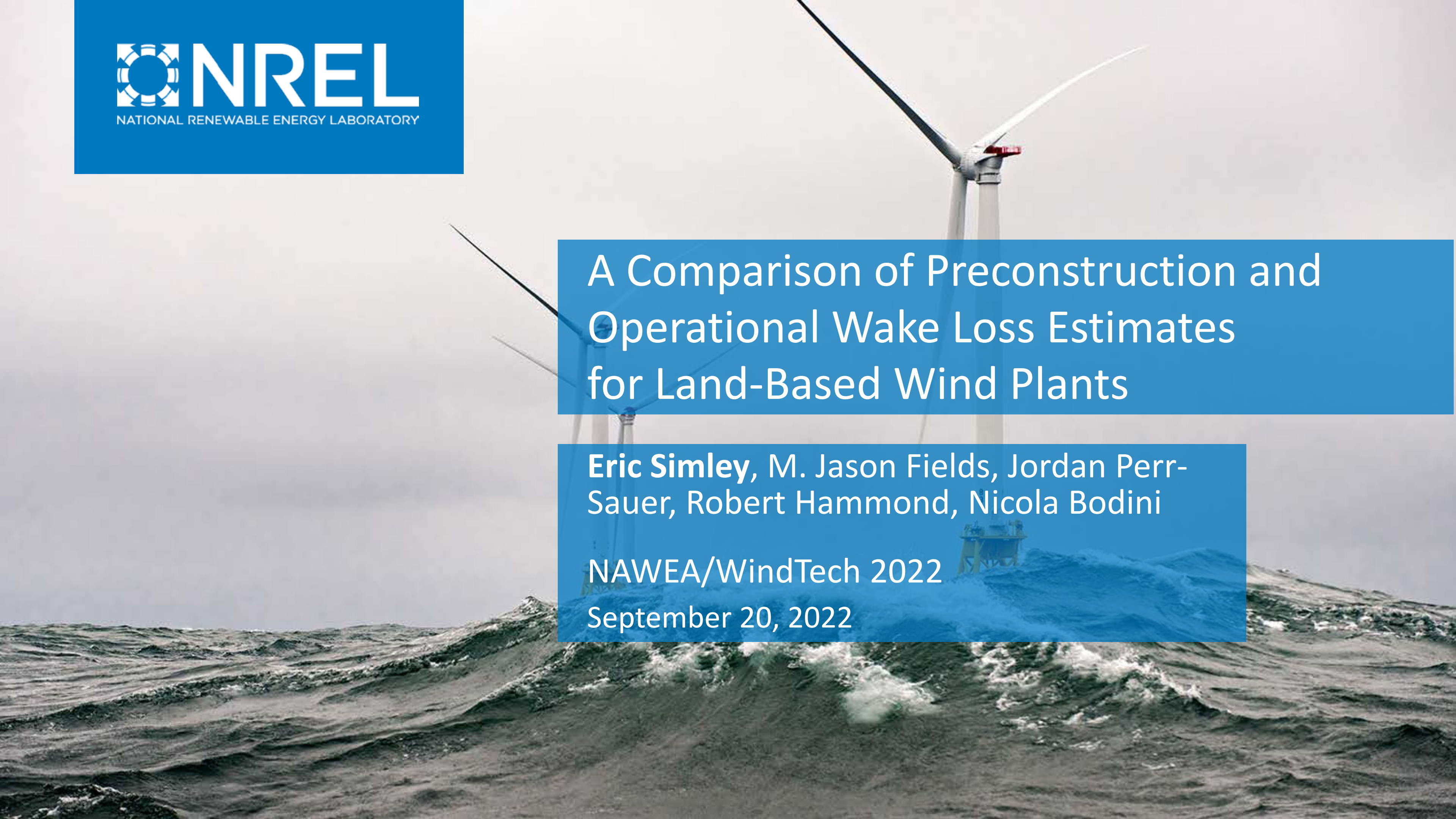


A Comparison of Preconstruction and Operational Wake Loss Estimates for Land-Based Wind Plants

Eric Simley, M. Jason Fields, Jordan Perr-Sauer, Robert Hammond, Nicola Bodini

NAWEA/WindTech 2022

September 20, 2022

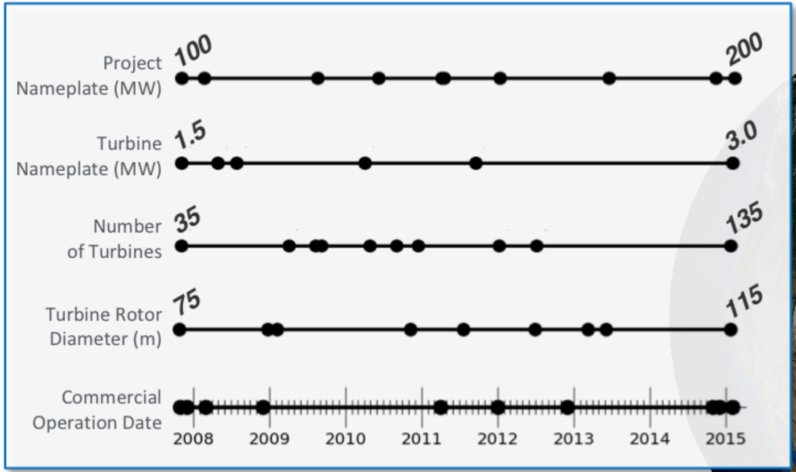
Outline

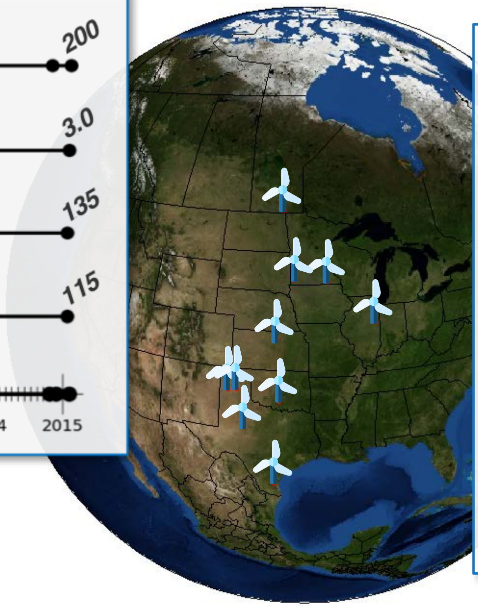
- Introduction to Wind Plant Performance Prediction (WP3) Benchmark project
- Overview of wind plants analyzed
- Operational wake loss estimation process
- Comparison between preconstruction and operational wake loss estimates.

Wind Plant Performance Prediction (WP3) Benchmark Project

Industrywide wind energy data sharing initiative to understand

- Bias between preconstruction energy yield assessment (EYA) estimates and operational energy production
- Sources of differences between EYA estimates and operational energy production.





