Large-Scale PV Plant Performance Benchmarking

Methodology and Results

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EPRI's SOL and Performance Benchmarking

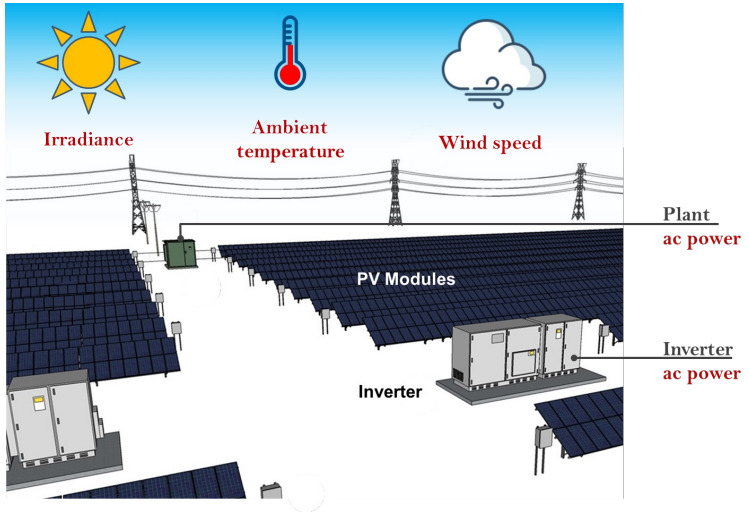
- **Solar Owner's League (SOL):**
  - Technically-focused user group for *large-scale PV plants*
  - Reduce costs, increase energy production and reliability, and operational capabilities for *large-scale PV plants*
- **SOL Benchmarking website** (subscriber):
  - Performance benchmarking across many metrics, including performance loss rate
  - Anonymized fleet-wide results. Plant-level, in-depth, time-series results

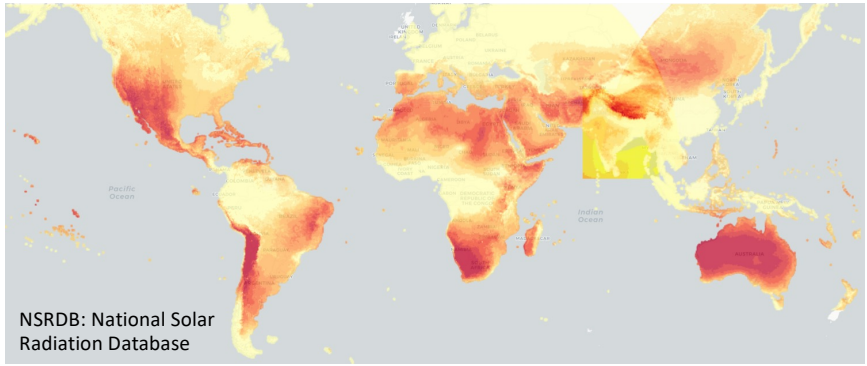
Presentation overview

- Data overview
- Data quality control
- Analysis methodology
  - Normalization
  - Irregular performance filter
  - Trend analysis
- Key results

Data overview

- SOL Benchmarking:
  - **27 plants (2.4 GW) complete,** ~35-40 more ongoing
- Measurements used
  - AC Power (**inverter level**), Weather (POA irradiance, temperature, wind speed)
    - When unavailable, temp. and wind data substituted from NOAA[1] or NSRDB[2]
- Additional added (from PVLIB)
  - Angle of incidence (AOI), clear sky irradiance
- Sampling
  - 1 or 5 minute – high resolution necessary for filtering outages, clouds, clipping
- Future
  - Satellite-based meteorological data
  - Energy – (distinguish power outages from data outages)
  - Automated/streaming data

