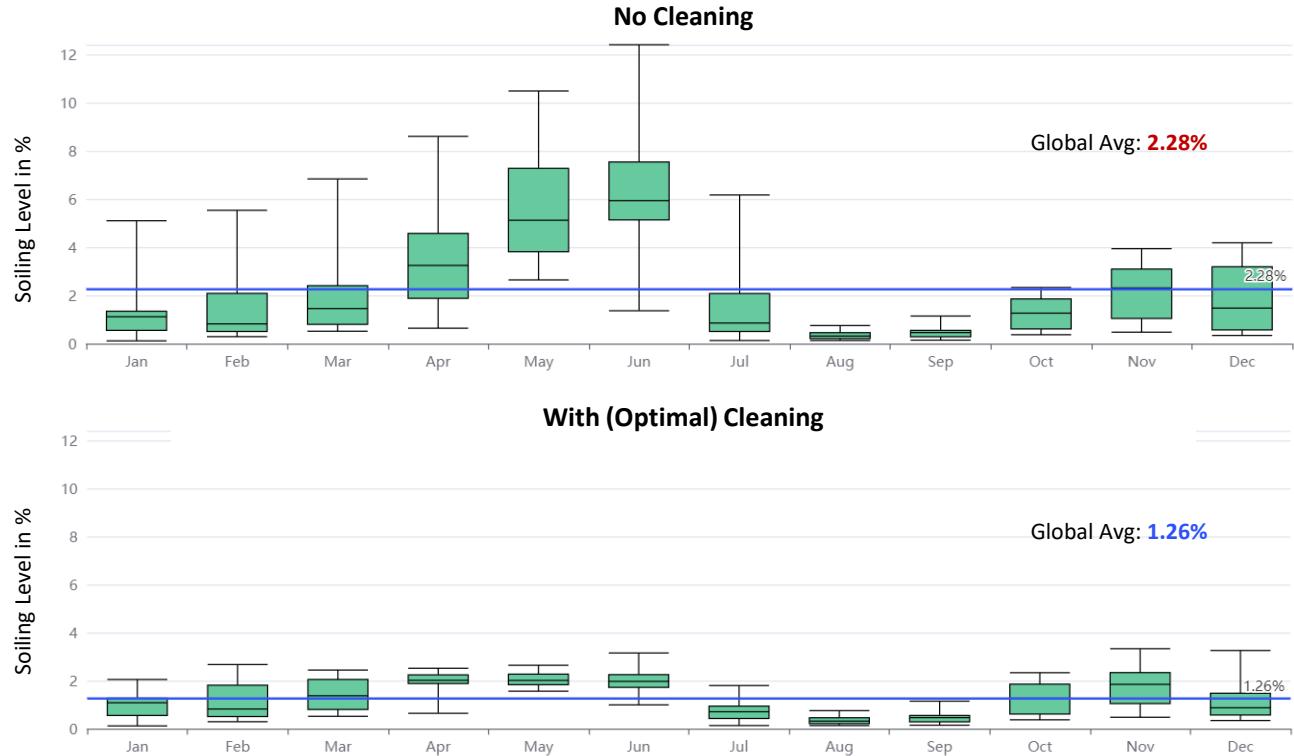
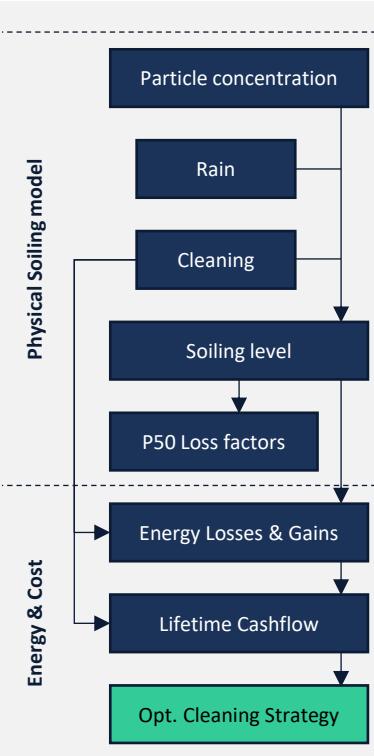
## Economic parameters

- Business model: purchase or service
- Purchase and replacement cost
- Commodity cost
- Labor rate
- Service fees
- ...

