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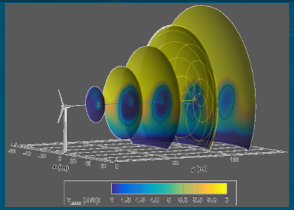
Performance Impact of Leading Edge Erosion from Simulation and Field Data



PRESENTED BY

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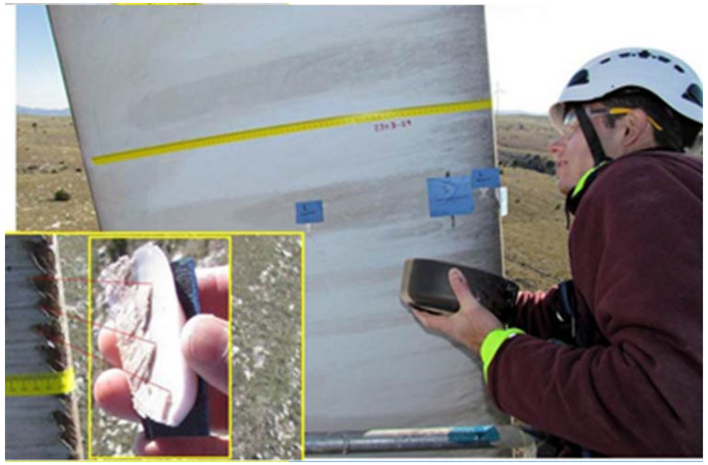
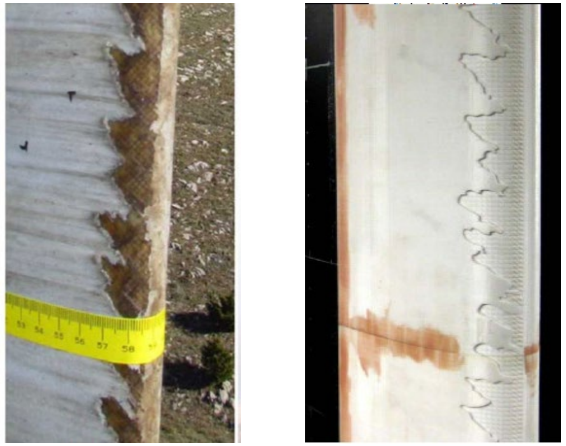
Introduction

- Leading edge erosion (LEE) is a prominent issue for wind turbine blade reliability, causing gradual performance decrease and persistent maintenance costs
- Main driver of erosion is the impact of rain droplets on leading edge of blade
- Erosion rate typically has an incubation period with little damage, then a linear growth period
- A 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



Field measurements of erosion[1, 2]



Category 4 erosion

[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.