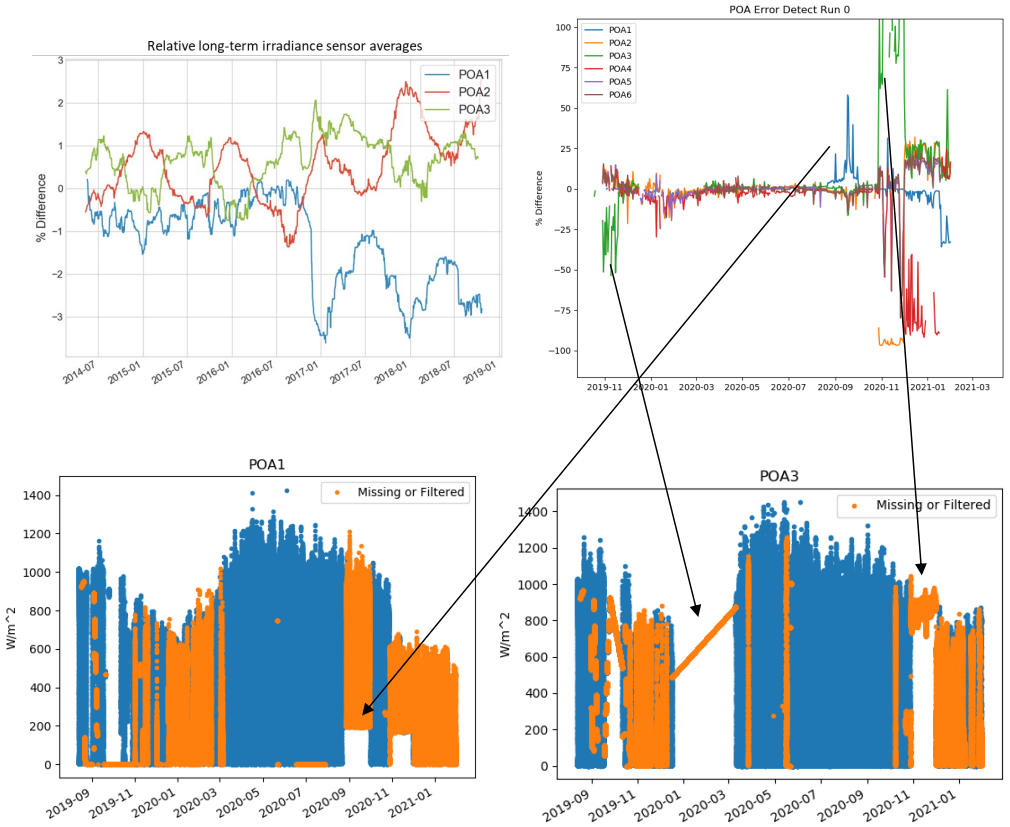



NSRDB: National Solar Radiation Database

1. https://www.ncdc.noaa.gov/cdo-web/datatools/lcd
2. https://nsrdb.nrel.gov/

Data Quality Control

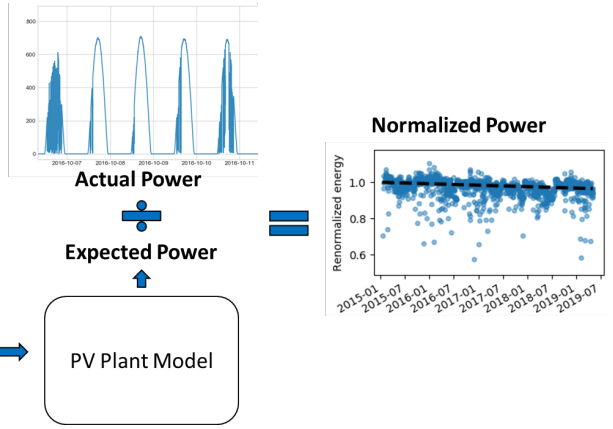
- Check for:
  - POA sensor error/miscalibration – largest source of error[1]
  - Interpolated/stuck (repeated) data
  - Daylight savings time shifts
  - Correct plant specs – nameplate DC, AC
  - Consistency, units, polarity

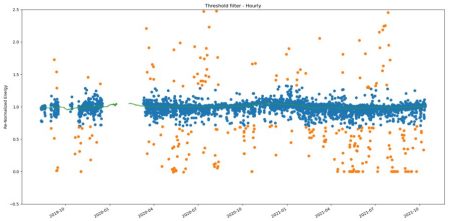


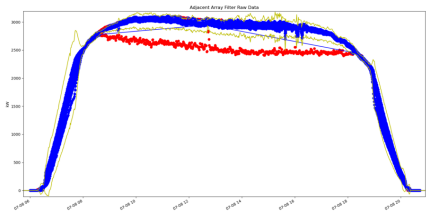
1. Irradiance Sensor Accuracy Assessment: (3002020233)

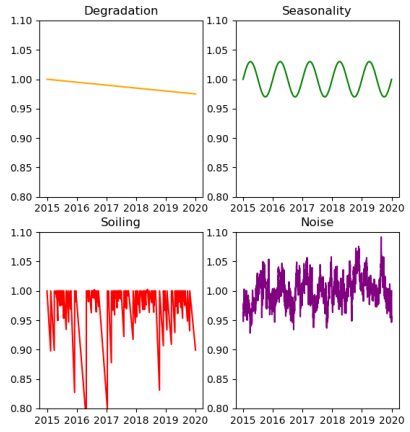
Analysis methodology

- 3-step Methodology
  - Normalization (mainly weather)
  - Irregular performance filter
  - Trend analysis
- Metrics calculated at each step
  - Plant health metrics use filtered data: “normal” state of operation, non-clipping



