Quantifying the Impact of the Disagreement in Estimates of Losses in Energy Yield Assessments of Wind Power Plants

Jordan Perr-Sauer, Jason Fields, Eric Simley, Joseph Lee, Rob Hammond

National Renewable Energy Laboratory

September 20-23rd, 2022

Presented at: NAWEA Wind Technology Conference, University of Delaware

Background

What is an Energy Yield Assessment?

Pre-Construction (EYA)

Preconstruction Data

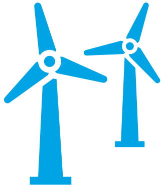
- Reanalysis
- Land Survey
- Turbine Information

Consultant (Participant)

- AEP Annual Energy Production (P50, P90)
- Wind Resource
- Loss Categories

EYA

Post-Construction (OA)



SCADA

Operational Data (Project)

- Wind speed
- Meter
- Turbine yaw

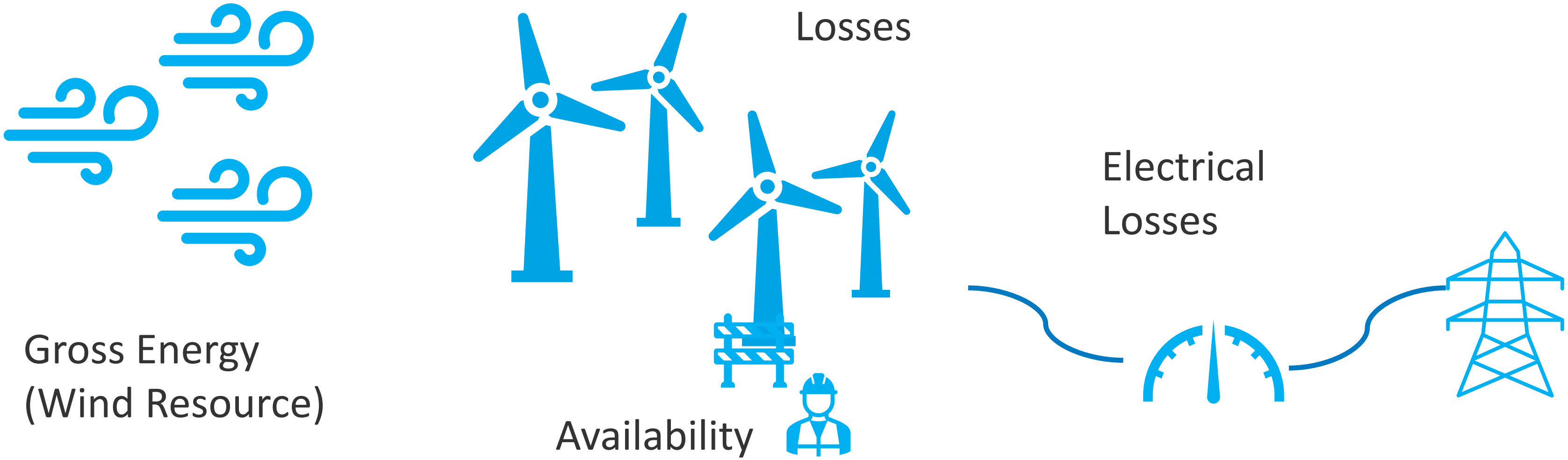
OpenOA

- AEP
- TIE
- Loss Categories

OA

Plant Loss Categories in EYAs

Using IEC 61400-15



Gross Energy (Wind Resource)

Wake Losses

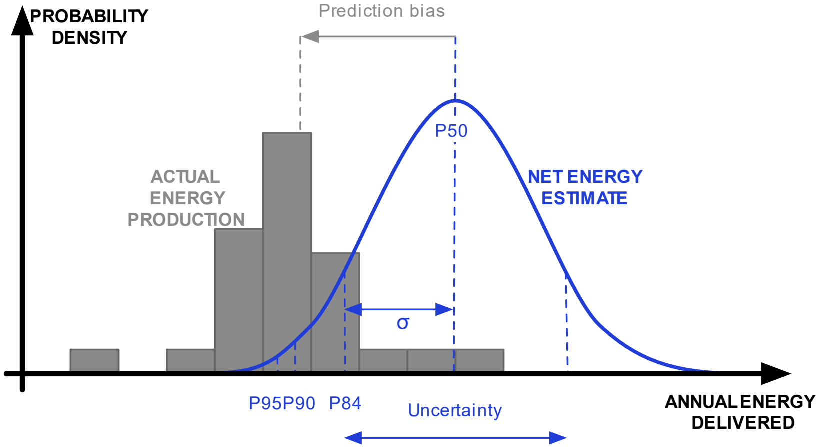
Turbine Losses

Availability Losses

Electrical Losses

Meter

Potential bias in EYA P50



Clifton, 2016

Pre-construction:

"How much energy will my wind plant produce if I build it?"

Annual Energy Production (AEP) P50:
50th percentile estimate of how much electricity will be produced in a year.

The actual energy produced by the plant may not line up with this estimate. How accurate are these estimates? Is there an industry-wide bias?

