Derivation and Applications of Filtered Temperature-Corrected Performance Ratio for Diagnosis of Under-performing Power Plants

Samantha Wilson, Steve Voss, Stephen Lightfoote

Agenda

- Overview of Power Factors and the drive platform
  - Focused on solar performance monitoring
- An introduction to filtered temperature-corrected performance ratio (FTCPR)
  - Comparison to other KPIs
  - Filters
    - Data Quality
    - Events
    - etc.
  - Formula
- Applications of FTCPR
  - Degraded classification
  - Soiling derate characterization
  - Wash optimization
  - DC health assessments
  - Benchmarking

POWERFACTORS

The Global Leader for Renewables Software Solutions

207+ GW
Managed Assets
(solar, wind, storage, hydro)

500+
Employees
Globally

Trusted by
500+
Global Customers

100+
Dedicated
Developers

18k+
Project Sites

62
Countries

$16 M
R&D Spend (2023)

Global HQ
San Francisco, CA

10
Global Offices

N.A.
- San Francisco, U.S.
- Burlington, U.S.
- Montréal, Canada

EMEA
- Athens, Greece
- Gothenburg, Sweden
- London, England
- Munich, Germany
- Seville, Spain

APAC
- Haryana, India
- Manila, Philippines

Power Factors Product Portfolio

Application Layers - Primary Users & Activities

Unity	APM (Drive & Greenbyte)	Drive O&M	BluePoint
Central Monitoring System	Asset Performance Management	Field Service Optimization	Commercial Asset Management
ROC Operators **Performance Analysts**	**Asset Managers** **ROC Operators** **Performance Analysts**	**Dispatch** **Technicians**	**Asset Managers** **Compliance Managers**
• Real Time Monitoring • Plant Control • Schematics • VPP • Market Integration	• Data Validation & Cleansing • Event Management • Troubleshooting for RCA • Portfolio Performance Roll-ups & visualizations	• Preventive Maintenance • Corrective Maintenance • Scheduling & Dispatch • Field Work Execution • Compliance Field Tasks	• Project Management • Contractual Compliance • Performance Reporting • Financial Reporting • Invoicing

Performance Management

Greenbyte | Drive

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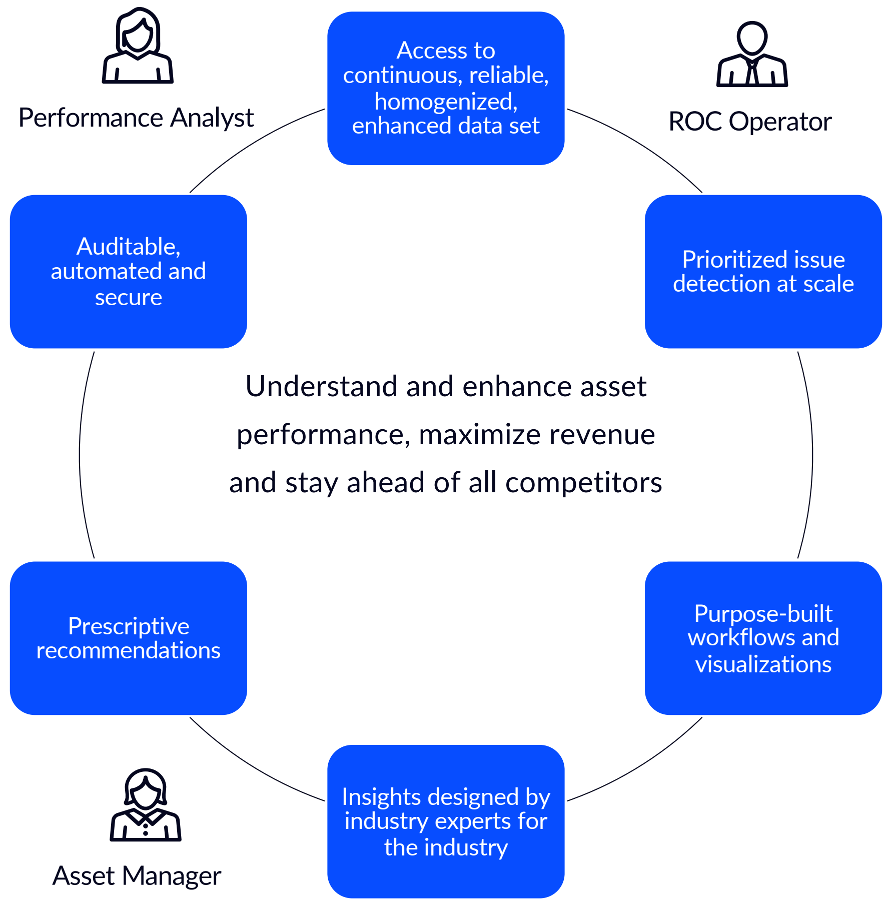

Filtered Temperature-Corrected Performance Ratio (FTCPR)

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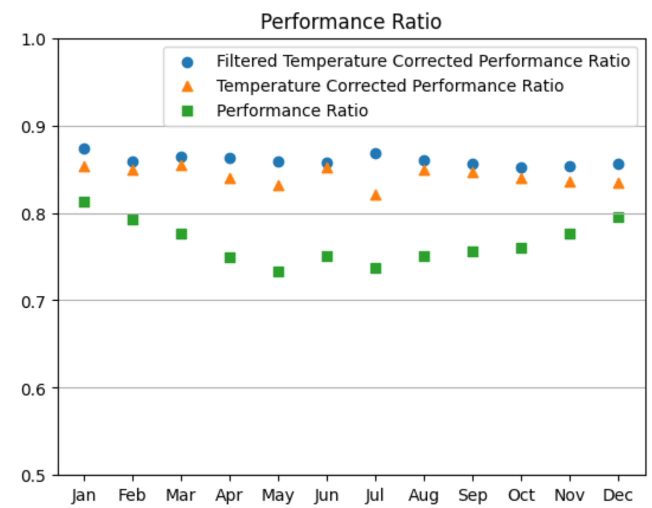
- An introduction to FTCPR
  - Comparison with other KPIs
- Filters
  - Remove low-quality measured data
    - Plane-of-Array irradiance
    - Module temperature
    - AC power at the inverter
  - Removing events
    - DC Outages
    - Inverter Outages
    - Clipping intervals
  - Remove shade
- Formula

Filtered temperature-corrected performance Ratio

An ideal plant performance KPI is:

- Not sensitive to data quality issues
- Is not sensitive to temporary events
  - Plant and inverter outages
  - Shading
  - Inverter clipping
- Captures performance of the DC array
- Has minimal seasonal variation



Based on these criteria we have developed the

filtered temperature corrected performance ratio (FTCPR)

Dierauf, T., Growitz, A., Kurtz, S., Cruz, J. L. B., Riley, E., and Hansen, C. Weather-Corrected Performance Ratio. United States: N. p., 2013. Web. doi:10.2172/1078057.

Filtering for data quality

The first step is to validate incoming timeseries.

