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Validating Impacts of Leading Edge Erosion Repairs on Wind Turbine Power Performance

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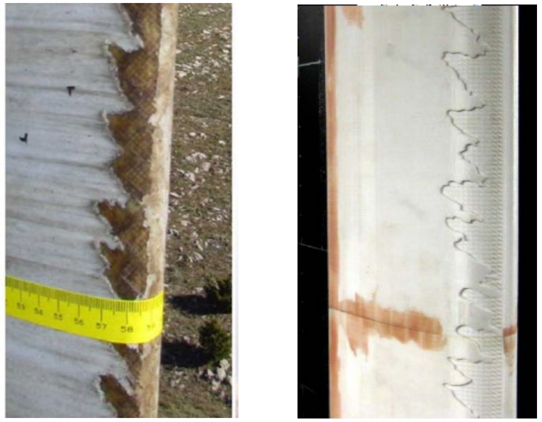
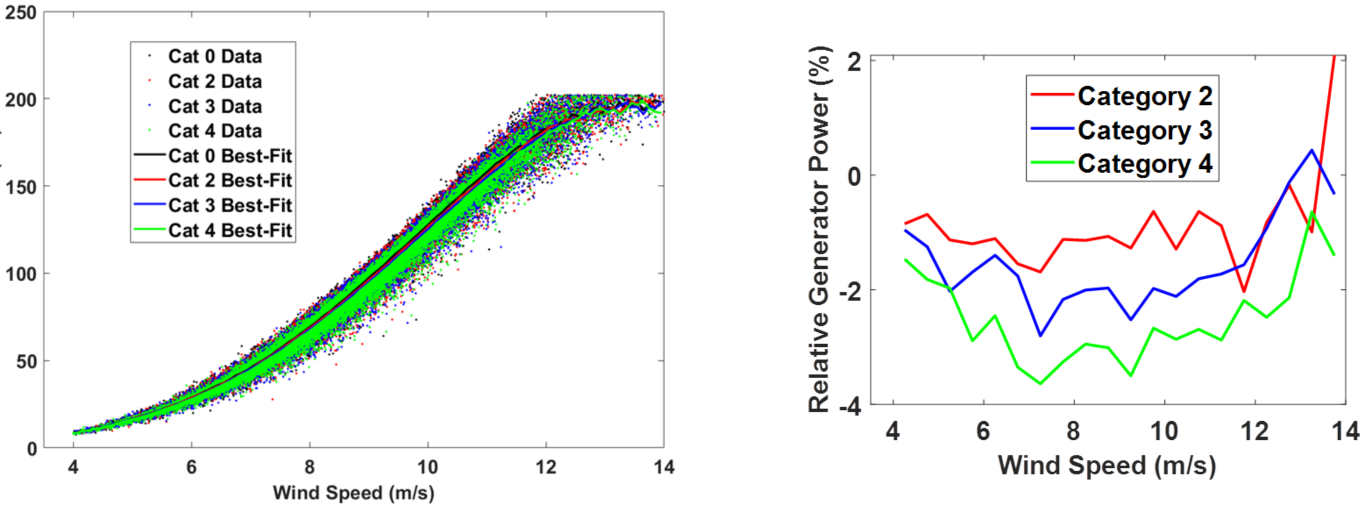
Measuring Power Loss due to Erosion

- A probabilistic model of the power loss due to erosion has been developed based on wind tunnel tests of simulated eroded airfoils
- The present work aims to validate the loss predicted in this model through the comparison of turbines with unrepaired LEE damage to repaired turbines with protection tape
- Local met tower data and archival wind plant SCADA data used from turbines classified as having undergone Category 4 erosion

Field measurements of erosion[1, 2]



Category 4 erosion wind tunnel tests



Probabilistic power curve model of erosion, categories 2-4[3]

[1] Maniaci, David Charles, Ed White, Benjamin Wilcox, Christopher Langel, Case Van Dam, and Paquette, Joshua. *Experimental Measurement and CFD Model Development of Thick Wind Turbine Airfoils with Leading Edge Erosion*. United States: N. p., 2017. Web. doi:10.1088/1742-6596/753/2/022013.