PRUF Benchmarking Initiative

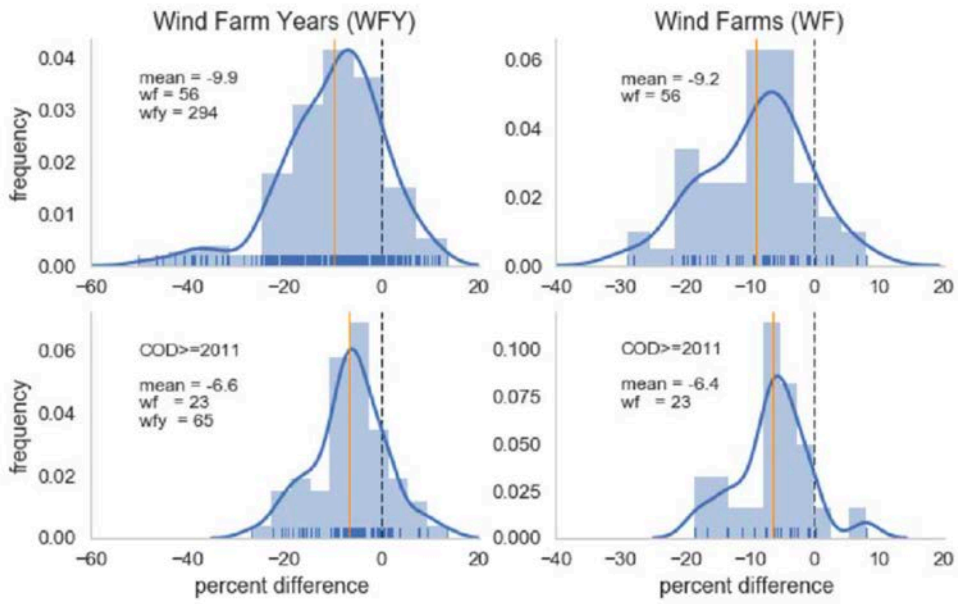
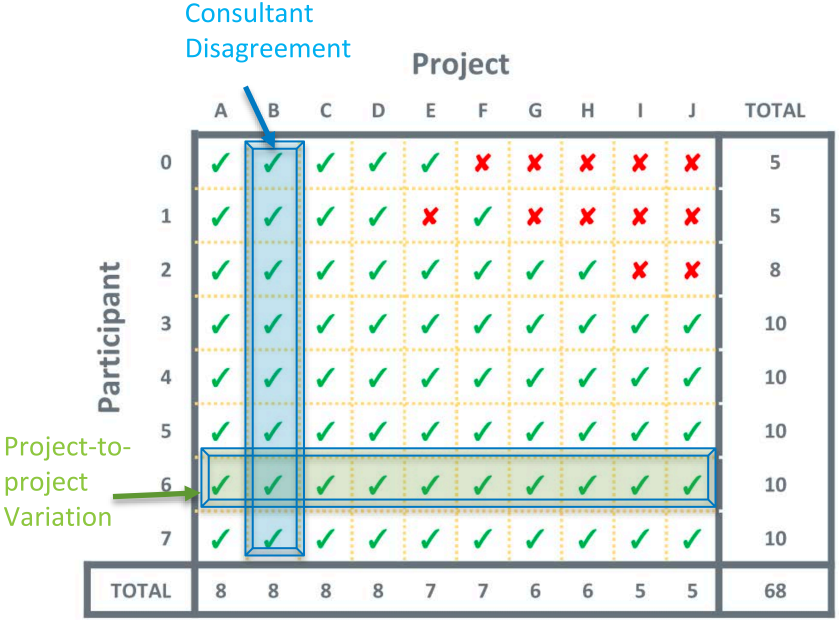


Figure 6. Raw results: The mean bias for WFYs and WFs is −9.9 and −9.2 respectively. The bias drops to −6.6 and −6.4 for projects that started after 2011.

Lunacek et al. 2018

Lunacek et al analyze 56 wind power plants and find a bias of 6.4% for projects commissioned after 2011.

