Best-Practices in PV Plant Performance Degradation Benchmarking

Impact of filtering criteria and aggregation methods

Daniel Fregosi, PhD
Solar Generation, EPRI
dfregosi@epri.com

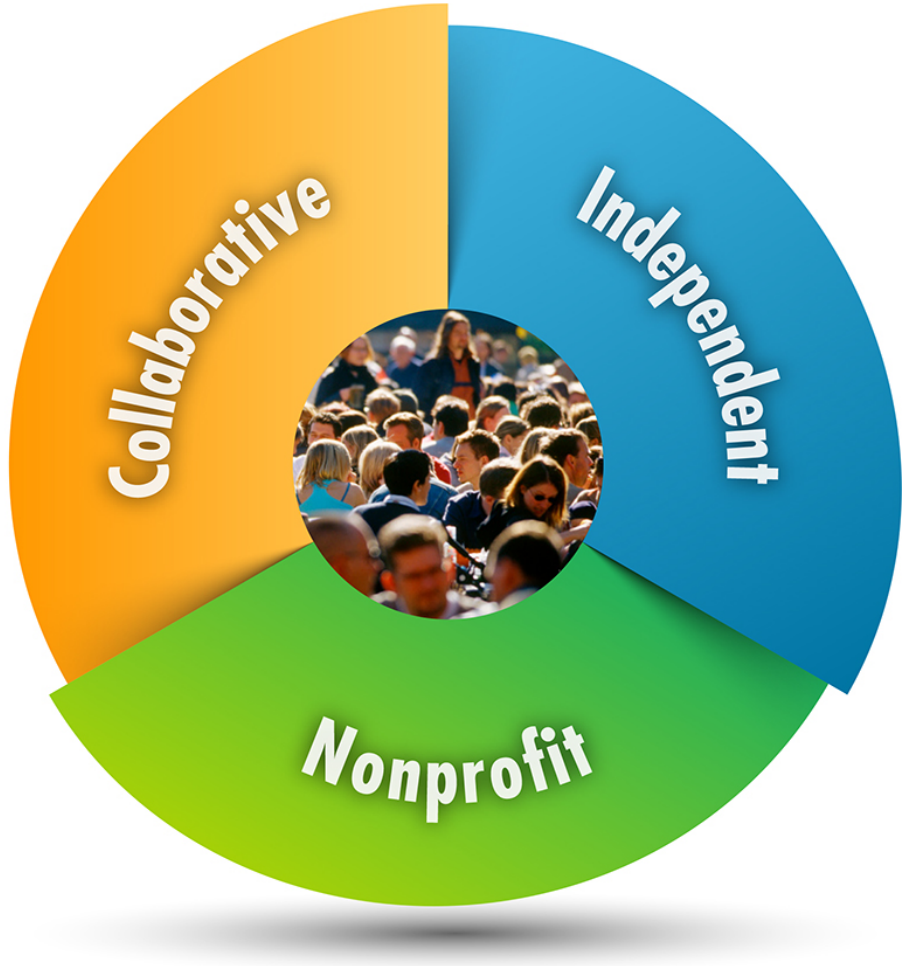
PV Systems Symposium
Albuquerque, NM
2019-05-14

What is the Electric Power Research Institute (EPRI)?

- **Mission**
  Advance *safe*, *reliable*, *affordable,* and *environmentally responsible* electricity for society through global collaboration, thought leadership and science & technology innovation

- **Members**
  450+ participants in more than 30 countries

EPRI members generate approximately 90% of the electricity in the United States.



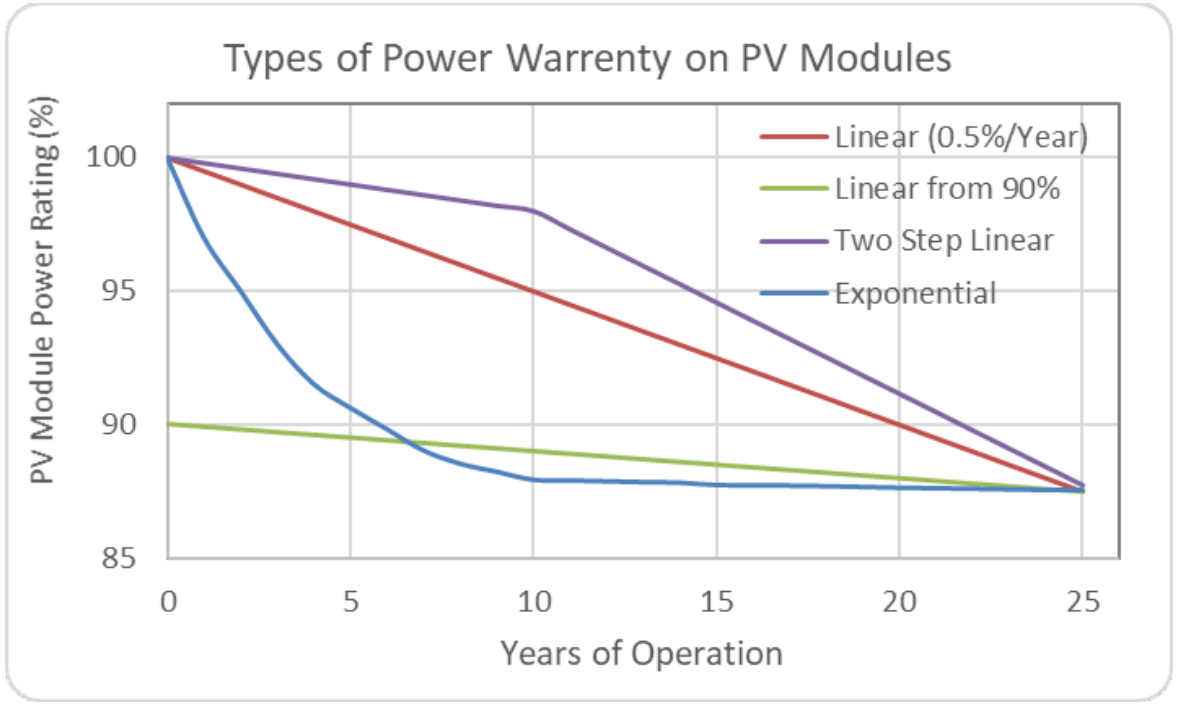
Knowing degradation is important for LCOE!

Degradation is a ***gradual and irreversible loss of performance***

- Measured by nameplate percent decrease over time (usually per year)
- Baselined against initial capacity (nameplate or performance)

The ***degradation rate*** *is* required…

- to estimate plant output energy over its lifetime
- to calculate the levelized cost of electricity (LCOE)



Example power warranties from PV module OEMs

$$LCOE\ (\$/kWh) = \frac{Lifetime\ Cost\ of\ a\ Plant\ (\$)}{Lifetime\ Energy\ Production\ (kWh)}$$

$$Lifetime\ Energy\ Production = f(Degradation\ Rate)$$

Lots of degradation data, what rate is right for large plants?

A wide ***variation*** of degradation rates is reported

- More than 11,000 degradation rates in almost 200 studies from 40 different countries

Most studies to-date analyze the degradation rate of a ***single module or a few modules per system***

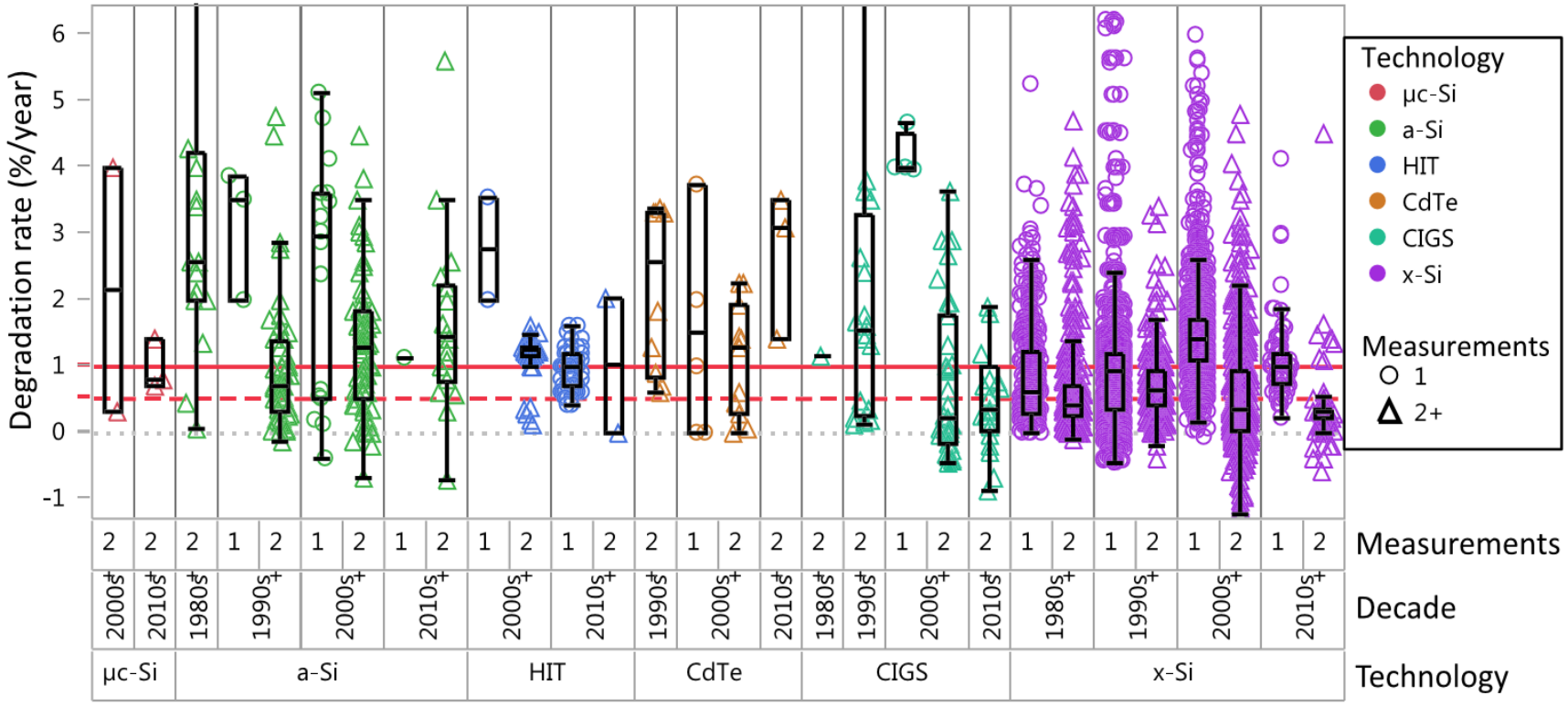


Image Source: Jordan, D.C., *et al*., (2016). "Compendium of photovoltaic degradation rates," *Prog. Photovolt.: Res. Appl.* 2016.

Degradation rate of components may not be appropriate for plants

Near-term Goal: Benchmark Degradation

- Large scale - using commonly available time-series data
- Opportunities and challenges with using performance data

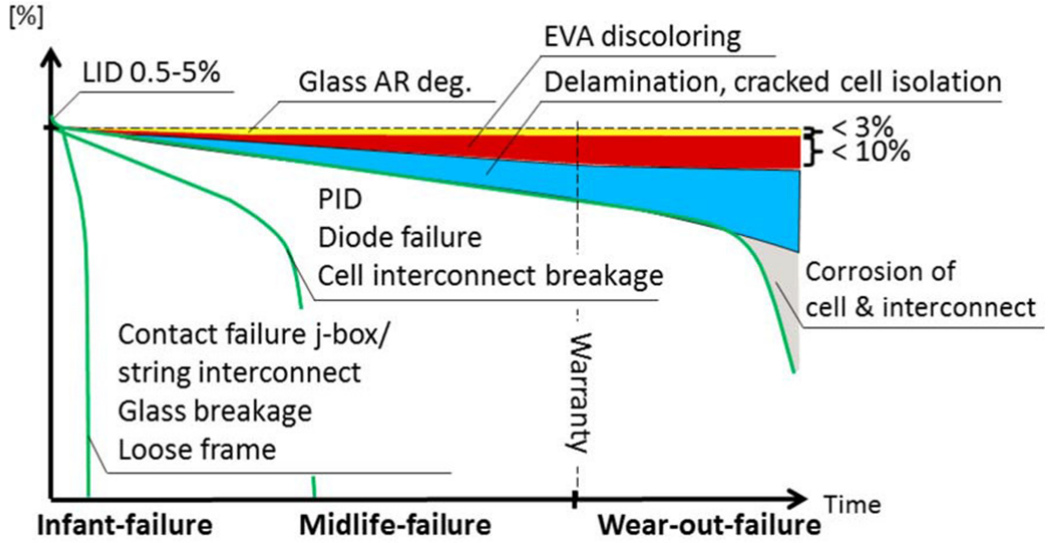


Image Source: *Review on Failures of PV Modules*. IEA-PVPS. Paris, France:2013.

Key Research Questions

- How do common industry values of 0.5 – 1.0%/yr compare reality for utility-scale plant-level degradation?
- How does the degradation rate of a plant or fleet compare across the industry?
- What factors influence degradation?

Objective and Approach

- Standardize calculation methodology for apples-to-apples comparison
- Intake data from EPRI members and external participants (allowing anonymization)
- Analyze degradation of participants' plants with RdTools Library
- Provide anonymized database of results

Industry-wide Conceptual Collaboration Model

Consistent calculation methodology to be developed.

Example dataset used to confirm analytical setup correct.