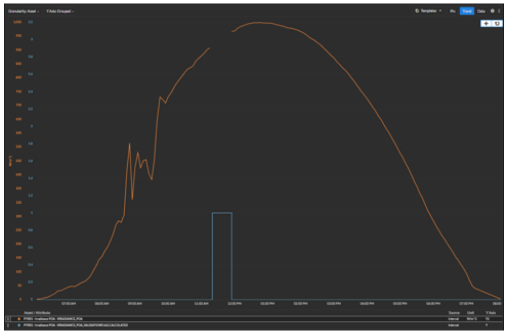
- AC Power Inverter
- Plane of array irradiance
- Module temperature

All time series data is checked for

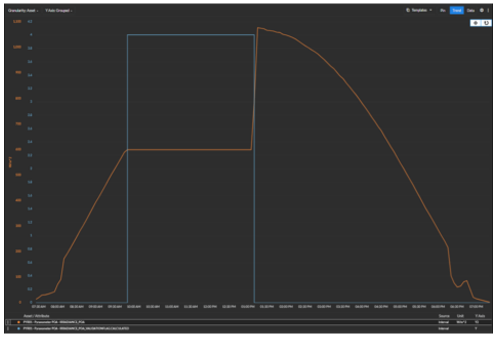
- Missing values
- Flatlines
- Constant slope
- Implausible jumps in value
- Out of reasonable range
- Large deviation from satellite reference data

All metadata is checked for:

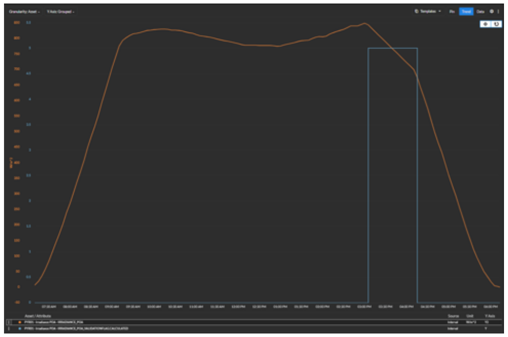
- Internal consistency with plant
- Data within reasonable range



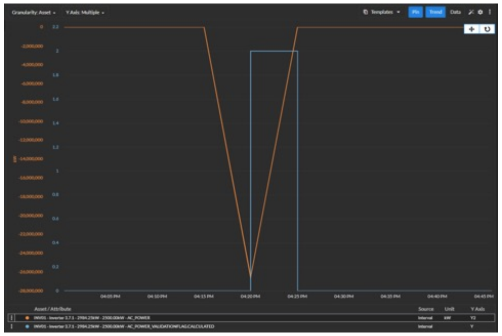
Missing Values



Flatline



Constant Slope

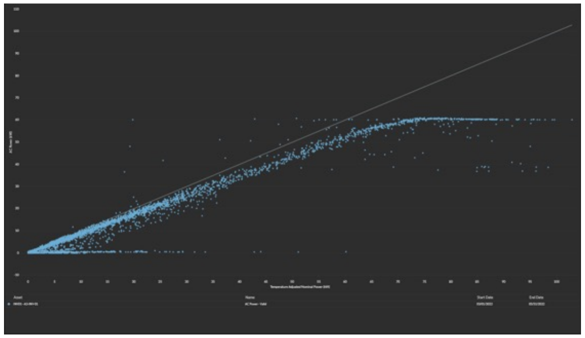


Implausible Jump in Value

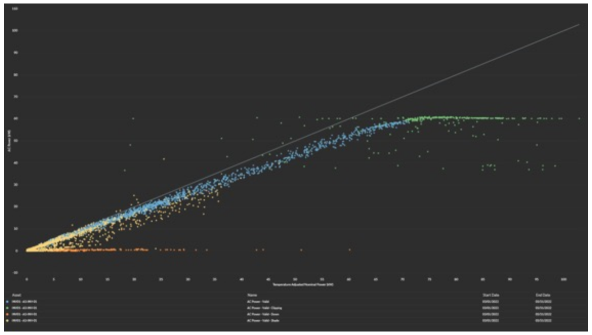
Simple event logic is used to remove certain events

After data quality is assessed we filter out basic logic based events like:

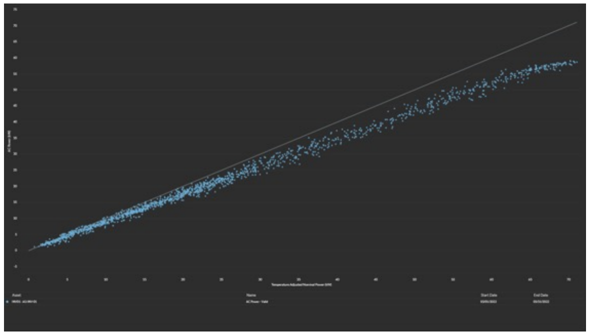
- Outages
  - Based on minimum power threshold
- Clipping
  - Based on maximum power threshold



All Intervals



Event Intervals Classified



Event Intervals Filtered

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Filtering out shade

Shade impacts on inverters are widespread

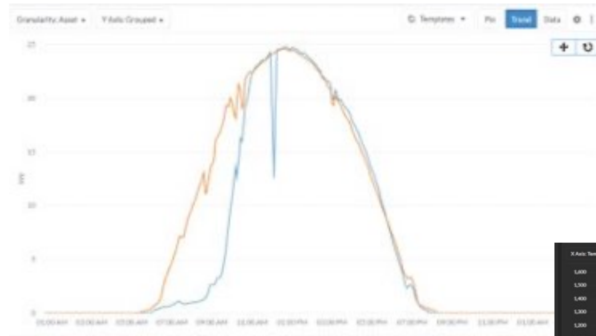
- **Row to row shade** is flagged through a 2D calculation

Even after removing row-to-row shading, shading loss is widespread due to

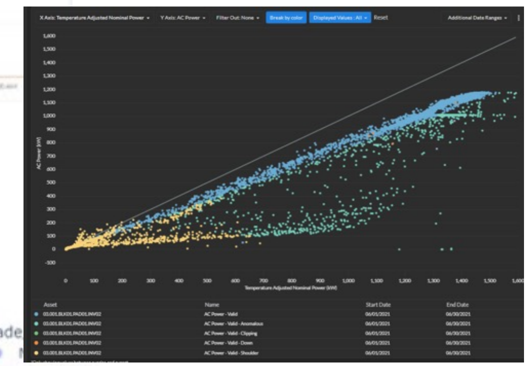
- **Obstructions**
- Bad metadata

To filter out shade we:

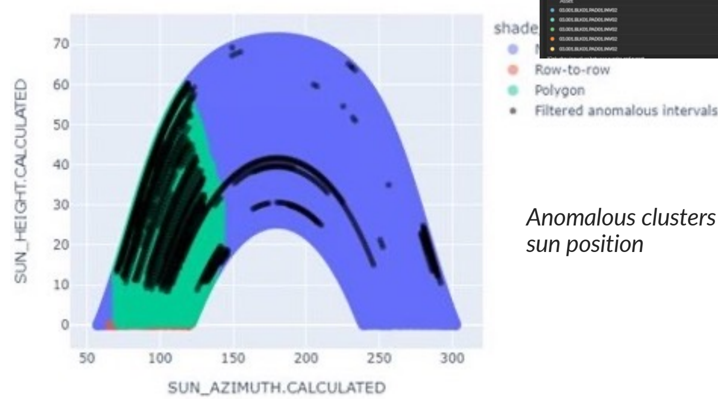
- Establish an "inverter twin"
- Identify **"Anomalous" intervals** outside the twins expected parameters
- Filter anomalous intervals for events and clear sky intervals
- Identify clusters of anomalous intervals by sun position



AC Power versus AC Power expected for a shaded day



Actual production versus temperature corrected nominal power showing anomalous intervals



Anomalous clusters are identified by sun position

Reno, M.J. and C.W. Hansen, "Identification of periods of clear sky irradiance in time series of GHI measurements" Renewable Energy, v90, p. 520-531, 2016.

Calculating temperature-corrected performance Ratio

The calculation relies on a limited set of measured timeseries and plant metadata

- Time series
  - Plane of Array irradiance
  - Module temperature
    - Can be measured or calculated from irradiance
  - Inverter AC power
- Metadata
  - DC capacity of the inverter
  - Module power temperature coefficient
  - Reference values, usually 1000 W/m^2 and 25°C

$$Inverter\ Nominal\ Power = (Inverter\ DC\ Capacity) * \frac{(Plane\ of\ Array\ Irradiance)}{(Reference\ Irradiance)}$$

$$Temperature\ Adjustment = \big(1 + (module\ temperature\ coefficient) * (Module\ Temperature\ - Reference\ temperature)\big)$$

$$\color{red}{\boldsymbol{Daily\ temperature\ corrected\ performance\ ratio}} = \frac{\sum(Inverter\ AC\ Power)}{\sum((Inverter\ Nominal\ Power) * (Temperature\ Adjustment))}$$

Dierauf, T., Growitz, A., Kurtz, S., Cruz, J. L. B., Riley, E., and Hansen, C. Weather-Corrected Performance Ratio. United States: N. p., 2013. Web. doi:10.2172/1078057.