# Optimal Cleaning Strategy



# Avg. Monthly Losses w and w/o Cleaning



# Lifetime cost comparison of different cleaning strategies



The image shows a tablet displaying the PV RADAR software interface. The left sidebar lists project steps: Project design, Layout, Define soiling conditions, Packages to compare, Financial model, and Results. The main area shows a bar chart titled "Total lifetime cost" in EUR for four strategies: Standard Tractor Dry - Service, optimal; Standard Tractor Wet - Purchase and operate, optimal; Standard Semi-Robot - Service, optimal; and No Cleaning. The "No Cleaning" strategy has the highest cost at approximately 13M EUR, while the other three are around 3M EUR. Below the chart, detailed financial data is provided for each strategy, including lifetime soiling losses, cleaning costs, production increases, technology used, number of systems, number of cleanings, minimum soiling to start cleaning, and average soiling level. Buttons for "REOPTIMIZE ALL" and "REOPTIMIZE" are present. To the right of the chart, there are two images: one of a tractor cleaning solar panels and another of a semi-robotic cleaning system.



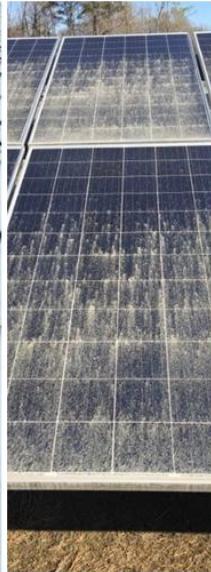
# Snow Soiling



Dust



Snow



Pollen

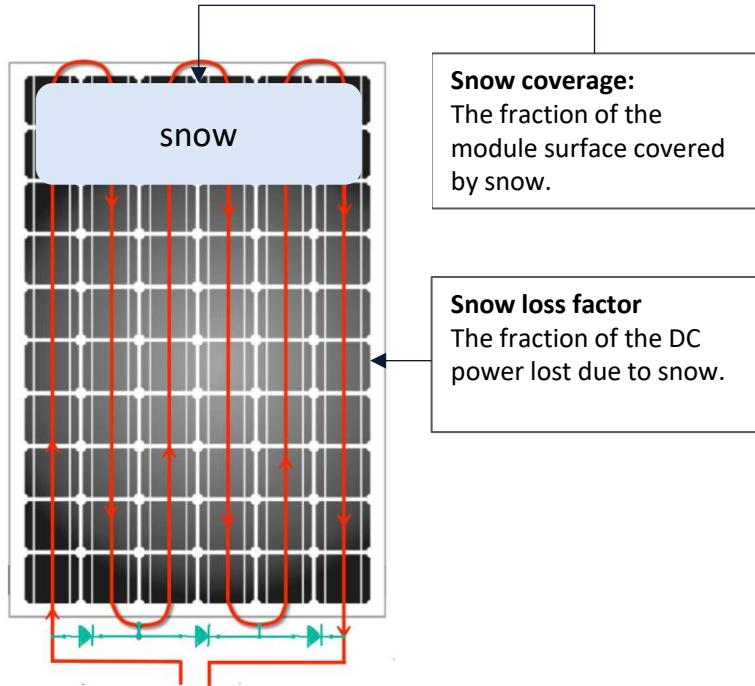


Agriculture



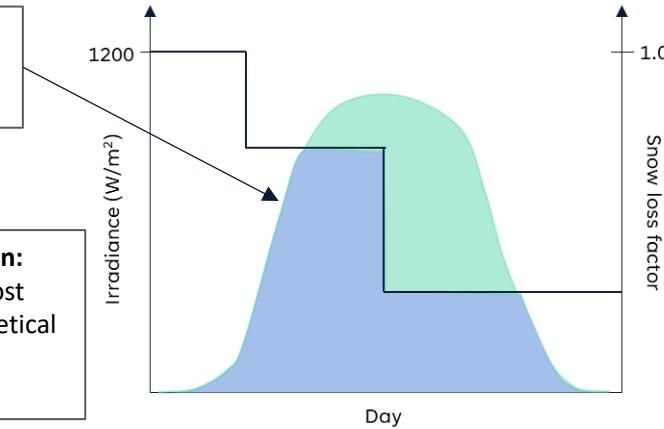
Birds

# Types of Snow Losses



**Snow energy loss:**  
The energy output lost due to snow

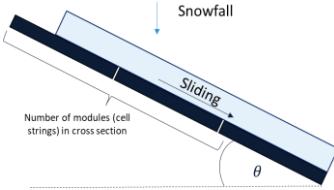
**Snow energy loss fraction:**  
The ratio of the energy lost (green) and total hypothetical energy (green + blue).