PRUF Benchmarking Dataset

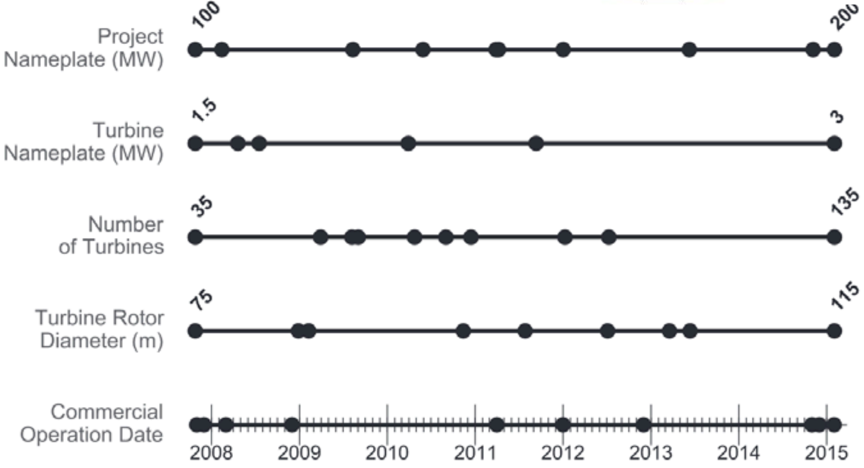


Consultant Disagreement

Project-to-project Variation

Project

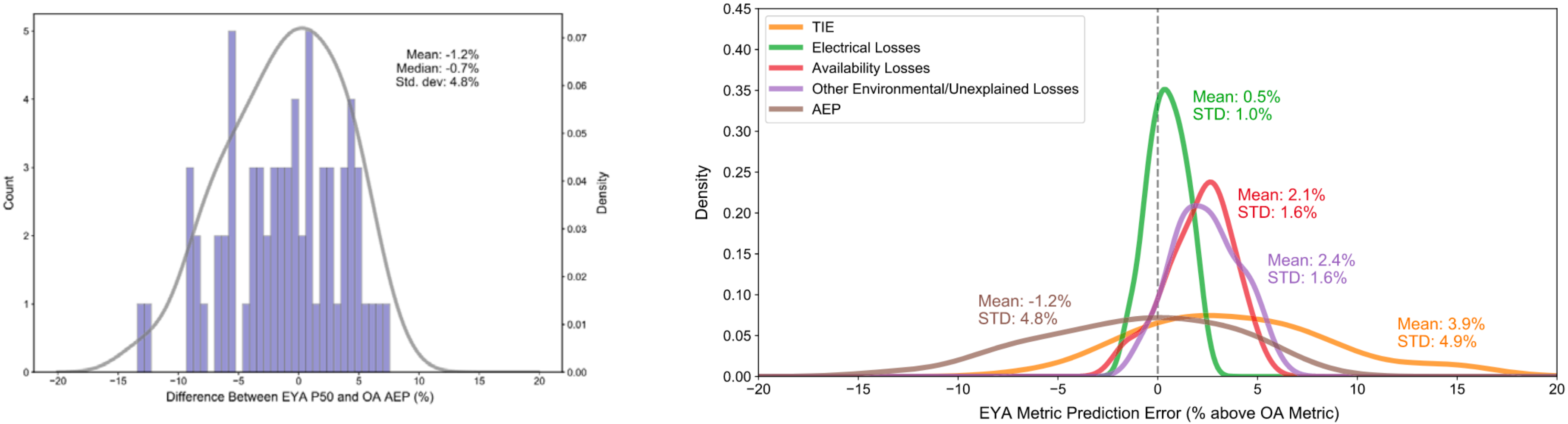
Participant	A	B	C	D	E	F	G	H	I	J	TOTAL
0	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	5
1	✓	✓	✓	✓	✗	✓	✗	✗	✗	✗	5
2	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	8
3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
TOTAL	8	8	8	8	7	7	6	6	5	5	68



Todd et al. 2022

P50 “Gap Analysis”

- Todd found no average bias (slight negative bias) in the PRUF dataset, but found a large spread in bias of loss estimates.



Todd et al. 2022

Unresolved Question

- **Question:** Which loss categories, if their estimation was improved, would have the greatest impact on improving AEP estimation?

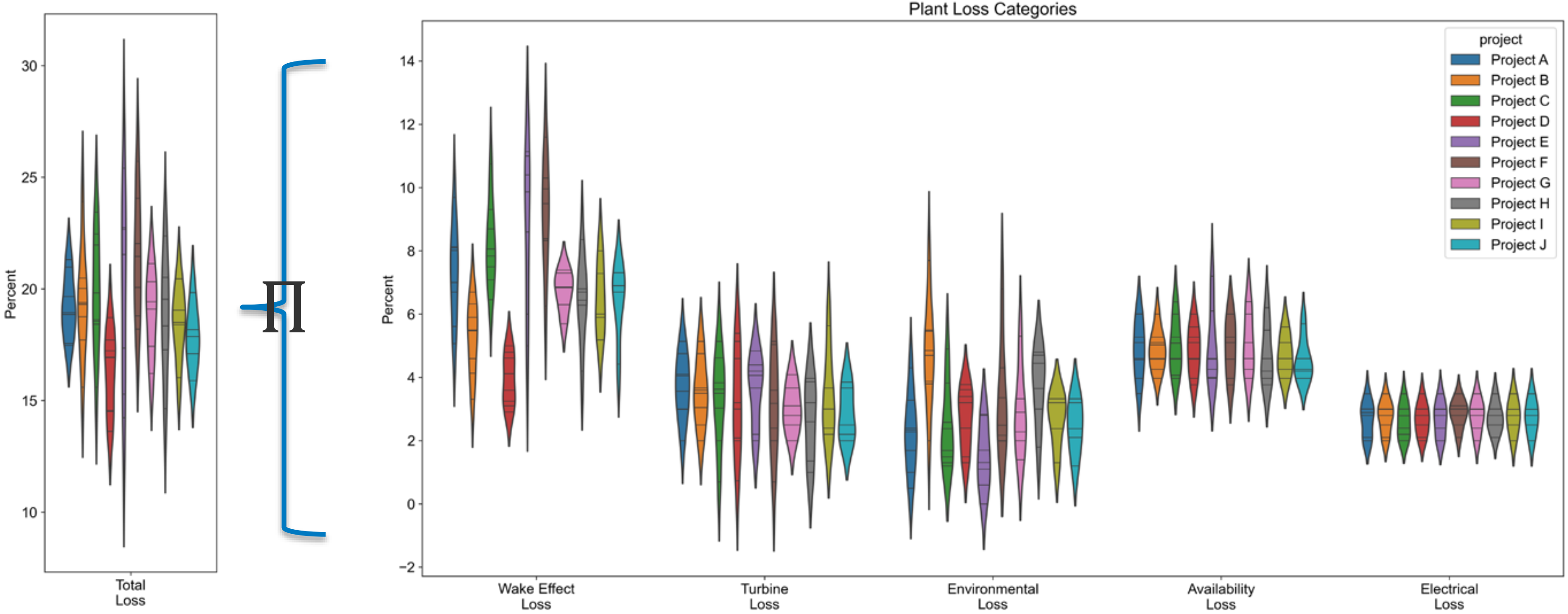
- **Approach:**
  - Focus on EYA variability only instead of EYA-OA Bias
  - Apply sensitivity analysis to quantify the impact.
    - Summary Statistics
    - OAT Sensitivity Analysis