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Applications of FTCPR

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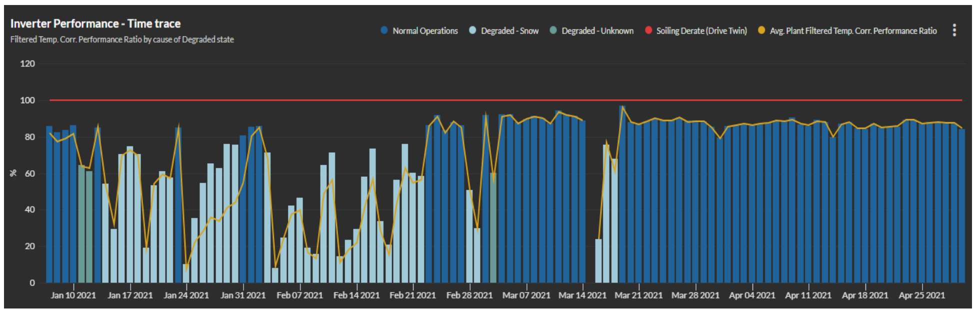
- Degraded classification
  - Use of FTCPR in machine learning classification
- Soiling Derate analysis
- Wash date optimization
- Comparison of FTCPR before and after DC health improvements
- Benchmarking performance

Applications of FTCPR: Degraded classification

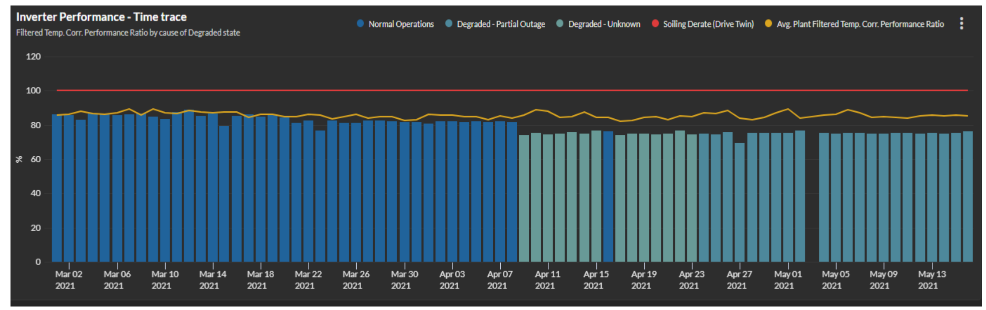
- **Supervised machine learning (ML) multi-class ensemble classification** model based primarily on daily FTCPR with ~70 features
- Inverter x day's performance classified as:
  - Normal Operations
  - Implausible
  - Incomplete
  - Degraded
    - Soiling
    - Partial DC Outage
    - Combiner Outage
    - Tracker Outage
    - Snow
    - Unknown
- Provides labels and associated probabilities which can be used to generate events and allocate lost energy.
- Objective is not only to identify and quantify **degraded performance losses**, but to assign a **root cause**, especially for controllable issues.

Daily FTCPR trends with classified loss categories

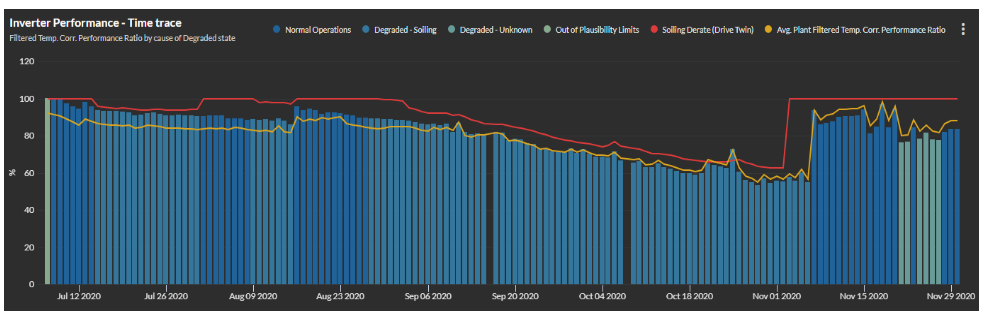
Snow



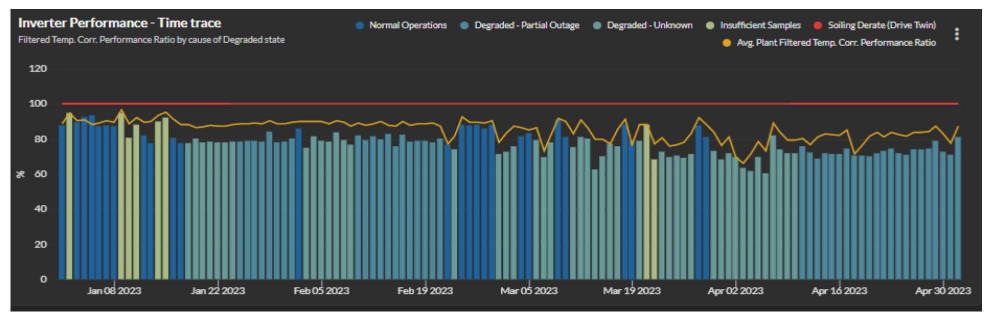
Combiner Outage



Soiling



Tracker Outage



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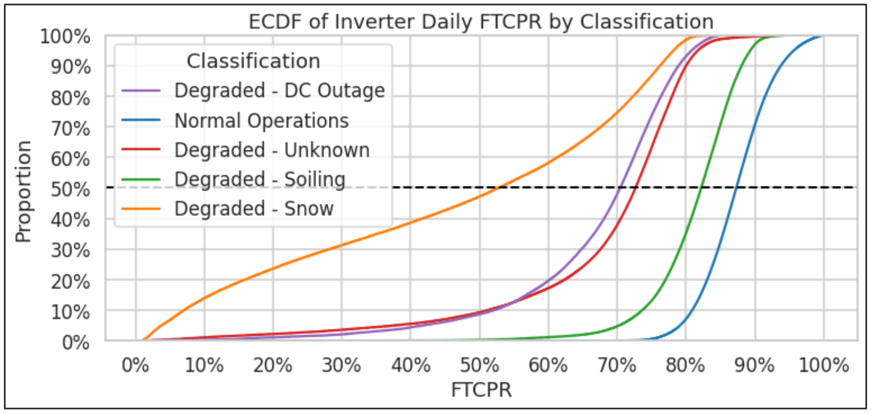
Overview of degraded classification results