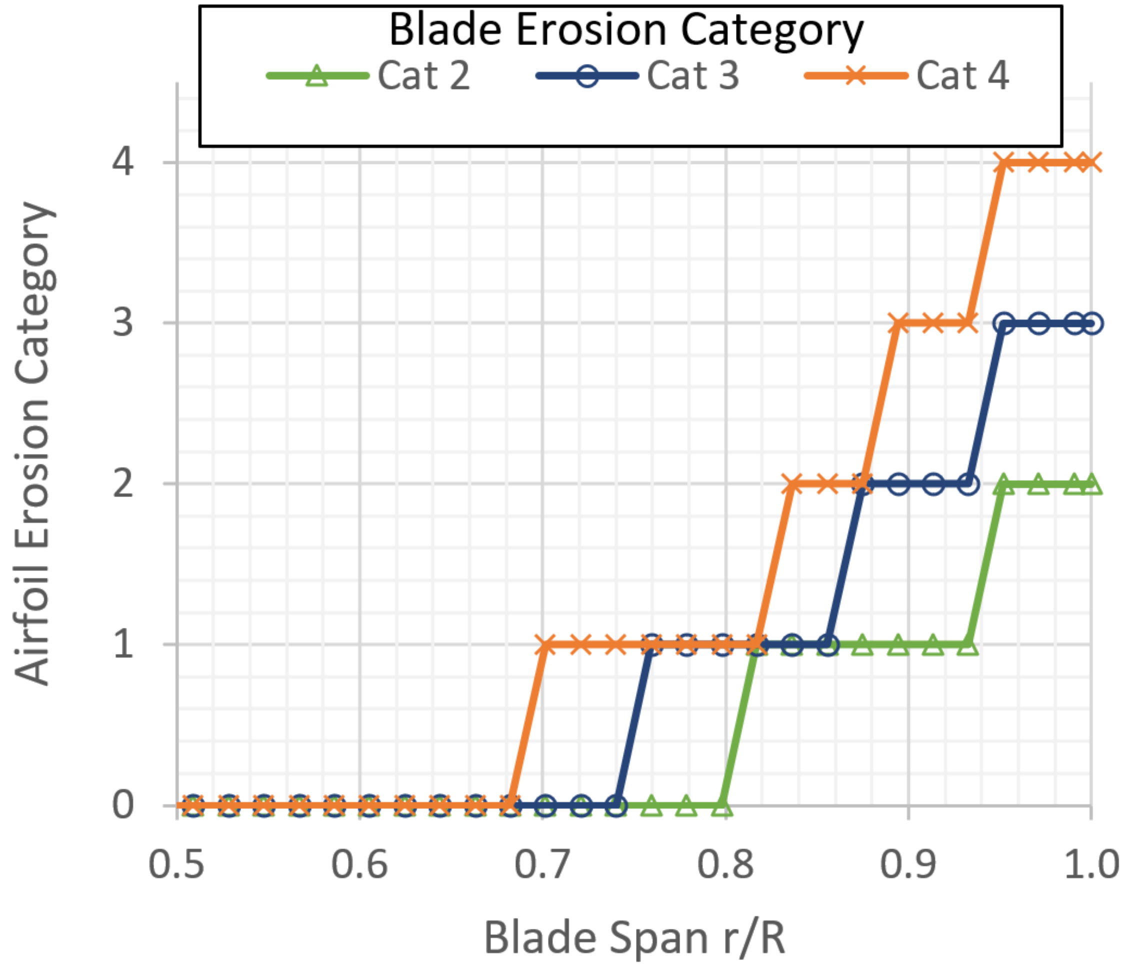
Examples of Erosion Categories

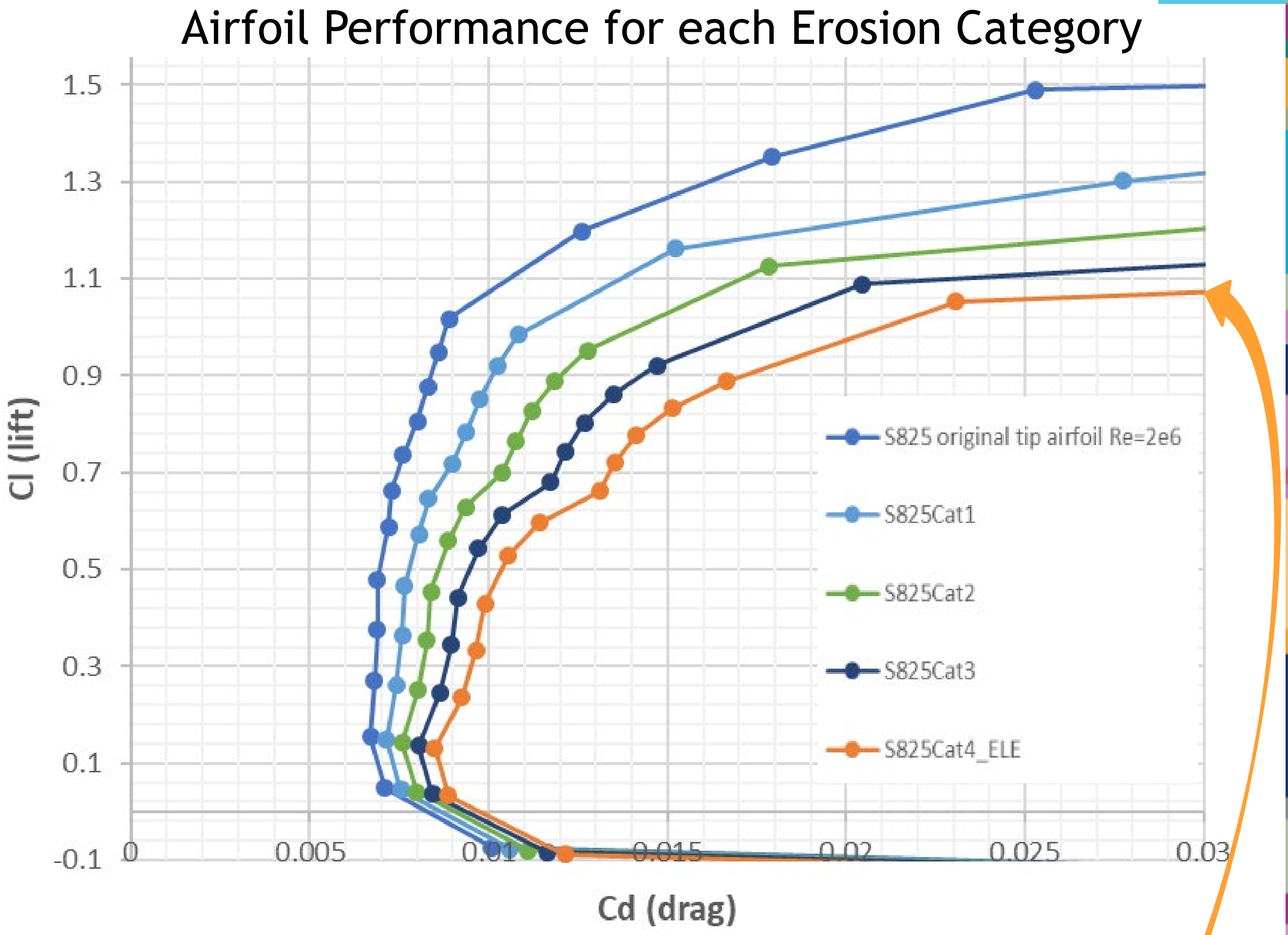
Cat 2

Cat 3

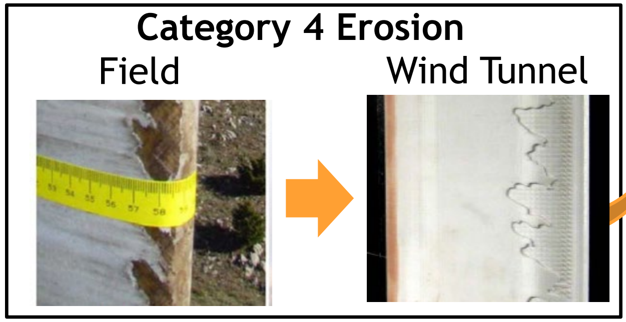
Cat 4

Erosion Performance Loss Model





- Erosion rates along blade span simulated using local blade velocity to the 6.7 exponent
- Airfoil performance based on wind tunnel tests of reproduced erosion and interpolation with the clean airfoil polar