Performance data (Fleet-A)

Performance data (Fleet-B)

Performance data (Fleet-C)

NRE Transforming ENE

Please Participate!

dfregosi@epri.com

Industry-wide benchmark database and anonymized datasets

(*As agreed by data owner*)

Unite parallel degradation analysis efforts currently underway

Calculating Degradation Rate:

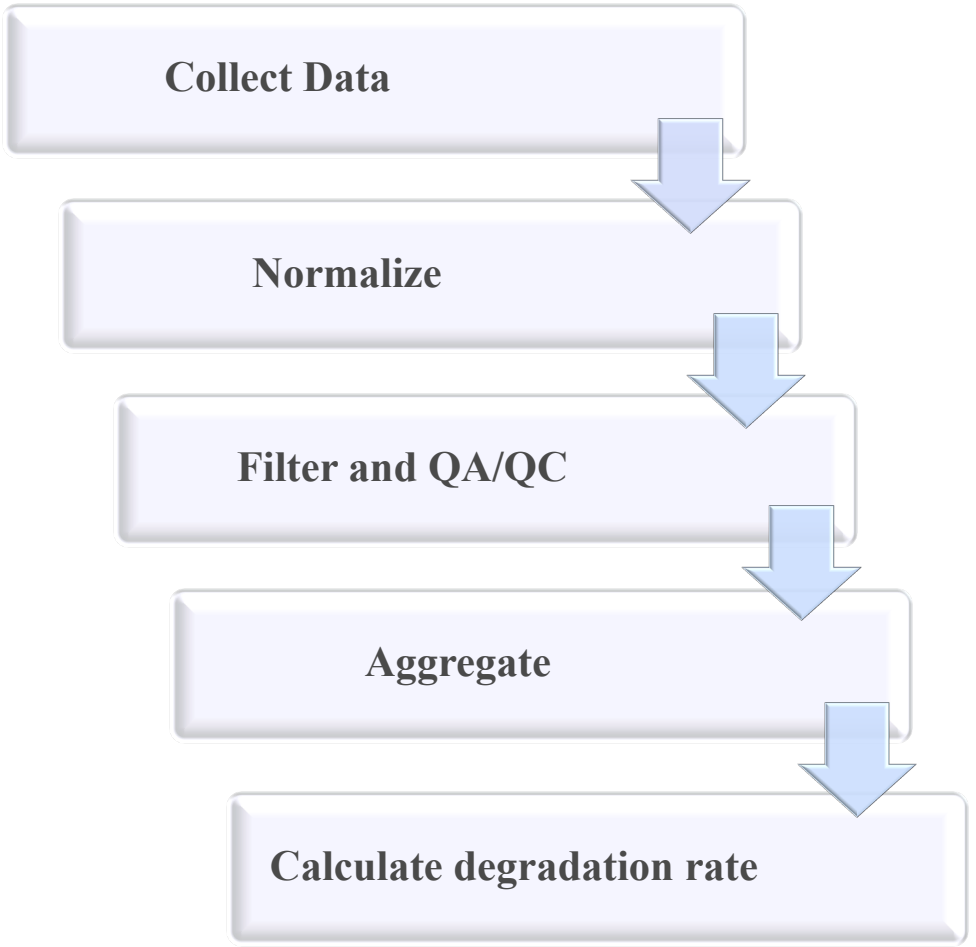
Analytical software package developed by NREL: RdTools

- Python-based software
- https://github.com/nrel/rdtools

Reference report

- D. Jordan et al. "Robust PV Degradation Methodology and Application", IEEE Journal of Photovoltaics, 2017

General steps to calculate degradation rate from performance data

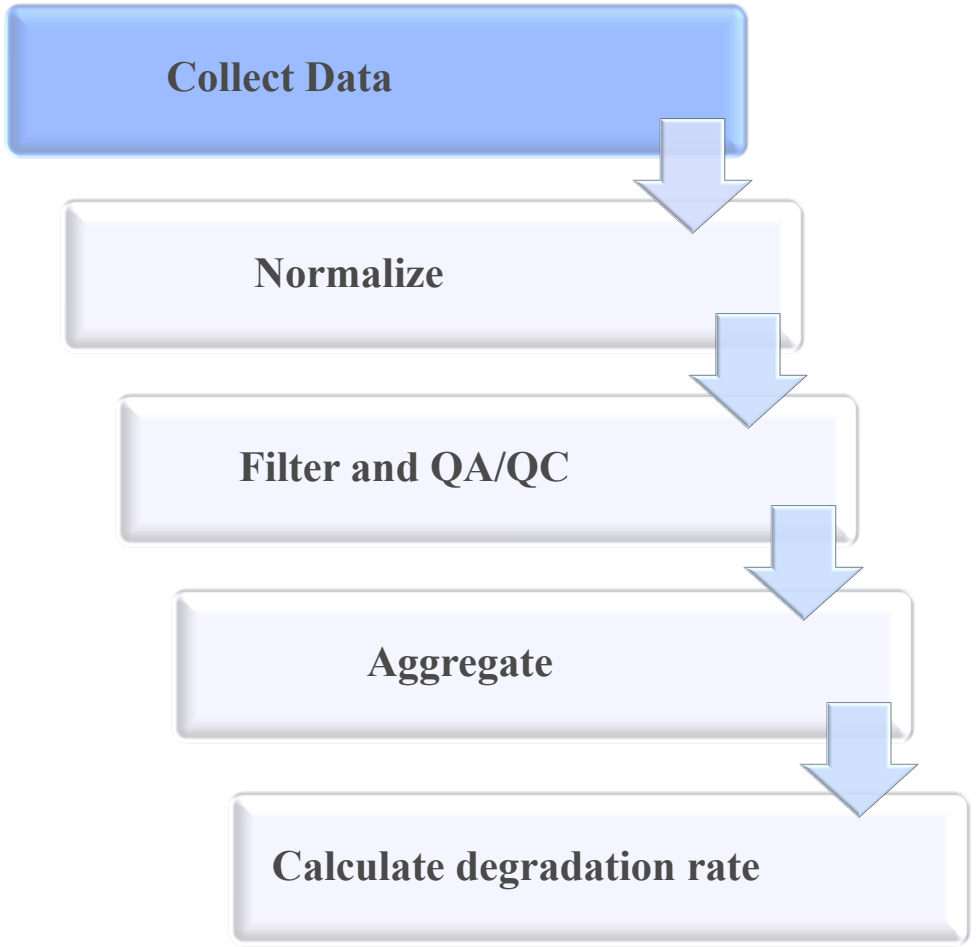


Calculating Degradation Rate:

- Power
- Weather
  - Plane-of-array irradiance
  - Ambient temperature
- Metadata
  - Nameplate capacity
  - Latitude and Longitude
  - Racking info (tilt angle, tracking, azimuth)
  - Module temperature coefficient

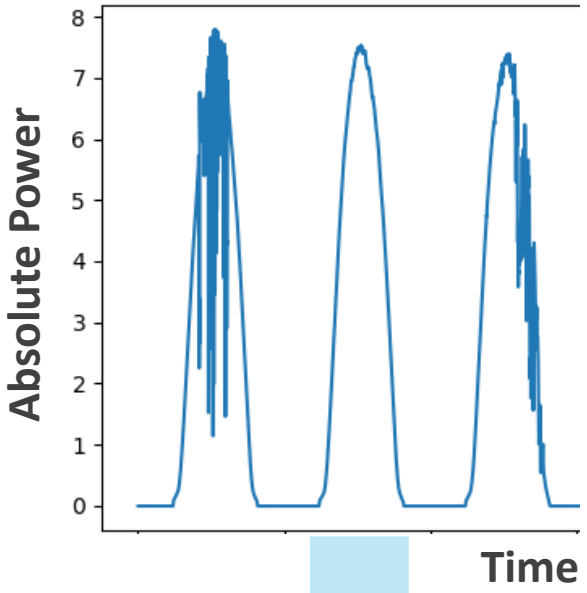
At least 2 years of performance data needed (longer preferred)

General steps to calculate degradation rate from performance data

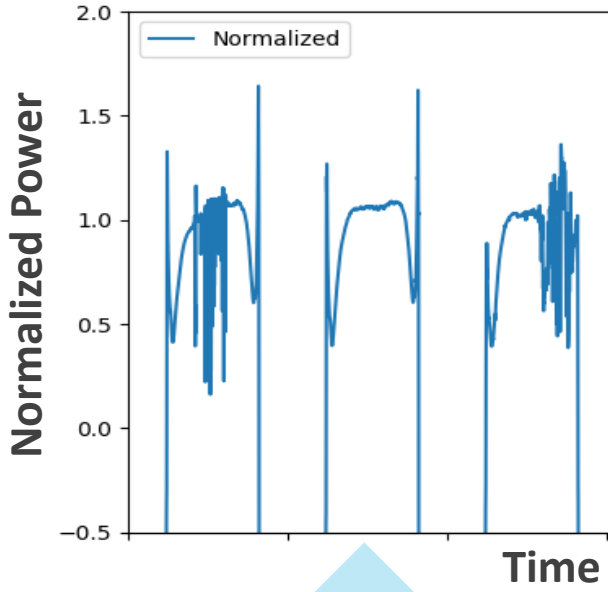


Calculating Degradation Rate: Year-on-Year Histograms

Power from revenue grade meter at interconnection



Temperature-corrected performance ratio



$$\frac{Actual\ (measured)}{Expected\ (modeled)} = \frac{\sum_i P_{AC}[kWh_{AC}]}{\sum_i \left(P_{Array} \cdot \left(\frac{G_{POA,i}}{G_{ref}} \right) \times \left(1 + C_t \cdot \left(T_{m,i} - T_{Ref} \right) \right) \right) [kWh_{DC}]}$$

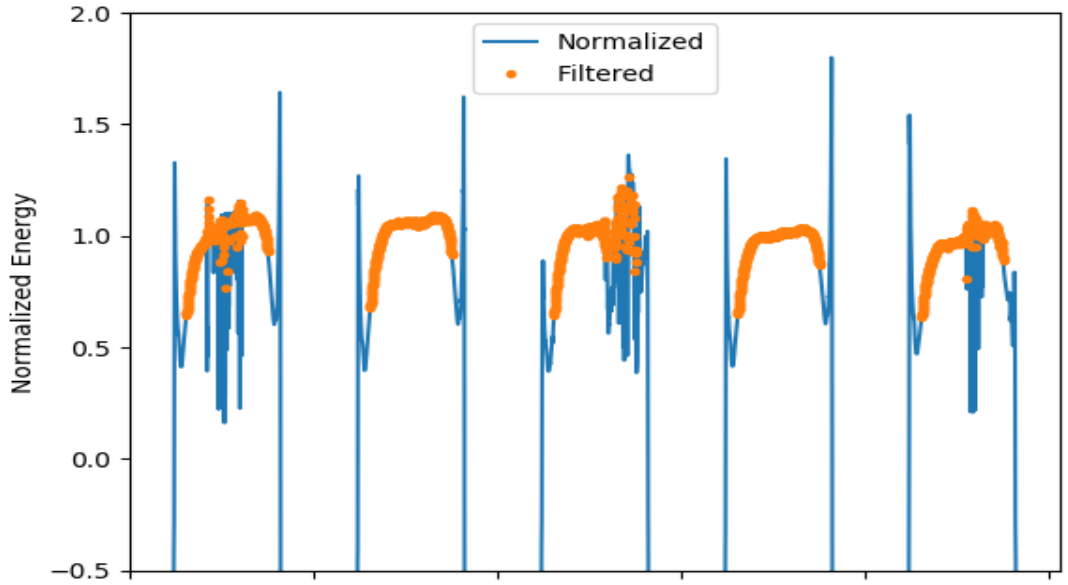
General steps to calculate degradation rate from performance data

- Collect Data
- Normalize
- Filter and QA/QC
- Aggregate
- Calculate degradation rate

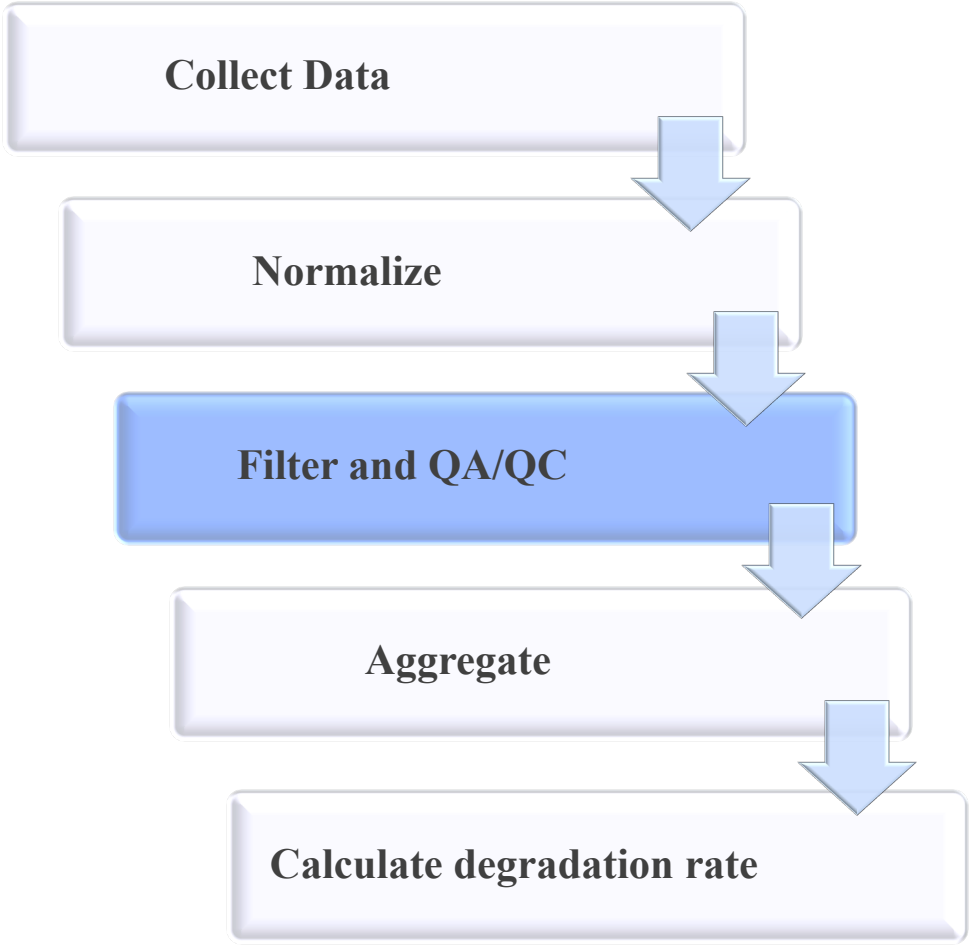
Calculating Degradation Rate: Year-on-Year Histograms

Remove factors outside of the scope of degradation

- Weather (irradiance, clear sky)
- Transients (ΔTemp. and ΔIrradiance)
- Clipping, site specific performance impacts, etc.