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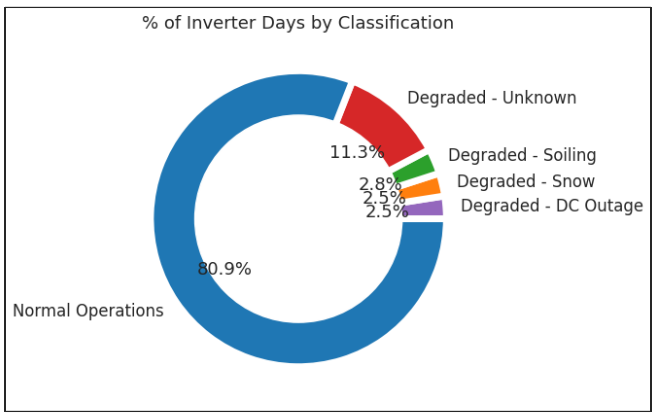
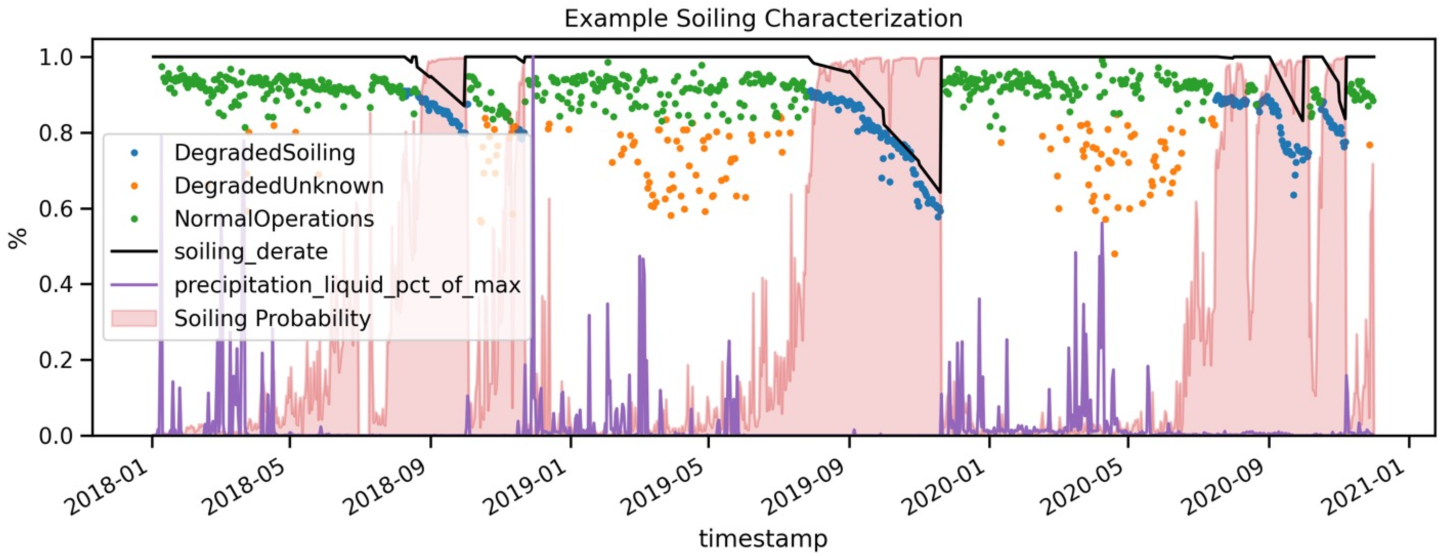


- Results of degraded classification running in production for ~4 years
  - 14.6 million inverter x days = 40k inverter x years
- Degraded unknown is still the biggest category
  - Next steps include allowing classification of multiple categories
  - Make DC outage detection more sensitive
  - More categories like curtailments, etc

Applications of FTCPR: Soiling Characterization

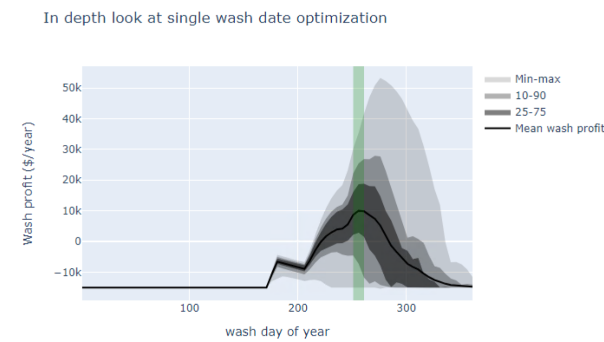
- If a day is classified as soiling, the soiling derate is extracted
- Modified form of Stochastic Rate and Recovery (SRR) method described in Deceglie et al. [1] Differences include:
  - Includes an additional monthly degree of freedom (piecewise Theil-Sen regression)



[1] Deceglie, Michael G., Micheli, Leonardo, and Muller, Matthew. Quantifying Soiling Loss Directly From PV Yield. United States: N. p., 2018. Web. doi:10.1109/JPHOTOV.2017.2784682.

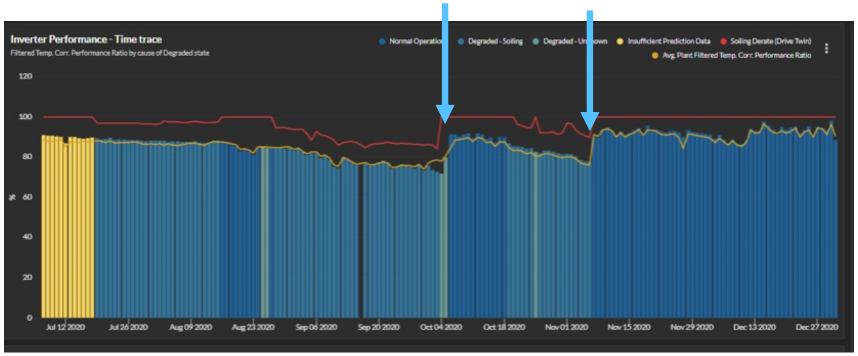
Applications of FTCPR: Wash Analysis and optimization

- Do I need to wash now?
  - If FTCPR shows no sign of classic soiling pattern, washing is unlikely to benefit plant
- When should I wash?
  - Wash optimization calculation based on
    - Historical soiling classification and derate analysis
    - Economics of plant
    - Historical precipitation data



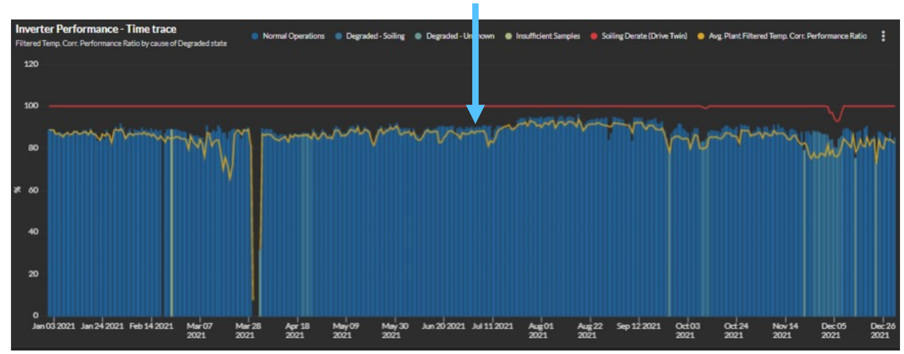
Plot of expected profit versus wash date

Wash *Rain*



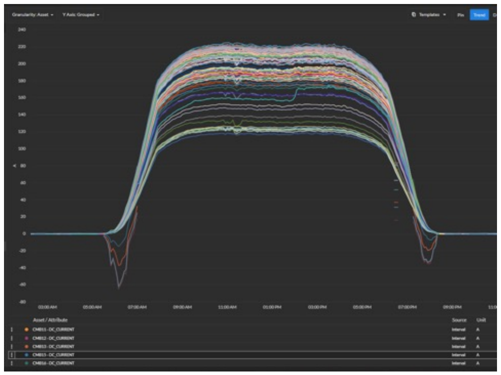
Daily FTCPR showing clear response to wash and rain events

