Fleet-scale PV Performance Analytics

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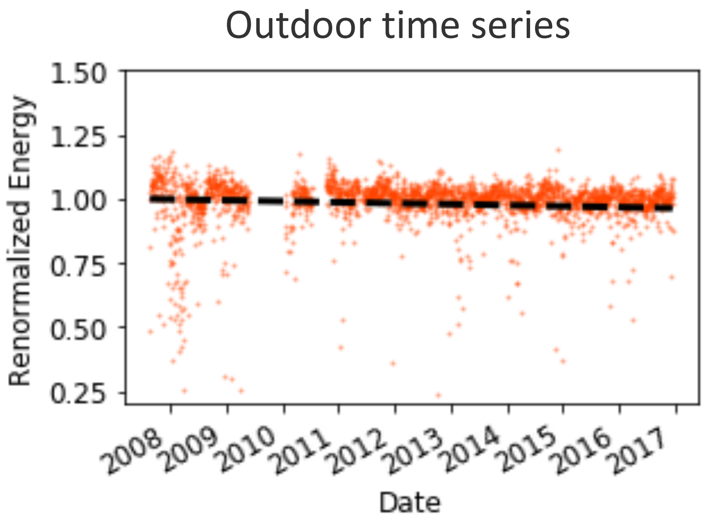
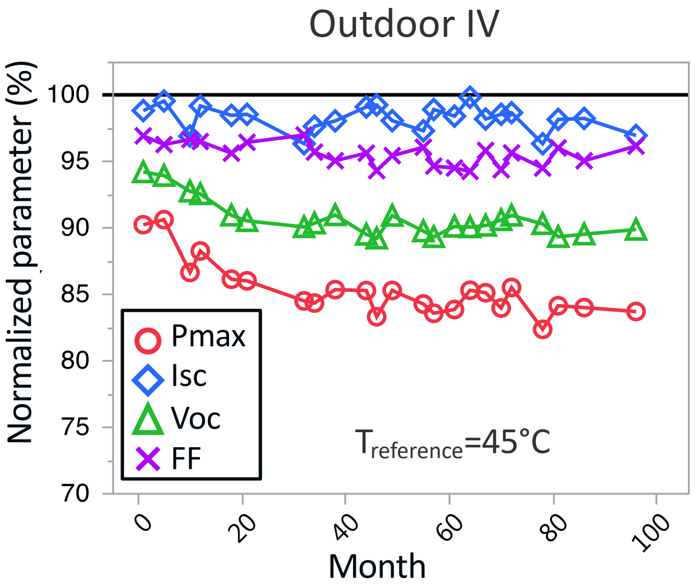
National Renewable Energy Laboratory

Sandia PV Systems Symposium 2019

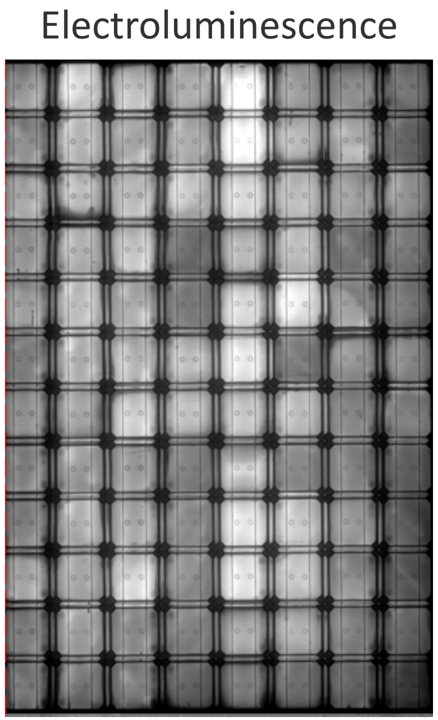
Case studies vs. fleet analysis





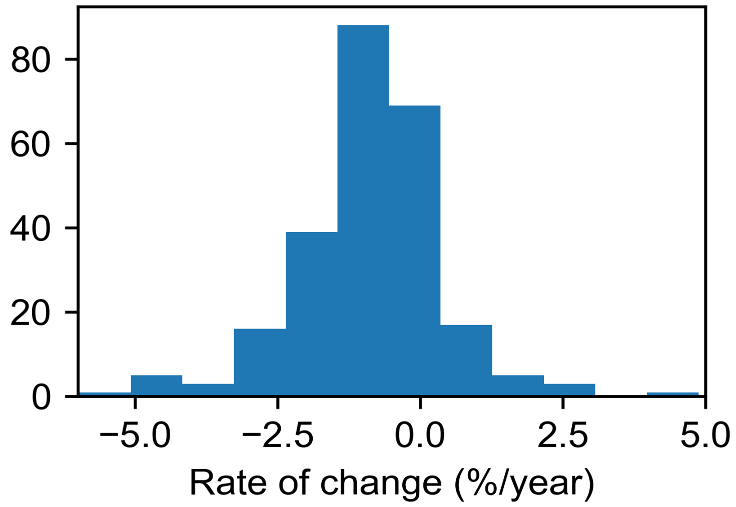
Case Study

Detailed analysis on a small number of systems



Fleet analysis

Trends in large numbers of systems



A Tale of Two Systems

Challenges with fleet scale analysis

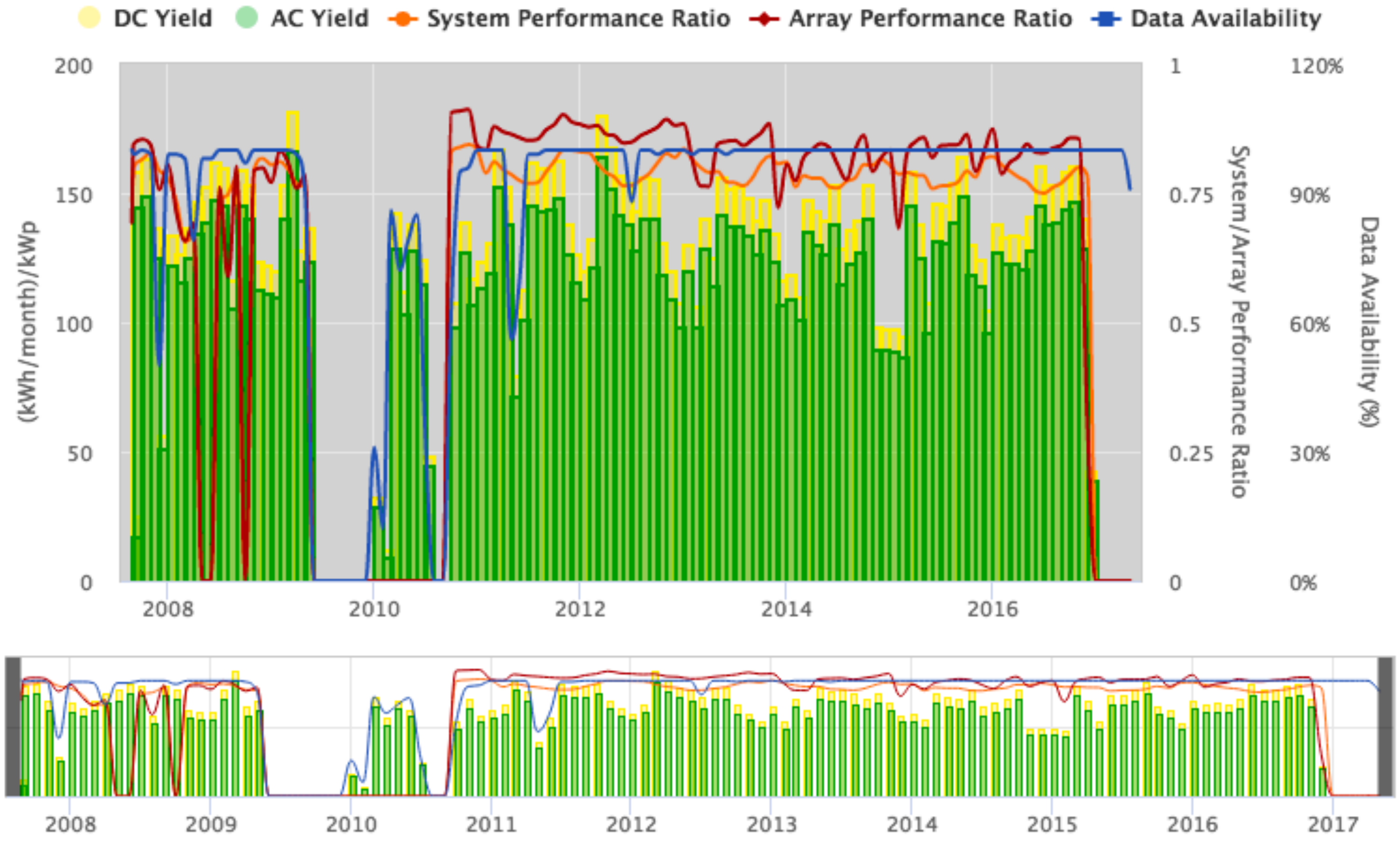
Comparison of two systems

System 1: Research system at NREL

PVDAQ Analysis & Download

[4] NREL x-Si #1

Latitude	39.7406
Longitude	105.1774
Elevation	1795.3 m
Azimuth	180
Tilt	40
Rating (DC)	1 kW
Module Mfg.	Sanyo
Module Type	HIP 200-BA3
Module Tech	1
Inverter Mfg.	SMA
Inverter Type	1800