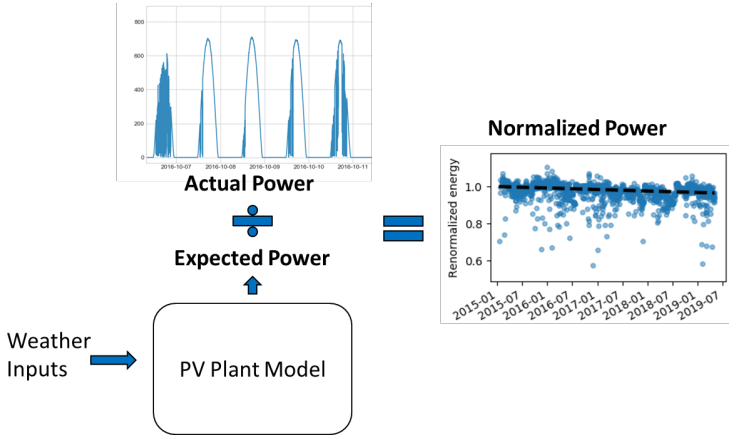


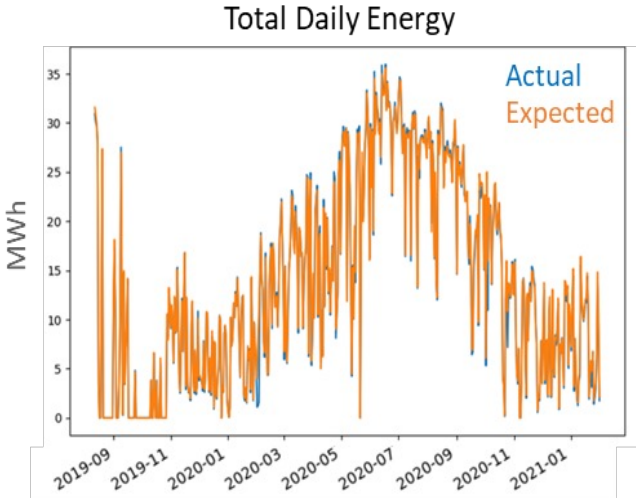




Normalization

- Objective: account for weather (and other) conditions by calculating "expected" plant production
  - Model: digital twin of the healthy plant
    - Use it to detect changes in performance, estimate energy loss, etc.
  - Model Notes:
    - Inverter level (detecting outages)
    - Trained on 1st year
      - Minimize soiling, degradation
  - 100% data driven models
    - Automated, scalable

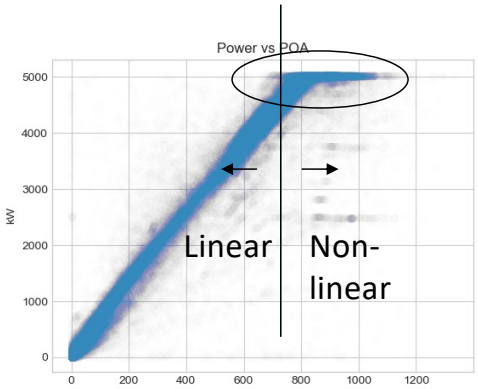


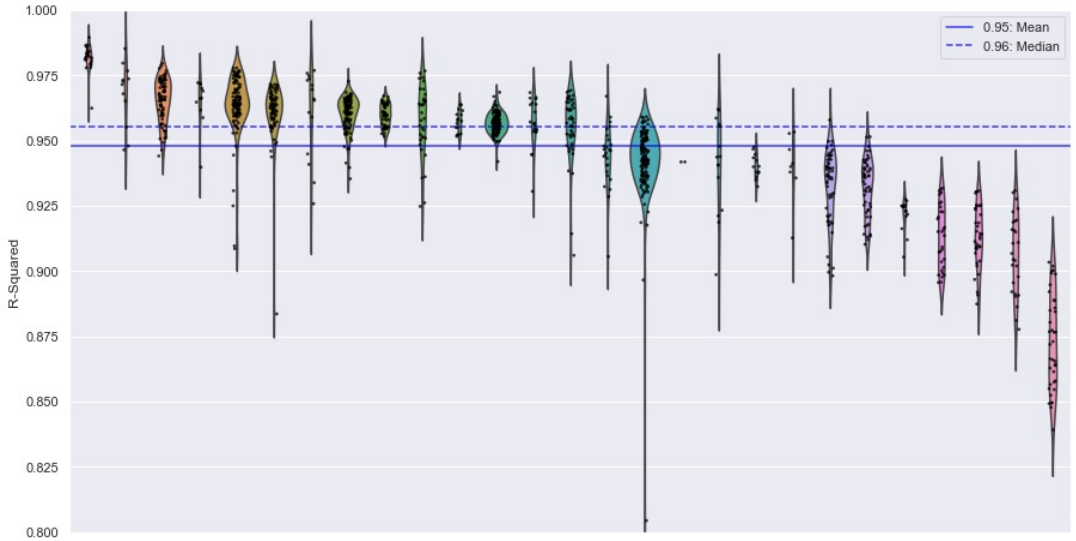


Normalization

- Model used: linear regression – P = f(POA, T_{amb}, Wind, AOI)
  - Input variable transformations (cos(AOI), log(POA))
  - 2nd order polynomial expansion
  - Model trained on linear region
    - Clipping is applied to linear model power estimates
- R-Squared: Mean 0.95, Median 0.96