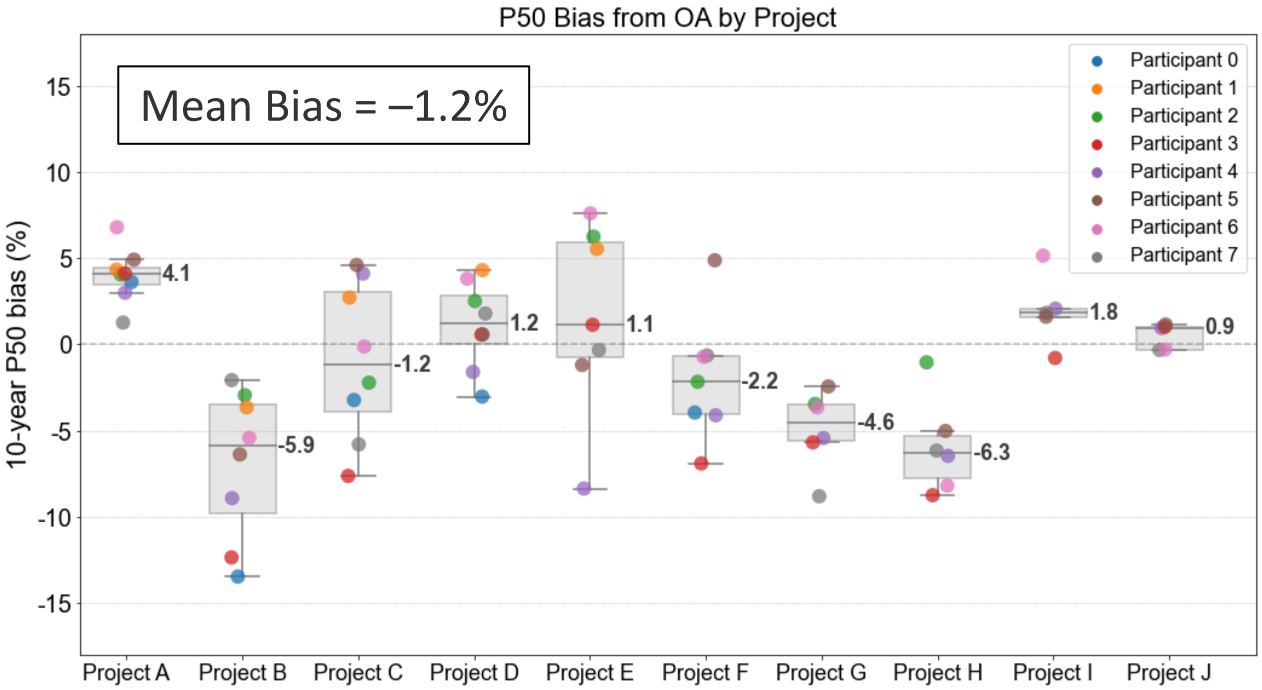
Project

Participant	A	B	C	D	E	F	G	H	I	J	TOTAL
0	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	5
1	✓	✓	✓	✓	✗	✓	✗	✗	✗	✗	5
2	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	8
3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
TOTAL	8	8	8	8	7	7	6	6	5	5	68

Fields et al. 2021. *Wind Plant Performance Prediction Benchmark Phase 1 Technical Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78715.

Wind Plant Performance Prediction (WP3) Benchmark Project

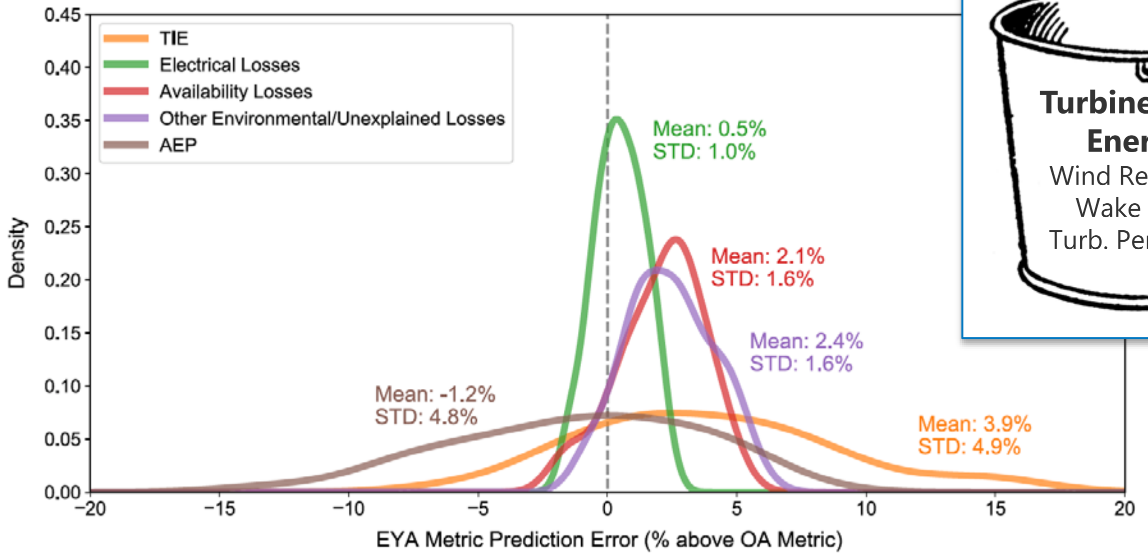
- Small overall bias between EYA estimates and operational energy production
- Large variability between projects and consultants.

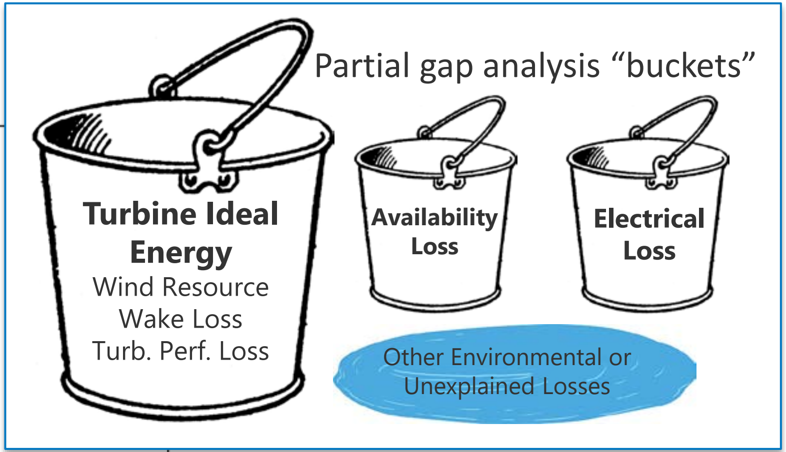


Fields et al. 2021. *Wind Plant Performance Prediction Benchmark Phase 1 Technical Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78715.

Wind Plant Performance Prediction (WP3) Benchmark Project

- “Gap analysis” to determine sources of differences between EYA estimates and operational energy production.