Aggregation Level: By Month

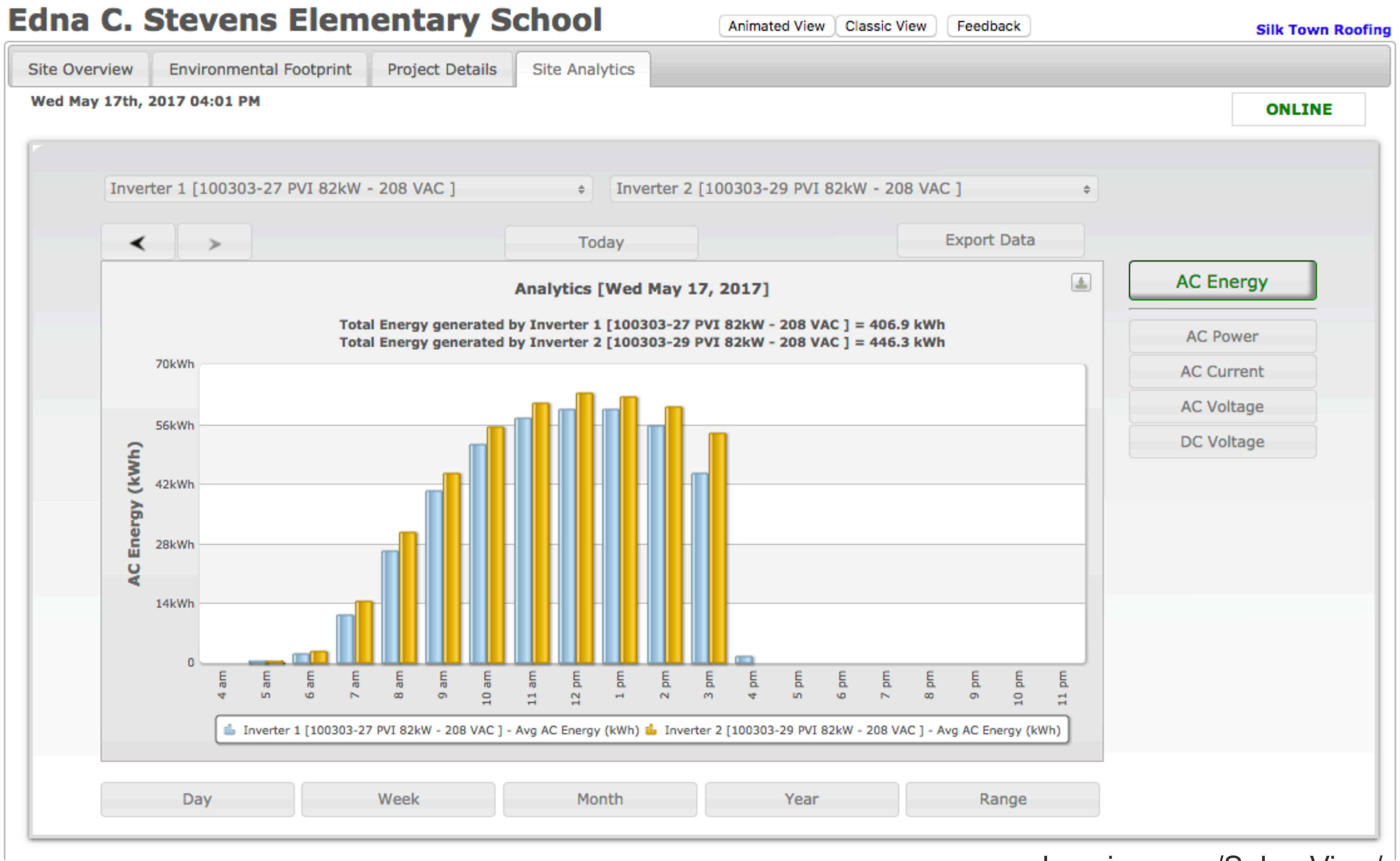
< System List

Download Data

maps.nrel.gov/pvdaq

Comparison of two systems

System 2: Elementary School in Connecticut



www.solrenview.com/SolrenView/mainFr.php?siteId=726

Comparison of two systems

Research system

- Metadata:
  - Location
  - System orientation
  - Module details
  - Inverter details
- Time series:
  - 1-minute
  - AC power/current/voltage
  - DC power/current/voltage
  - Ambient temperature
  - Inverter temperature
  - 3 module temperatures
  - Plane-of-array irradiance
  - DAS diagnostics

Elementary school

- Metadata:
  - Location
  - Module details
  - Inverter details
- Time series:
  - 5-minute
  - AC power/current/voltage
  - DC voltage

Comparison of two systems

Research system

- Metadata:
  - Location
  - System orientation
- Tim
  - AC power/current/voltage
  - DC power/current/voltage
  - Ambient temperature
  - Inverter temperature
  - 3 module temperatures
  - Plane-of-array irradiance
  - DAS diagnostics

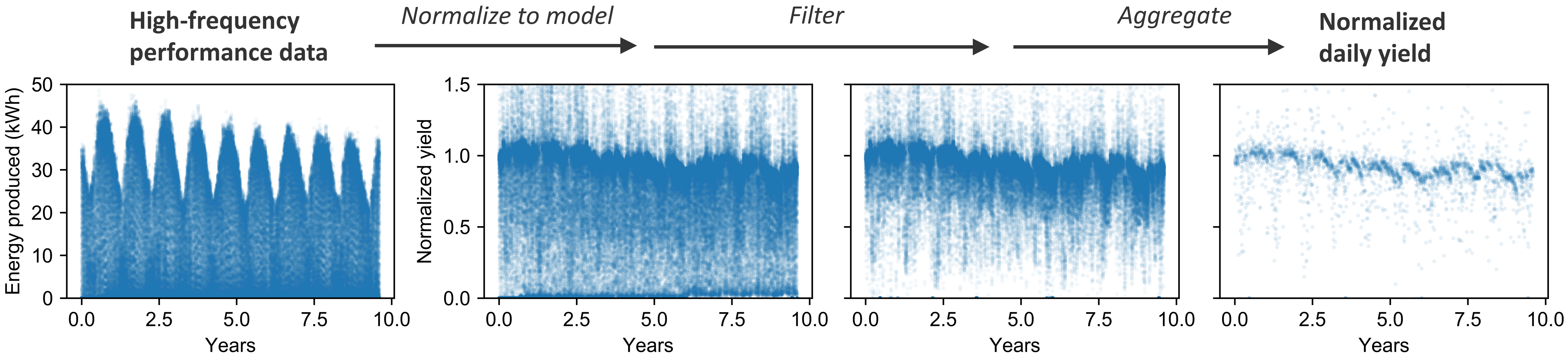
Elementary school

- Metadata:
  - Location
  - Module details
  - AC power/current/voltage
  - DC voltage

Goal:

Robust analytics that enable comparisons between data sets from disparate systems