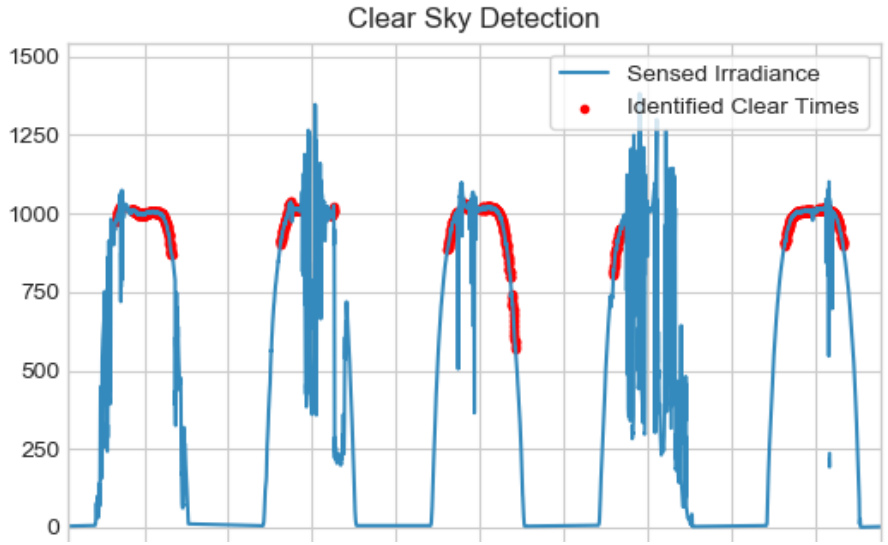
$$[a, b] \rightarrow [1, a, b, ab, a^2, b^2]$$





Use of clear-sky irradiance for PLR (trend) analysis

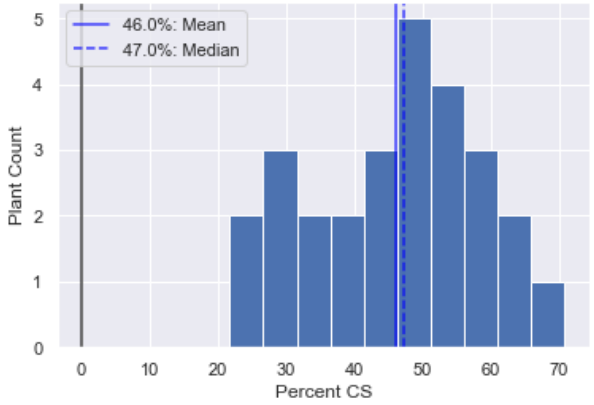
- Irradiance sensors often drift, causing a perceived shift in performance on the same order of magnitude as PLR
- Irradiance during clear-sky times can be estimated using lookup tables/functions[1]
  - Clear sky times can be identified by the irradiance or power profile[2]

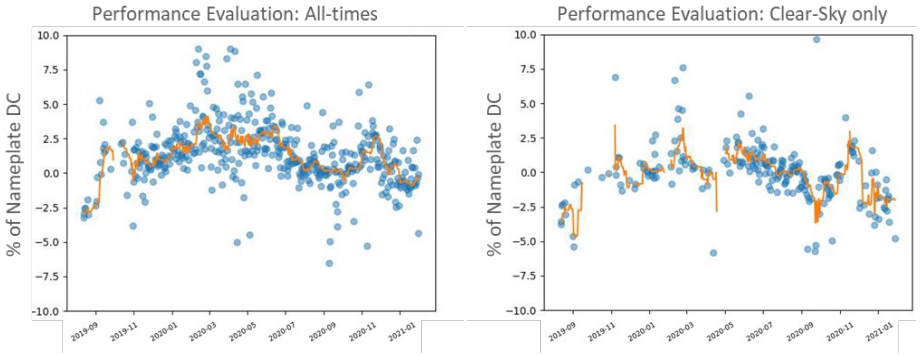


1. Reno, M.J. and C.W. Hansen, "Identification of periods of clear sky irradiance in time series of GHI measurements" Renewable Energy, 2016.
2. https://pvlib-python.readthedocs.io/en/v0.9.1/reference/generated/pvlib.location.Location.get_clearsky.html

Use of clear-sky irradiance for PLR (trend) analysis

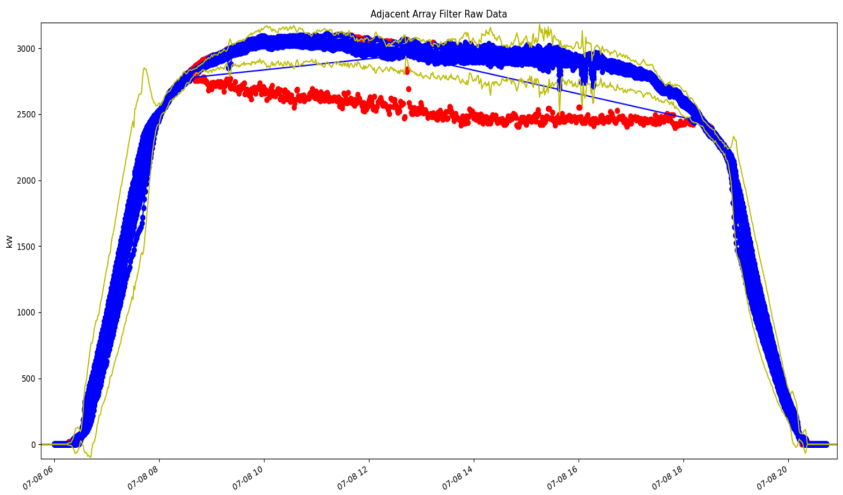
- Impacts of using Clear-Sky irradiance on normalization
  - Slightly improved model error: 10% vs 11%
    - Reduced variability, transposition error
  - Smaller fraction of the data
    - Average clear-sky duration: 46%