The Data

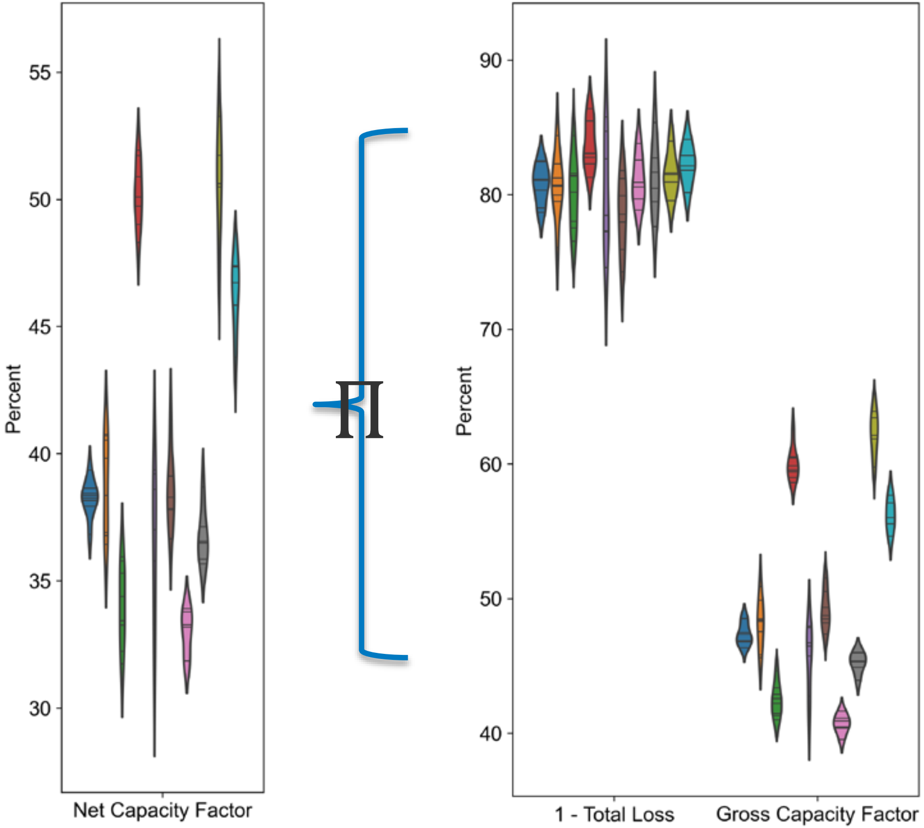
Plant Loss Categories

$$Total\ Loss = 1 - \prod \{1 - x \mid x \in Plant\ Losses\}$$

- Each violin is a wind power plant



Net Capacity Factor



$$Net\ Capacity\ Factor = \underbrace{Gross\ Capacity\ Factor} * \underbrace{(1 - Total\ Loss)}$$

These quantities are efficiencies, not losses.

Problem Overview

Net Capacity Factor is the quantity of interest (QOI)

- Normalized by nameplate
- It is in units of %

Loss Relation:

$$Total\ Loss = 1 - \prod \{1 - x \mid x \in Plant\ Losses\ \}$$

$$Net\ Capacity\ Factor = Gross\ Capacity\ Factor * (1 - Total\ Loss)$$

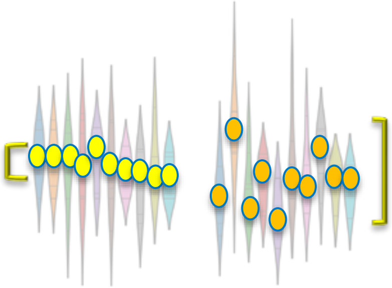
$$Net\ Energy = Nameplate * 8760 * Net\ Capacity\ Factor$$

Questions:

1. Which loss categories, if their estimation was improved, would have the greatest impact on improving AEP estimation?
2. Which loss categories contribute most to the…
    a) Project-to-project variability of the net capacity factor?
    b) Consultant disagreement of the net capacity factor?