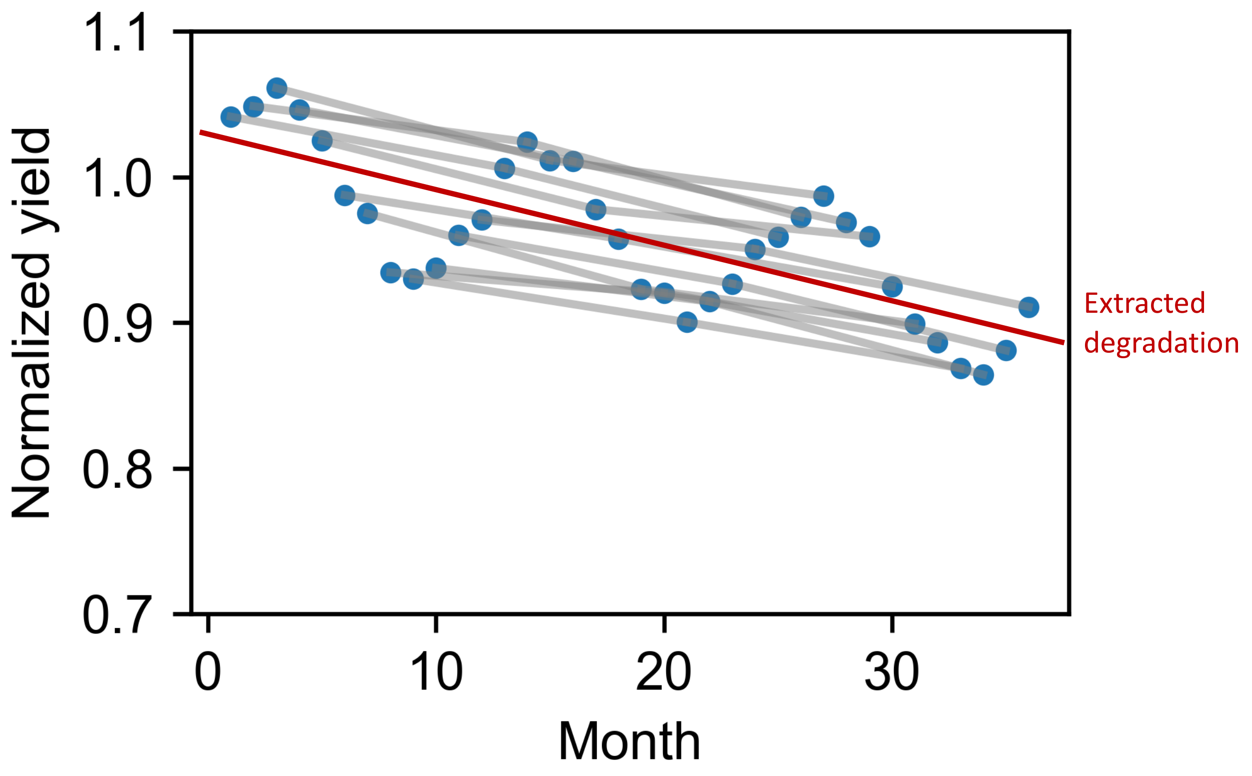
Analysis Framework



- First three steps (above) give a normalized daily yield
- Analyze the normalized yield for **soiling** and **degradation**
  - Utilize robust calculations
  - Pay attention to the uncertainty in the results
- Enabled by open source python library: RdTools (nrel.gov/pv/rdtools.html)

Degradation analysis

Year-on-year degradation analysis

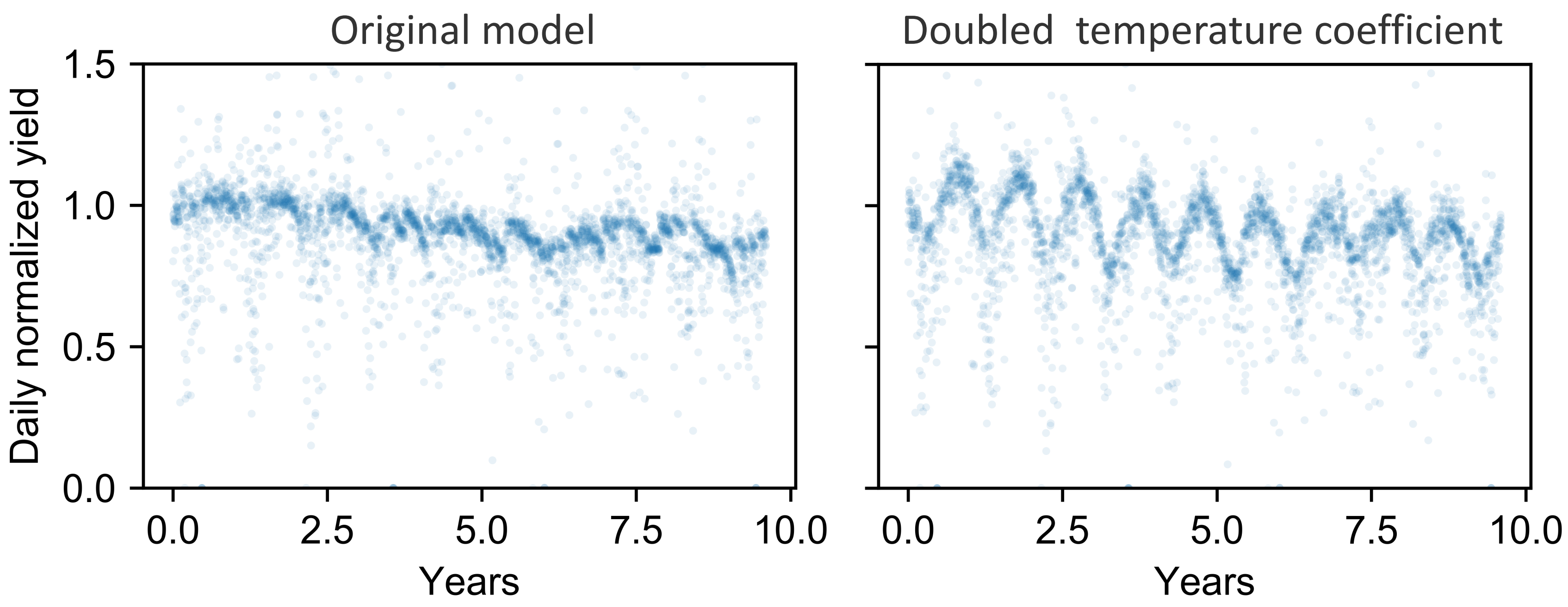


- Year-on-year is robust to seasonality and outliers
- Steps:
  - Compare each day (or week, month, etc.) to its corresponding day a year later
  - Calculate the median of all year-on-year slopes
- Pay attention to the confidence interval

E. Hasselbrink, M. Anderson, Z. Defreitas, et al., "Validation of the PVLife model using 3 million module- years of live site data," PVSC, p.0007, 2013

Jordan, Deceglie, & Kurtz. "PV degradation methodology comparison—A basis for a standard." PVSC, p.0273, 2016