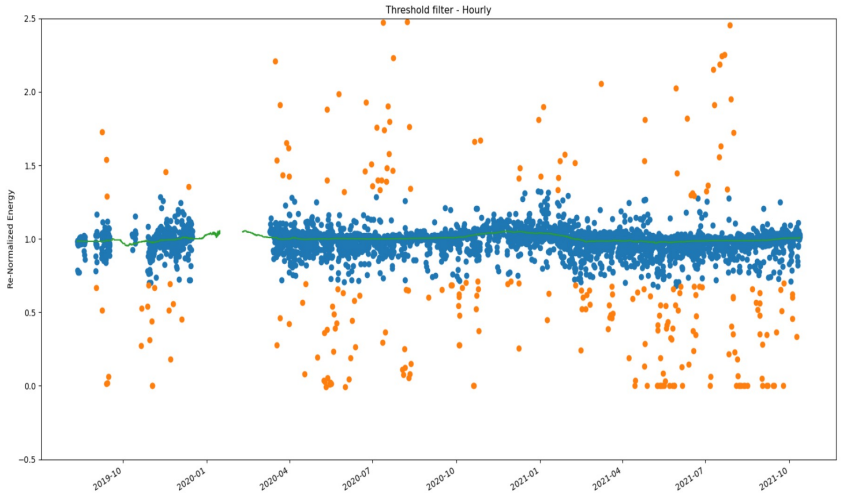




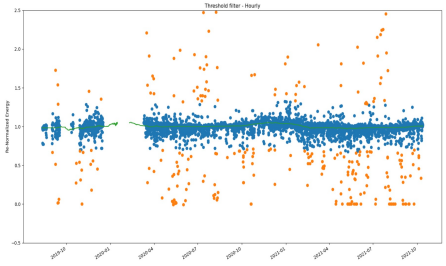
Irregular Performance Filters

- Irregularities can mask the “normal” performance of the plant
  - Flag temporary performance issues
- Detection:
  - Adjacent array
  - Time/threshold based





Trend Analysis



- Normalized data: remaining components
  - Trend (PLR), seasonal, soiling, noise
  - Year-on-year method[1] isolates trend from seasonal, and is resilient to outliers