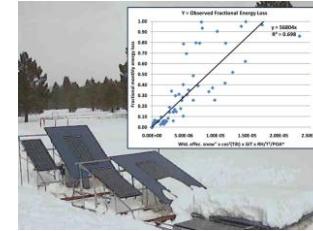
# Popular Snow Loss Models



Marion

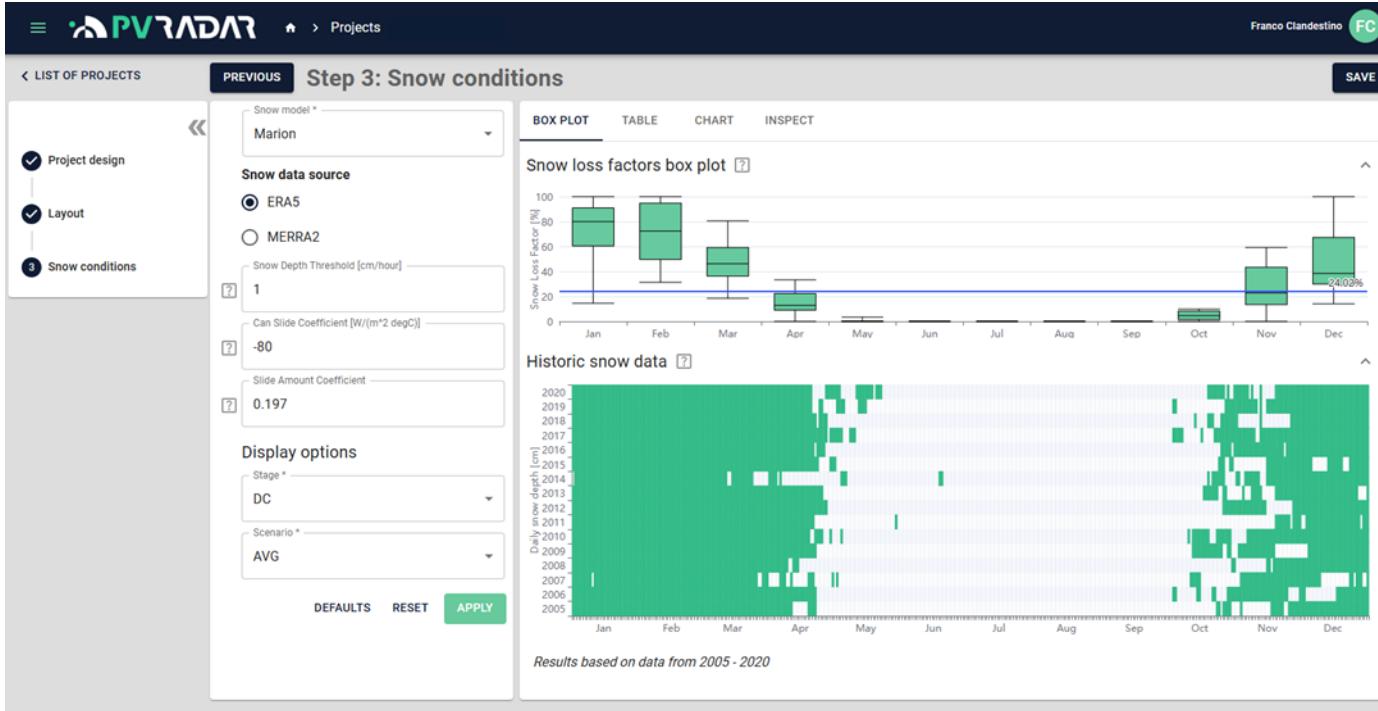


Townsend



General idea	Snow accumulates and slides off	Empirical model
Inputs	<ul style="list-style-type: none"><li>• Snowfall (hourly)</li><li>• Tamb (hourly)</li><li>• POA (hourly)</li><li>• Array geometry</li></ul>	<ul style="list-style-type: none"><li>• Snowfall (daily)</li><li>• Tamb (monthly avg.)</li><li>• POA (monthly sum)</li><li>• RH (monthly avg.)</li><li>• Array geometry</li></ul>
Output	<ul style="list-style-type: none"><li>• Snow coverage</li><li>• Snow loss factor (hourly)</li></ul>	<ul style="list-style-type: none"><li>• Snow loss factor (monthly)</li></ul>
Validation	Based on 2 years of data for 6 PV sites in Colorado and Wisconsin. Fixed tilt only.	Based on a fixed-tilt array with different inclinations. Not validated for tracker systems but provides suggestions.