Wash



Daily FTCPR showing no response to wash for high performing inverter

Applications of FTCPR: Case study on DC Health



Combiners with variable number of strings and in various states of health

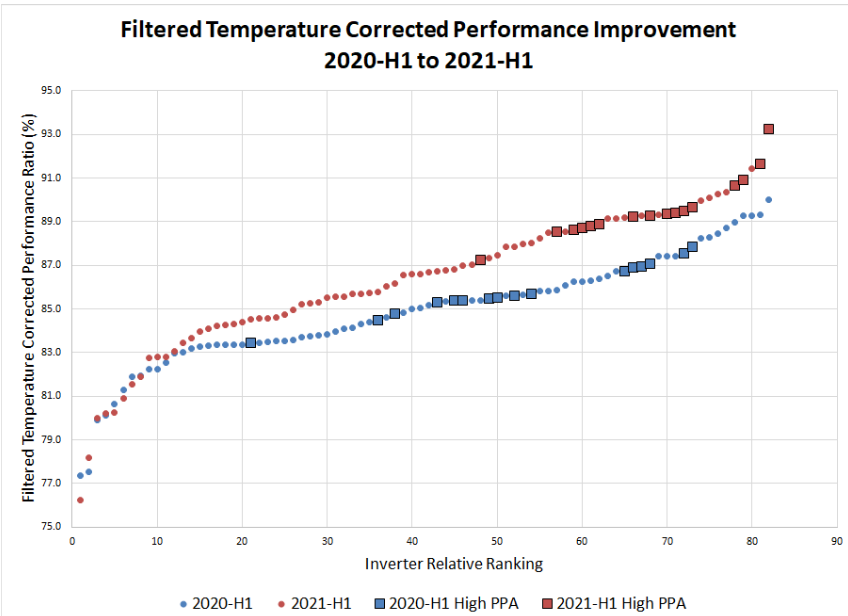
- DC current data at the combiner level is collected and analyzed
  - Current is normalized using combiner metadata
- Strings offline is estimated
- Based on number of strings offline, maintenance work can be better targeted

Combiners | Recombiners | Estimated Strings Offline | Search

	Recombiner	CMB01	CMB02	CMB03	CMB04	CMB05	CMB06	CMB07	CMB08	CMB09	CMB10	CMB11	CMB12	CMB13	CMB14	CMB15	CMB16	CMB17	CMB18
BLK01.PAD01.INV01	RCB01	1	1	0	1	0	1	0	0	1	1	0	0	0	0	0	3		
BLK01.PAD02.INV01	RCB01	3	0	0	0	0	0	0	0	0	2	0	4	0	4	0	0		
BLK01.PAD03.INV01	RCB01	0	0	0	1	0	0	0	2	3	1	0	0	0	0	0	0		
BLK01.PAD04.INV01	RCB01	0	0	0	0	1	0	0	0	0	0	2	0	0	4	2	0		
BLK01.PAD05.INV01	RCB01	0	0	0	0	0	0	2	0	0	0	0	3	0	1	1	0	1	0
BLK01.PAD06.INV01	RCB01	0	1	3	0	0	2	0	0	0	0	2	0	0	0	0			
BLK01.PAD07.INV01	RCB01	0	0	2	0	2	0	2	0	1	1	0	0	2	0	4	0	0	0
BLK01.PAD08.INV01	RCB01	0	0	1	0	0	0	1	0	1	3	0	3	5	4	0	1	0	0

DC current is normalized versus learned properties or metadata and turned into estimated strings offline

FTCPR for quantifying impact of combiner maintenance actions



Comparison of all inverters ranked by FTCPR
Squares show higher PPA rate inverters

- Between 2020 to 2021 there was no change in personnel
- Maintenance was adjusted to focus on
  - High revenue inverters
  - Combiners that are significantly underperforming
- All inverters improved
  - High revenue inverters improved greatly

	Low Revenue	High Revenue	Difference
2020-H1	84.7%	85.9%	1.2%
2021-H1	85.6%	89.6%	4.0%
Improvement	0.9%	3.7%	

Improvements were concentrated on high PPA rate sites

Applications of FTCPR: Benchmarking

- FTCPR can be benchmarked globally
- Alternatively, it can be broken down by:
  - Plant Capacity
  - Plant commission date
  - Manufacture/model for:
    - Modules
    - Inverters
    - Etc.
  - Location
  - Mounting type (shown at right)
  - Etc.
- This allows users to check performance both globally and versus peers

Comparison between Fixed tilt and HSAT versus black, global FTCPR distribution

Future Work and Conclusions

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- Filtering is the most important step of FTCPR
  - Temperature correction to reduce seasonality
  - Data quality
  - Simple events
  - Shade
- Filtered temperature corrected performance ratio is the main performance KPI used by Drive
  - Machine learning classification
  - Soiling analysis
  - Wash optimization
  - DC health analysis
  - Benchmarking
- Future work
  - Continuous improvement of the degraded classifier
    - Multiple categorizations
    - Increased sensitivity to DC outages
  - Continue benchmarking

THANK YOU!