[2] Ehrmann, Robert S., and White, E. B. *Effect of Blade Roughness on Transition and Wind Turbine Performance*.. United States: N. p., 2015. *Preprint, Web*. https://www.osti.gov/servlets/purl/1427238.

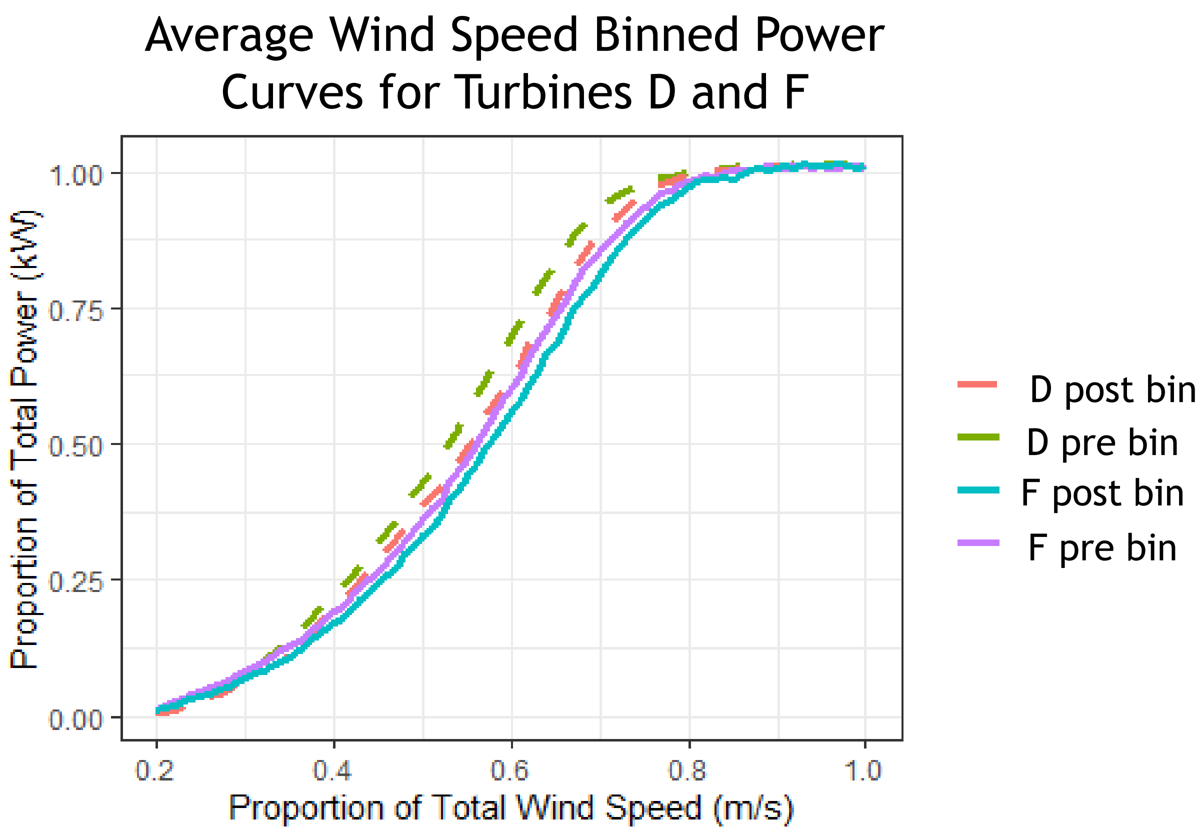
[3] Maniaci, D.C., Westergaard, C., Hsieh, A., and Paquette, J.A., Uncertainty Quantification of Leading Edge Erosion Impacts on Wind Turbine Performance, in Torque 2020. 2020.