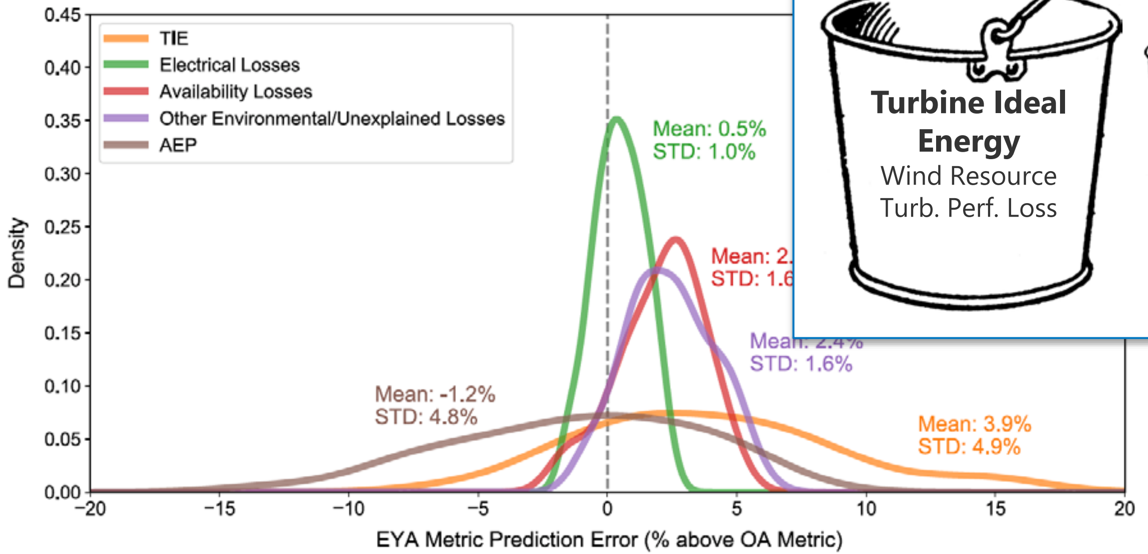


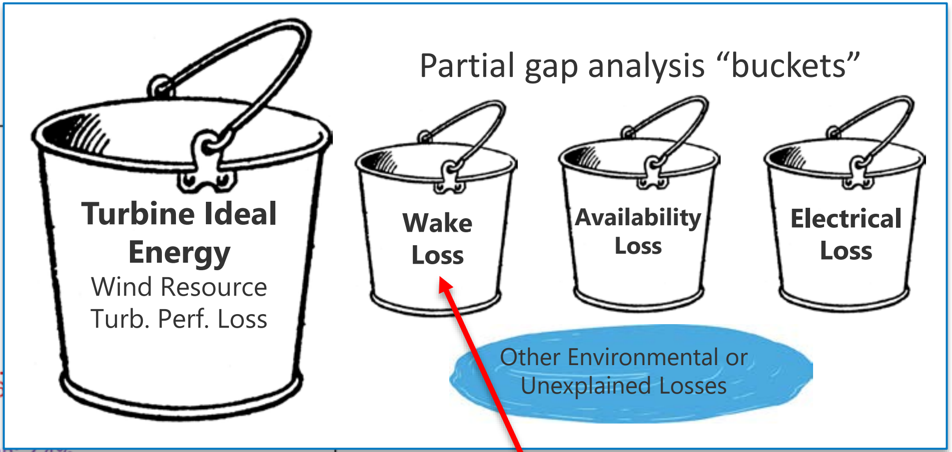


Todd et al. 2022. “An Independent Analysis of Bias Sources and Variability in Wind Plant Pre-Construction Energy Yield Estimation Methods.” *Wind Energy* 2022: 1–16. https://doi.org/10.1002/we.2768.

Wind Plant Performance Prediction (WP3) Benchmark Project

- "Gap analysis" to determine sources of differences between EYA estimates and operational energy production.





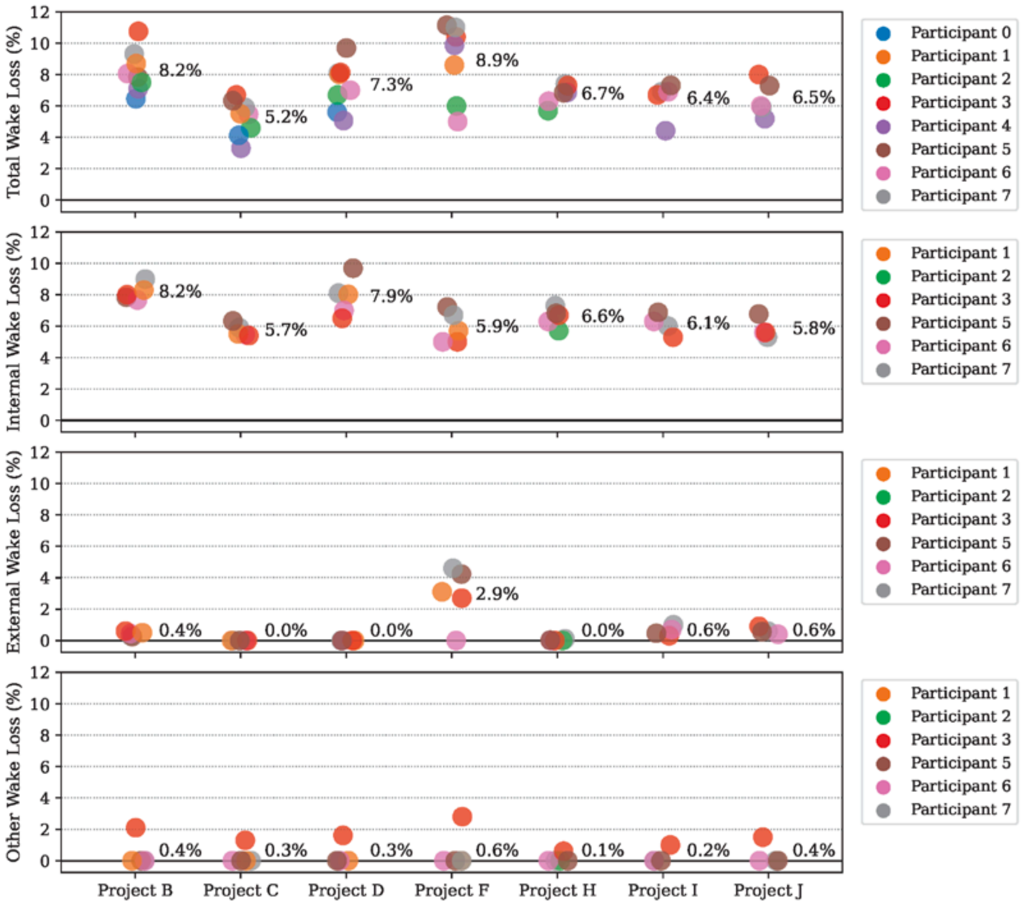
Objective of this research

Wake losses are one of the largest loss categories in the EYA process.

Todd et al. 2022. "An Independent Analysis of Bias Sources and Variability in Wind Plant Pre-Construction Energy Yield Estimation Methods." *Wind Energy* 2022: 1–16. https://doi.org/10.1002/we.2768.

EYA Wake Loss Estimates

- 7 projects chosen for wake loss analysis
- Consultants provide wake loss estimates as part of EYA process
- EYA wake loss categories
    - Internal
    - External
    - Future
    - Other.



Overview of Wind Plants

- Operational wake loss estimation process assumes simple terrain and no external wake effects from neighboring wind plants.

Wind Plant	EYA Internal wake loss	EYA External wake loss	Elevation Std. Dev. (m)	Ruggedness Index (RIX)*	Number of years of data
B	8.2%	0.4%	4.8	0.0	1.5
C	5.7%	0.0%	2.4	0.0	1.6
D	7.9%	0.0%	4.4	0.0	2.3
F	5.9%	2.9%	1.0	0.002	0.7
H	6.6%	0.0%	4.6	0.003	2.6
I	6.1%	0.6%	22.6	0.035	0.9
J	5.8%	0.6%	13.7	0.002	1.3

*Mortensen et al. 2008. "Field Validation of the RIX Performance Indicator for Flow in Complex Terrain." Proc. *European Wind Energy Conference and Exhibition.* Brussels, Belgium. 2008.