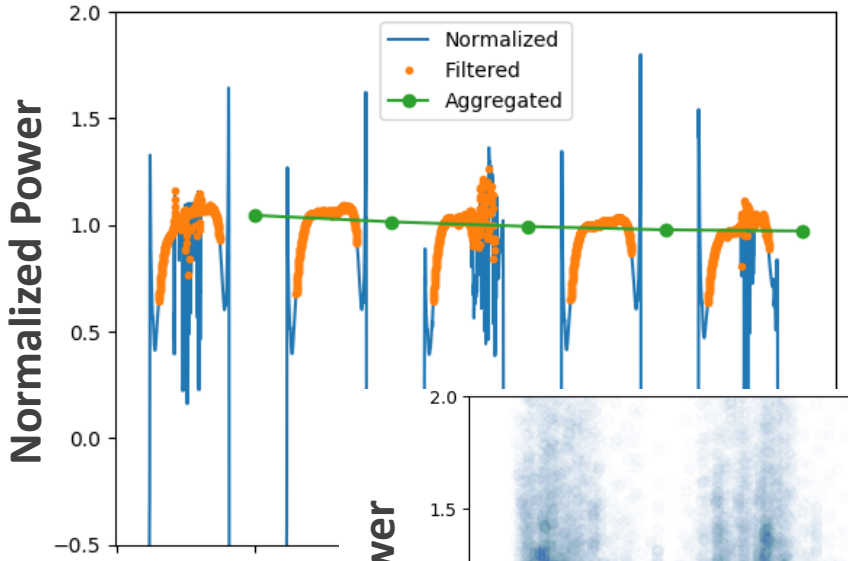


General steps to calculate degradation rate from performance data

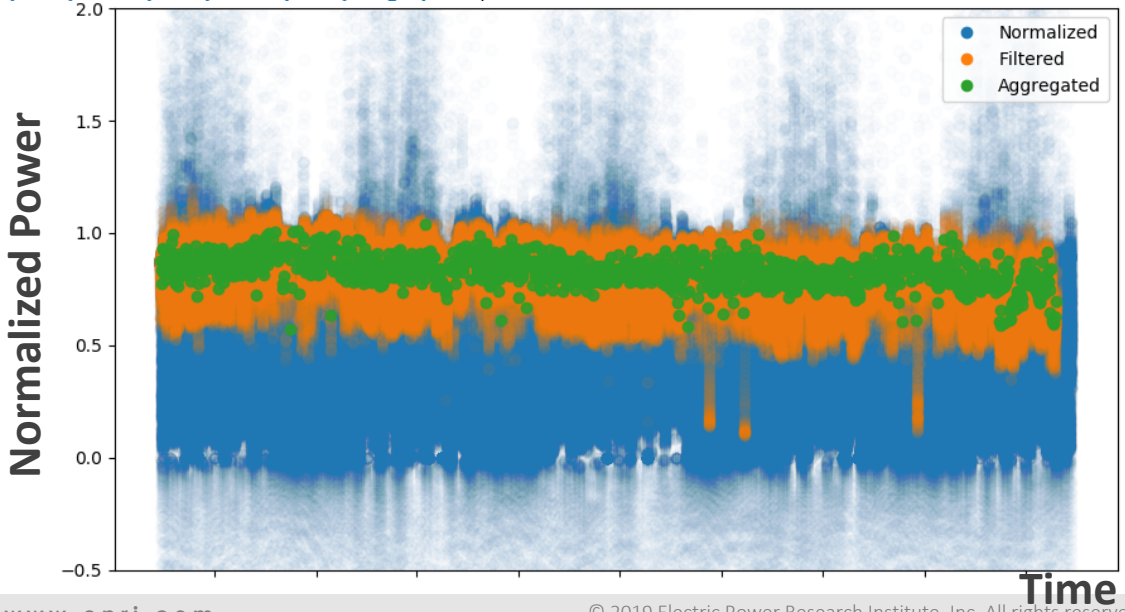


Calculating Degradation Rate: Year-on-Year Histograms

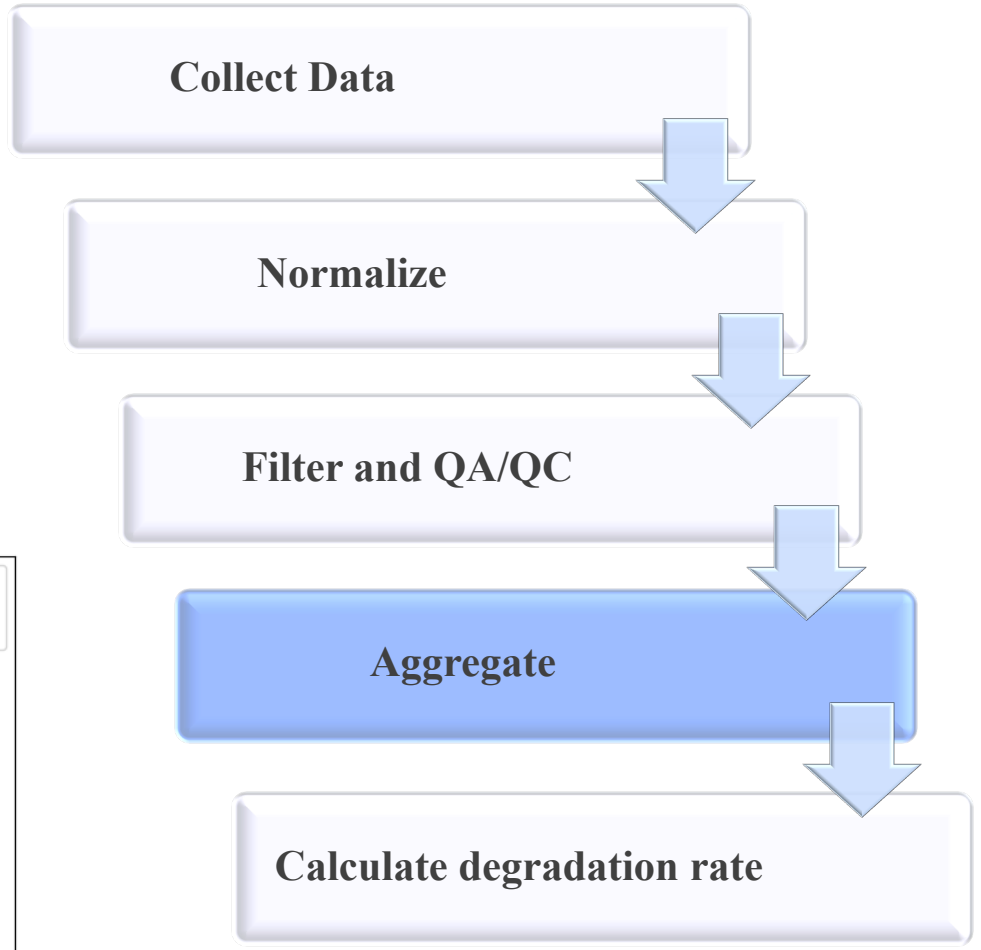
- Aggregation period can be minutes, hours, days, etc.



Green dots are daily averages of performance ratio.