Year-on-year is robust

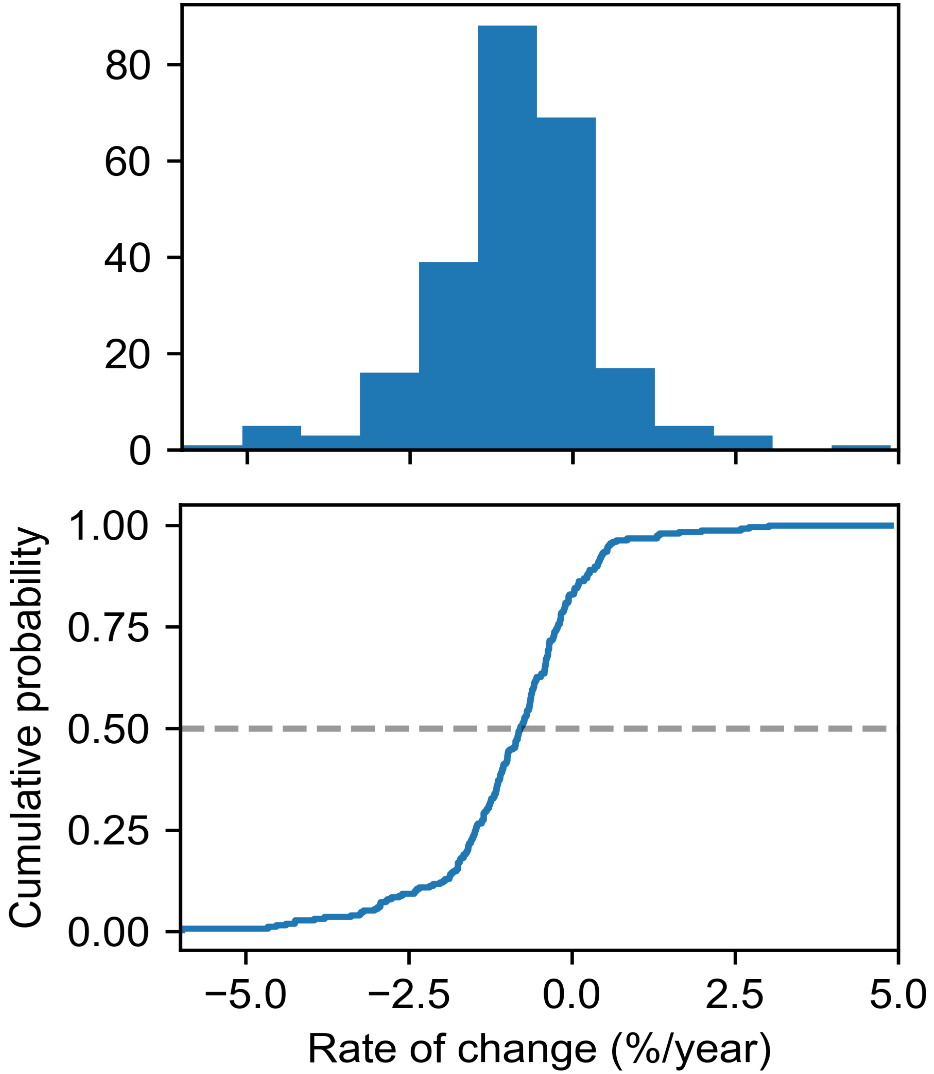


P50 Rd: -2.2 %/year
Conf. Int.: –2.5 to –1.8 %/year

P50 Rd: -1.9 %/year
Conf. Int.: –2.5 to –1.3 %/year

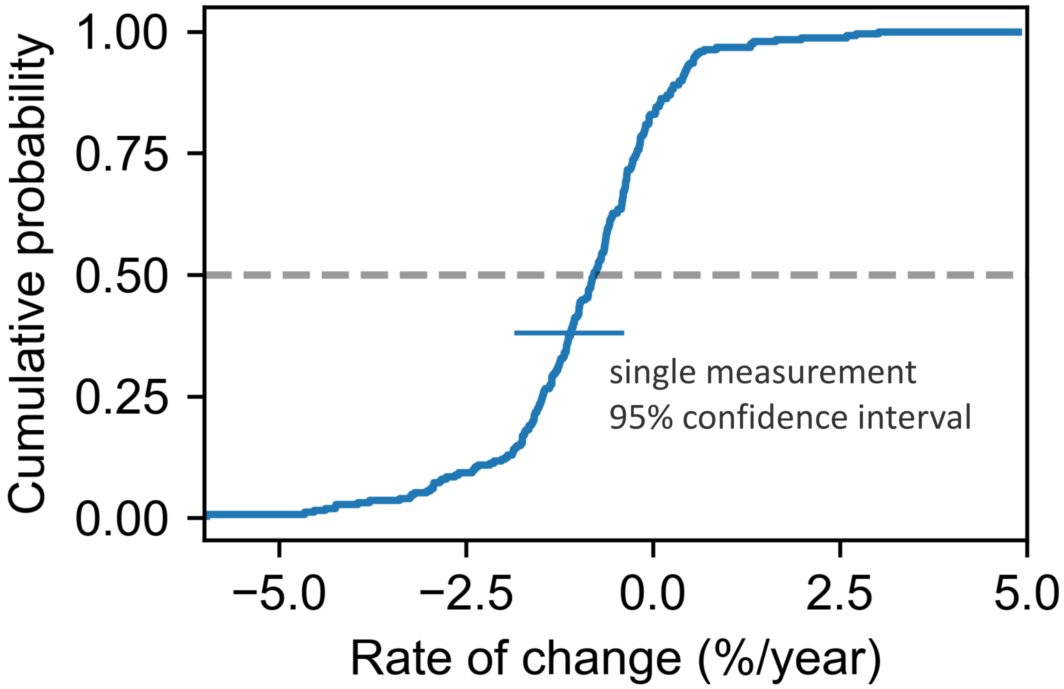
- Example: intentionally induced seasonality
- Results remain consistent
- Confidence interval appropriately expands
- **A very detailed performance model isn't needed**

Cumulative distribution functions (CDFs)



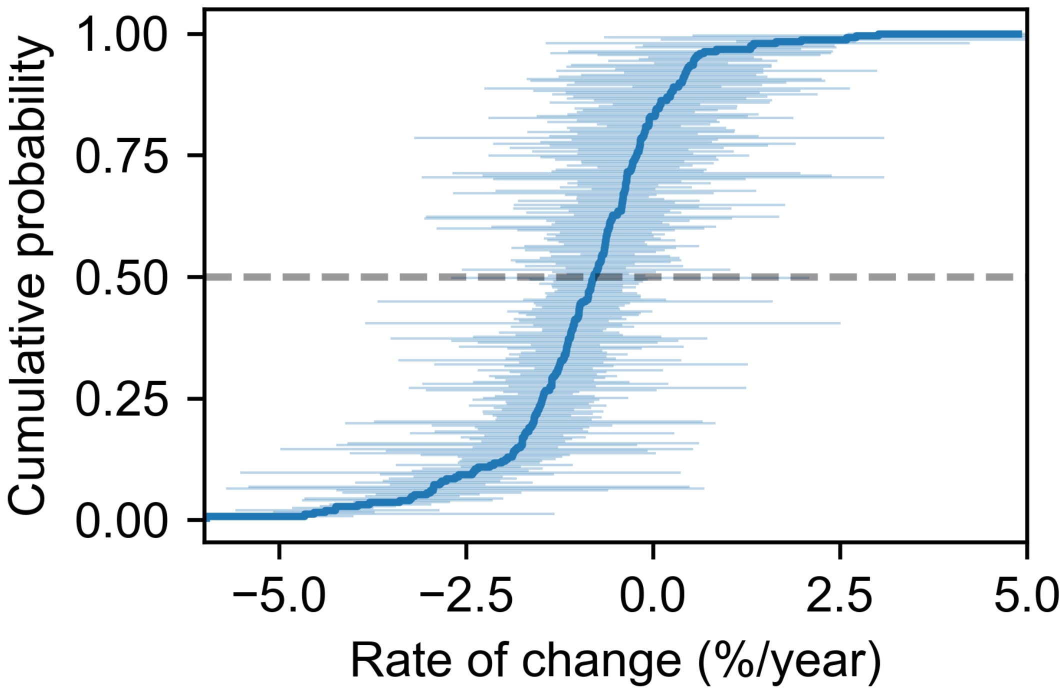
CDFs provide a way to visualize distributions, independent of bin size

CDFs with individual confidence intervals



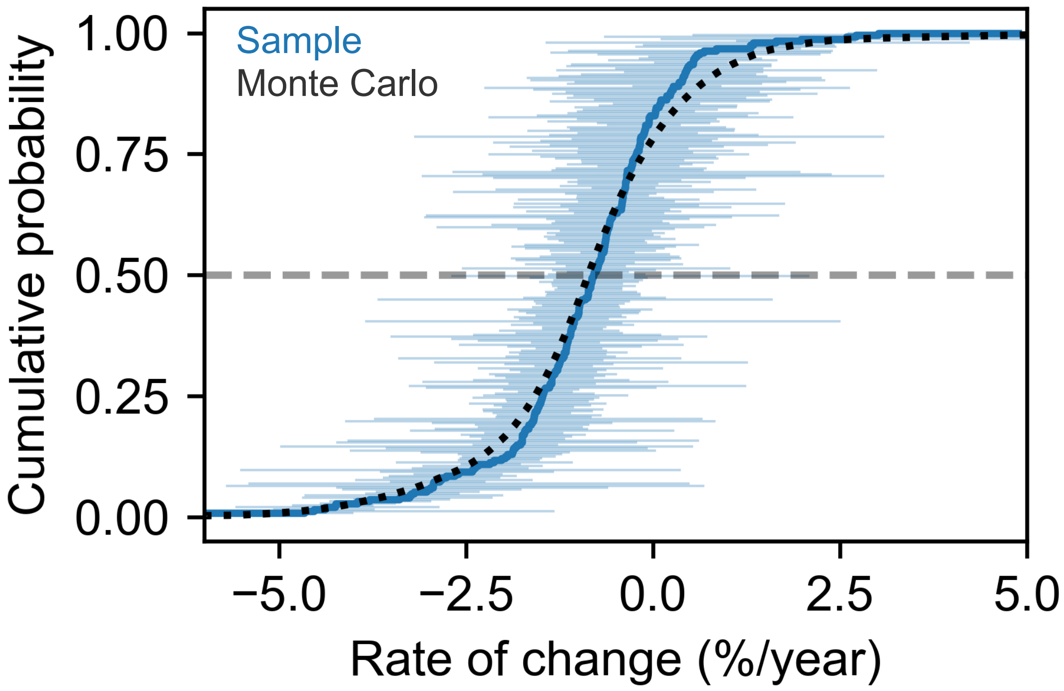
Every measurement on the CDF has its own uncertainty

CDFs with individual confidence intervals



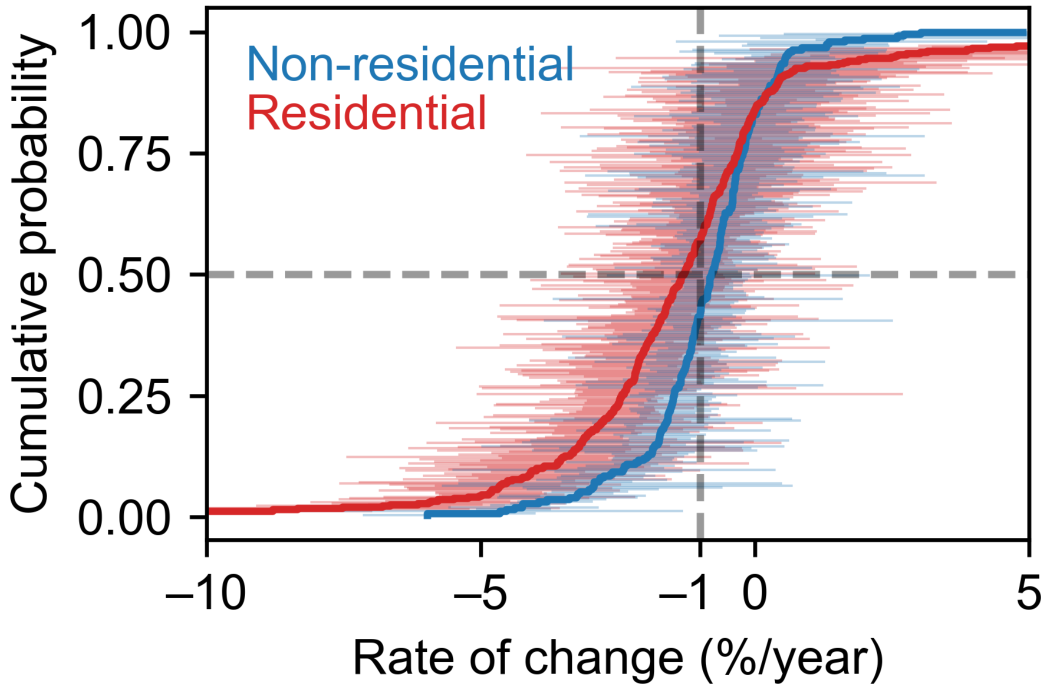
We can include each measurement's 95% confidence interval on the plot