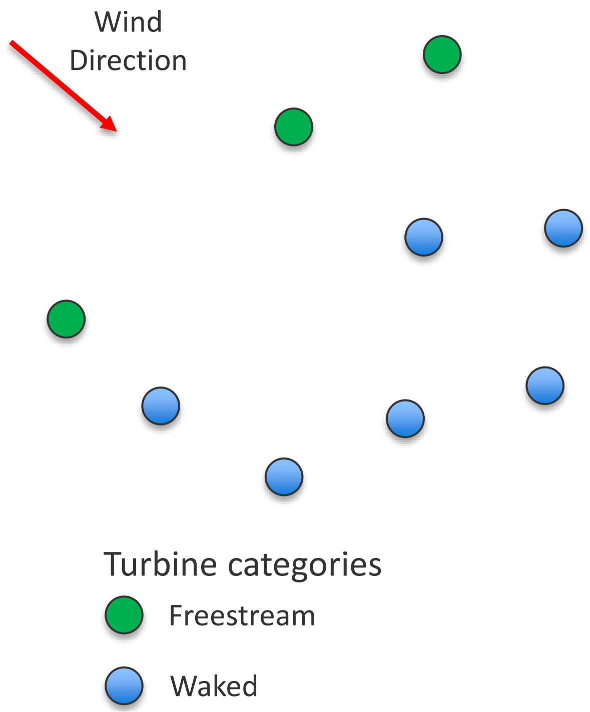
Basic Wake Loss Estimation Process

- Wind plant wake losses estimated using 10-minute SCADA data

$$\text{Wake Losses} = 1 - \frac{\text{Actual Energy}}{\text{Potential Energy}}$$

$$= 1 - \frac{\sum_{i=1}^{N_S} \sum_{j=1}^{N_T} P_{i,j}}{\sum_{i=1}^{N_S} N_T \bar{P}_{i,\text{freestream}}}$$

- N_S : Number of 10-minute samples in data set
- N_T: Number of turbines in wind plant
- $P_{i,j}$: Power at time *i* for turbine *j*
- $\bar{P}_{i,\text{freestream}}$: Average power of freestream turbines at time *i*



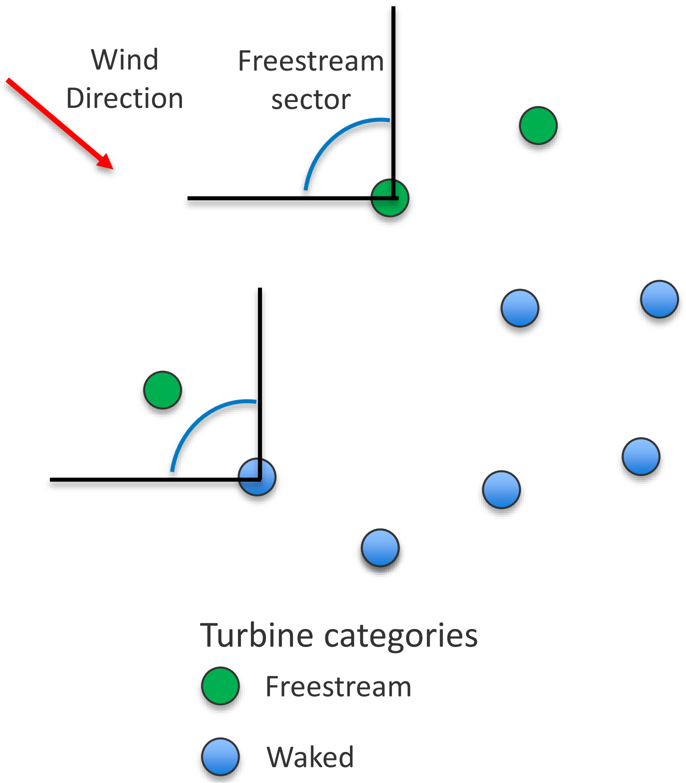
Barthelmie and Jensen. 2010. “Evaluation of Wind Farm Efficiency and Wind Turbine Wakes at the Nysted Offshore Wind Farm,” *Wind Energy* 13(6): 573–586. https://doi.org/10.1002/we.408.

Nygaard. 2015. “Systematic Quantification of Wake Model Uncertainty.” In *Proc. EWEA Offshore*.

El-Asha et al. 2017. “Quantification of Power Losses due to Wind Turbine Wake Interactions Through SCADA, Meteorological and Wind LiDAR Data.” *Wind Energy.* 20(11): 1823–1839. https://doi.org/10.1002/we.2123.

Determining Freestream Turbines

- A turbine is treated as freestream if there are no other upstream turbines within the “freestream sector.”
- Wind direction is computed as either:
  - The mean wind direction measured by all reliable turbines in the wind plant
  - The wind direction measured by sensors on a met tower.
- Wind direction signals calibrated to true north by comparing directions of observed and expected wake losses.



Wake Loss Estimation Process: Correcting for Derated Turbines

- Wind plant wake losses estimated using 10-minute SCADA data

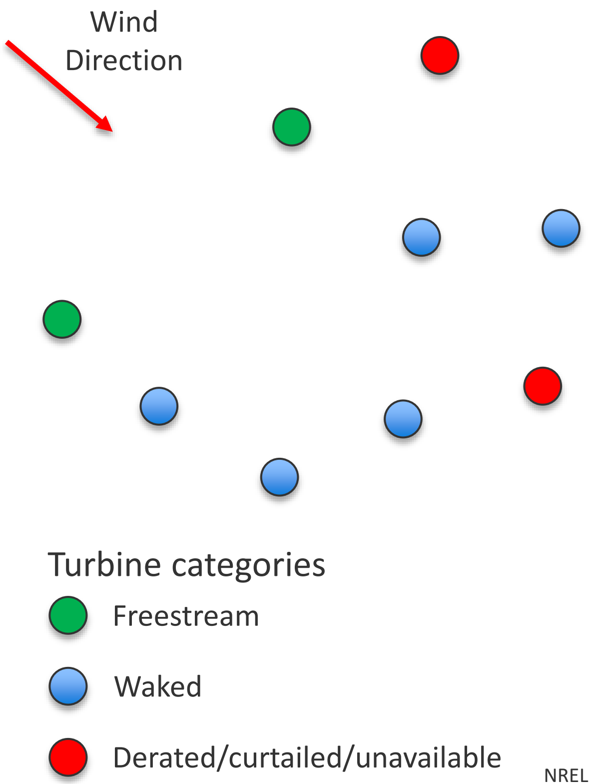
$$\text{Wake Losses} = 1 - \frac{\text{Actual Energy}}{\text{Potential Energy}}$$

$$= 1 - \frac{\sum_{i=1}^{N_S} \sum_{j=1}^{N_T} P_{i,j}}{\sum_{i=1}^{N_S} \left(\underbrace{\sum_{j \in \{Derate\}} P_{i,j}} + \underbrace{(N_T - N_D)\bar{P}_{i,\text{freestream}}} \right)}$$

Sum of derated/curtailed/unavailable turbine power

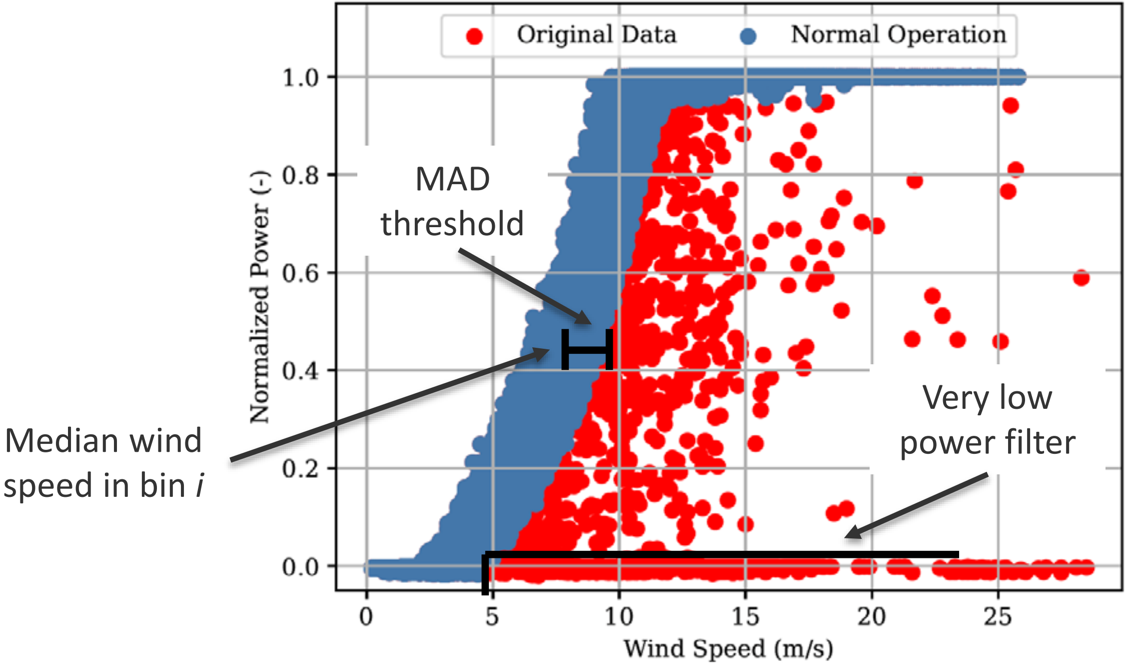
Mean power of freestream turbines in normal operation