Contact information:
samantha.wilson@powerfactors.com

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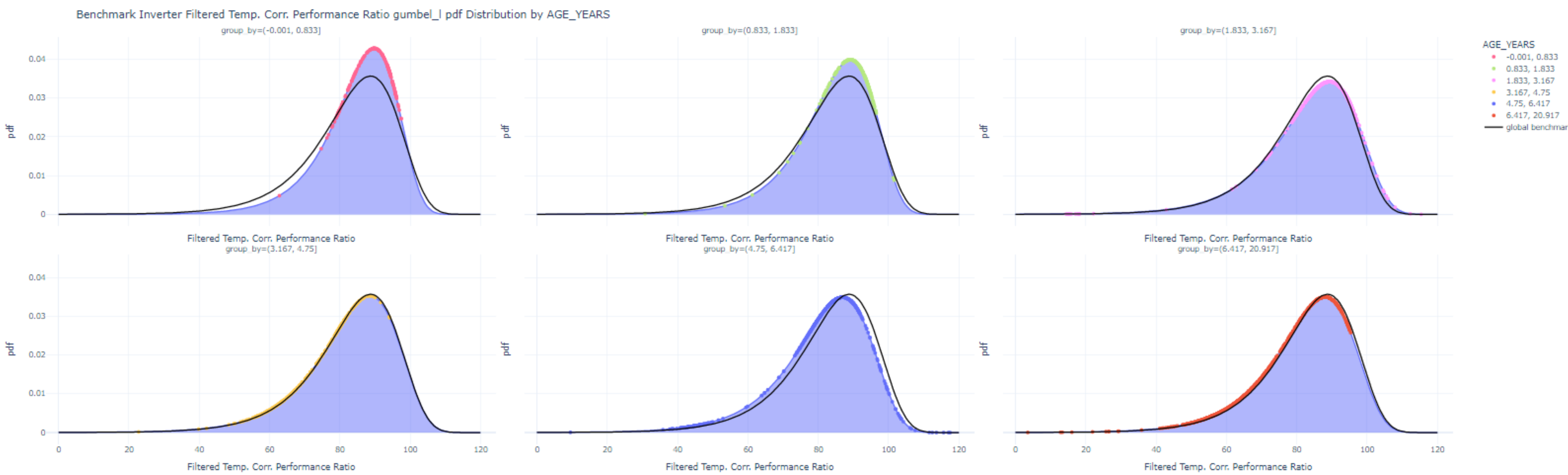
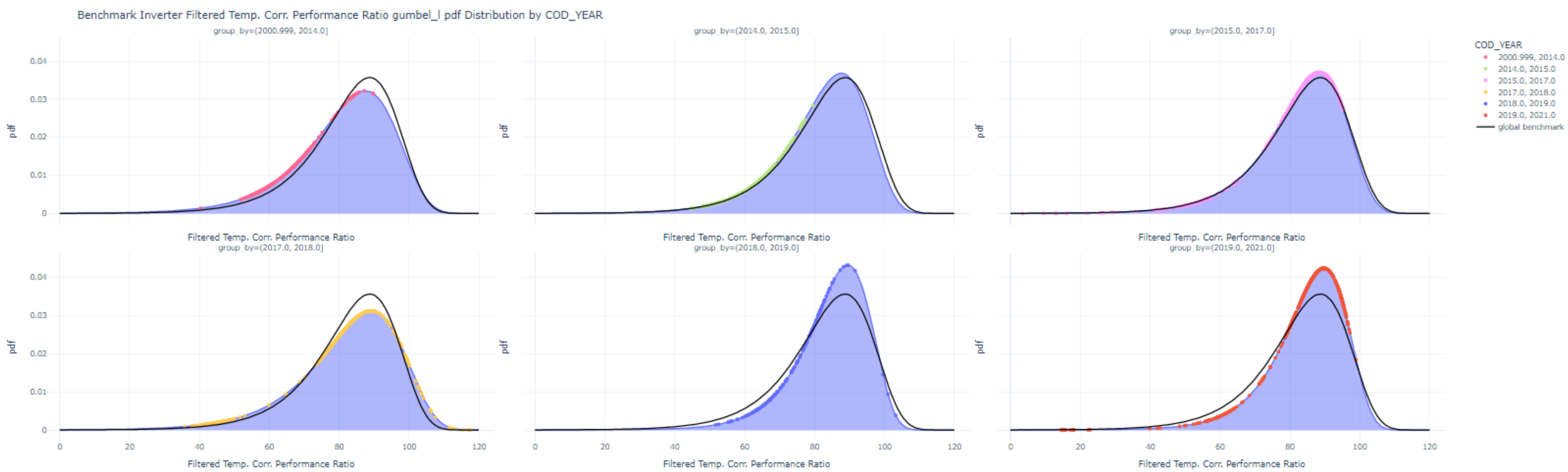
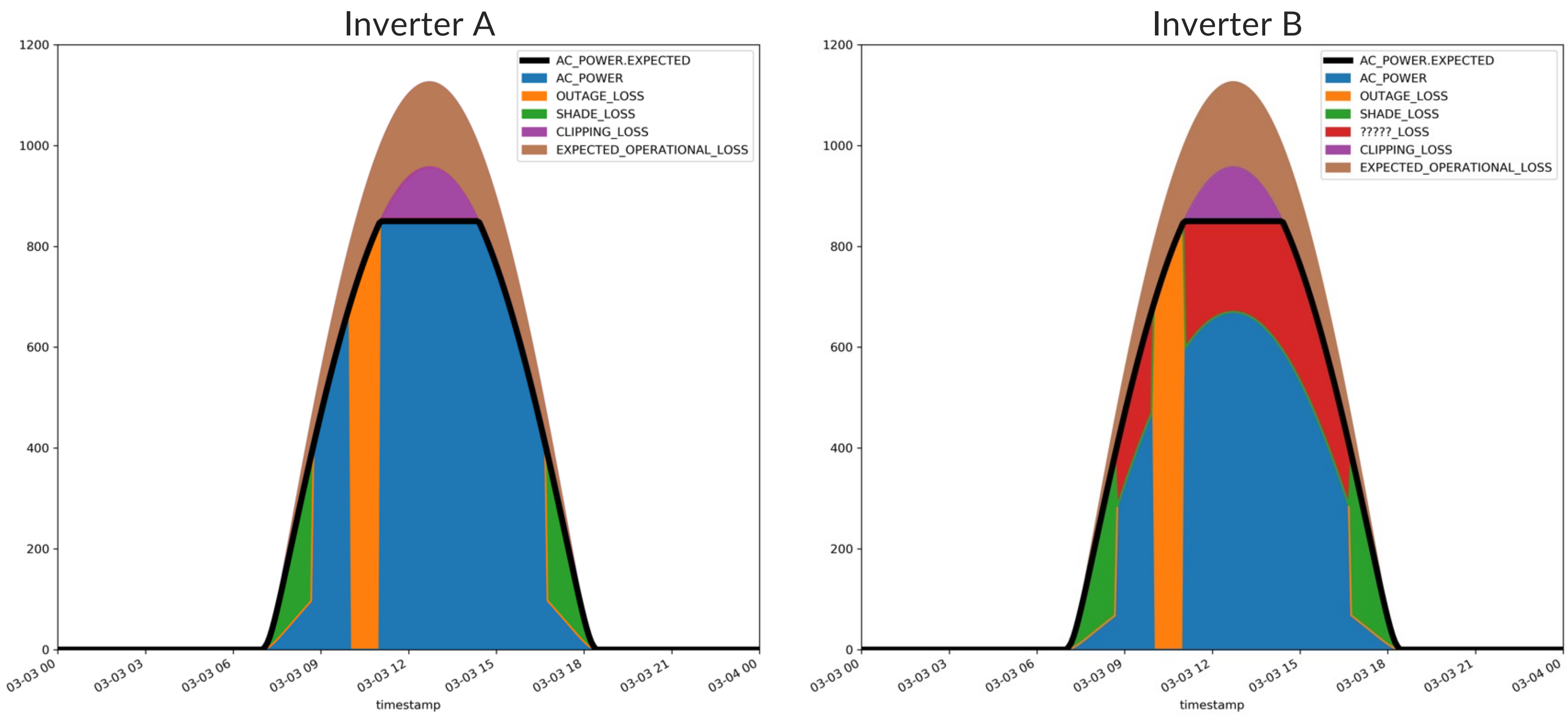
FTCPR Benchmarking: By Age in Years



FTCPR Benchmarking: By COD Year



Overview: Technical Background



Methodology: Daily Filtered Temperature Corrected Performance Ratio (FTCPR)

- Daily average of Eqn. 2 [2] with filters to exclude:
  - Curated Irradiance POA
  - Outages
  - Clipping / Overdesign
  - Shading
  - Curtailment
- Robust and stable through time in the absence of asset performance issues or sensor bias.

$$(1) \quad PR = \frac{\sum_i EN_{AC\_i}}{\sum_i \left[P_{STC} \left(\frac{G_{POA\_i}}{G_{STC}} \right) \right]}$$

$$(2) \quad PR_{corr} = \frac{\sum_i EN_{AC\_i}}{\sum_i \left[P_{STC} \left(\frac{G_{POA\_i}}{G_{STC}} \right) \left(1 - \frac{\delta}{100} \left(T_{cell\_typ\_avg} - T_{cell\_i} \right) \right) \right]}$$

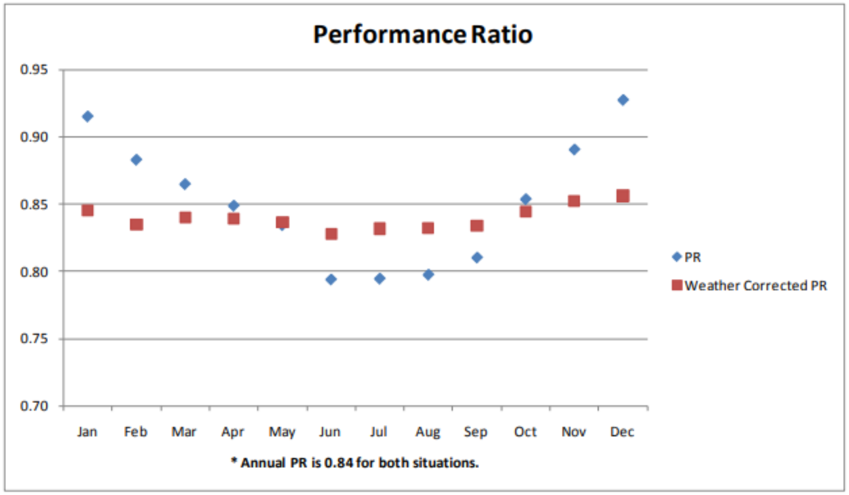


Figure 2. Corrected and uncorrected PR from simulated results.