Data Input and Filter Method

- Local met tower data and archival wind plant SCADA data used from turbines classified as having undergone Category 4 erosion
  - Measurements included windspeed, wind direction, temperature, atmospheric pressure, power production, nacelle direction, and other channels observed from January 2016-June 2020
- Field observations for power production were compared to expected values from rated power curve for associated turbine model
  - Involved linearly approximating field values to rated curve and taking difference between observed power and expected power values, then filtering out records with higher differences
- Additionally, differences between wind speeds recorded at turbine hub height vs nearby met tower considered
  - Records with turbine wind speeds of absolute differences greater than 1.5 m/s from met tower wind speeds were filtered out

Fitting Power Curves using Average Wind Speed Bins

- For each turbine, all power observations were averaged across 1% wind speed bins to produced binned average wind speed power curve
- This was used to compare with the reference power curve, which recorded expected power values for 0.5 m/s divisions ranging from 3-15 m/s
- Binned power curves produced for observations before and after each turbine repair date

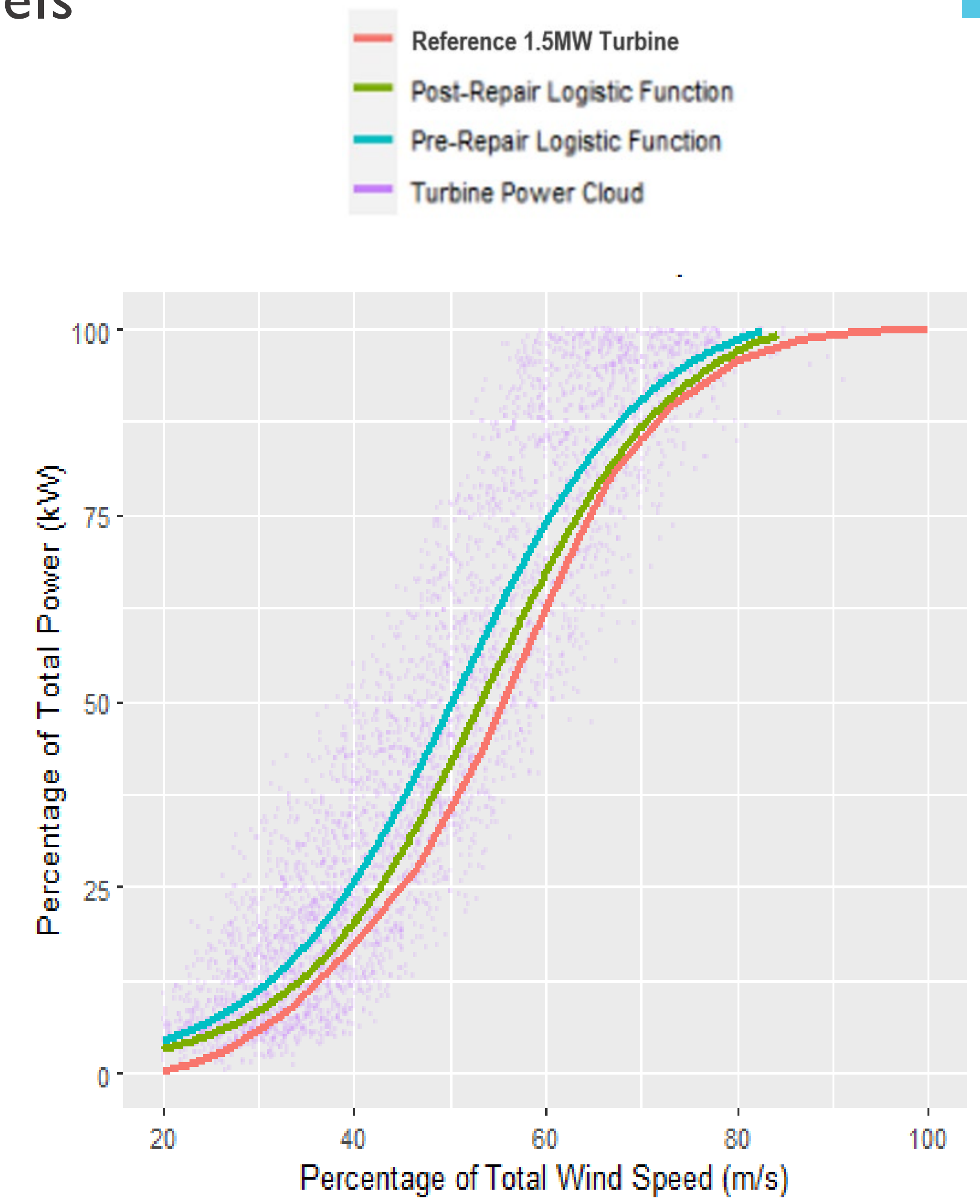


Fitting Power Curves using Regression Models

- Additionally, for each month, power curves graphed for each turbine and fitted using three-parameter logistic function
  - Used to capture slope and boundary conditions of wind power curve, where the slope of the power curve is zero up to the cut-in wind speed and at rated wind speed
- Values filtered started at cut-in wind speed of 3 m/s, or normalized value of 20% of rated wind speed of 15 m/s

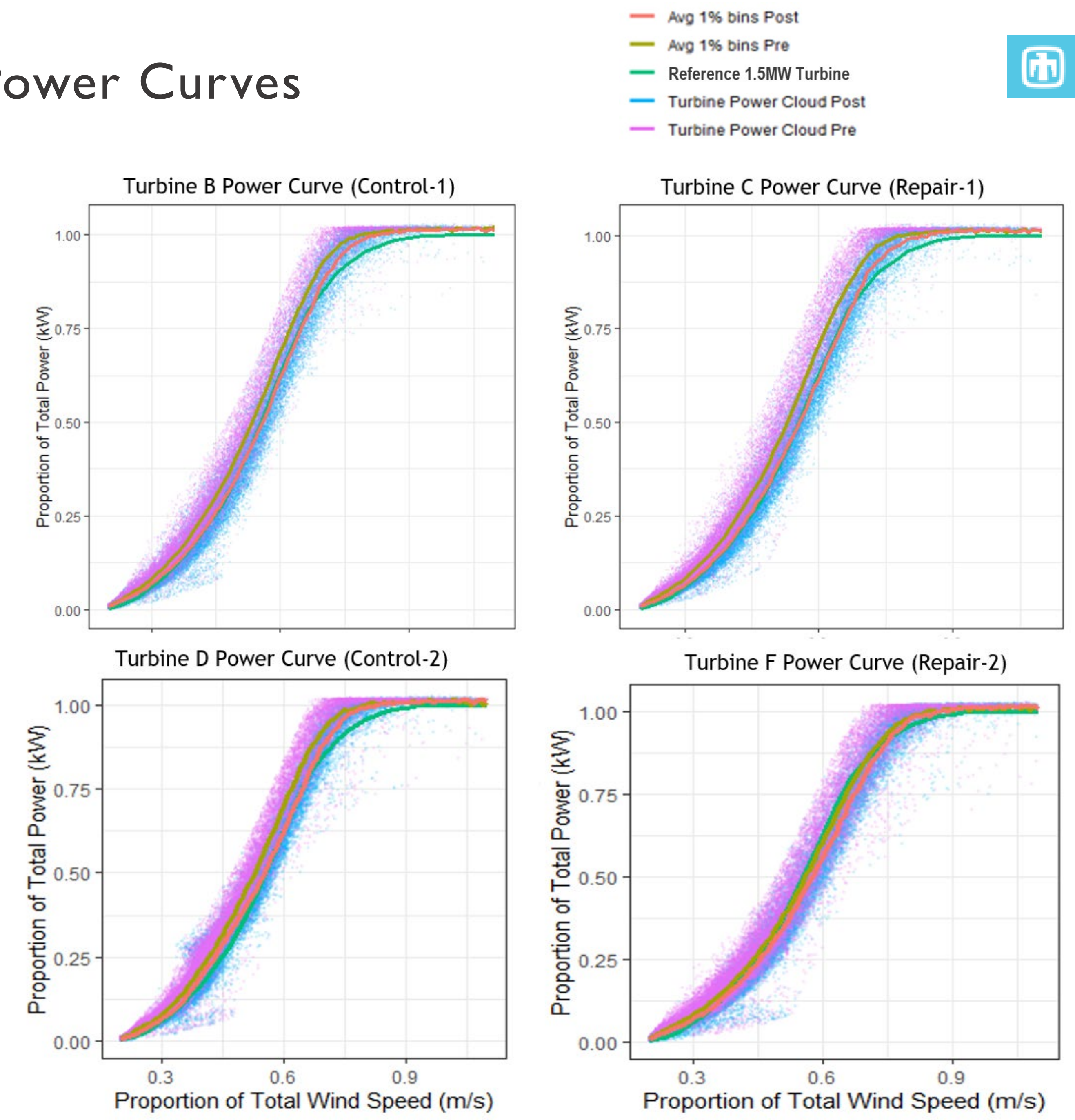
$$P = \frac{\phi_1}{1 + \exp\left(\frac{\phi_2 - S}{\phi_3}\right)}$$