# Snow Loss Factor Boxplot in PVRADAR Web-App



# From Snow Loss Factor to Snow Energy Losses



PV RADAR Projects Step 3: Snow conditions

Project design Layout ③ Snow conditions

Snow model: Marion

Snow data source: ERA5

Snow Depth Threshold [cm/hour]: 1

Can Slide Coefficient [W/(m^2 degC)]: -80

Slide Amount Coefficient: 0.197

Display options: Stage: DC, Scenario: AVG

BOX PLOT TABLE CHART INSPECT

Snow energy loss charts

Monthly energy

Results based on data from 2005 - 2020

Energy breakdown

Energy Loss due to snow: 7.43%  
Energy without snow: 92.57%

Month	Energy Loss due to snow (MWh)	Energy without snow (MWh)
1	~1k	~2k
2	~2k	~13k
3	~5k	~12k
4	~10k	~15k
5	~18k	~21k
6	~15k	~20k
7	~22k	~22k
8	~12k	~14k
9	~10k	~11k
10	~3k	~4k
11	~2k	~3k
12	~1k	~2k

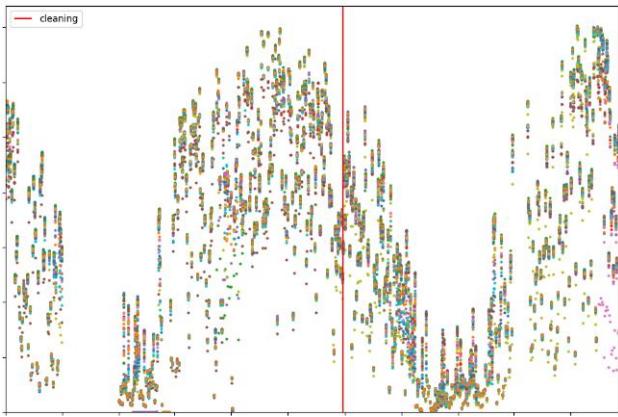
# Organic / Pollen Soiling



# Location in Germany: 50% of inverters cleaned after 4 years

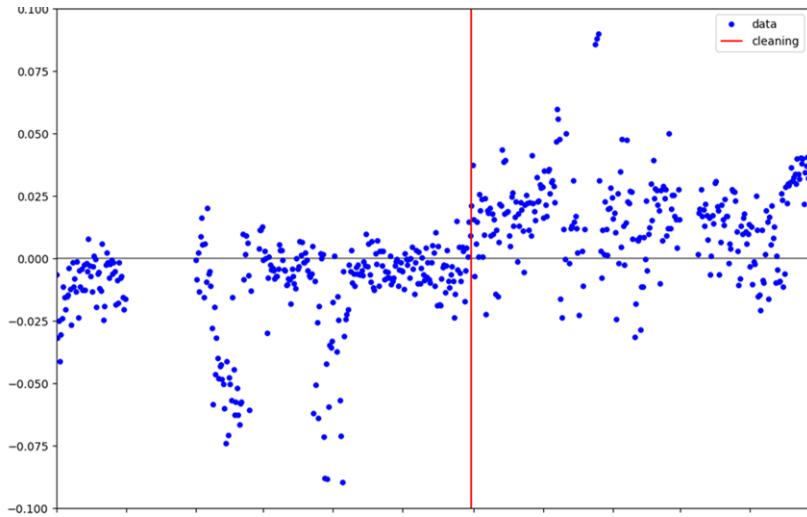