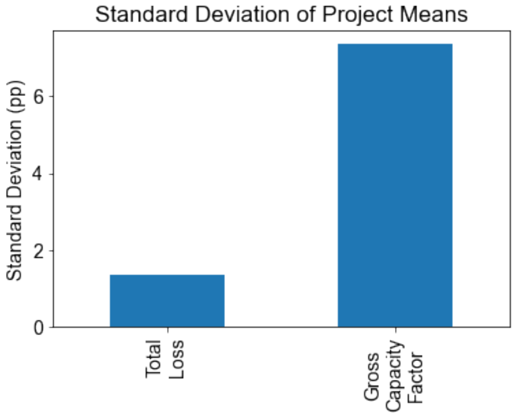
Project-to-project variation

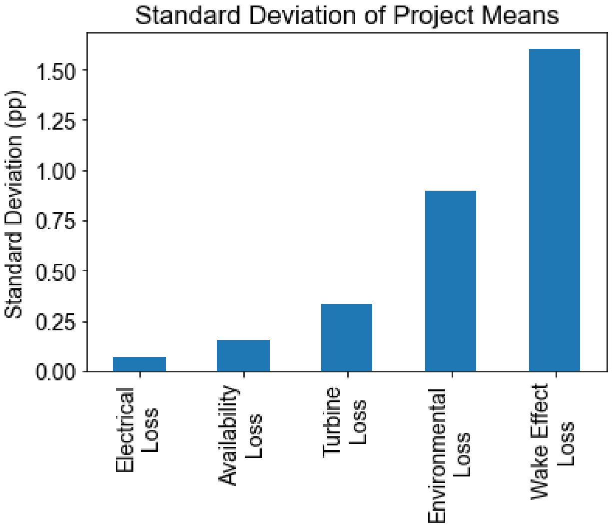
Project-to-Project Variation



Standard deviation of project means:

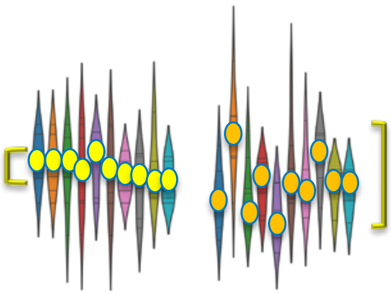
+ Basic statistics
+ Simple interpretation
+ Meaningful units
- Does not take consultant-to-consultant disagreement into account





Project-to-Project Variation

”probability that the population mean is the same for all projects”

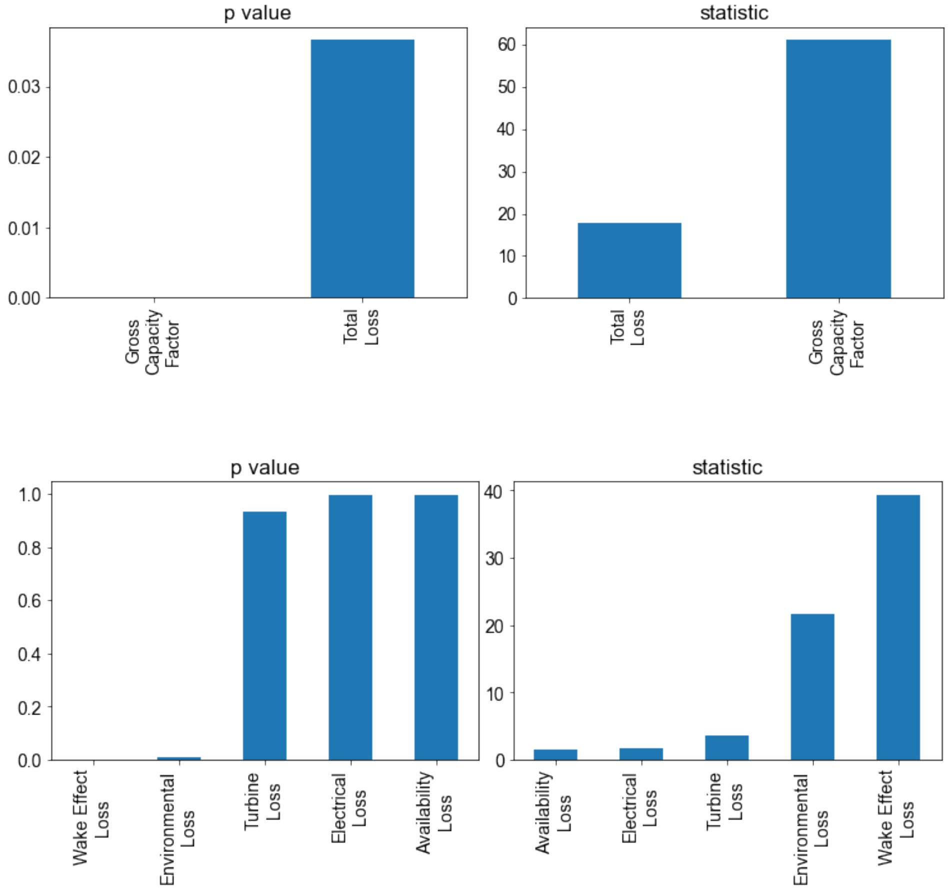


One-Way ANOVA Kruskal-Wallis:

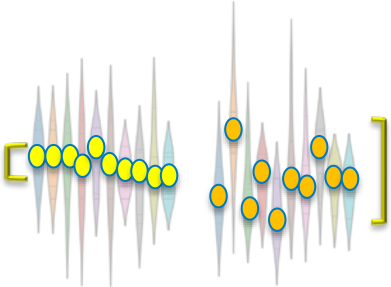
+ Takes consultant-to-consultant disagreement into account