P = power
S = speed
Φ_i = smoothing parameter



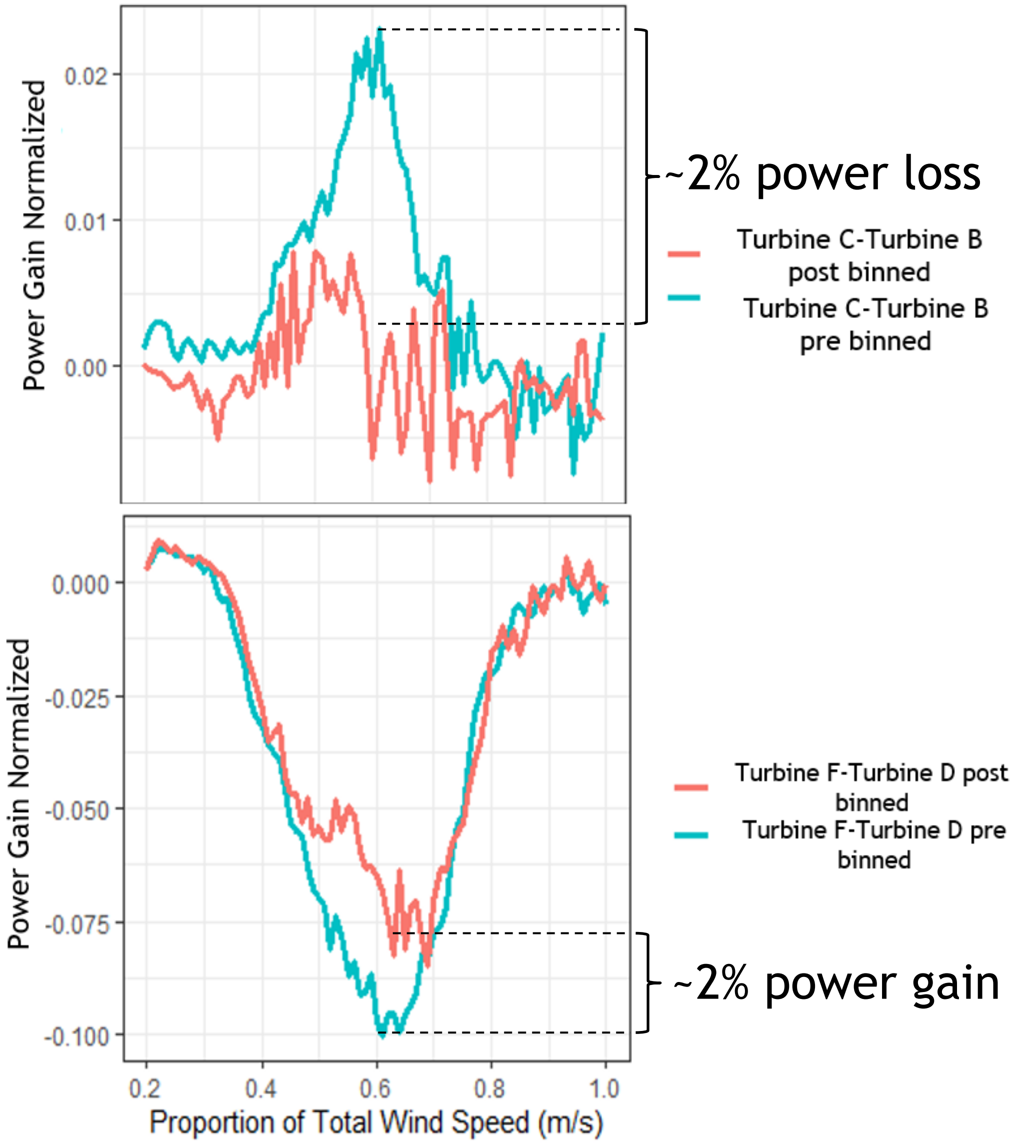
Comparing Turbine Pairs– Overall Power Curves