Uncertainty in the distribution



- Monte Carlo to include the effect of individual CIs on full distribution
- Resample the data (with replacement) within the individual confidence intervals many times
- CDF of this Monte Carlo resampling follows the original closely
- **For fleet-scale studies, we can sacrifice some site-level precision**

Example: residential vs. non-residential



- Analyzed 634 subarrays from 503 PV systems in the United States
- 387 residential systems
- 116 larger, non-residential systems
- Negative rate of change = degradation (-1%/year indicated)
- Residential systems tended to degrade more rapidly
- 29% of residential and 38% of non-residential systems degraded slower than -0.5%/year

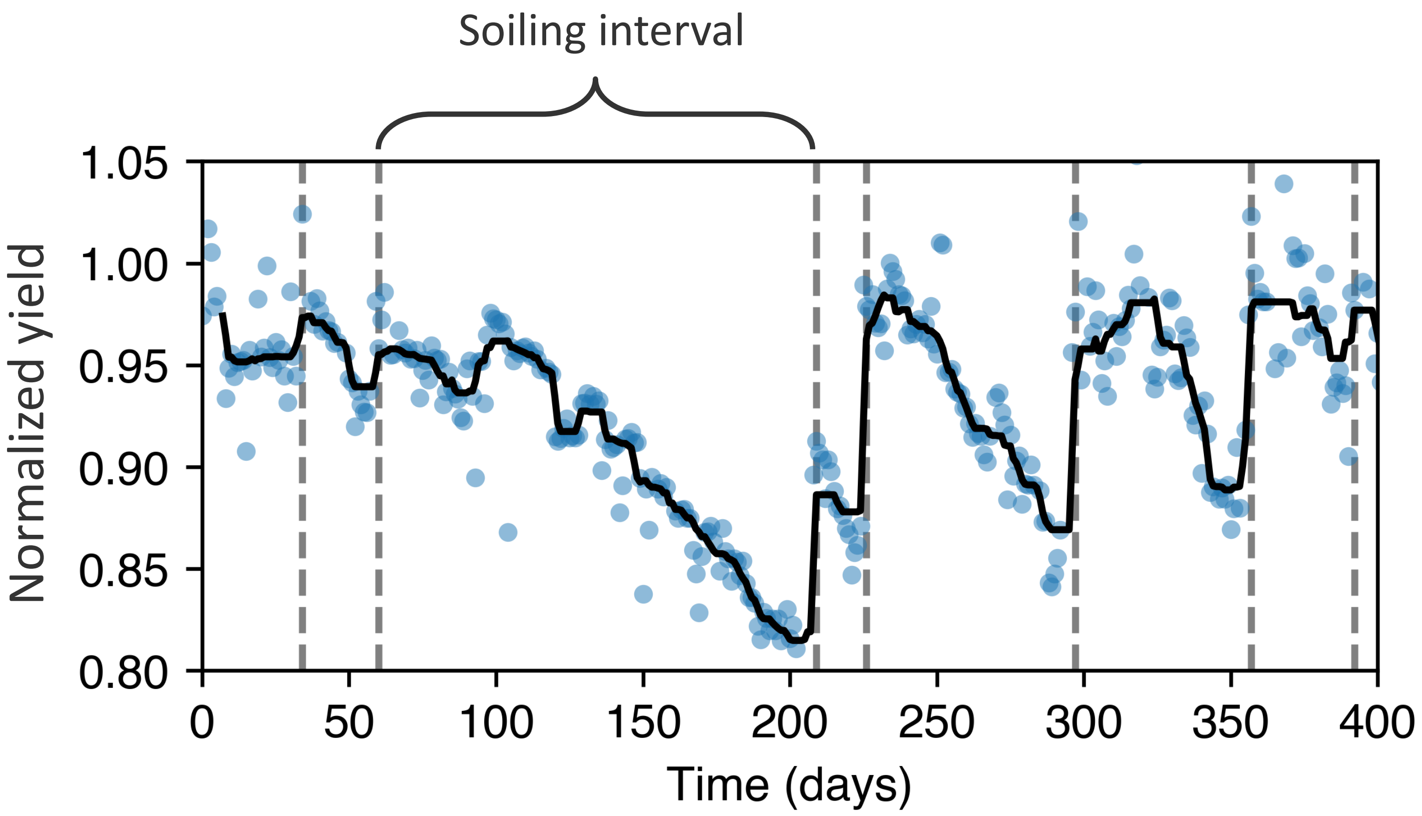
Deceglie et al. IEEE JPV 9(2), pp. 476–482, 2019

Soiling analysis

Stochastic rate and recovery (SRR)

Step 1: Detect soiling intervals

Stochastic rate and recovery (SRR) soiling analysis

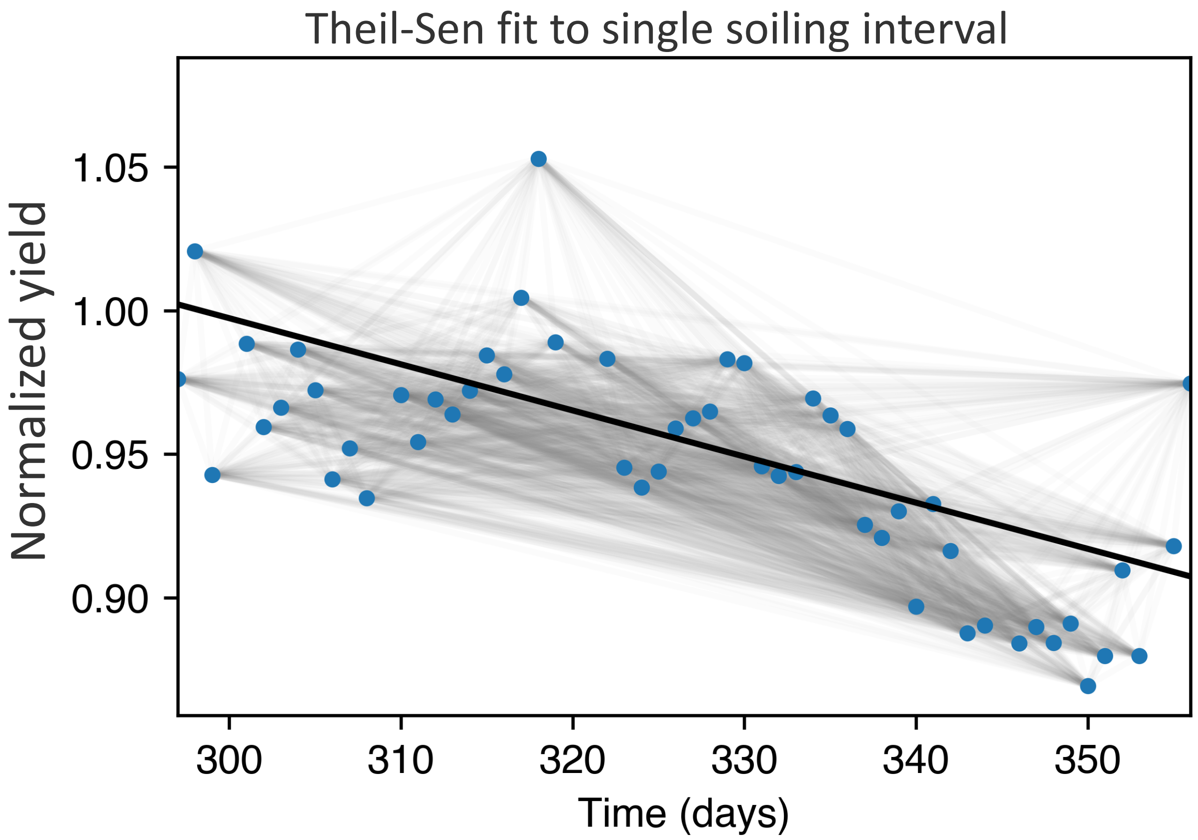


- Operate on normalized daily yield (blue dots)
- Use rolling median (black line) to detect positive steps, interpreted as cleaning events (dashed lines)