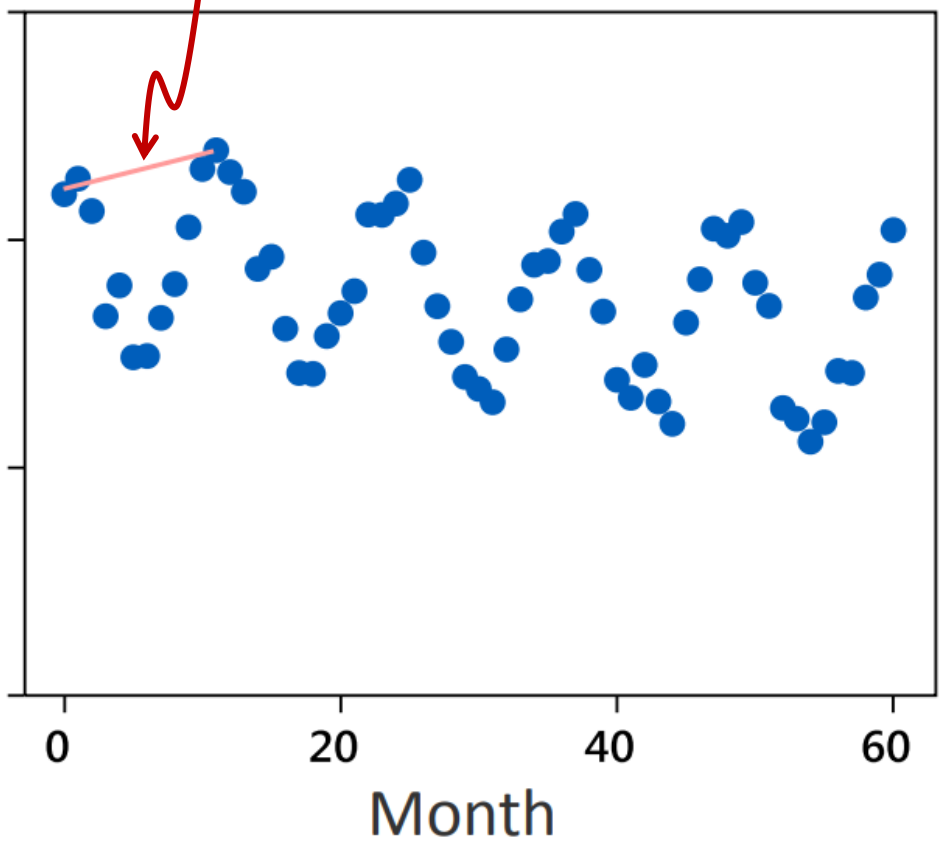


General steps to calculate degradation rate from performance data

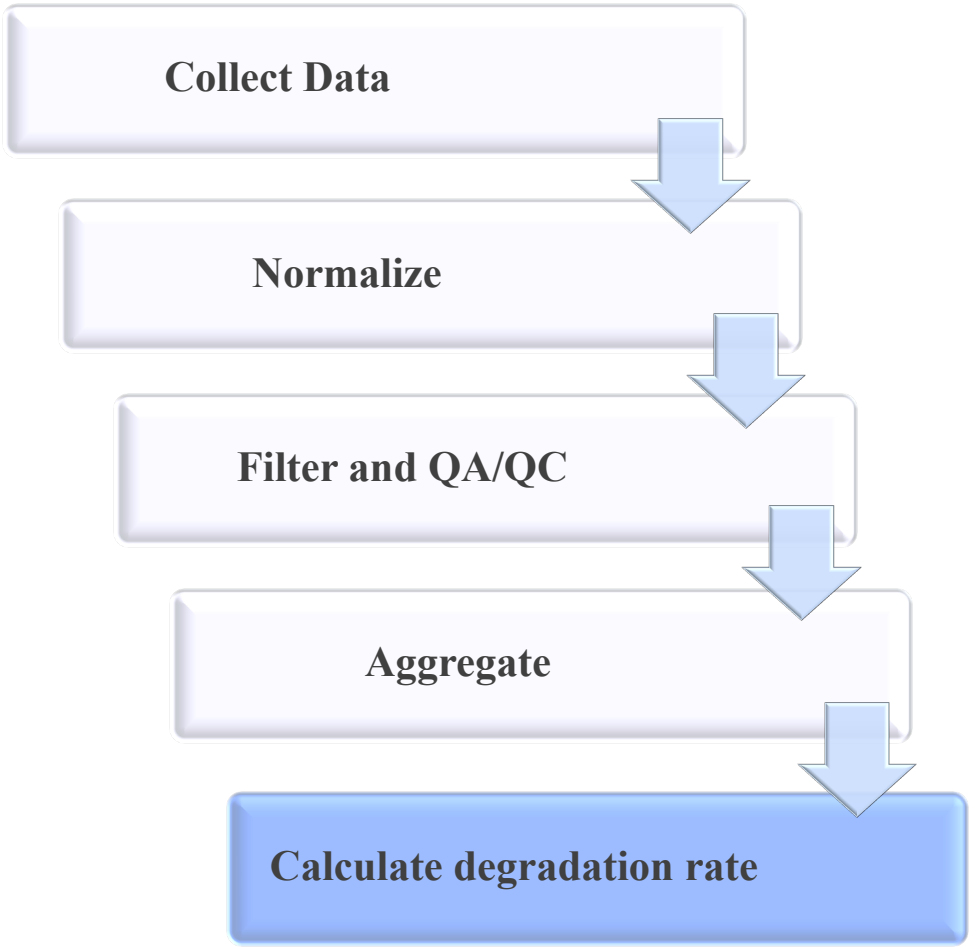


Calculating Degradation Rate: Year-on-Year Histograms

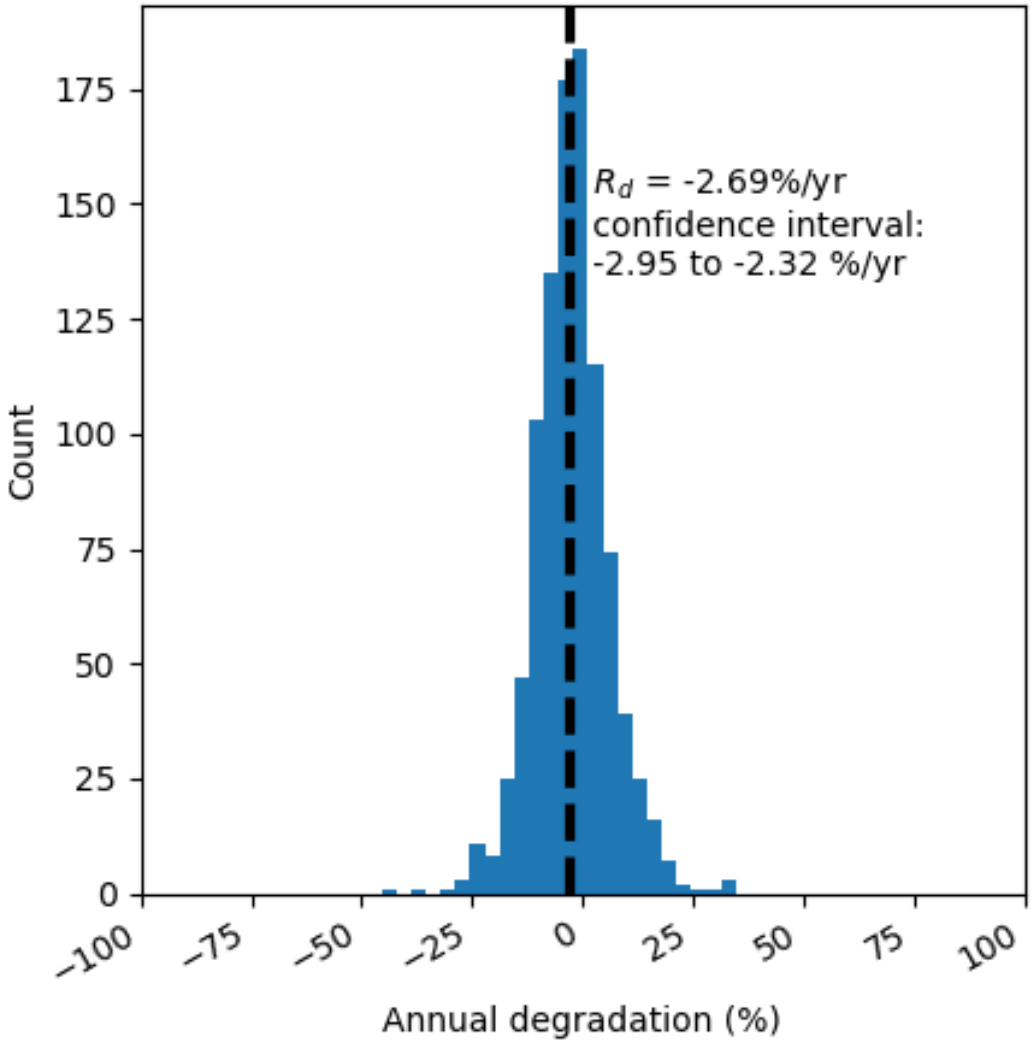
Compare aggregated point from one year to the next.
Example of daily aggregation: Jan. 1, *2000* to Jan. 1, *2001*



General steps to calculate degradation rate from performance data



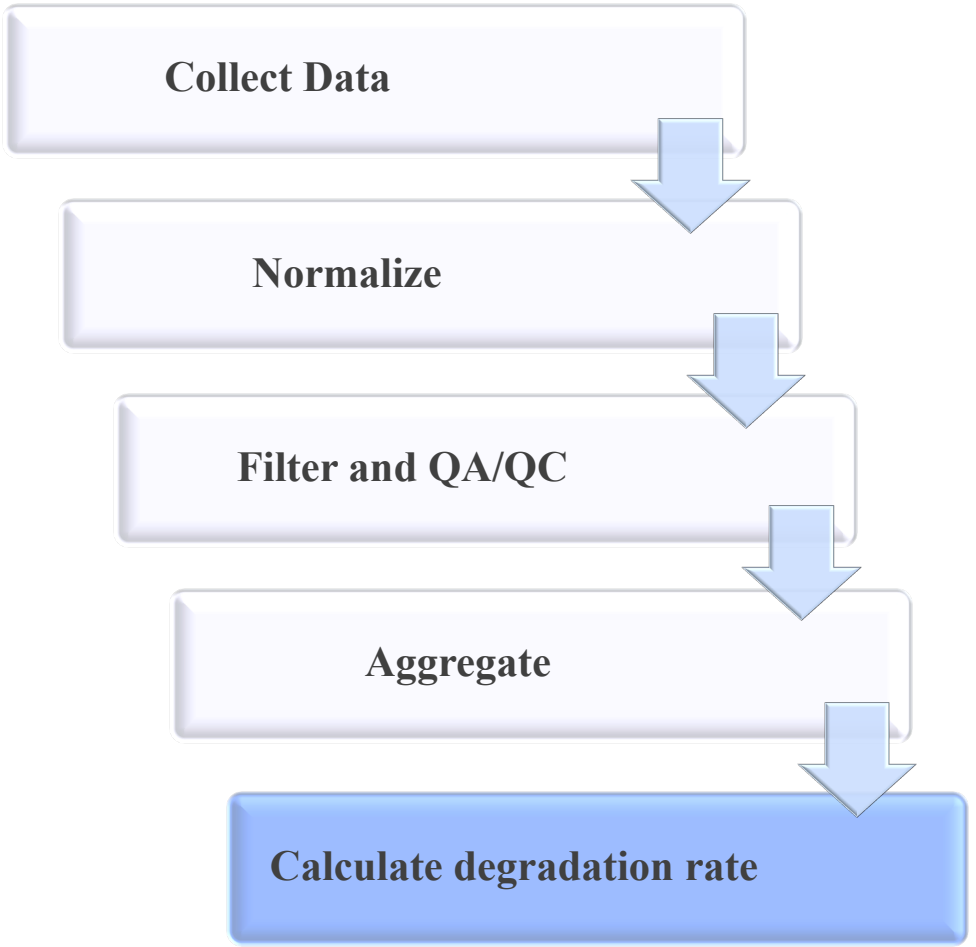
Calculating Degradation Rate: Year-on-Year Histograms



Plot histogram of power change.

Use ***median*** value as the degradation rate.

General steps to calculate degradation rate from performance data



Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?

Pre-Processing Filters (IEC 61724-3 Suggested)	
Missing Data	Remove
Multiple Sensors (Irradiance /Temp)	If drift: remove data, else: average
Power	0-1.02*Nameplate AC
POA	-6 to 1500 W/m^2
Ambient Temp	-30 to 50 °C

"Default" Filter Settings	
Irradiance	Clear Sky
Temperature	Sensed Ambient
POA Filter	200-1200 W/m^2
Clipping Filter	Power < 99% of 98th Percentile
Clear Sky Index	±20% of Sensor
Aggregation	Daily

Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?
2. What is inside/outside envelope of degradation?
    1. Uncorrected maintenance? Foliage growth? Inverter issues?
    2. Is it feasible to separate?
    3. Rename to performance loss rate?

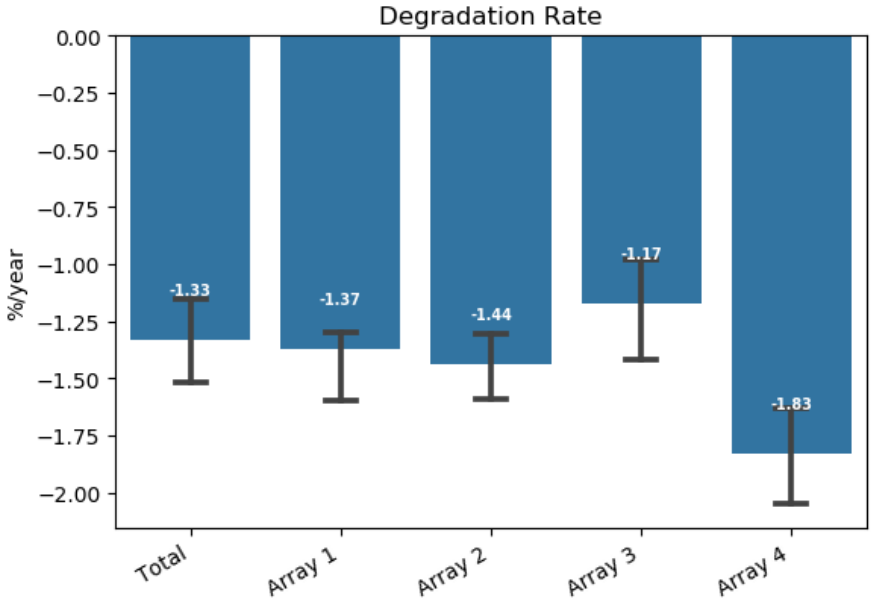
Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?
2. What is inside/outside envelope of degradation?
3. What is the sensitivity to errors in estimating clear sky irradiance?
    1. Tracking Angle
    2. Cloud Detection
    3. Timestamp

Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?
2. What is inside/outside envelope of degradation?
3. What is the sensitivity to errors in estimating clear sky irradiance?
4. How can calculated results be validated?