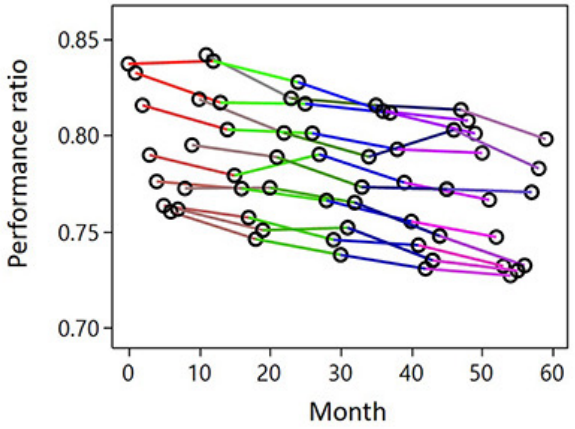


Image Source: NREL - https://www.nrel.gov/pv/rdtools.html

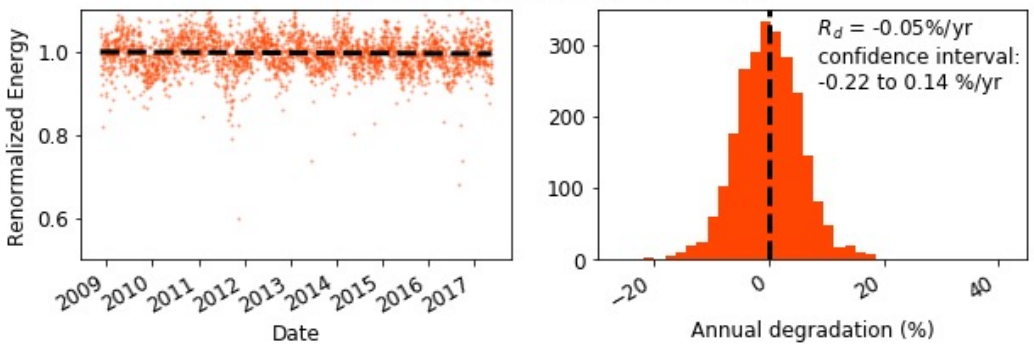


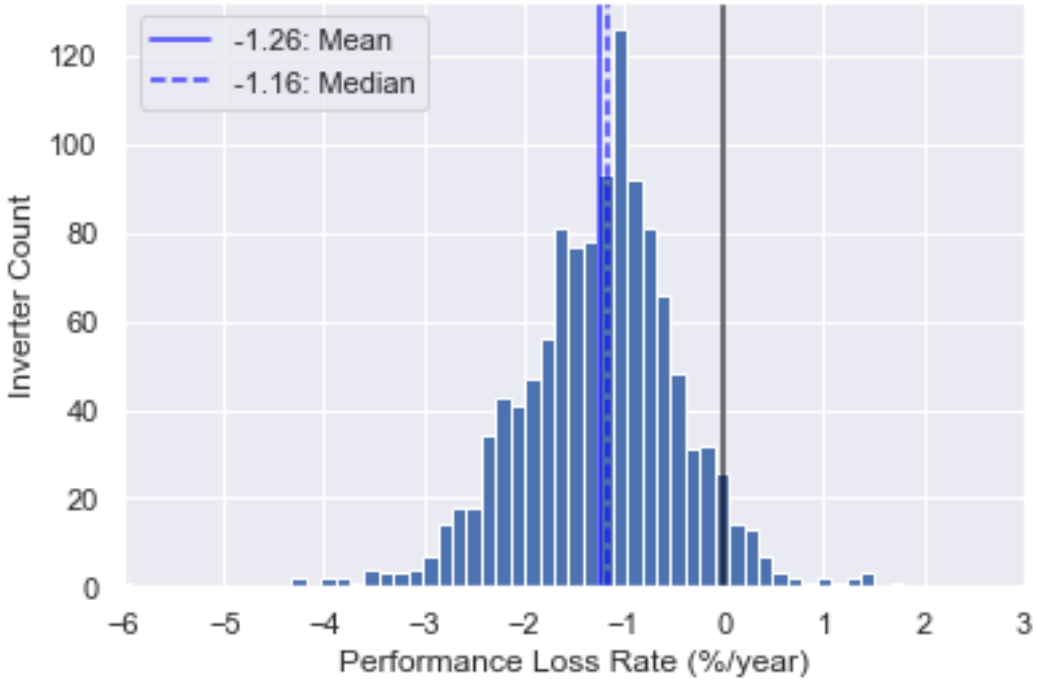
Image Source: NREL - https://rdtools.readthedocs.io/en/stable/

1. Dirk Jordan, Chris Deline, Sarah Kurtz, Gregory Kimball, Michael Anderson, "Robust PV Degradation Methodology and Application", IEEE Journal of Photovoltaics, 8(2) pp. 525-531, 2018 DOI: 10.1109/JPHOTOV.2017.2779779

Results

Performance Loss Rate

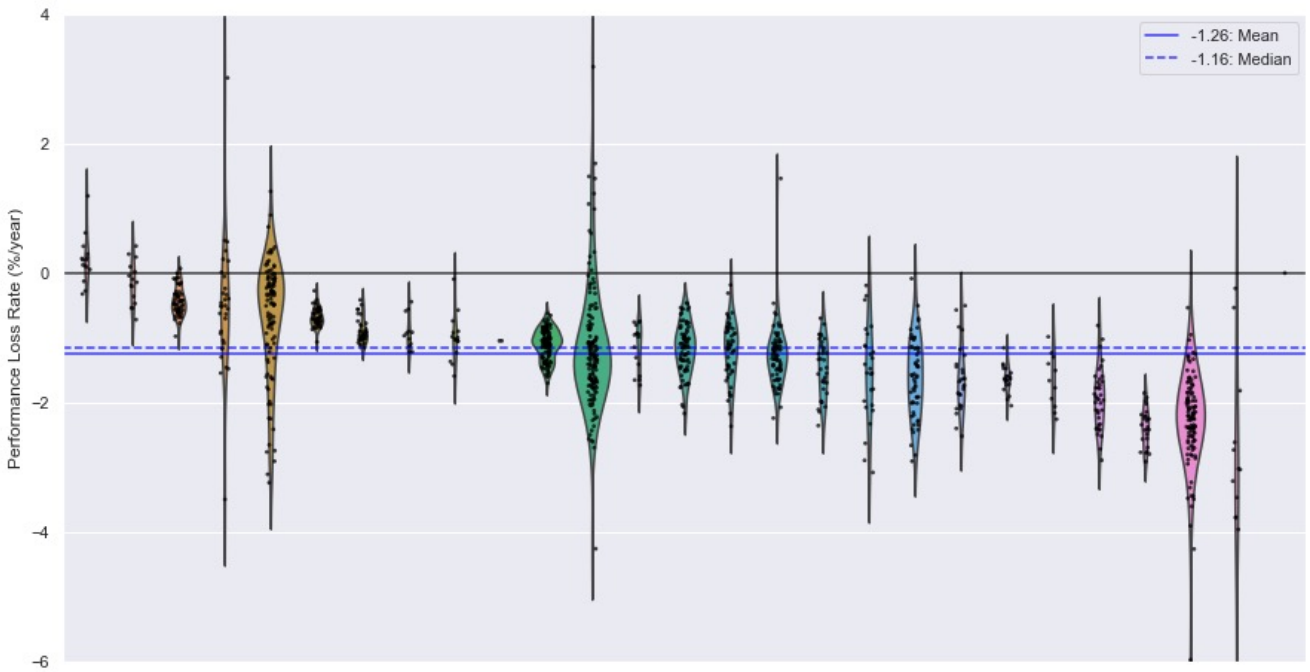
- Median: -1.16, Mean -1.26
  - 1200 inverters
  - Slightly asymmetric: poor performing outliers
- Slightly lower than other industry estimates
  - -0.75 %/yr[1]
  - -1 %/yr[2]
- Different methodology and analysis choices yield different results[3,4,5]