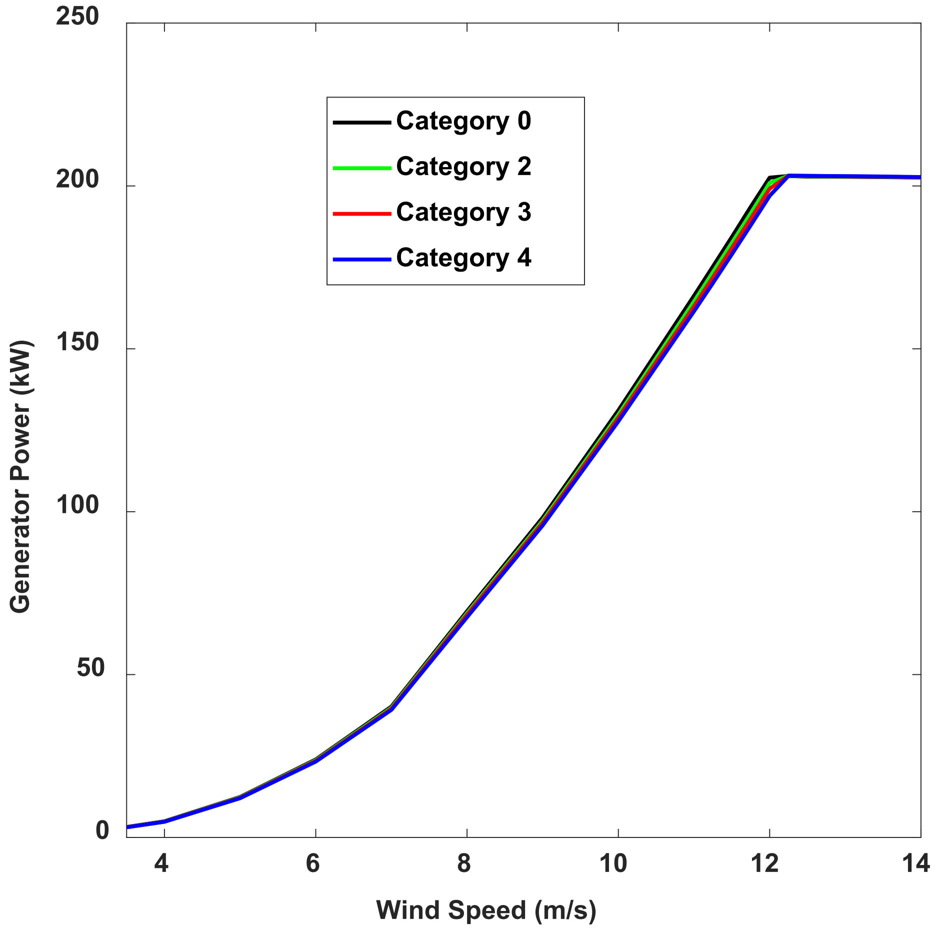


[3] Maniaci, D.C., Westergaard, C., Hsieh, A., and Paquette, J.A., Uncertainty Quantification of Leading Edge Erosion Impacts on Wind Turbine Performance, in Torque 2020.

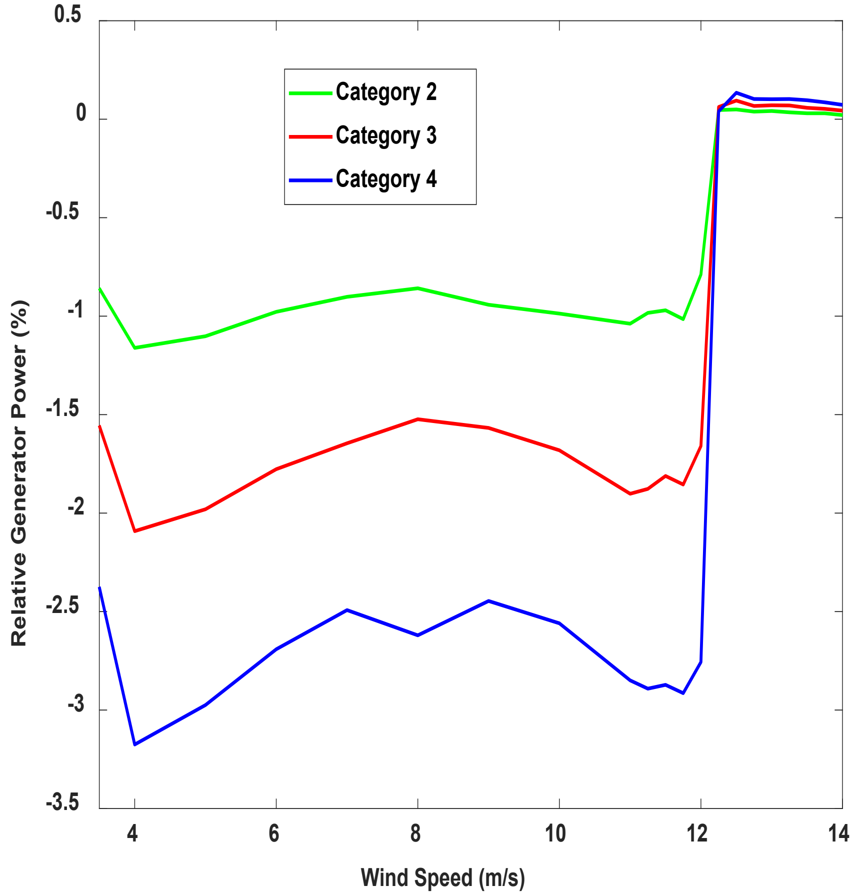
Erosion Model: Steady State Power Curve Erosion Effect