1 MW, 2012, Fixed Tilt



-1.33

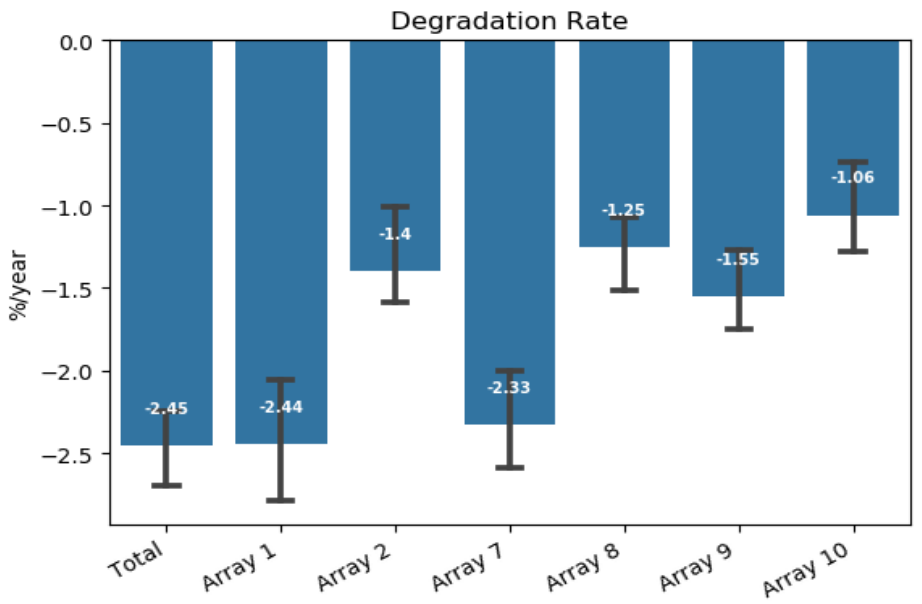
-2.45

YoY, Median Rd, 68% Confidence Interval

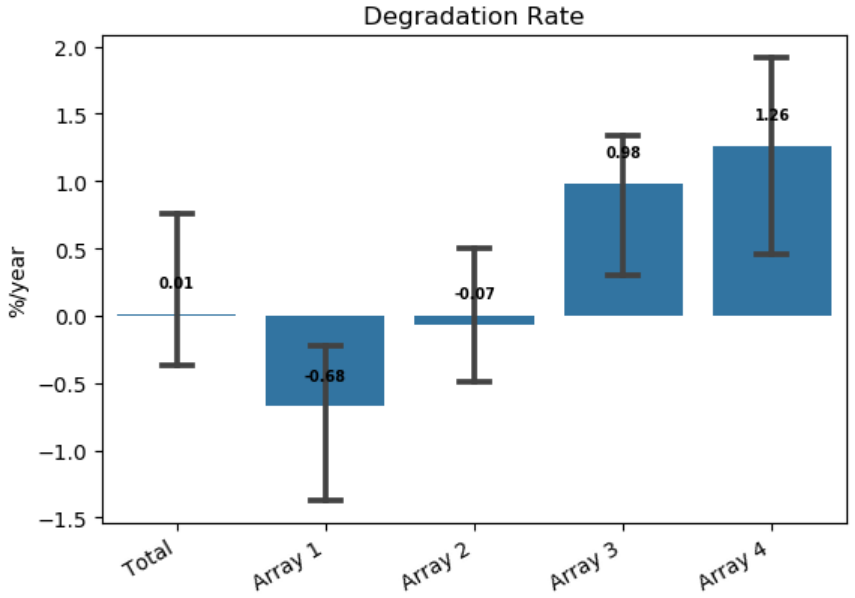
0.01

-2.08

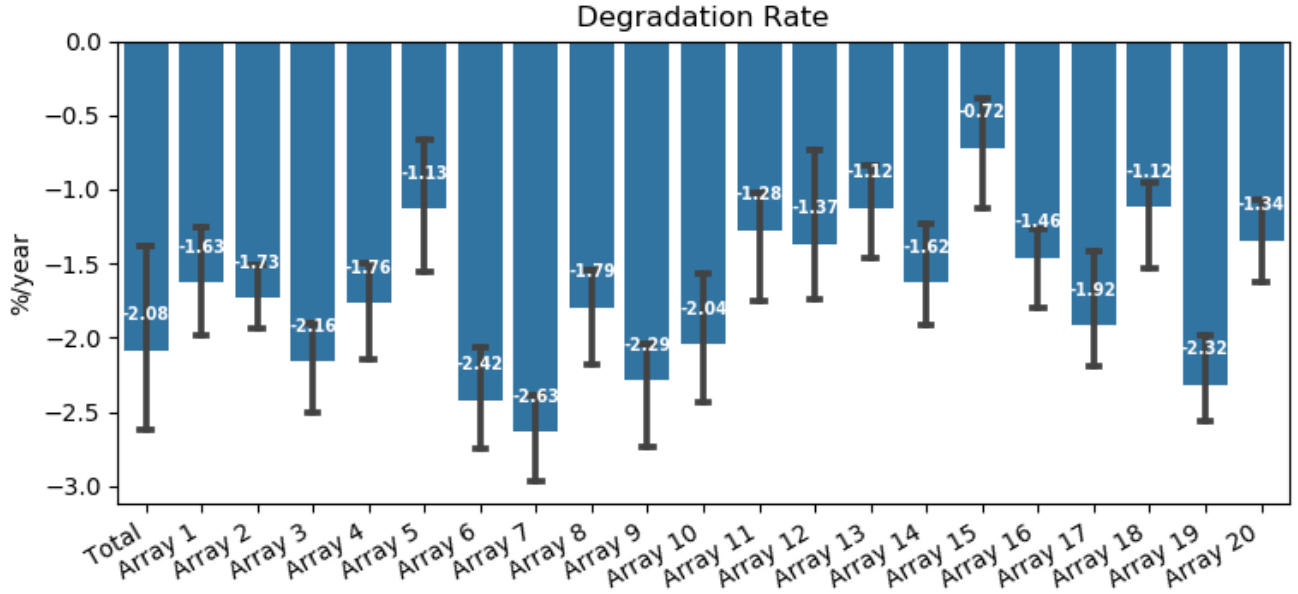
10 MW, 2014, Fixed Tilt



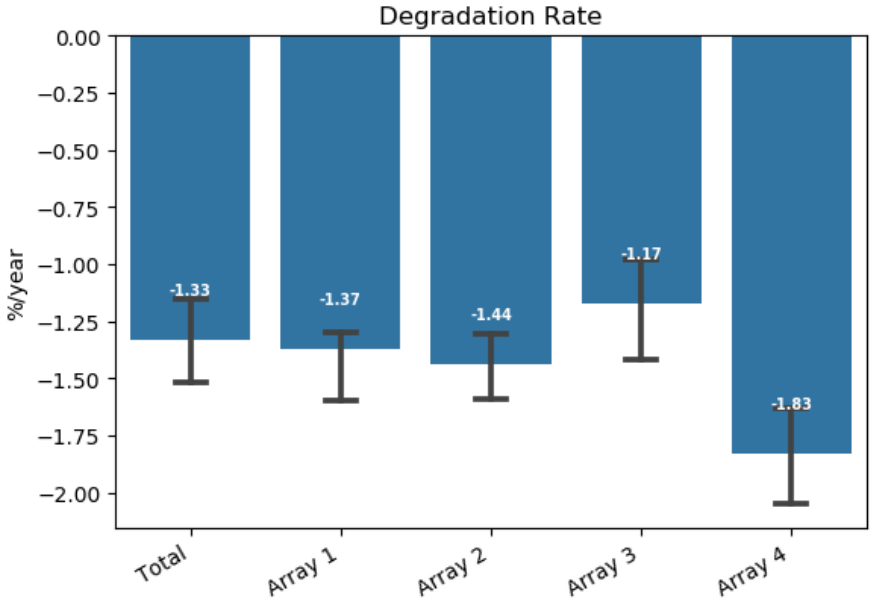
7 MW, 2015, Single-Axis Tracking



26 MW, 2016, Single-Axis Tracking



1 MW, 2012, Fixed Tilt



-1.33

-2.45

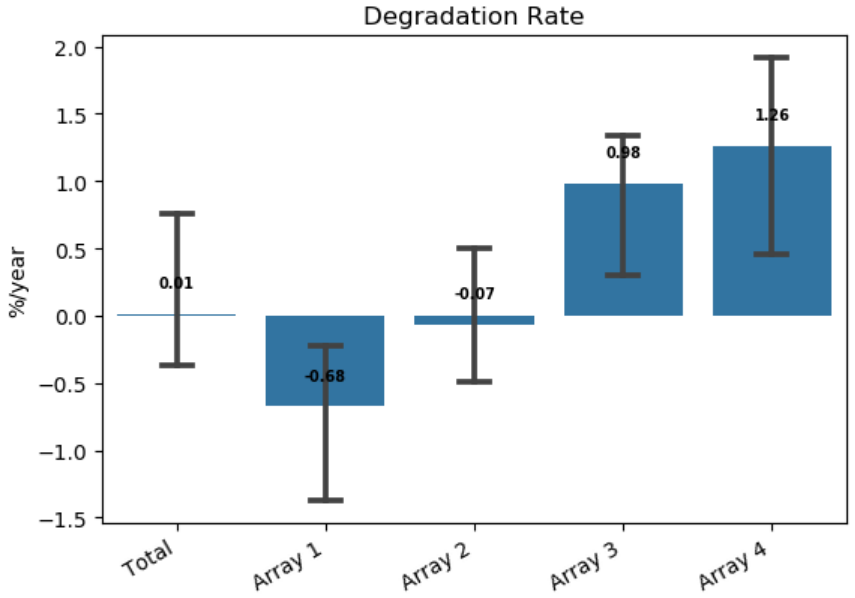
YoY, Median Rd, 68% Confidence Interval

0.01

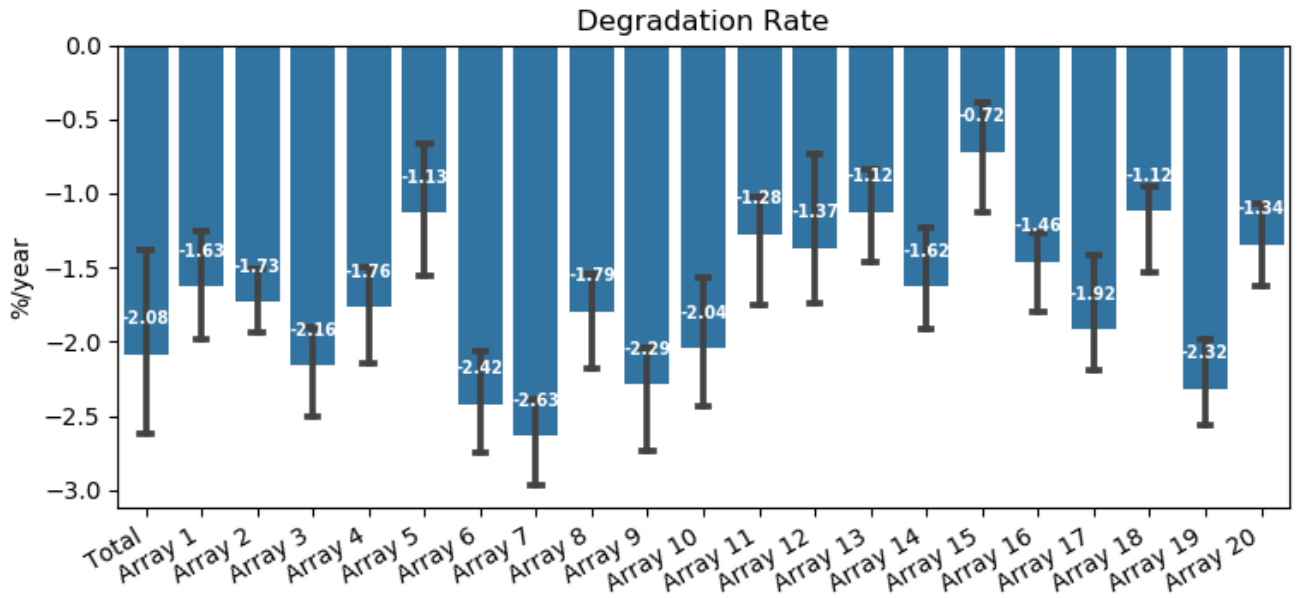
-2.08

- Calculated degradation rates are greater than the oft-assumed 0.5% - 1.0% per year.
- Applying analysis at inverter level offers opportunities for targeted investigation and remediation.
- Newly applied methodology to tracking requires further validation

7 MW, 2015, Single-Axis Tracking



26 MW, 2016, Single-Axis Tracking



Sensitivity to filter parameter selection

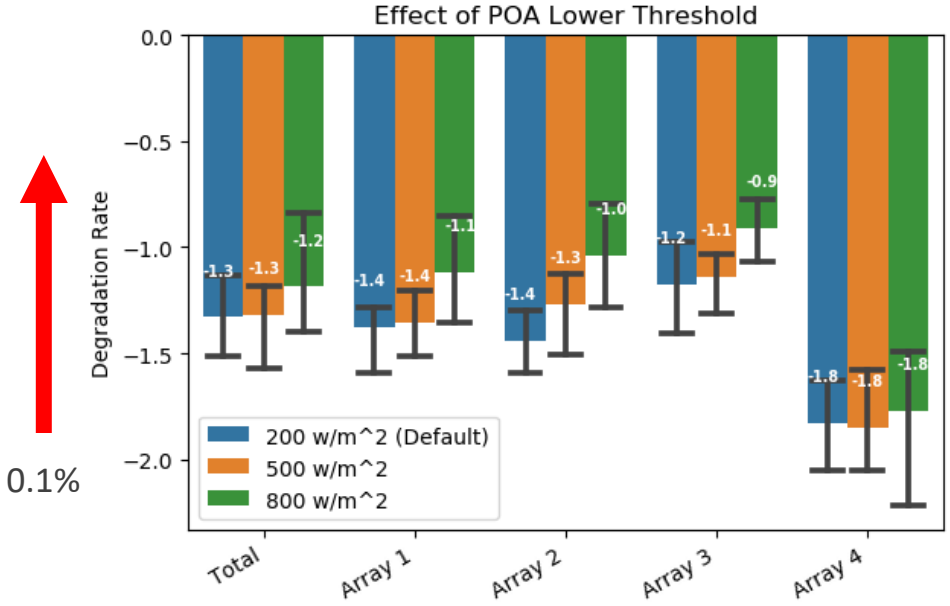
Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?

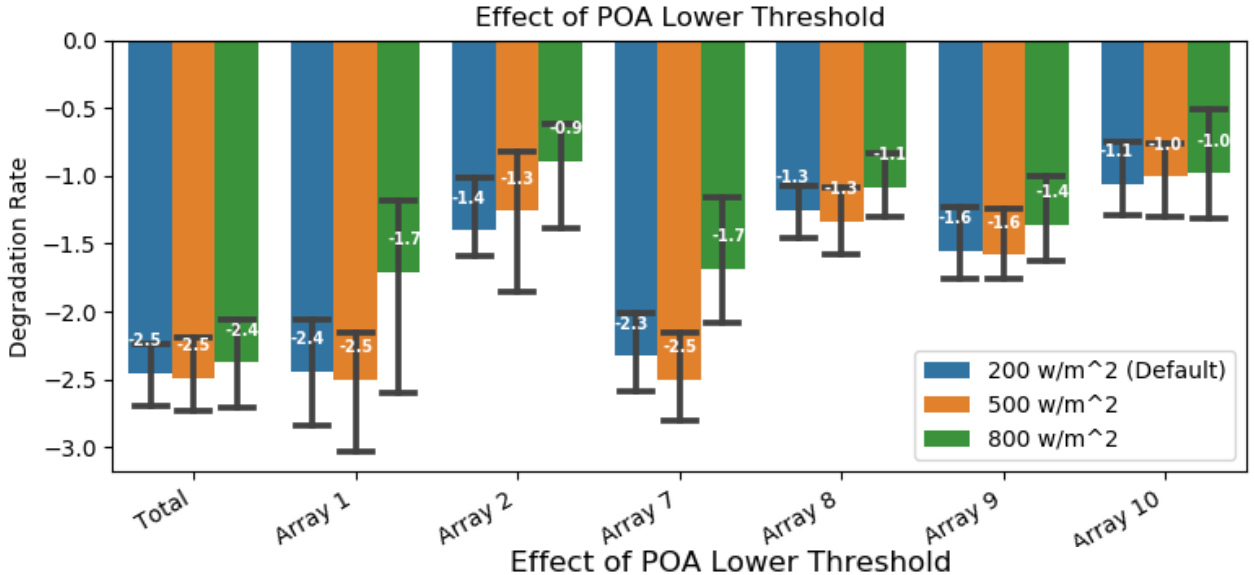
Pre-Processing Filters (IEC 61724-3 Suggested)	
Missing Data	Remove
Multiple Sensors (Irradiance /Temp)	If drift: remove data, else: average
Power	0-1.02*Nameplate AC
POA	-6 to 1500 W/m^2
Ambient Temp	-30 to 50 °C

"Default" Filter Settings	
Irradiance	Clear Sky
Temperature	Sensed Ambient
POA Filter	200-1200 W/m^2
Clipping Filter	Power < 99% of 98th Percentile
Clear Sky Index	±20% of Sensor
Aggregation	Daily