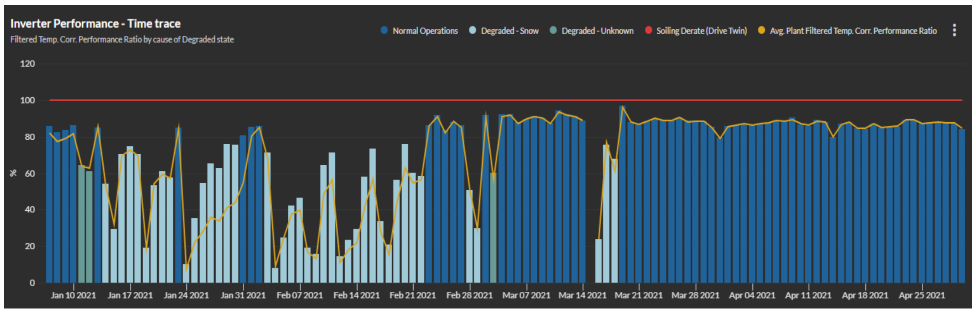
[2] Dierauf, T., Growitz, A., Kurtz, S., Cruz, J. L. B., Riley, E., and Hansen, C. Weather-Corrected Performance Ratio. United States: N. p., 2013. Web. doi:10.2172/1078057.

Methodology: Degraded Classifier

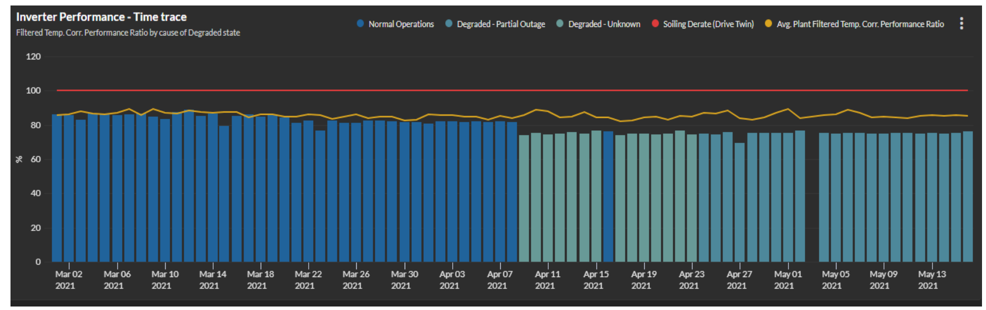
- Supervised machine learning (ML) multi-class ensemble classification model
- Inverter x day's performance classified as:
  - Normal Operations
  - Implausible
  - Incomplete
  - Degraded
    - Soiling
    - Partial DC Outage
    - Snow
    - Unknown
- Provides labels and associated probabilities which can be used to generate Events and allocate Lost Energy.
- Objective is not only to identify and quantify degraded performance losses, but to assign a Root Cause, especially for controllable issues.

Approach: Automated Detection - Expert System

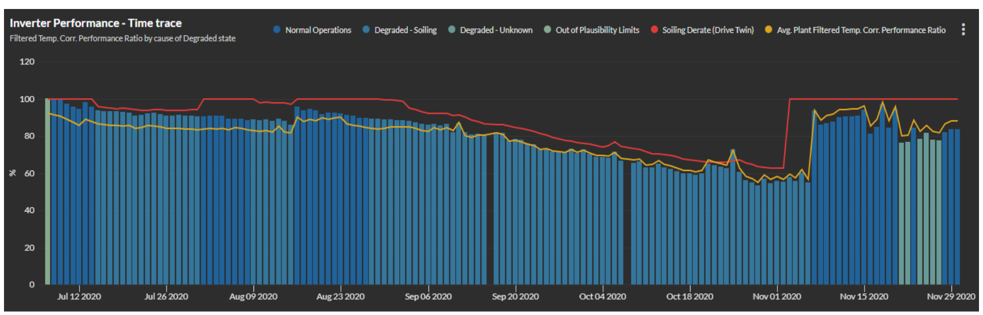
Snow



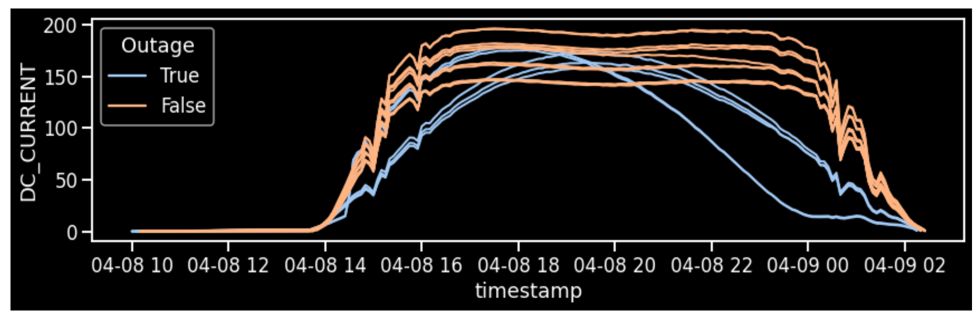
Combiner Outage



Soiling



Tracker Outage



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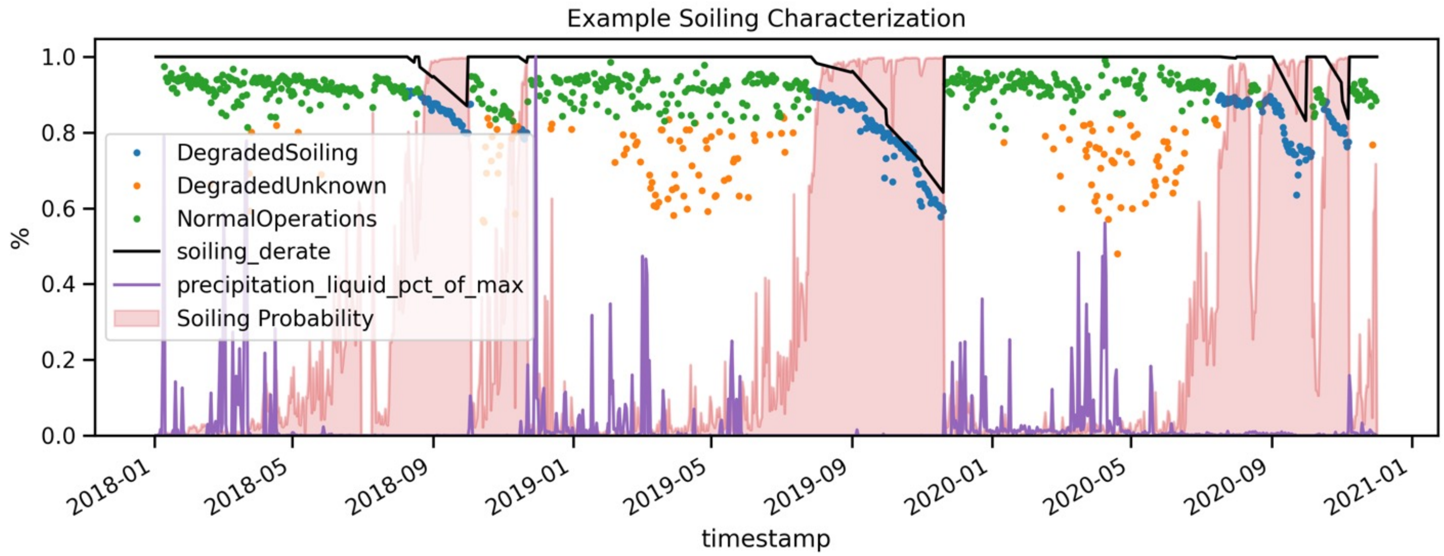
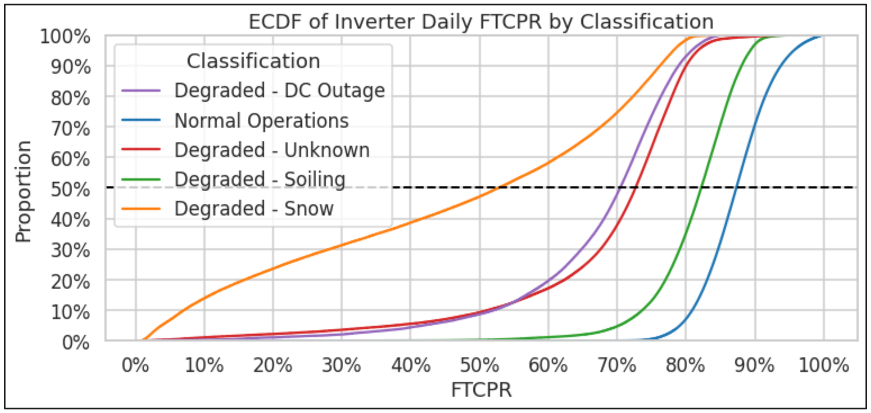
Methodology: Soiling Characterization