- Steady state power curve of the NRT* turbine simulated using AeroDyn from the OpenFAST code suite

Steady power curve



Difference in steady power curves



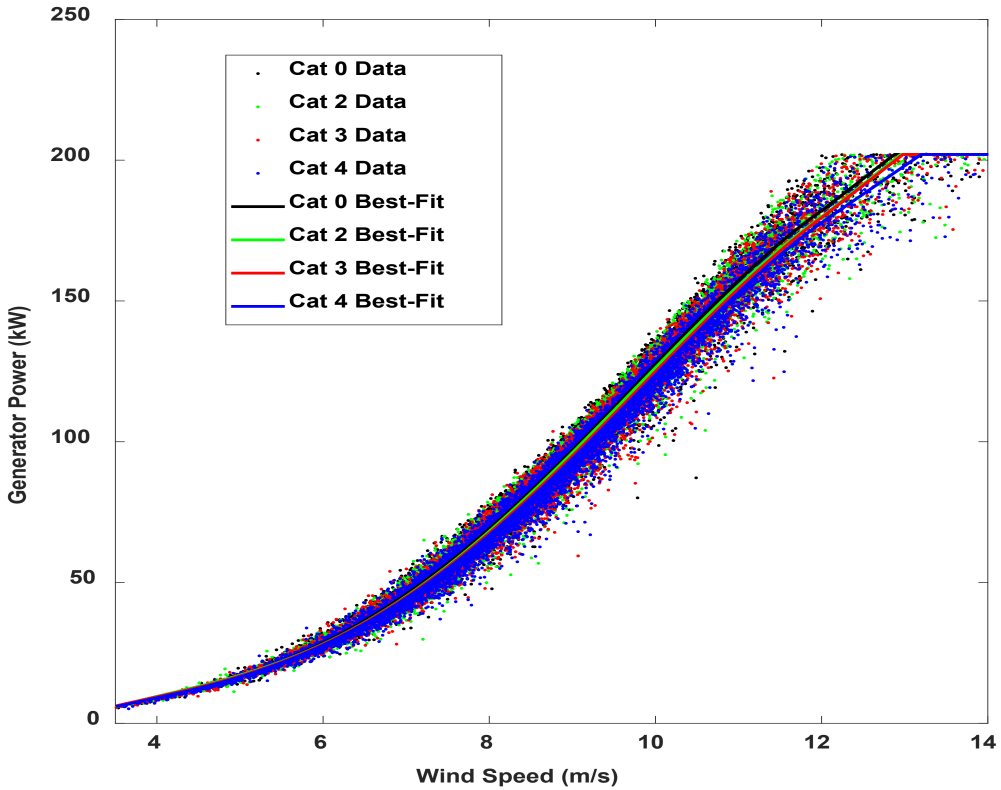
*NRT (National Rotor Testbed) is deployed at Sandia's SWiFT facility, it is 27m diam. functionally scaled version of a 2000's era utility turbine.

[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.