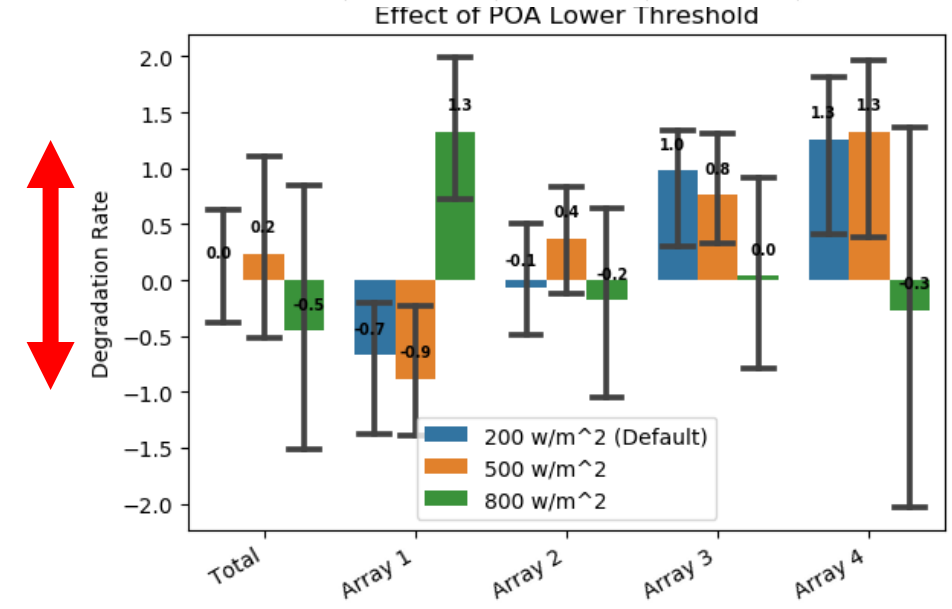
Filter Settings – POA Irradiance Threshold



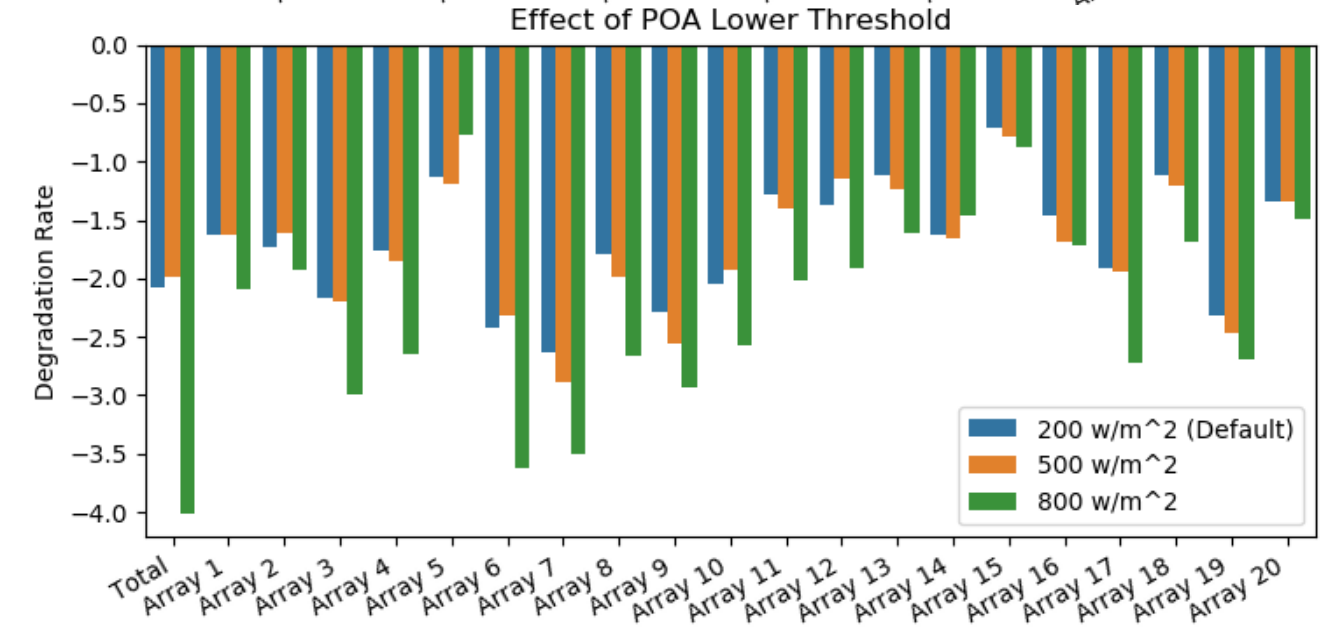
0.1%



0.1%



1.9%



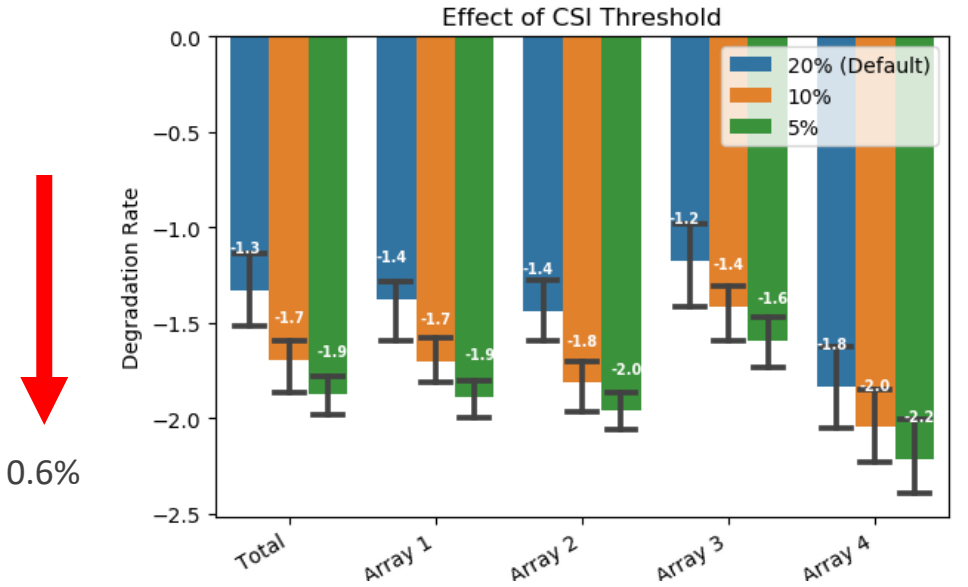
Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?

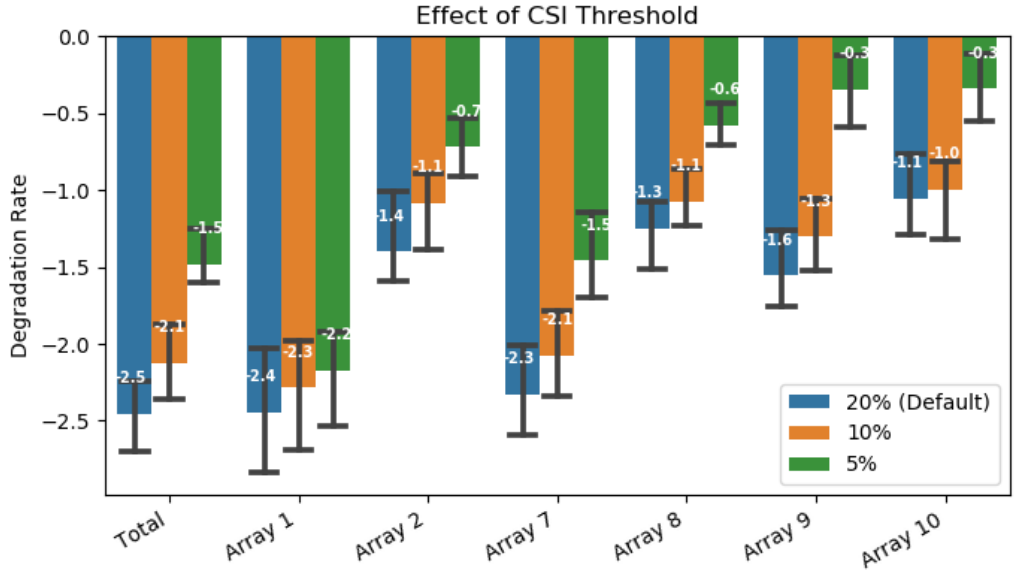
Pre-Processing Filters (IEC 61724-3 Suggested)	
Missing Data	Remove
Multiple Sensors (Irradiance /Temp)	If drift: remove data, else: average
Power	0-1.02*Nameplate AC
POA	-6 to 1500 W/m^2
Ambient Temp	-30 to 50 °C

"Default" Filter Settings	
Irradiance	Clear Sky
Temperature	Sensed Ambient
POA Filter	200-1200 W/m^2
Clipping Filter	Power < 99% of 98th Percentile
Clear Sky Index	±20% of Sensor
Aggregation	Daily

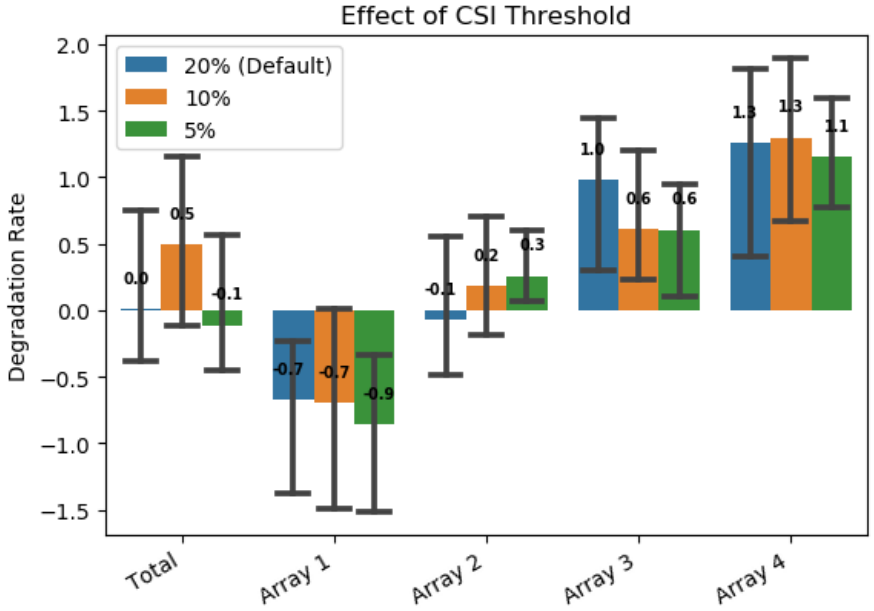
Filter Settings – Clear Sky Index Threshold



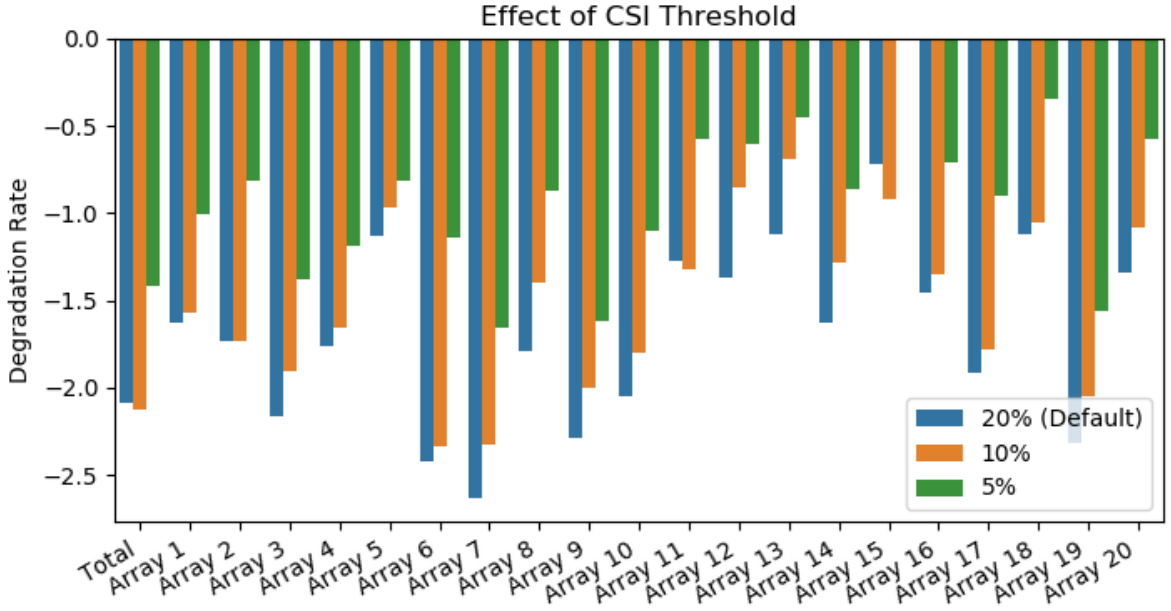
0.6%



1%



0.7%



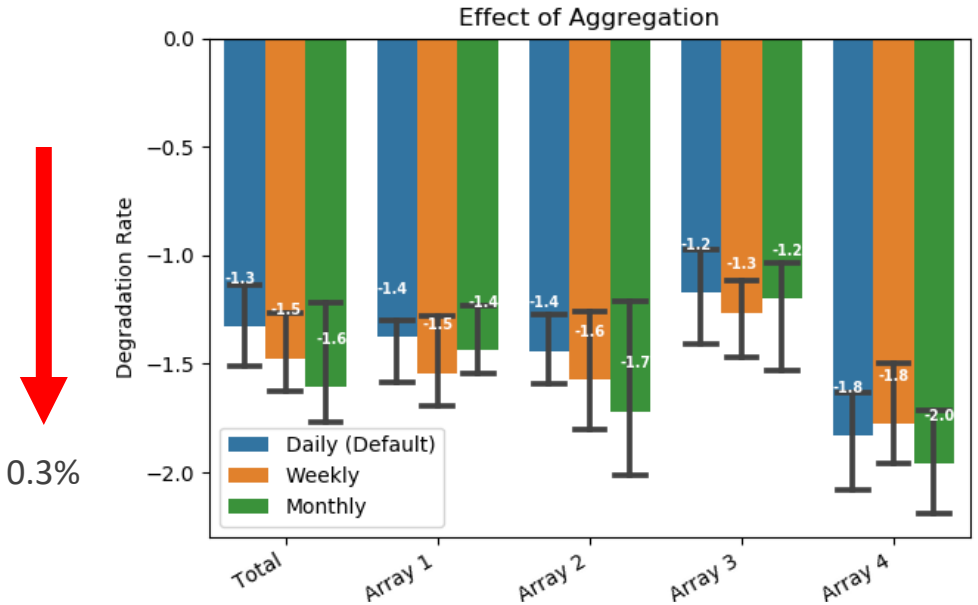
Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?