- Soiling impacts derived directly from on-site irradiance and power measurements.
  - Fleet scale assessment possible with this method
- Modified form of Stochastic Rate and Recovery (SRR) method described in Deceglie et al. [1] Differences include:
  - Soiling periods labeled from Degraded Classifier
  - Includes an additional monthly degree of freedom (piecewise Theil-Sen regression)



[1] Deceglie, Michael G., Micheli, Leonardo, and Muller, Matthew. Quantifying Soiling Loss Directly From PV Yield. United States: N. p., 2018. Web. doi:10.1109/JPHOTOV.2017.2784682.

Motivation



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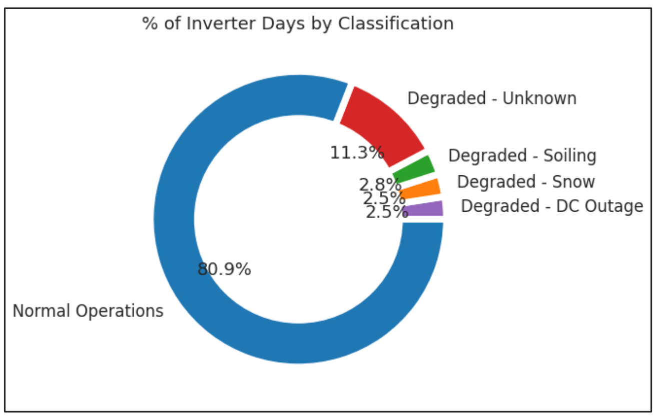
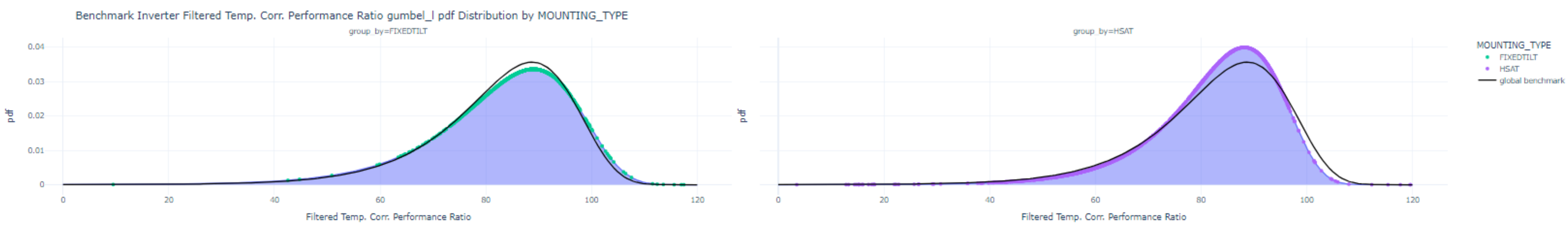


- Dataset:
  - Filtered Temperature Corrected Performance Ratio (FTCPR) filters out constrained operation and outages
  - 14.6 million inverter x days = 40k inverter x years
- <u>As a fleet, we're leaving up to 3.8% of energy on the table.</u>
- Broader industry numbers could be worse…
- We need smarter operations!

FTCPR Benchmarking: By Mounting Type



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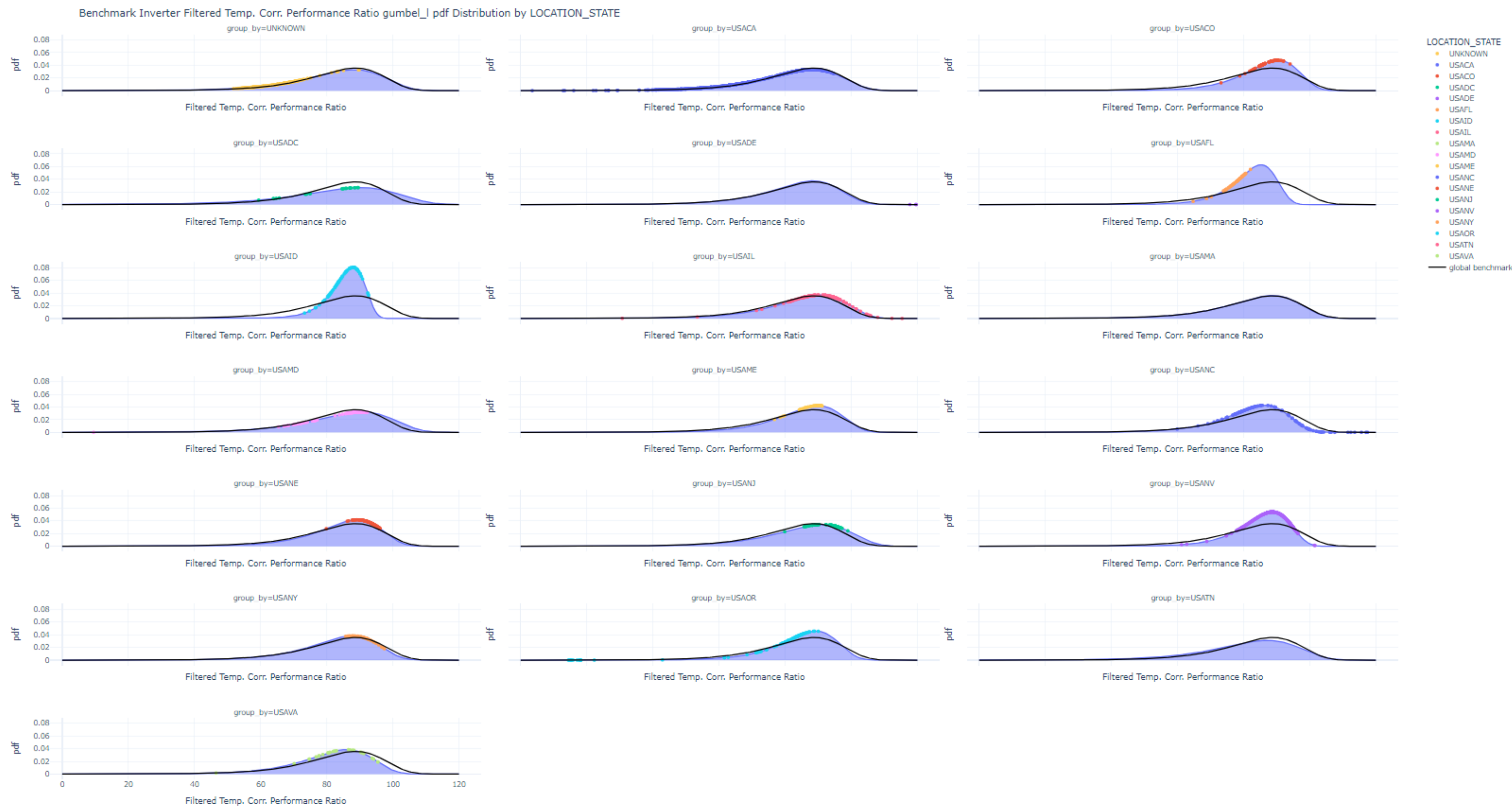
FTCPR Benchmarking: By State



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