Deceglie et al. IEEE JPV 8(2), pp. 547-551, 2018

Step 2: Fit each soiling interval

Stochastic rate and recovery (SRR) soiling analysis



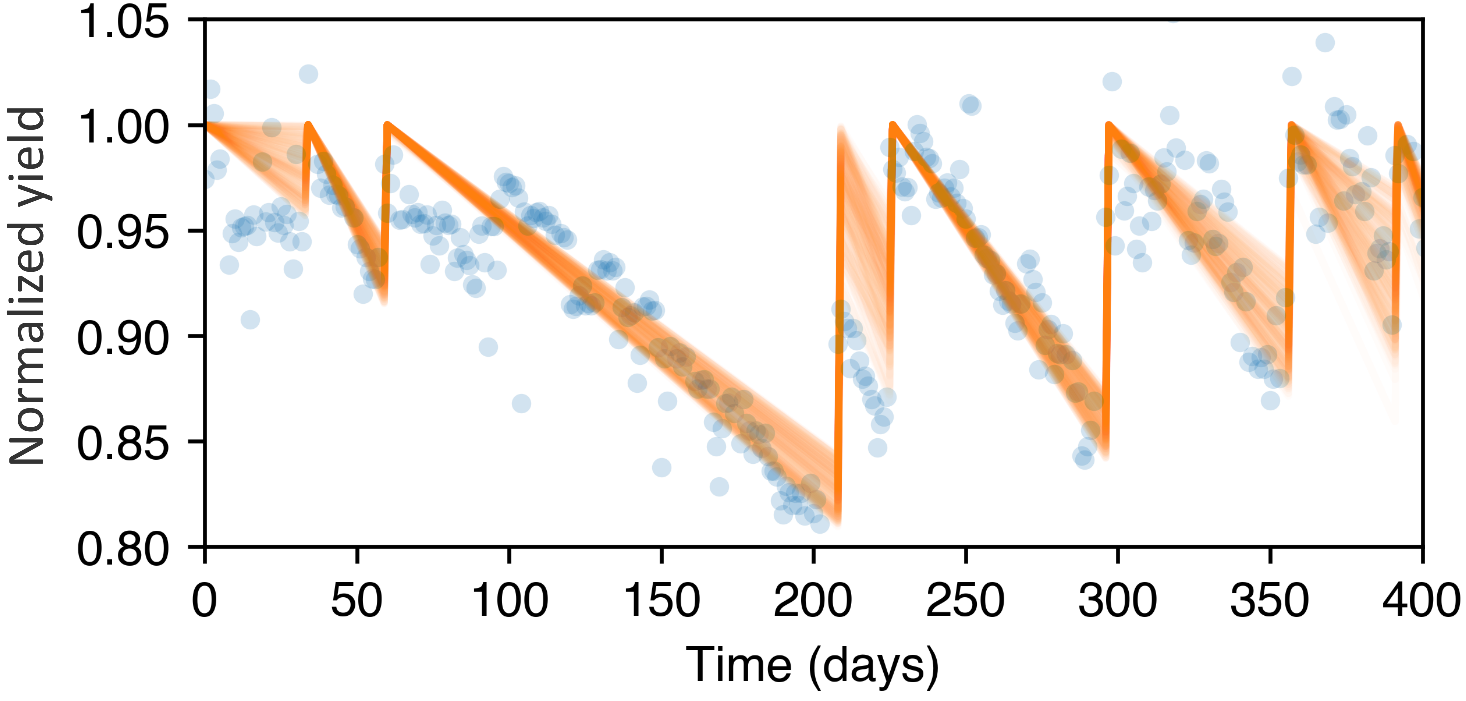
- Fit each interval identified in step 1 with the Theil-Sen method
  - Median of point-to-point slopes
  - Robust to outliers
- Keep track of the slopes, intercepts and uncertainty

Deceglie et al. IEEE JPV 8(2), pp. 547-551, 2018

Step 3: Monte Carlo of possible profiles

Stochastic rate and recovery (SRR) soiling analysis

Monte Carlo realizations (orange) of possible soiling profiles

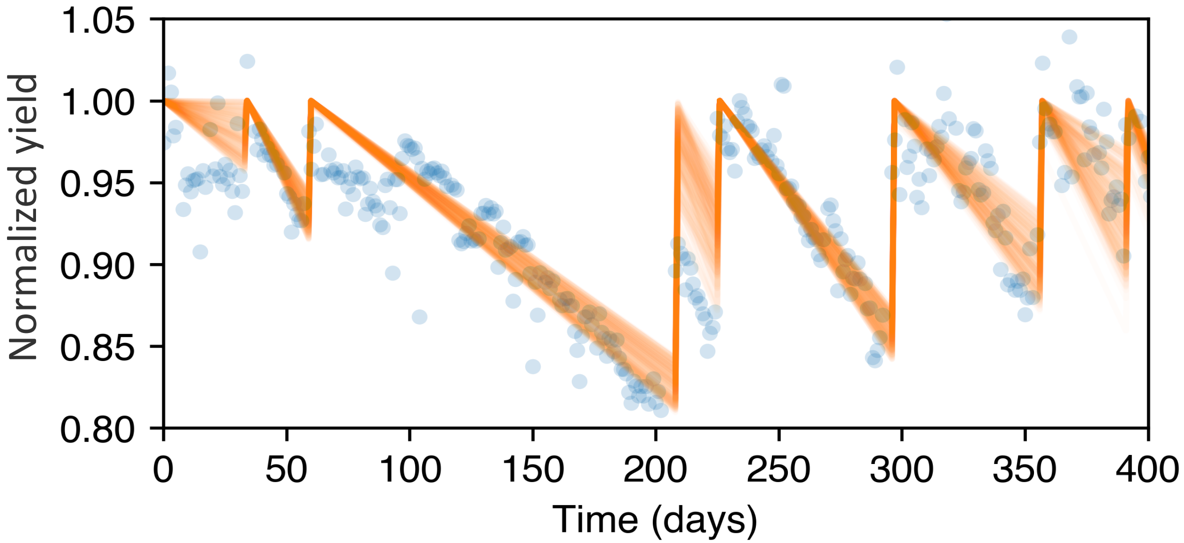


Generate possible soiling profiles from the slopes, uncertainties, and recoveries extracted for each interval

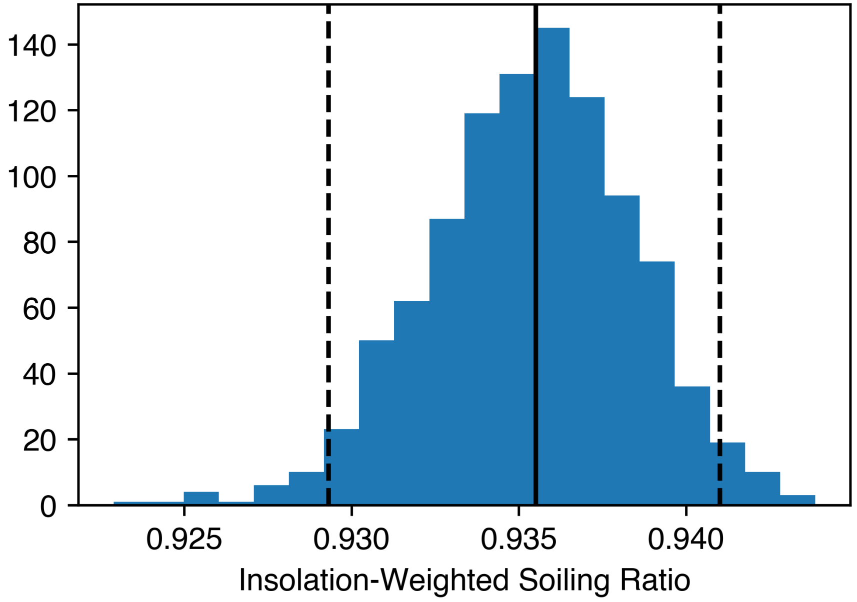
Deceglie et al. IEEE JPV 8(2), pp. 547-551, 2018