- N_S : Number of 10-minute samples in data set
- N_T : Number of turbines in wind farm
- N_D : Number of derated/curtailed/unavailable turbines
- $P_{i,j}$: Power at time *i* for turbine *j*
- $\bar{P}_{i,\text{freestream}}$: Average power of freestream turbines at time *i*



Wake Loss Estimation Process: Identifying Derated Turbines

- Derated/curtailed/unavailable turbines are flagged for each 10-minute sample
- Power curve outlier detection based on median absolute deviation (MAD) threshold from median wind speed in different power bins.



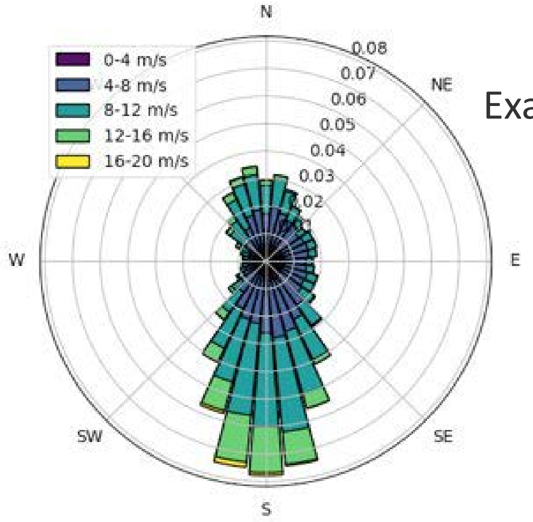
Wake Loss Estimation Process: Long-Term Correction

- Long-term correction based on historical wind data from ERA5 and MERRA2 reanalysis products
- Potential and actual plant power binned by hourly wind direction and corrected freestream wind speed from SCADA data
- Long-term potential and actual energy determined using long-term bin frequencies from 10 to 20 years of reanalysis data.

Long-term wake losses

$$= 1 - \frac{\sum_{i=1}^{N_{Bin}} Freq_i \times \bar{P}_{\text{Actual},i}}{\sum_{i=1}^{N_{Bin}} Freq_i \times \bar{P}_{\text{Potential},i}}$$

Wind Direction Bin	Corrected Wind Speed Bin	Potential Plant Power	Actual Plant Power	Reanalysis Long-Term Frequency
0°	8 m/s	109	102	0.02
5°	9 m/s	130	120	0.015
…	…	…	…	…



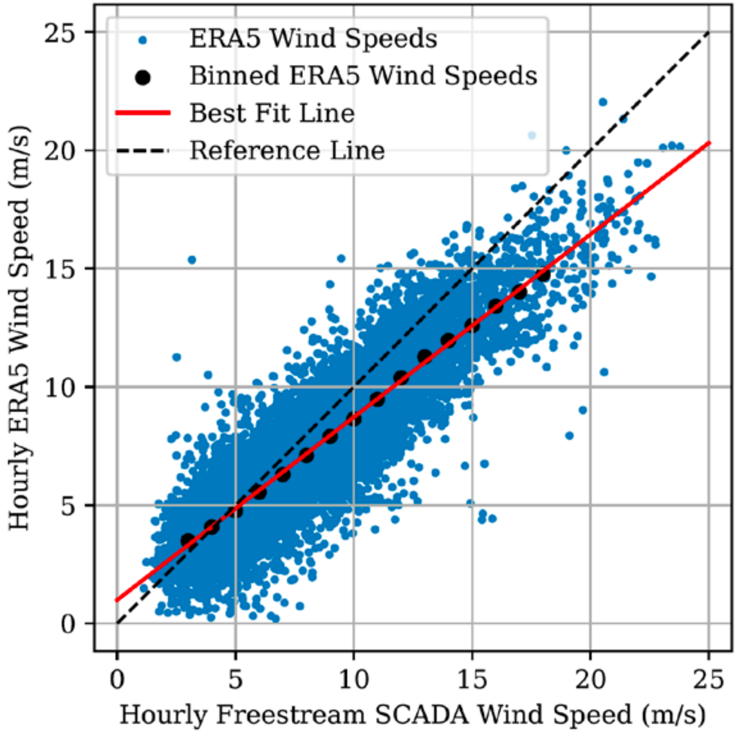
Example wind rose for U.S. Great Plains

Wake Loss Estimation Process: Long-Term Correction

- Long-term correction based on historical wind data from ERA5 and MERRA2 reanalysis products
- Potential and actual plant power binned by hourly wind direction and corrected freestream wind speed from SCADA data
- Long-term potential and actual energy determined using long-term bin frequencies from 10 to 20 years of reanalysis data.

Long-term wake losses

$$= 1 - \frac{\sum_{i=1}^{N_{Bin}} Freq_i \times \bar{P}_{\text{Actual},i}}{\sum_{i=1}^{N_{Bin}} Freq_i \times \bar{P}_{\text{Potential},i}}$$



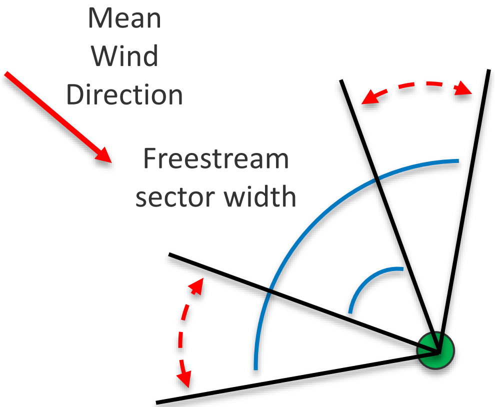
- Linear regression model used to identify and correct biases between SCADA and reanalysis wind speeds.

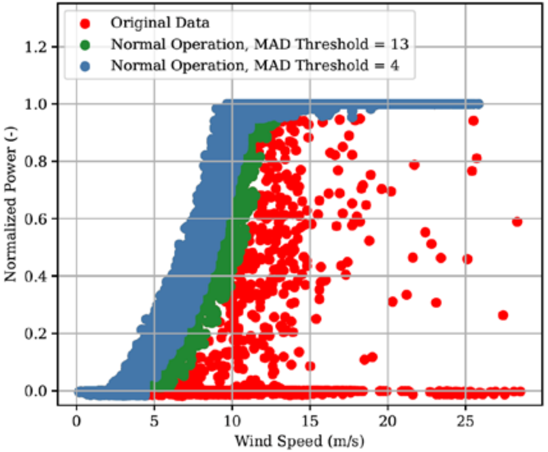
Wake Loss Estimation Process: Uncertainty Quantification

Monte Carlo sampling used to quantify uncertainty in wake loss estimates

- Set of 10-minute samples randomly resampled with replacement (bootstrapping)
- Set of freestream turbines randomly resampled with replacement
- Freestream sector width sampled between 50° and 110°
- Power curve filter parameters used to identify derated turbines
- Reanalysis product to use for long-term correction (ERA5 or MERRA2)
- Number of years to use for long-term correction (10–20 years).