1. Jordan DC, Anderson K, Perry K, et al. Photovoltaic fleet degradation insights. Prog Photovolt Res Appl. 2022;1-10. doi:10.1002/pip.3566
2. Bolinger M, Gorman W, Millstein D, Jordan D, J. Renewable Sustainable Energy 12, 2020.
3. B. Paudyal, M. Bolen, and D. Fregosi, “PV Plant Degradation Assessment: Significance of Data Filtering and Aggregation,” in IEEE PVSC, Chicago, Ill, 2019
4. D. C. Jordan et al., "Reducing Interanalyst Variability in Photovoltaic Degradation Rate Assessments," in IEEE Journal of Photovoltaics, Jan. 2020
5. A. J. Curran, C. Birk Jones, S. Lindig, J. Stein, D. Moser and R. H. French, "Performance Loss Rate Consistency and Uncertainty Across Multiple Methods and Filtering Criteria," 2019 IEEE PVSC

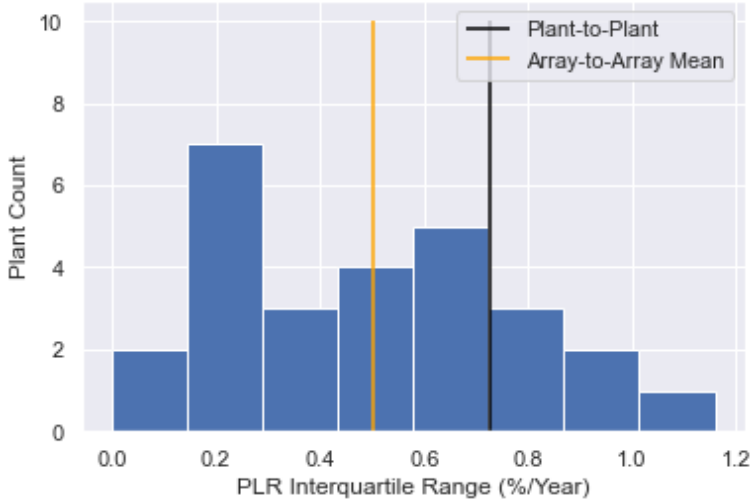
Performance Loss Rate

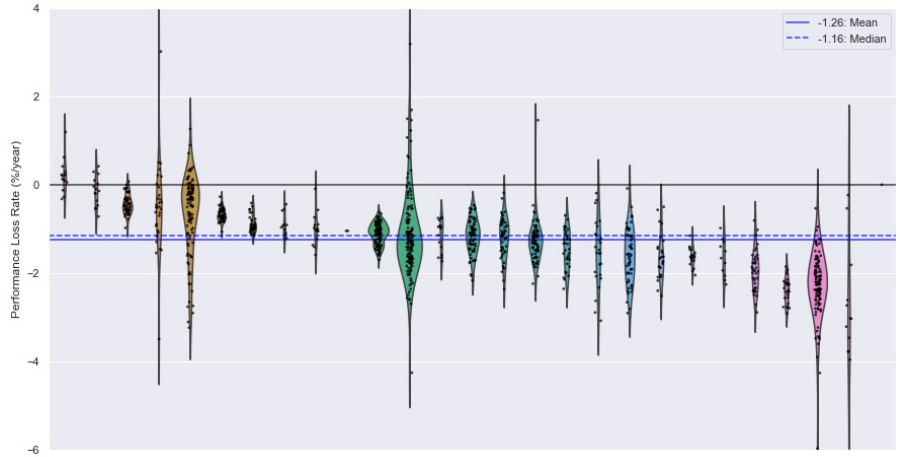
- Plant-by-plant breakdown
  - Fairly wide distributions within a plant ~ 1-2%



Performance Loss Rate

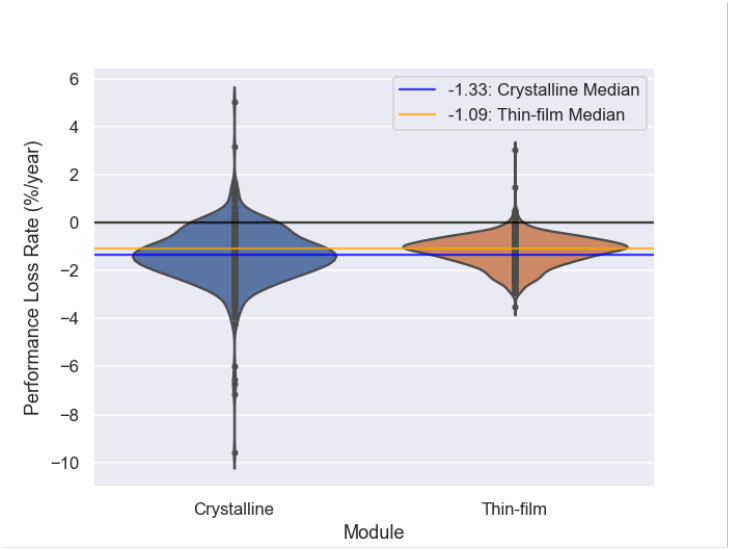
- Plant-to-plant range slightly higher than intra-plant range
  - Plant-to-plant factors
    - Module degradation-global, climate, soiling, maintenance level
  - Array-to-array factors
    - BOS faults, module degradation-individual, inverter, localized soiling/shading (vegetation)