+ Nonparametric, no violated assumptions (data is heteroscedastic, as we will see next)

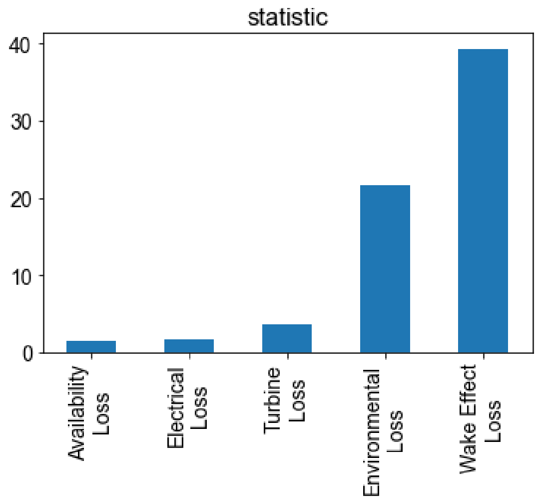
- H-statistic is hard to interpret

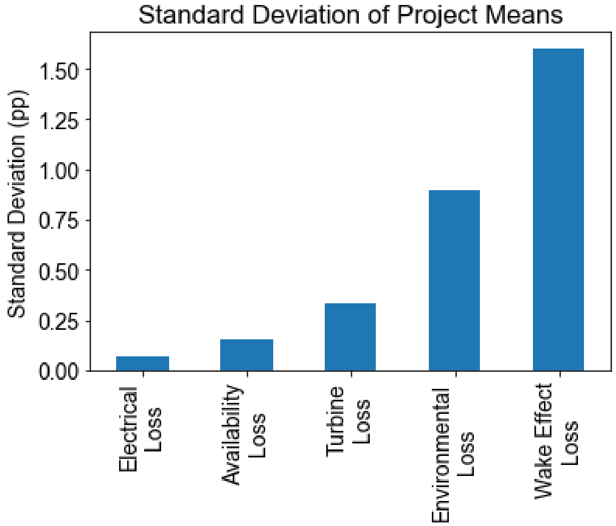


Project-to-Project Variation Summary



1. Which loss category is most important in determining the magnitude of net energy?

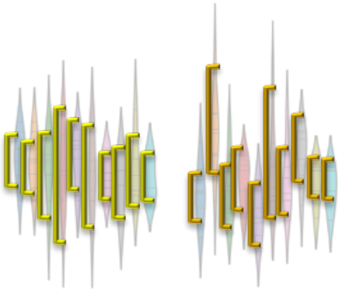


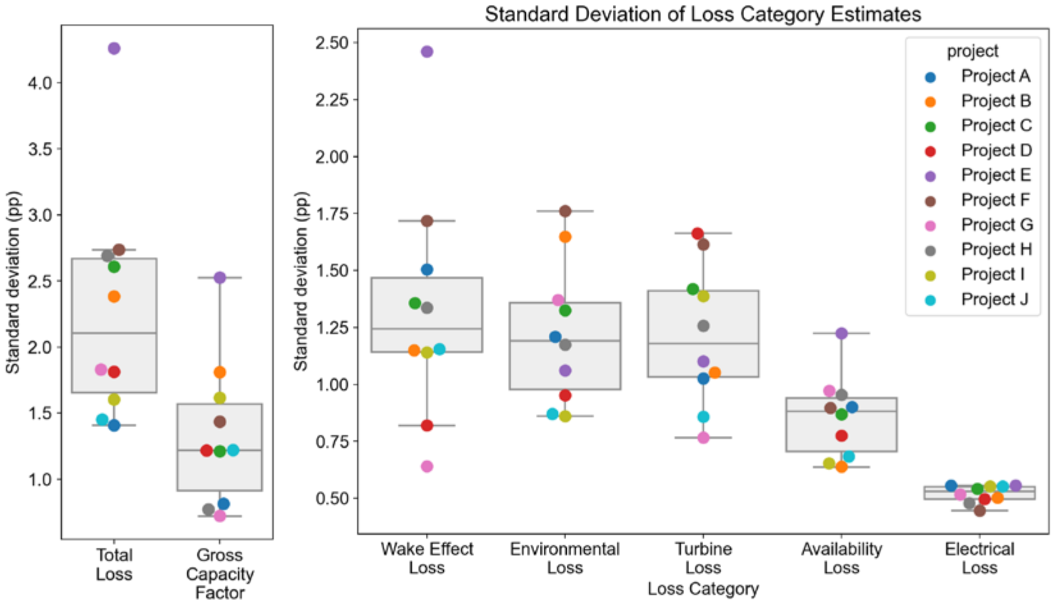


Less Variation → More Variation

Consultant disagreement

Consultant Disagreement





Standard deviation of each project-loss, keeping the projects separated.

+ Basic statistic, easy to interpret
+ Provides us with a sense of how difficult the metric is to predict.
- Does not take into account how the losses will ultimately impact net energy.