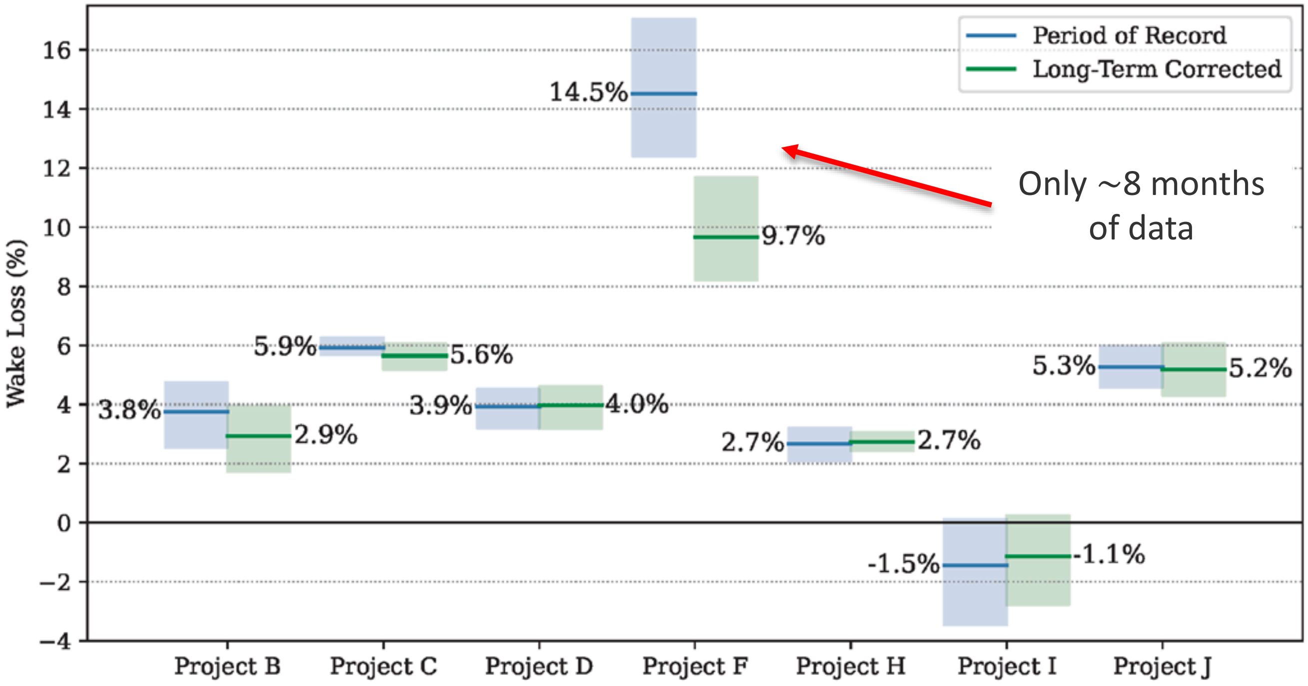
Used to determine 95% confidence interval





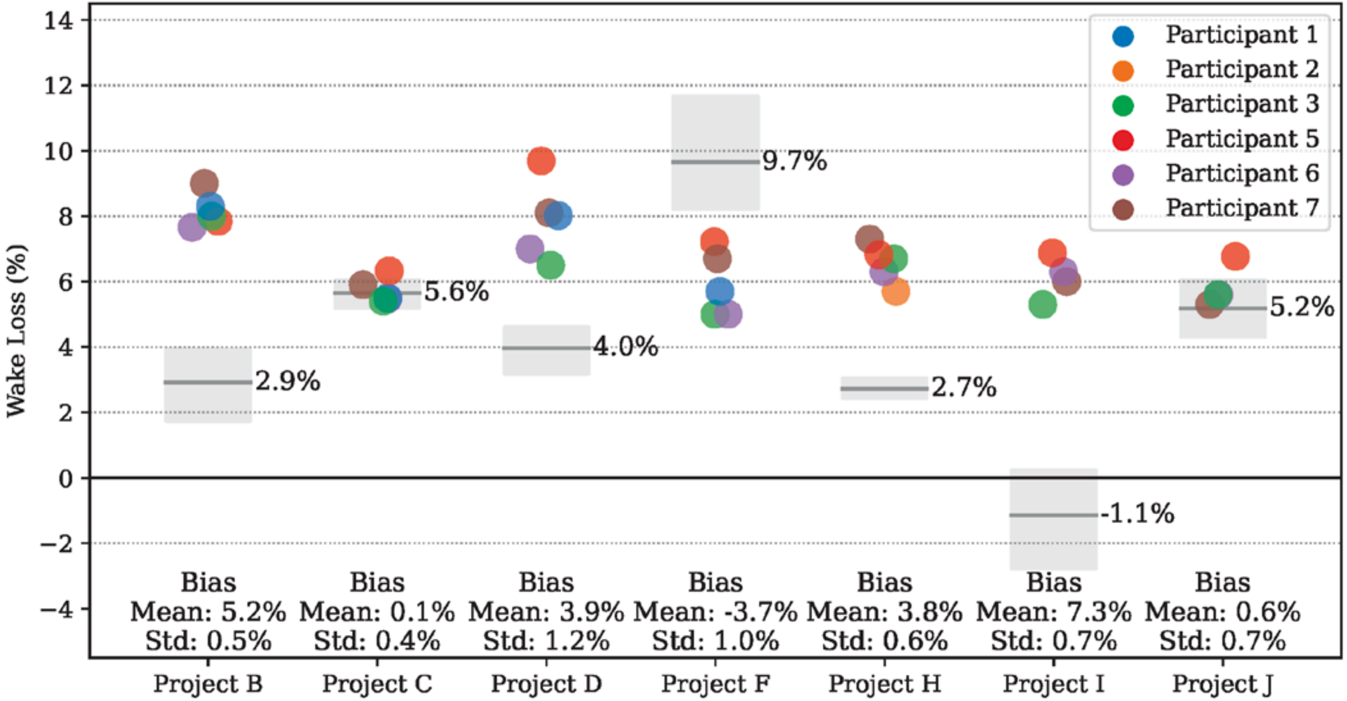
Wake Loss Estimation Results: Long-Term Correction

Long-term correction typically changes period of record (POR) wake loss estimates by less than 1 percentage point.