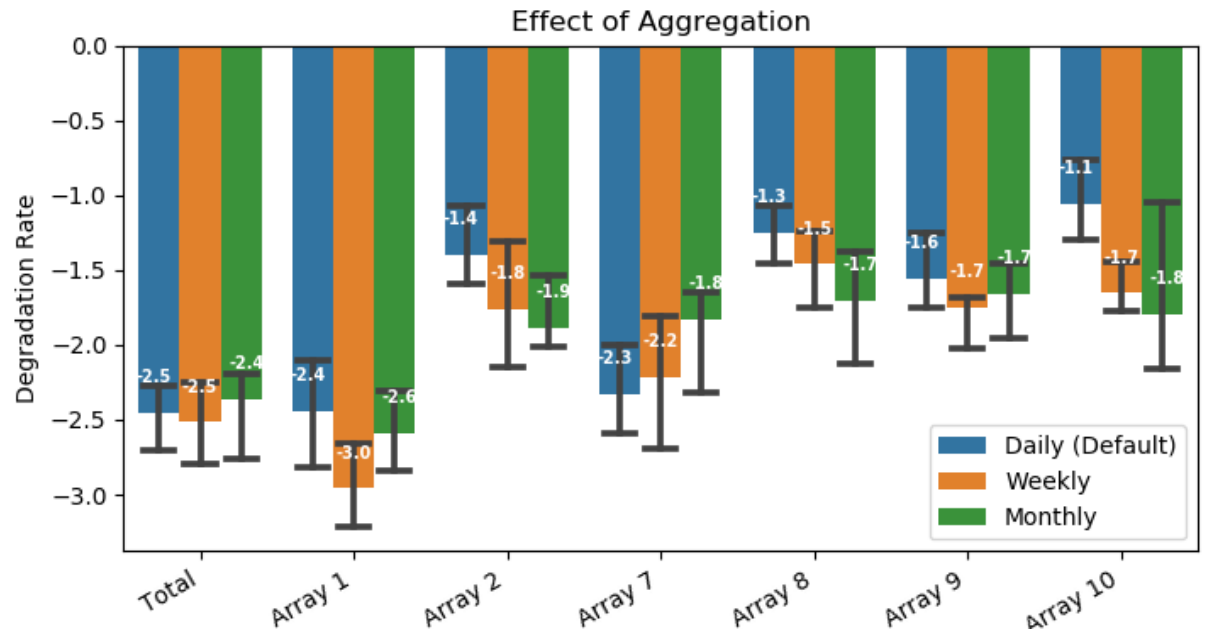
Pre-Processing Filters (IEC 61724-3 Suggested)	
Missing Data	Remove
Multiple Sensors (Irradiance /Temp)	If drift: remove data, else: average
Power	0-1.02*Nameplate AC
POA	-6 to 1500 W/m^2
Ambient Temp	-30 to 50 °C

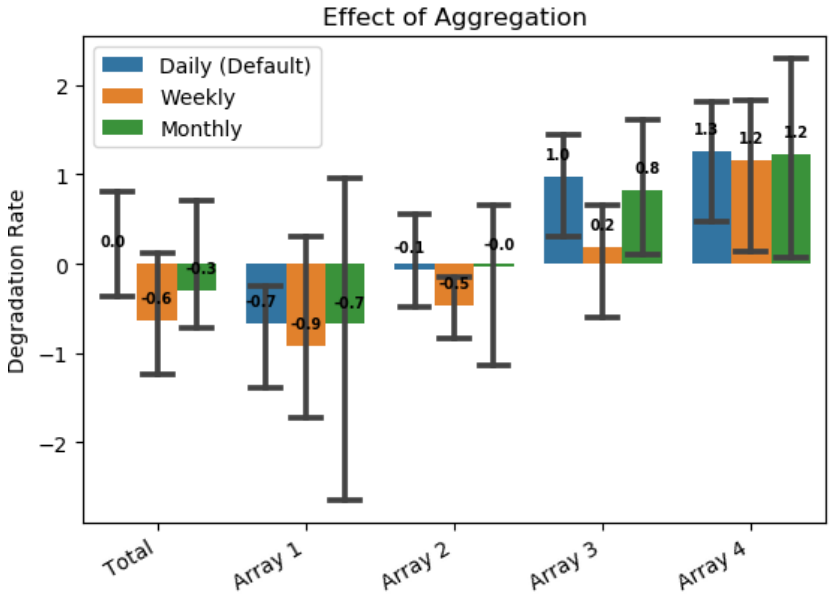
"Default" Filter Settings	
Irradiance	Clear Sky
Temperature	Sensed Ambient
POA Filter	200-1200 W/m^2
Clipping Filter	Power < 99% of 98th Percentile
Clear Sky Index	±20% of Sensor
Aggregation	Daily

Filter Settings – Aggregation Frequency

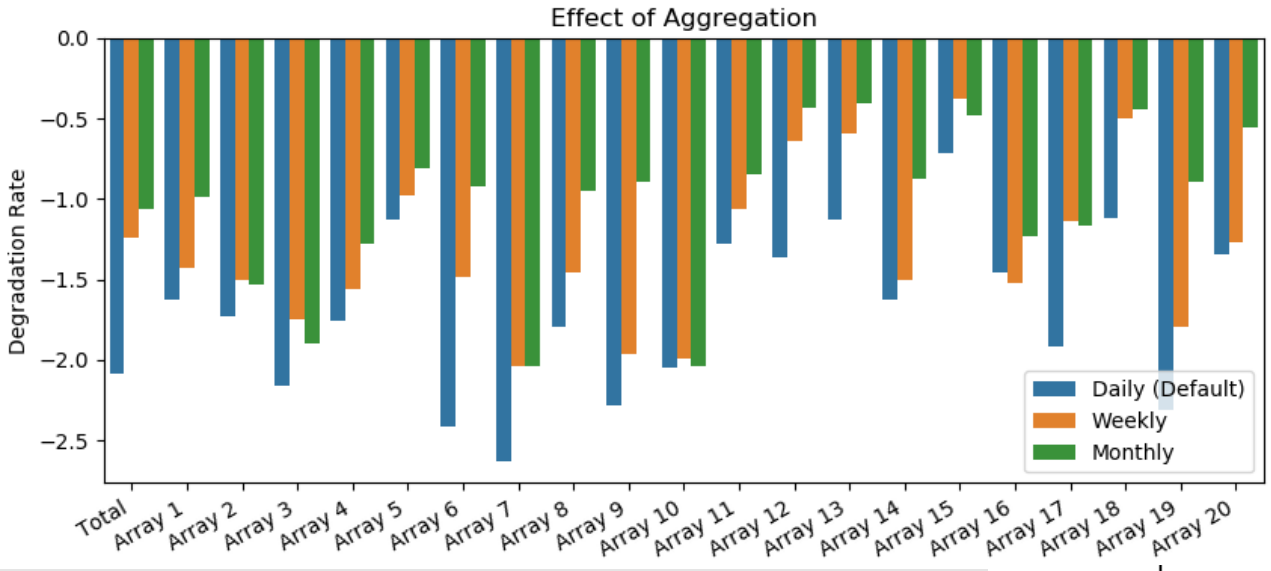


0.3%





1%



Best Practices Questions

1. What are the proper filtering criteria and aggregation methods?
    1. Analysis shows variation in results depending settings
    2. Highlights need for validation

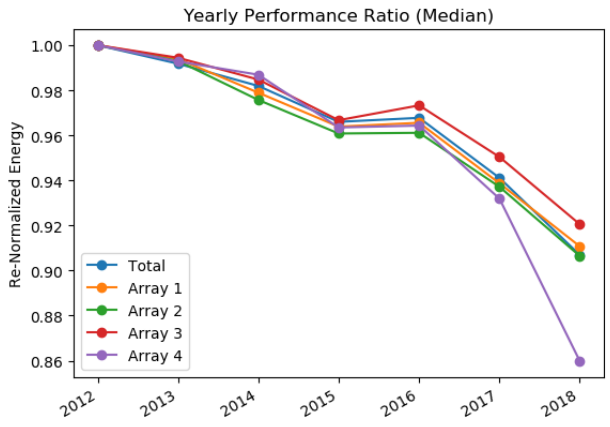
Need for a standardized calculation methodology

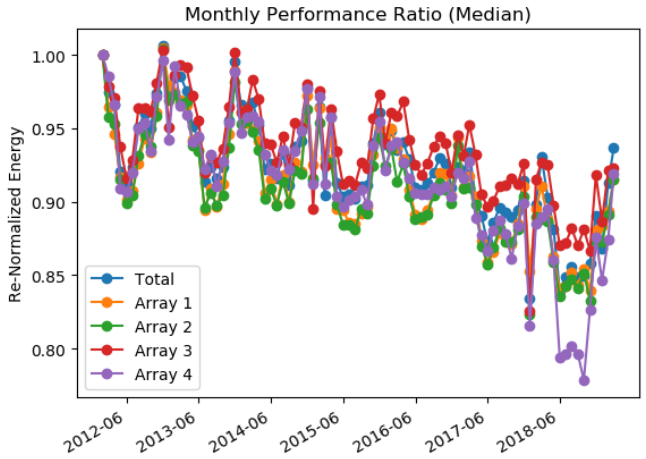
Standardized methodology should:

- Use fixed setting to provide apples-to-apples comparison
  - Useful for benchmarking plant performance
- Be applicable on large scale
  - Use only commonly recorded data
  - Not requiring customization for site-specific factors like
    - Maintenance events
    - Specific environmental conditions
    - Array configuration (size, tracking, dc:ac ratio, PV technology, etc.)
- Be robust against common errors in data/metadata
- Include a validation methodology

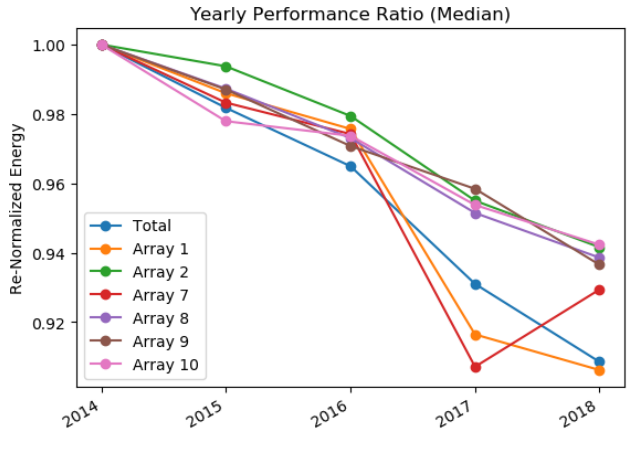
Together...Shaping the Future of Electricity