- While power curves for turbine look similar, slight differences in overall area toward region 3 contribute to greater differences in power performance
- Overall, turbines generated less power after the repairs to turbines C and F
  - Therefore we must compare the relative power loss for both turbines
- If turbines C and F had better relative performance, we can conclude the repair was effective
- For each month, power curves graphed for each turbine and fitted using three-parameter logistic function



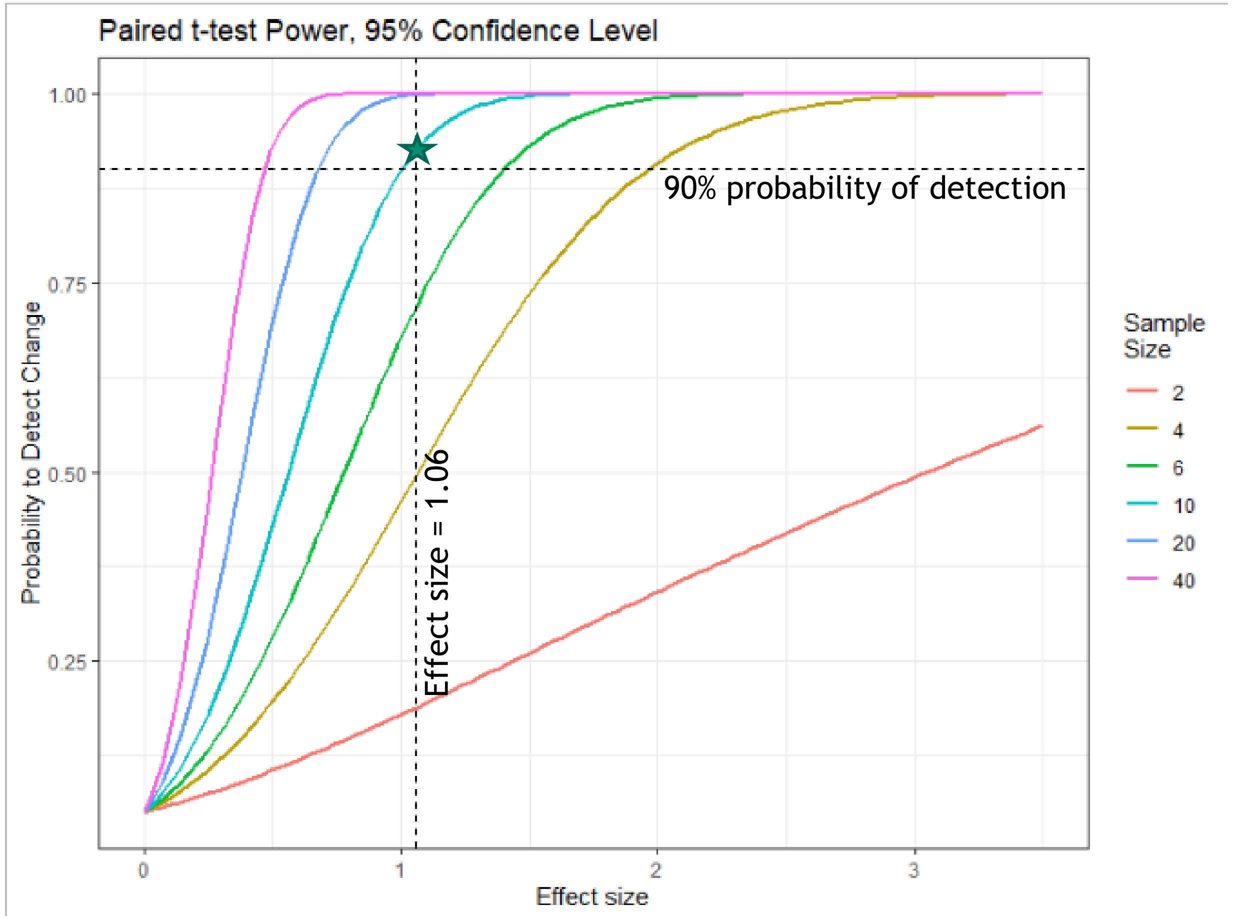
Comparing Turbine Pairs– Relative Power Differences

- Turbine C was generating 1-2% more power for the same wind speed in middling wind speeds, with approximately equal production at the extremes
  - After repairs that advantage largely disappeared, resulting a net loss in relative power gain
- Turbine F was generating 5-8% less power for the same wind speed in middling wind speeds, with approximately equal production at the extremes
  - After repairs that disadvantage was mitigated slightly, resulting a net gain in relative power gain of 1-2% across middling wind speeds



Estimation of Required Turbine Pair Sample Size

- Modeled the likelihood of detecting an increase in the relative power output of a set of turbine pair samples with a given sample size using a one-sample t-test of differences
- Assumed the mean difference is 3% based on the modeling results
- Estimated the corrected standard deviation is as 2.8%
  - Based on 2 turbine pair samples with +2 and -2% change in power, then the effect size is 1.06
- 10 turbine pair samples would be needed to have a >90% probability of detecting a 3% change in power due to erosion repairs given a 2.8% power difference standard deviation



$$Effect\ size = \frac{Expected\ power\ difference}{Standard\ deviation\ in\ power\ difference} = \frac{3\%}{2.83\%} = 1.06$$

Conclusion and Future Work

- The comparative turbine analysis of the field data showed strong dependence on correcting for turbine to turbine power production variability, with one turbine pair showing a relative improvement after the repair and one showing a relative loss
- A longer period of post-repair data is needed to test corrections for the effects of seasonal variability
- The impact of the LEE repair appears most noticeably in middle wind speeds, primarily in upper Region 2 operation
- The field data analysis showed a peak power loss lower than the model predictions in repaired versus unrepaired power at all wind speeds, with higher discrepancies near cut-in and rated wind speeds

Future work:

- Continued analysis over a longer time period and using more turbine pairs
- Develop a probabilistic simulation of site conditions and an uncertainty analysis of the field data for a more direct comparative analysis, including uncertainty in repaired condition
- Release field data power performance analysis software openly and support use by external partners

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