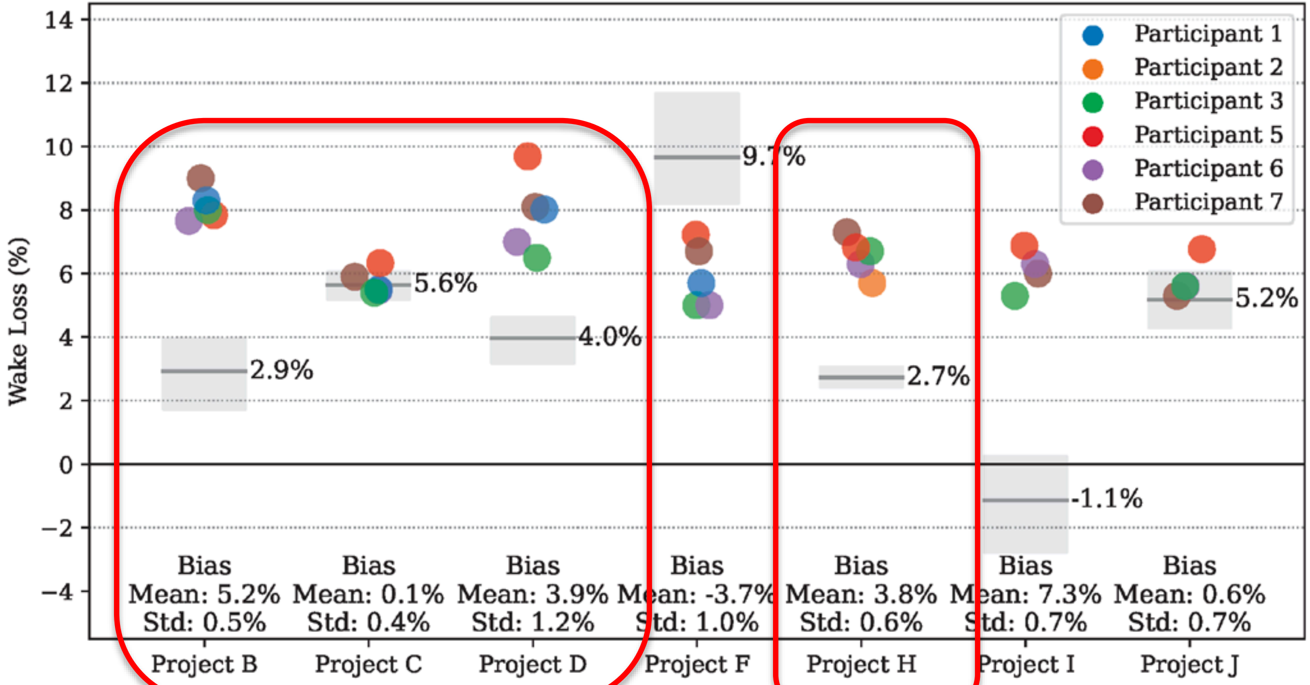
Comparison of EYA and Operational Wake Loss Estimates

EYA estimates typically greater than operational wake losses.



Comparison of EYA and Operational Wake Loss Estimates

Simple terrain and low external wake effects.



Wind Plant	EYA External wake loss	Elevation Std. Dev. (m)	Rugged-ness Index (RIX)
B	0.4%	4.8	0.0
C	0.0%	2.4	0.0
D	0.0%	4.4	0.0
F	2.9%	1.0	0.002
H	0.0%	4.6	0.003
I	0.6%	22.6	0.035
J	0.6%	13.7	0.002

Comparison of EYA and Operational Wake Loss Estimates

Complex terrain and significant external wake effects.

Operational wake loss estimates less reliable.

Wind Plant	EYA External wake loss	Elevation Std. Dev. (m)	Rugged-ness Index (RIX)
B	0.4%	4.8	0.0
C	0.0%	2.4	0.0
D	0.0%	4.4	0.0
F	2.9%	1.0	0.002
H	0.0%	4.6	0.003
I	0.6%	22.6	0.035
J	0.6%	13.7	0.002

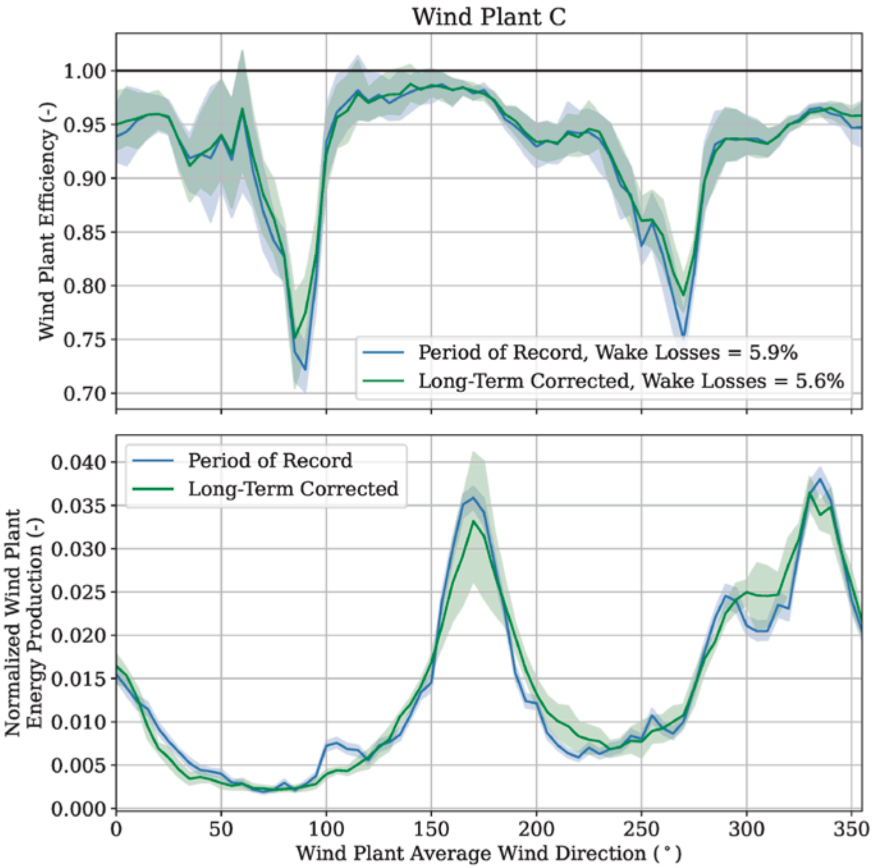
Operational Wake Loss Estimates vs. Wind Direction: Project C

- Simple terrain
- No significant external wake effects

- Low EYA estimation bias.

EYA External wake loss	Elevation Std. Dev. (m)	Ruggedness Index (RIX)
0.0%	2.4	0.0

Operational wake loss POR	Operational wake loss Long-Term Corrected	EYA Internal wake loss	EYA Estimation Bias
5.9%	5.6%	5.7%	0.1%



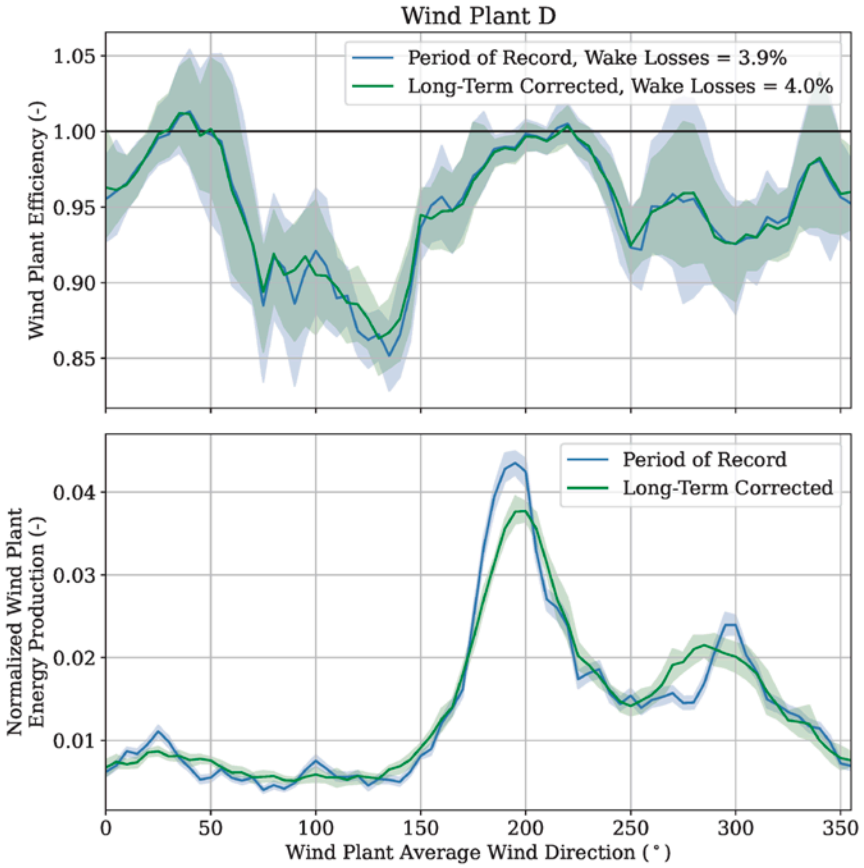
Operational Wake Loss Estimates vs. Wind Direction: Project D

- Simple terrain
- No significant external wake effects

- Large EYA estimation bias.