Raw data: total daily yield per inverter



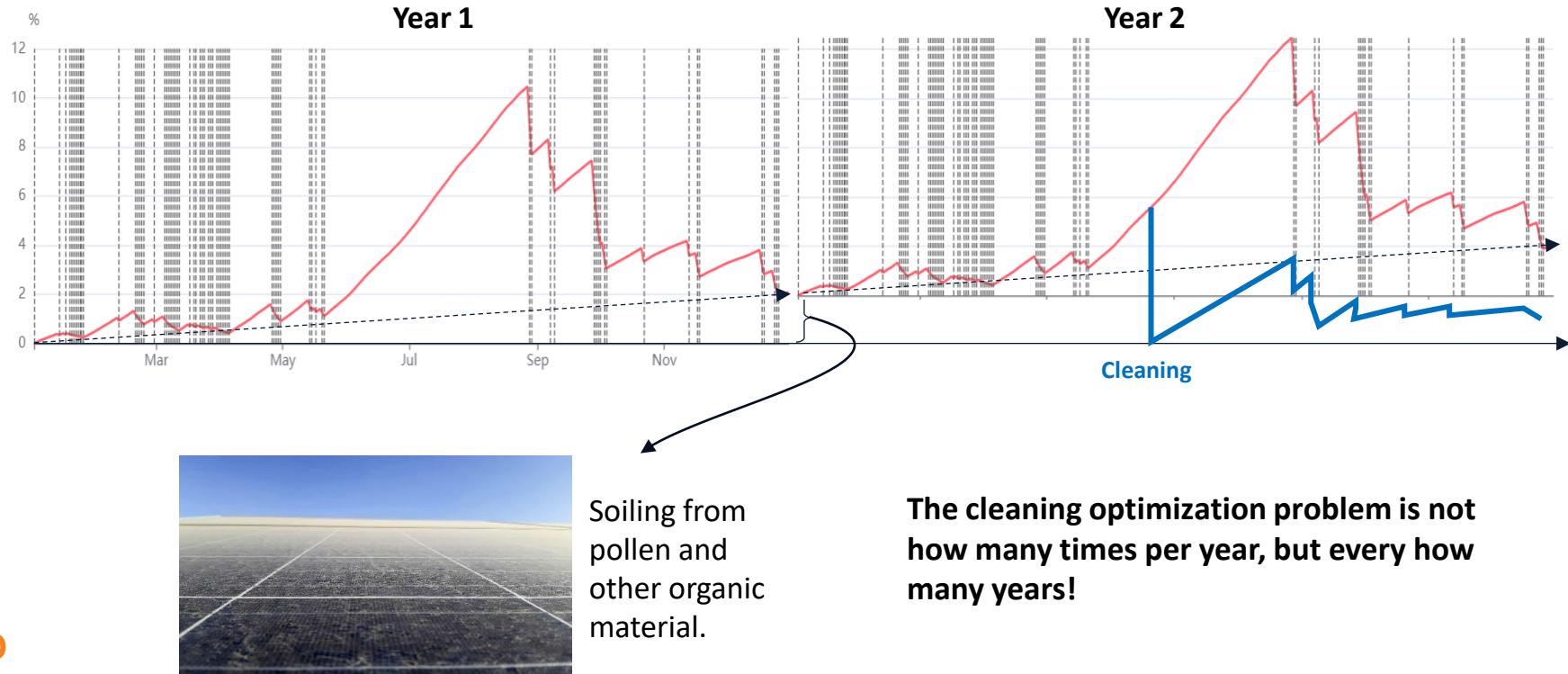
filters out:  
low irradiance  
partial shading  
inverter issues  
...

Relative production increase comparing cleaned  
and uncleaned inverters.



$$\Delta = \frac{\text{avg}(P_{\text{with cleaning}}) - \text{avg}(P_{\text{no cleaning}})}{\text{avg}(P_{\text{with cleaning}})}$$

# The problem of Hard or Sticky Soiling



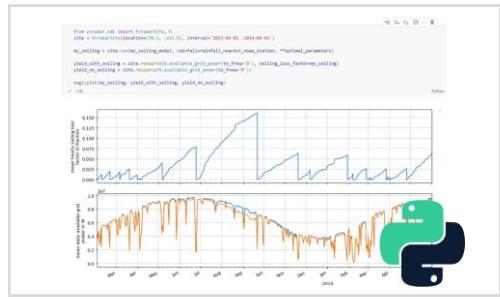
# PVRADAR – TRANSPARENT MODELING YOU CAN TRUST

## Modeling Platform



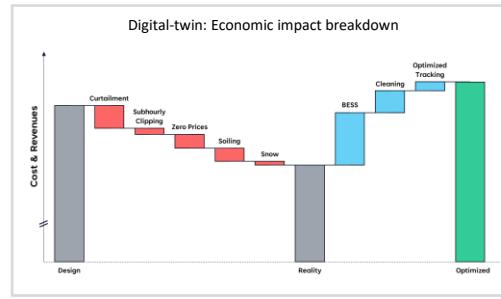
Ready to use tools for soiling & snow loss estimation and cleaning optimization

## Python Package



Toolbox to develop and validate your own internal models

## Custom Developments



Custom digital twins to quantify site specific losses and gains

Visit us as booth C5.370F

# Thank You