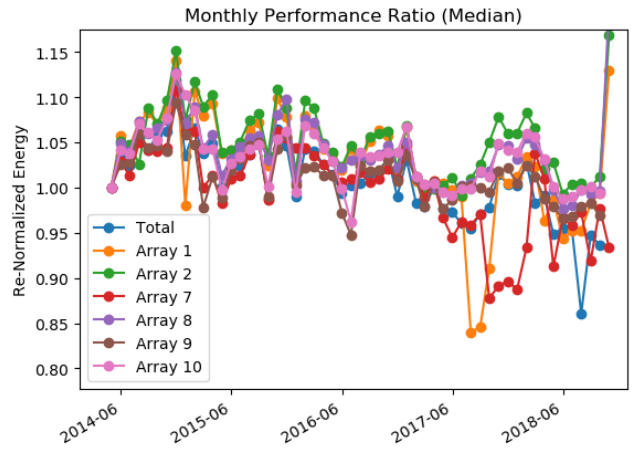
1 MW, 2012, Fixed Tilt -1.33



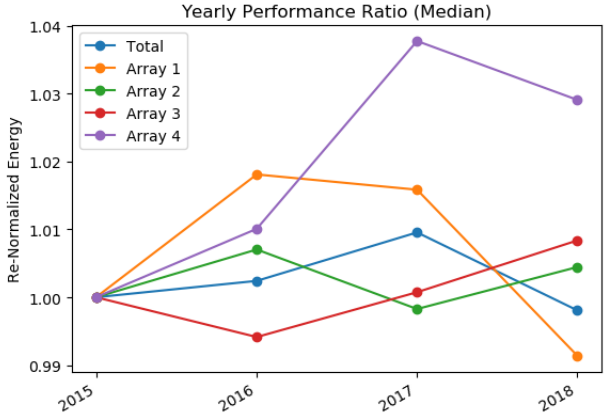


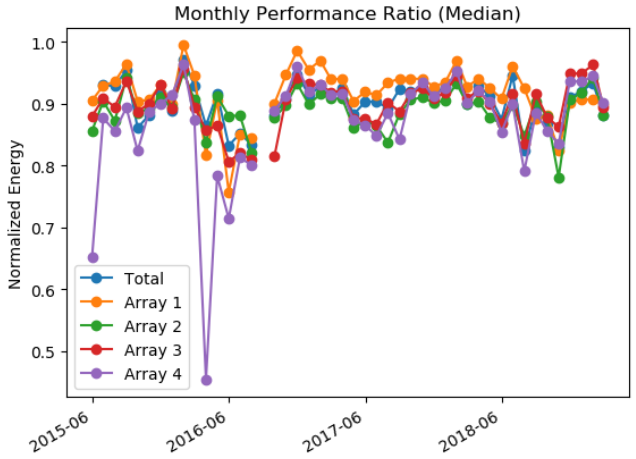
9.6 MW, 2014, Fixed Tilt -2.45



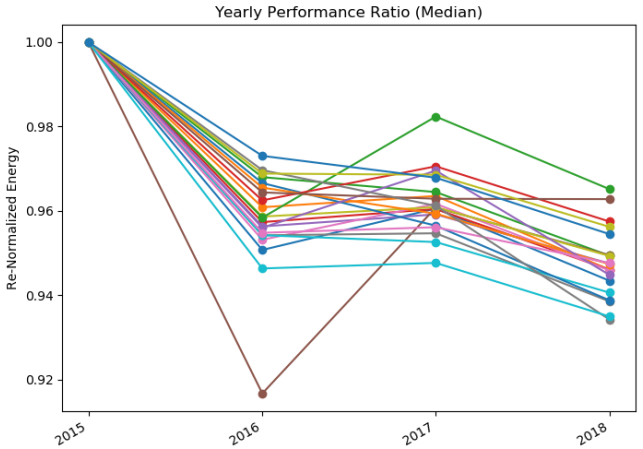


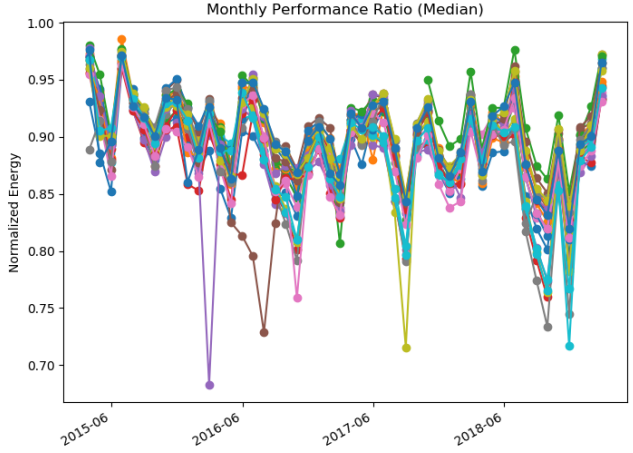
7 MW, 2015, Single-Axis Tracking 0.01

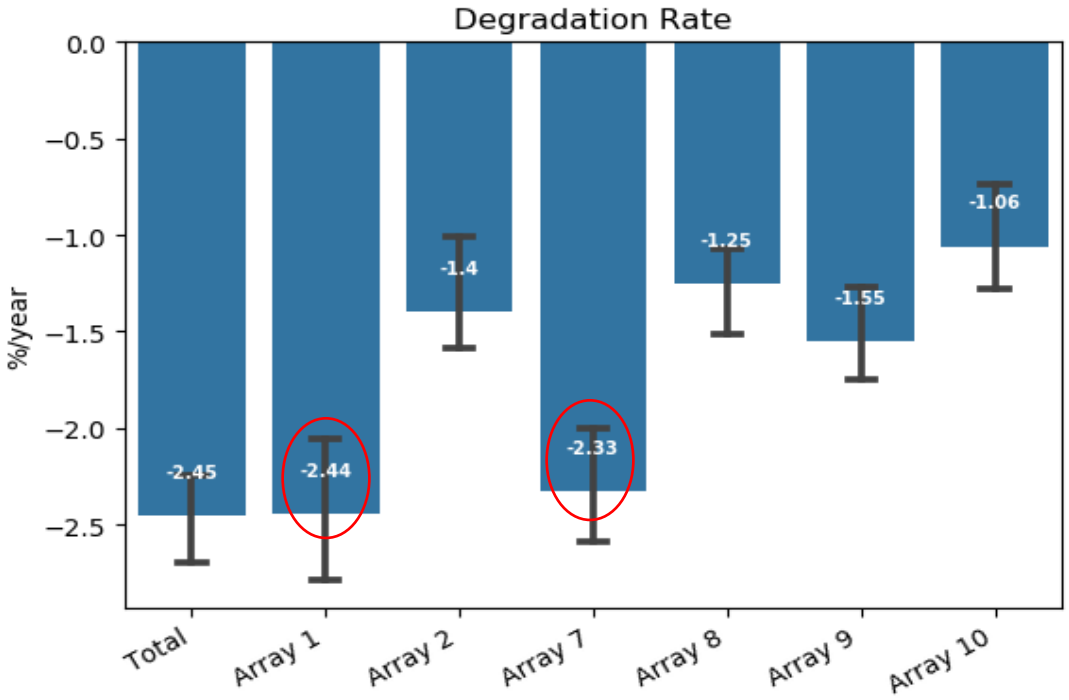




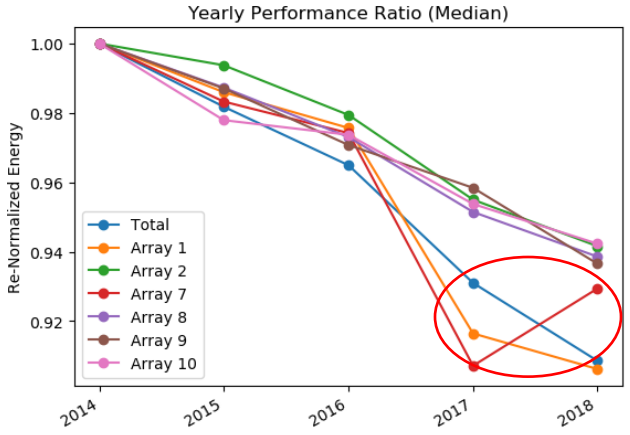
26 MW, 2016, Single-Axis Tracking -2.08

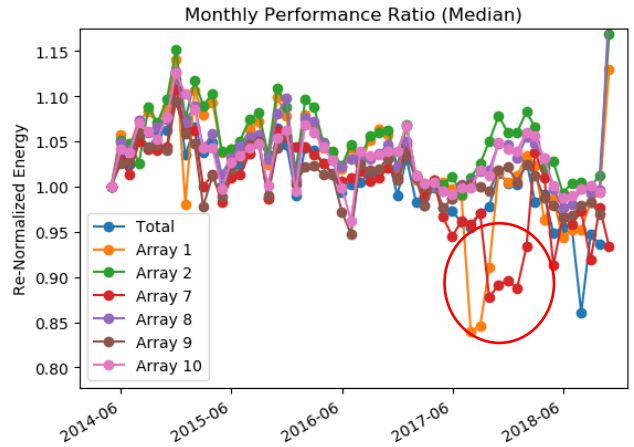


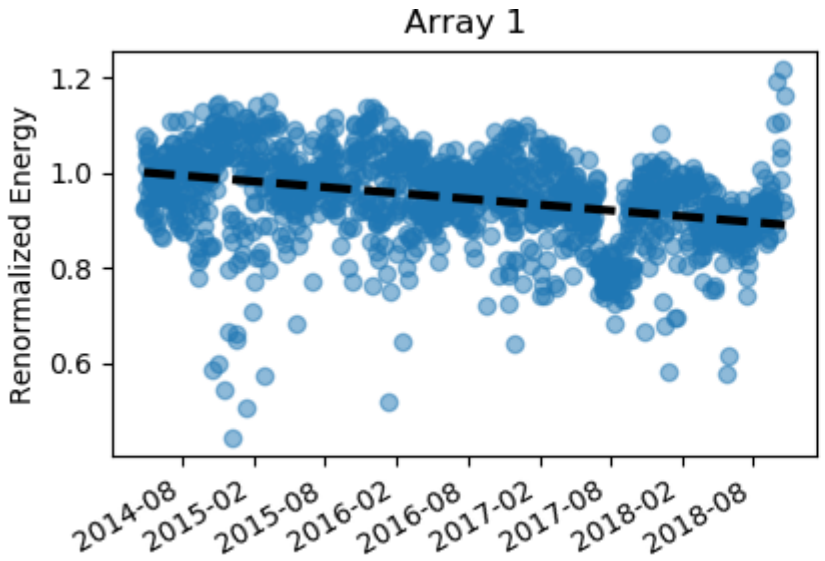


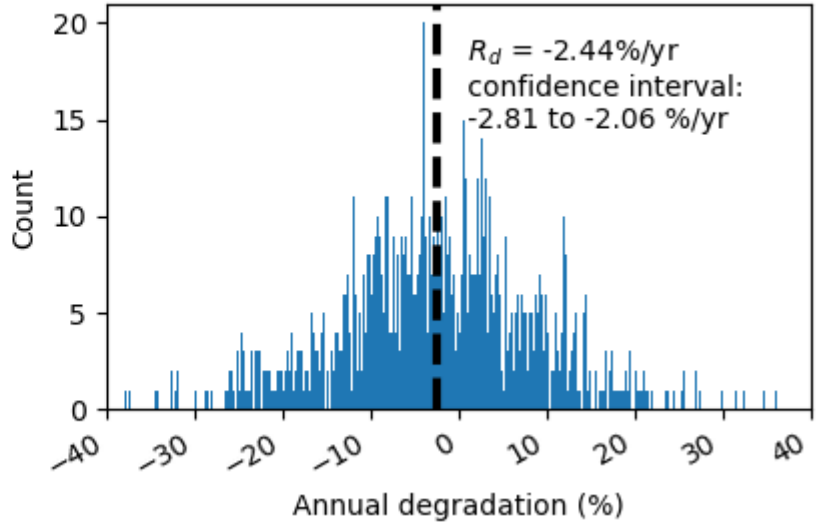


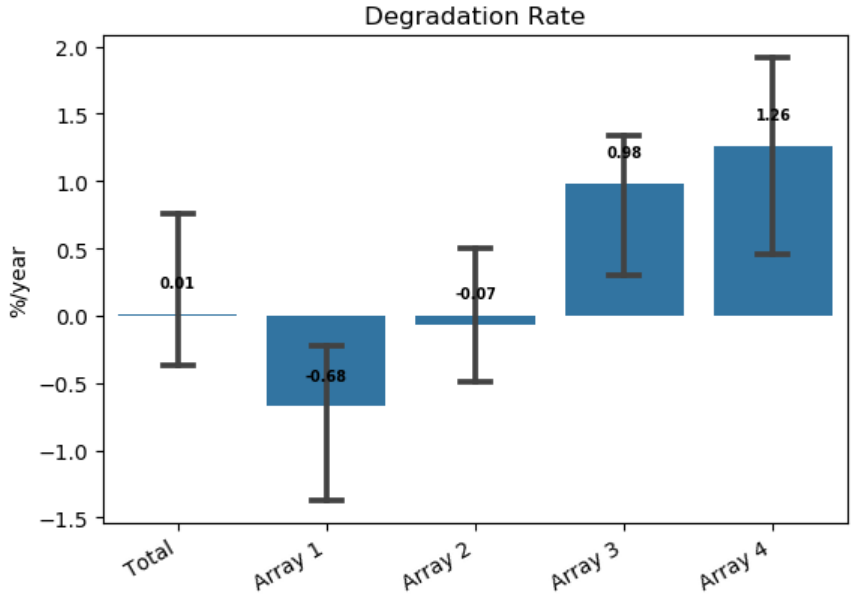
9.6 MW, 2014, Fixed Tilt -2.45

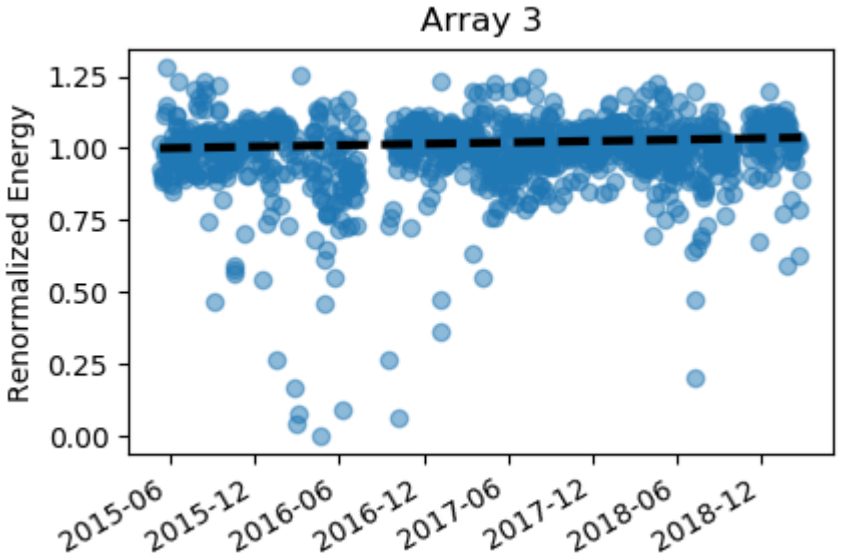












7 MW, 2015, Single-Axis Tracking

0.01