EYA External wake loss	Elevation Std. Dev. (m)	Ruggedness Index (RIX)
0.0%	4.4	0.0

Operational wake loss POR	Operational wake loss Long-Term Corrected	EYA Internal wake loss	EYA Estimation Bias
3.9%	4.0%	7.9%	4.0%



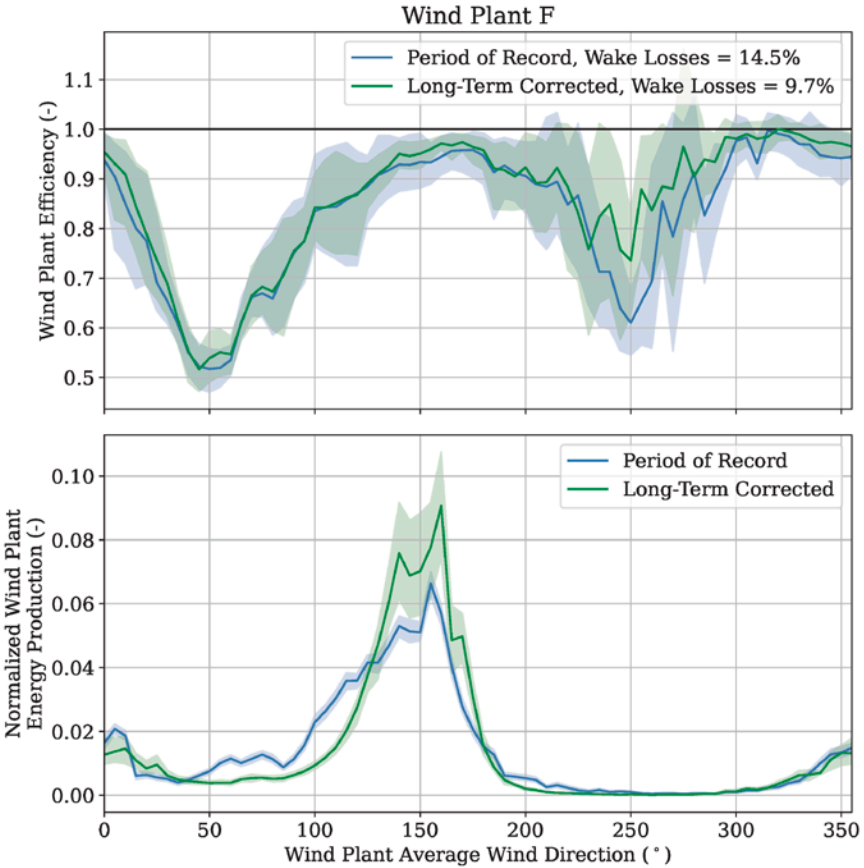
Operational Wake Loss Estimates vs. Wind Direction: Project F

- Simple terrain
- Large external wake effects

- Large negative EYA estimation bias.

EYA External wake loss	Elevation Std. Dev. (m)	Ruggedness Index (RIX)
2.9%	1.0	0.002

Operational wake loss POR	Operational wake loss Long-Term Corrected	EYA Internal wake loss	EYA Estimation Bias
14.5%	9.7%	5.9%	-3.7%



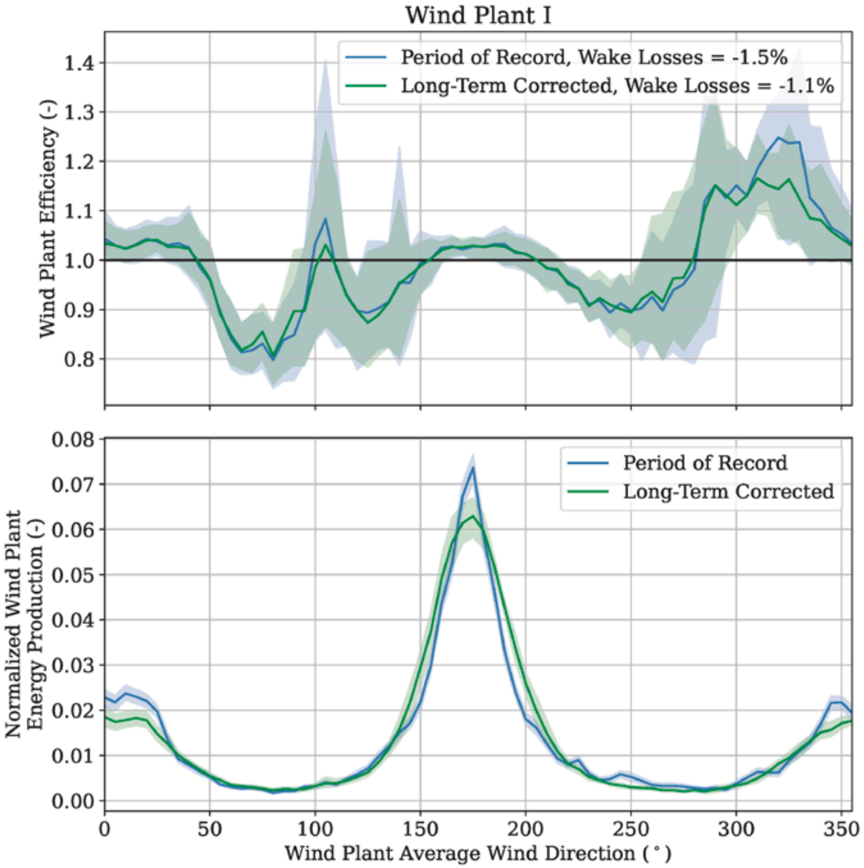
Operational Wake Loss Estimates vs. Wind Direction: Project I

- Complex terrain
- Moderate external wake effects

- <u>Negative</u> wake loss estimate
- Large EYA estimation bias.

EYA External wake loss	Elevation Std. Dev. (m)	Ruggedness Index (RIX)
0.6%	22.6	0.035

Operational wake loss POR	Operational wake loss Long-Term Corrected	EYA Internal wake loss	EYA Estimation Bias
-1.5%	-1.1%	6.1%	7.1%



Conclusions

- Augmented a commonly used wake loss estimation method based on SCADA data
  - Long-term correction
  - Account for derated/curtailed/unavailable turbines
  - Monte Carlo parameter sampling for uncertainty quantification
- Method assumes simple terrain and no external wake effects
- Preconstruction wake loss estimates generally greater than (or equal to) operational wake losses for wind plants investigated
- Future research should address operational wake loss estimation for projects with nonuniform wind resource, external wake effects, and multiple turbine types.
- Operational wake loss estimation method to be released in OpenOA V3 this year: https://github.com/NREL/OpenOA/
- Overview of WP3 Benchmark project:

Fields et al. 2021. *Wind Plant Performance Prediction Benchmark Phase 1 Technical Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78715. https://www.nrel.gov/docs/fy22osti/78715.pdf.

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