Final step: calculate soiling loss

Stochastic rate and recovery (SRR) soiling analysis



Extract total soiling losses



Extract soiling interval statistics

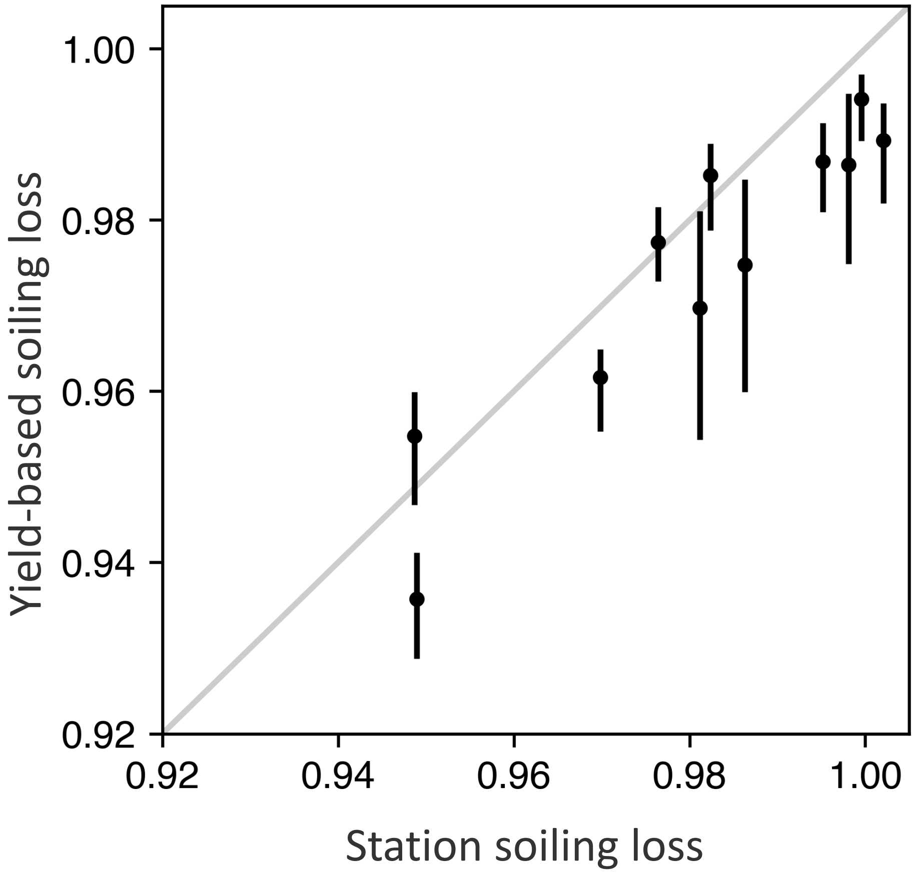
	start	end	slope	slope_low	slope_high	inferred_start_loss	inferred_end_loss	length	valid
0	2008-11-13 00:00:00+09:30	2008-12-11 00:00:00+09:30	-0.001289	-0.003674	0.000000	1.020397	0.984317	28	True
1	2008-12-12 00:00:00+09:30	2009-03-20 00:00:00+09:30	0.000000	0.000000	0.000000	0.980044	0.994708	98	False
2	2009-03-21 00:00:00+09:30	2009-03-24 00:00:00+09:30	0.000000	0.000000	0.000000	0.987630	1.023365	3	False
3	2009-03-25 00:00:00+09:30	2009-05-28 00:00:00+09:30	-0.000558	-0.000874	-0.000244	1.039202	1.003482	64	True
4	2009-05-29 00:00:00+09:30	2009-08-11 00:00:00+09:30	-0.000534	-0.000724	-0.000310	1.036823	0.997294	74	True

Analyze Monte Carlo realizations and interval fits:

- Insolation-weighted average soiling ratio
- Statistics of each soiling interval (e.g. soiling rate)

Deceglie et al. IEEE JPV 8(2), pp. 547-551, 2018

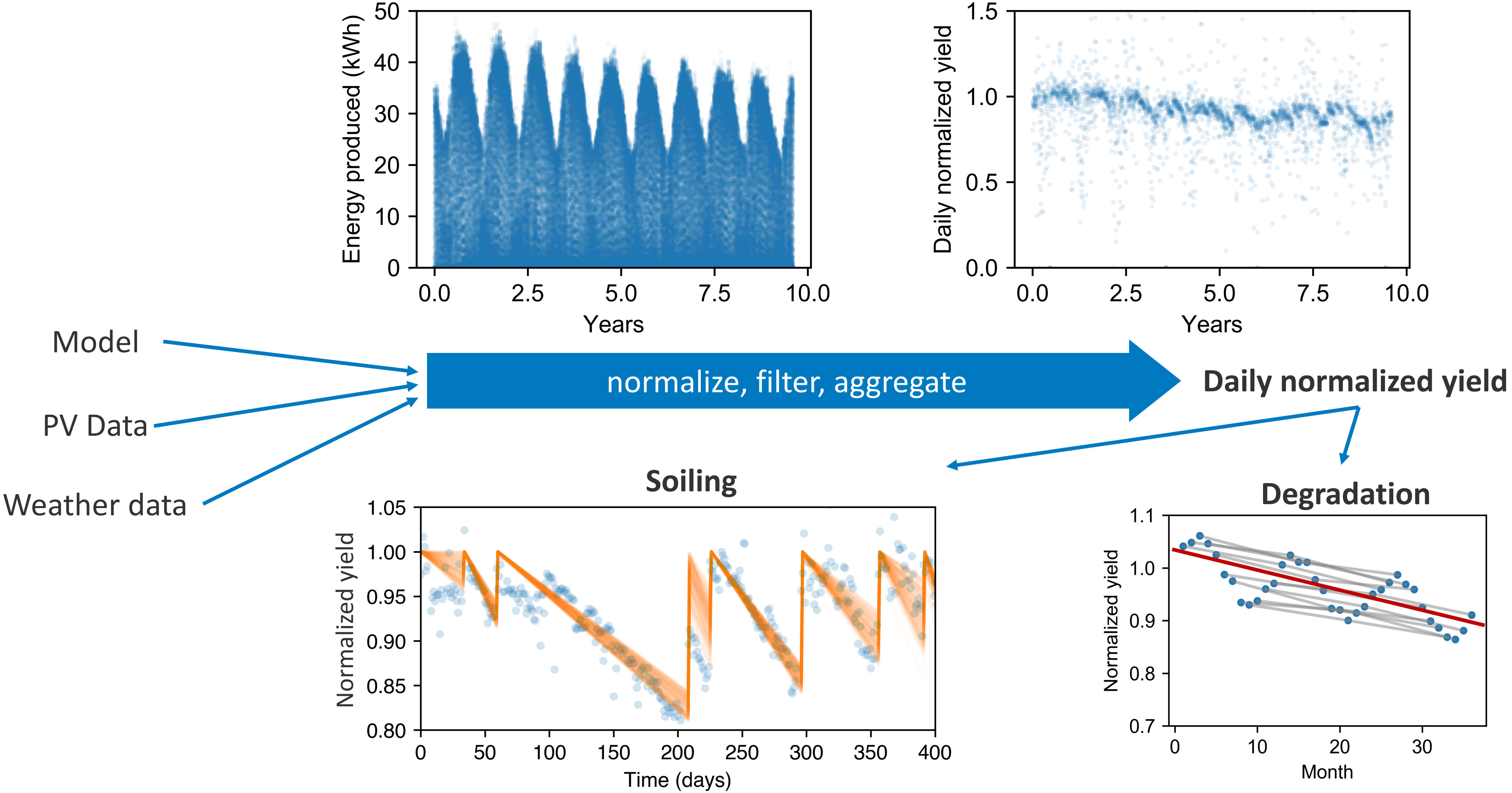
Soiling analysis: validation



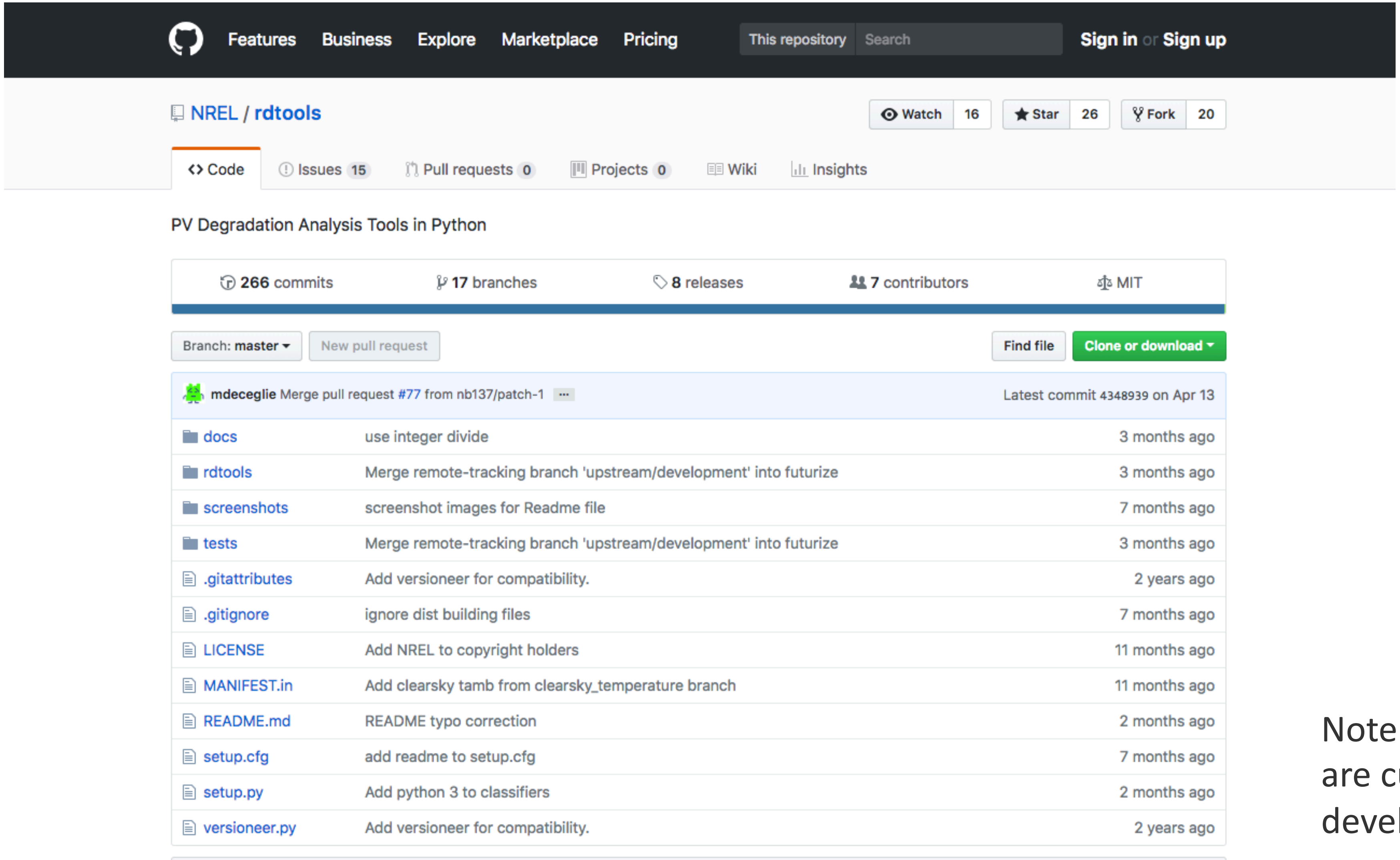
- Applied calculations to the clean module in a soiling station
- Outperformed fixed soiling rate models
- Bias is likely in the **station** soiling ratio, due to co-soiling of modules between cleaning