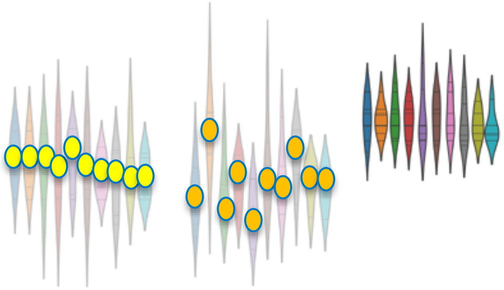
Key Findings

- On average, the disagreement in total loss is larger than the disagreement in gross.
- Of the plant loss categories, Wake, Environmental, and Turbine have the most disagreement.

Sensitivity Analysis (Add One In)

How can we combine these perspectives to understand the source of uncertainty in the net energy estimate?

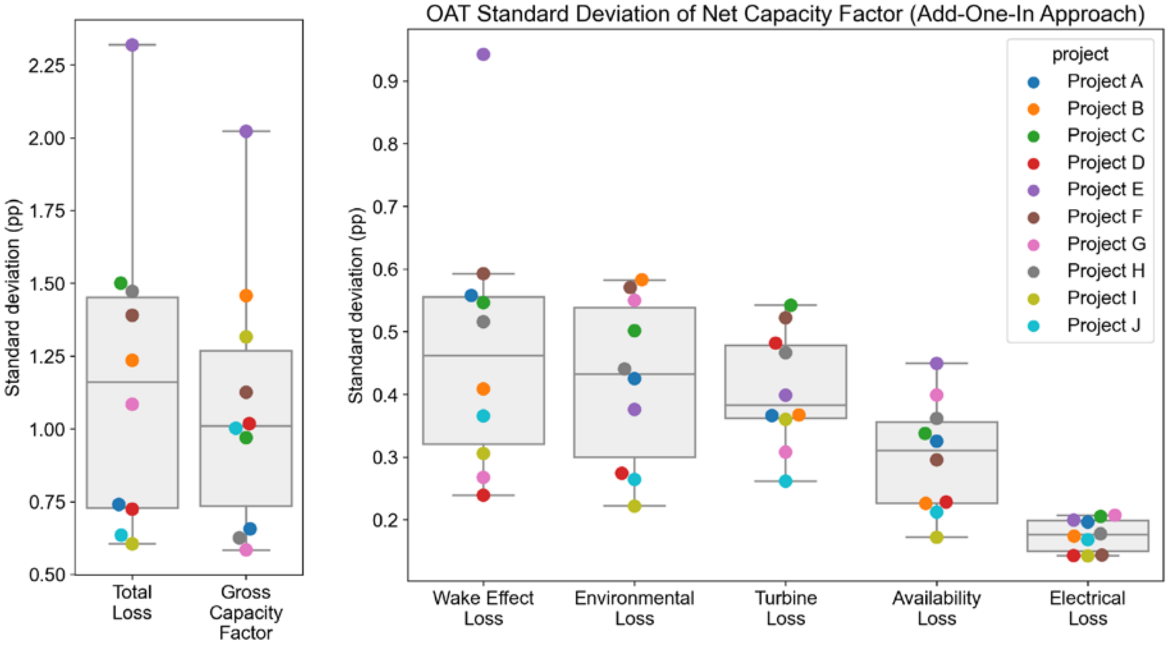
(If we assume normality and no intra-category correlation, this can be done analytically, with uncertainty propagation, as standard deviation scales with the magnitude.)



$$Net\ Capacity\ Factor = Gross\ Capacity\ Factor\ * \prod Losses$$

"The standard deviation of the total loss if every other loss was known perfectly."

Sensitivity Analysis (Add One In)



Key Findings

Disagreement in gross energy has similar impact as the total loss to the disagreement in net energy.

Wake effect, turbine, and environmental losses are the categories with the largest impact on consultant disagreement.

More contribution ← Less Contribution

Summary

Summary

Project-to-project variation

1. Standard deviation of the means of project losses
2. ANOVA (Kruskal-Wallis)

Key Findings:
Gross capacity factor has greater project-to-project variation then total losses.

Wake, Turbine, and Environmental have the most project-to-project variation among the plant losses.

Consultant Disagreement

1. Standard deviation of project losses
2. OAT Sensitivity Analysis (standard deviation of net capacity factor)

Key Findings:
Gross capacity factor and total losses have similar consultant disagreement.

Disagreement in gross capacity factor has a greater impact on the net capacity factor disagreement due to its relative magnitude.

Of the plant loss categories reducing disagreement; Wake, Turbine, and Environmental losses would have the biggest impact on reducing the disagreement in net energy.

References

- Clifton, Andrew, Smith, Aaron, and Fields, Michael. *Wind Plant Preconstruction Energy Estimates. Current Practice and Opportunities*. United States: N. p., 2016. Web. doi:10.2172/1248798.
- M. Lunacek *et al.*, "Understanding Biases in Pre-Construction Estimates," vol. 1037, p. 62009, Jun. 2018, doi: 10.1088/1742-6596/1037/6/062009.
- J. Perr-sauer *et al.*, "OpenOA : An Open-Source Codebase For Operational Analysis of Wind Farms," vol. 6, pp. 6–8, 2021, doi: 10.21105/joss.02171.
- A. C. Todd *et al.*, "An independent analysis of bias sources and variability in wind plant pre-construction energy yield estimation methods," *Wind Energy*, p. we.2768, Jul. 2022, doi: 10.1002/we.2768.