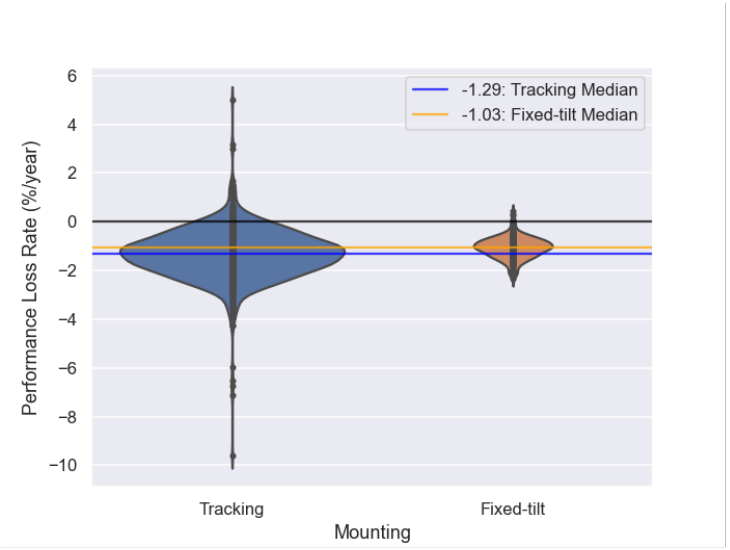




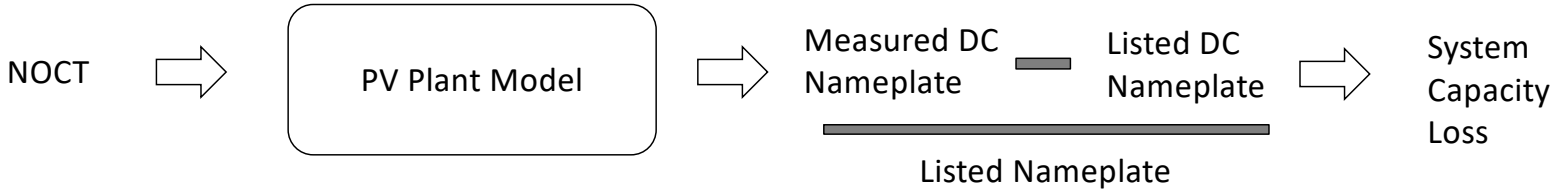
Performance Loss Rate

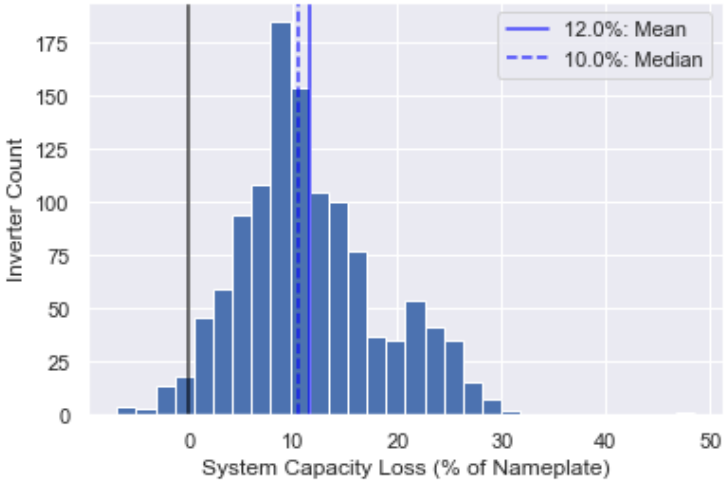
- Small differences in module technology and mounting
  - Need more data points for significance

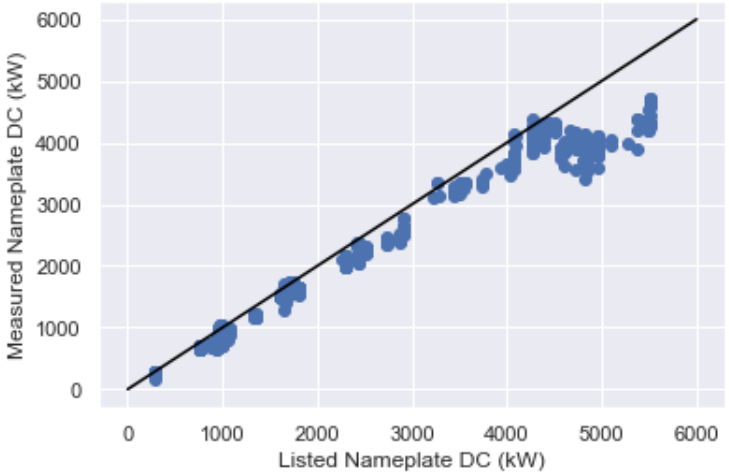




System Capacity Loss







- System capacity loss and PLR are better ways to analyze plant efficiency
  - Clipped energy is effectively counted against a plants Performance Ratio

Future Work

- Further automate data intake, quality control
- Further reduce model error for Normalization
  - More sophisticated, non-linear regression models
  - Measure impact of satellite data, additional model inputs
- Incorporate decomposition algorithms for trend analysis
  - Irregular performance, trend, seasonality, soiling
- Website improvements
  - Plant-specific view (user-controlled)
  - Plotting functionality
  - Additional filters
  - Add more data/users!