Deceglie et al. IEEE JPV 8(2), pp. 547-551, 2018

Analysis workflow



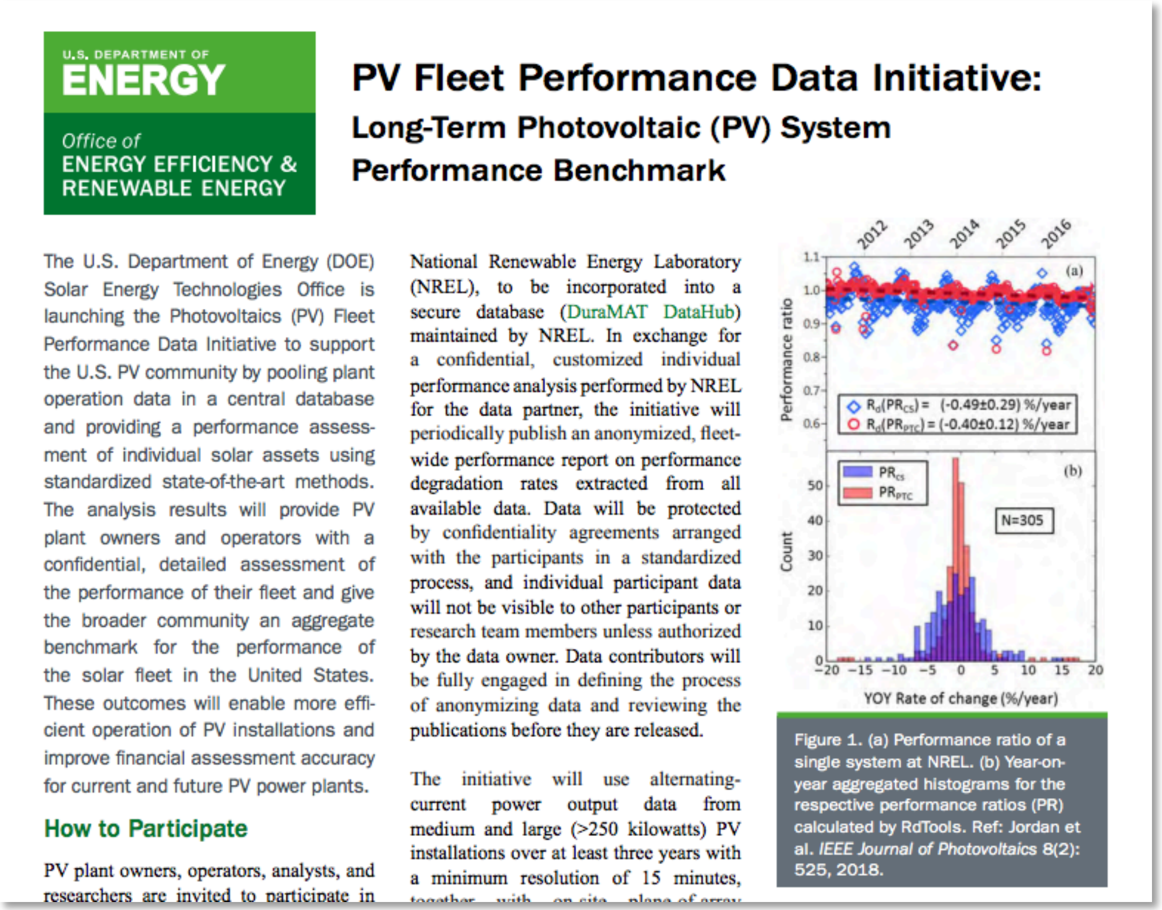
All this is available in RdTools



Note: soiling methods are currently in the development branch

- Read me and examples: https://github.com/NREL/rdtools
- Install: pip install rdtools

Opportunity to work together



U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

PV Fleet Performance Data Initiative:
Long-Term Photovoltaic (PV) System Performance Benchmark

The U.S. Department of Energy (DOE) Solar Energy Technologies Office is launching the Photovoltaics (PV) Fleet Performance Data Initiative to support the U.S. PV community by pooling plant operation data in a central database and providing a performance assessment of individual solar assets using standardized state-of-the-art methods. The analysis results will provide PV plant owners and operators with a confidential, detailed assessment of the performance of their fleet and give the broader community an aggregate benchmark for the performance of the solar fleet in the United States. These outcomes will enable more efficient operation of PV installations and improve financial assessment accuracy for current and future PV power plants.

How to Participate

PV plant owners, operators, analysts, and researchers are invited to participate in National Renewable Energy Laboratory (NREL), to be incorporated into a secure database (DuraMAT DataHub) maintained by NREL. In exchange for a confidential, customized individual performance analysis performed by NREL for the data partner, the initiative will periodically publish an anonymized, fleet-wide performance report on performance degradation rates extracted from all available data. Data will be protected by confidentiality agreements arranged with the participants in a standardized process, and individual participant data will not be visible to other participants or research team members unless authorized by the data owner. Data contributors will be fully engaged in defining the process of anonymizing data and reviewing the publications before they are released.

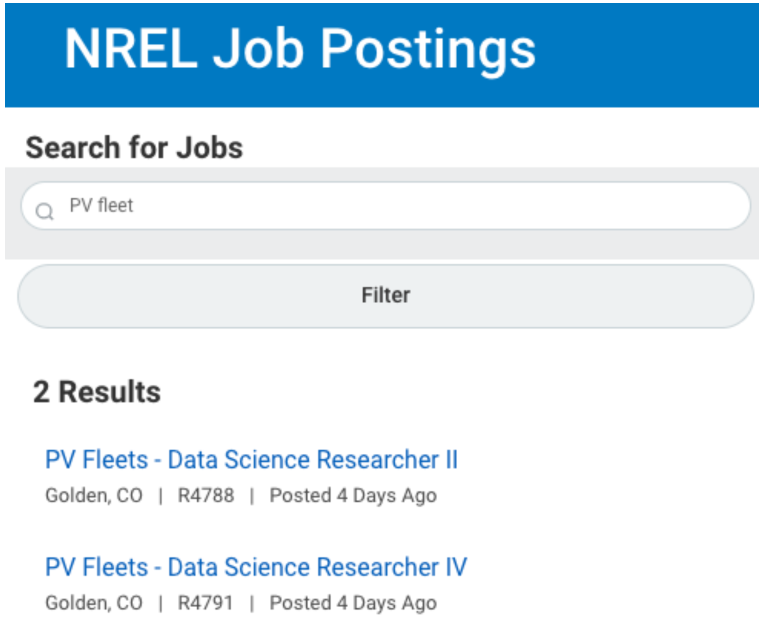
The initiative will use alternating-current power output data from medium and large (>250 kilowatts) PV installations over at least three years with a minimum resolution of 15 minutes,

Figure 1. (a) Performance ratio of a single system at NREL. (b) Year-on-year aggregated histograms for the respective performance ratios (PR) calculated by RdTools. Ref: Jordan et al. *IEEE Journal of Photovoltaics* 8(2): 525, 2018.

https://www.energy.gov/eere/solar/downloads/photovoltaic-fleet-performance-data-initiative

Contacts: Tassos.Golnas@ee.doe.gov and Inna.Kozinsky@ee.doe.gov

Learn about your fleet's performance or come help with the analysis!



https://www.nrel.gov/careers/find-job.html

Conclusion

- Fleet-scale analysis enabled by open-source RdTools elucidates system degradation and soiling trends
- Challenges with soiling and drifting sensors
  - Clearsky detection and filtering:
    - *Jordan et al. JPV 8(2) pp. 525–531*
    - *Ellis et al. "Automatic Detection of Clear-sky Periods From Irradiance Data" JPV (in press)*
  - Soiled sensors :
    - *DeFreitas et al. "Evaluating the Accuracy of Various Irradiance Models in Detecting Soiling of Irradiance Sensors" PVSC 2019 (in prep)*
- We can tolerate moderate system-by-system uncertainty in fleet-scale analyses
- Use lowest-common denominator analysis
- Raise the common denominator: invest in data quality upfront:
  - Standard and documented naming conventions
  - Standard and documented DAQ systems and met packages
  - Standard and documented aggregation/averaging and time zone information
- Fleet analyses can identify underperforming systems for further investigation

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Thank you

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