Thank You

www.nrel.gov

NREL/PR-2C00-83809

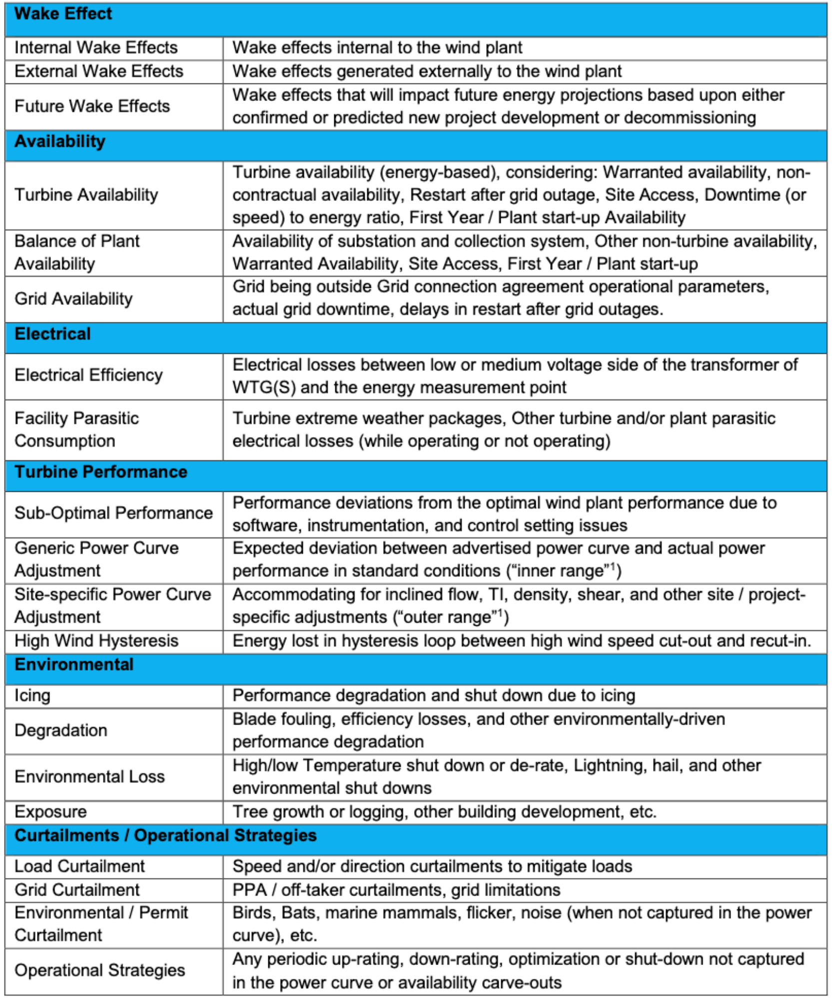
NREL

Transforming ENERGY

IEC 61400-15 Working Group Update 2

https://zenodo.org/record/3952717

Table 1: Loss Framework



Wake Effect	
Internal Wake Effects	Wake effects internal to the wind plant
External Wake Effects	Wake effects generated externally to the wind plant
Future Wake Effects	Wake effects that will impact future energy projections based upon either confirmed or predicted new project development or decommissioning
Availability	
Turbine Availability	Turbine availability (energy-based), considering: Warranted availability, non-contractual availability, Restart after grid outage, Site Access, Downtime (or speed) to energy ratio, First Year / Plant start-up Availability
Balance of Plant Availability	Availability of substation and collection system, Other non-turbine availability, Warranted Availability, Site Access, First Year / Plant start-up
Grid Availability	Grid being outside Grid connection agreement operational parameters, actual grid downtime, delays in restart after grid outages.
Electrical	
Electrical Efficiency	Electrical losses between low or medium voltage side of the transformer of WTG(S) and the energy measurement point
Facility Parasitic Consumption	Turbine extreme weather packages, Other turbine and/or plant parasitic electrical losses (while operating or not operating)
Turbine Performance	
Sub-Optimal Performance	Performance deviations from the optimal wind plant performance due to software, instrumentation, and control setting issues
Generic Power Curve Adjustment	Expected deviation between advertised power curve and actual power performance in standard conditions (“inner range”[1])
Site-specific Power Curve Adjustment	Accommodating for inclined flow, TI, density, shear, and other site / project-specific adjustments (“outer range”[1])
High Wind Hysteresis	Energy lost in hysteresis loop between high wind speed cut-out and recut-in.
Environmental	
Icing	Performance degradation and shut down due to icing
Degradation	Blade fouling, efficiency losses, and other environmentally-driven performance degradation
Environmental Loss	High/low Temperature shut down or de-rate, Lightning, hail, and other environmental shut downs
Exposure	Tree growth or logging, other building development, etc.
Curtailments / Operational Strategies	
Load Curtailment	Speed and/or direction curtailments to mitigate loads
Grid Curtailment	PPA / off-taker curtailments, grid limitations
Environmental / Permit Curtailment	Birds, Bats, marine mammals, flicker, noise (when not captured in the power curve), etc.
Operational Strategies	Any periodic up-rating, down-rating, optimization or shut-down not captured in the power curve or availability carve-outs