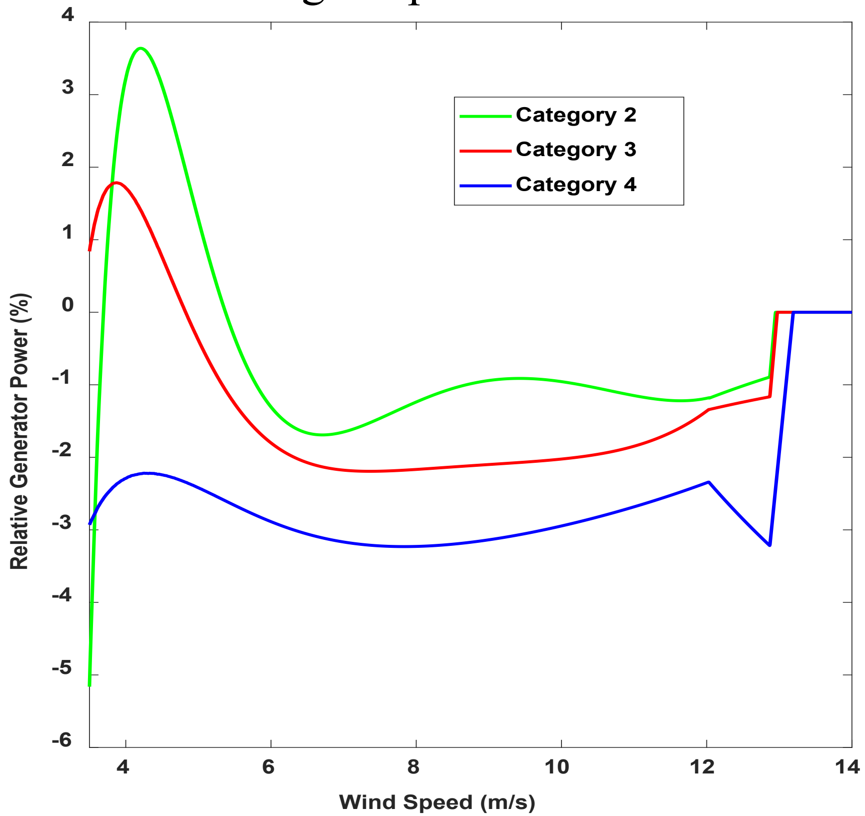
Erosion Model: Probabilistic Power Curve Uncertainty Analysis

- Monte Carlo sampling was conducted to randomly sample 10,000 simulations, each 10 minutes long, for each of the four erosion categories
- Dakota[5] used for UQ analysis, with TurbSim[4] for inflow and OpenFAST[4] for turbine simulation
- Uncertain aleatoric parameters: hub-height wind speed, turbulence intensity, shear exponent, air density, yaw offset, collective blade pitch
  - Power increase at low wind speeds due to small number of samples relative to inflow variance

Power curve cloud



Change in power curve fit



[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
[4] NWTC Information Portal (OpenFAST)," ed. https://nwtc.nrel.gov/OpenFAST. Last modified 14-June-2016; Accessed 05-December-2019
[5] Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.0 User's Manual. Sandia National Laboratories. SAND2014-4633.

Erosion Model: AEP Impact from Probabilistic Power Curve Analysis

- Annual energy production relative to no erosion for a range of mean wind speeds using a Rayleigh wind distribution, based on the probabilistic power curve cloud results.

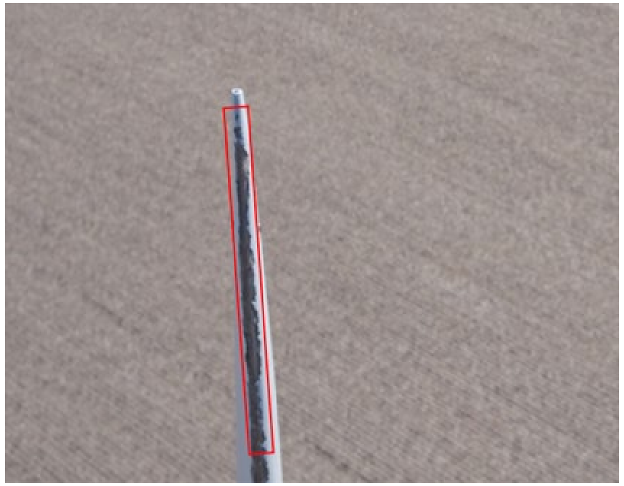
Annual Energy Production Loss due to Erosion, Model Predicted

	Mean Wind Speed (m/s)				
Erosion Category	4	6	7.5	8.5	10
0	0.0%	0.0%	0.0%	0.0%	0.0%
2	-1.0%	-0.9%	-0.7%	-0.6%	-0.4%
3	-1.9%	-1.6%	-1.3%	-1.1%	-0.8%
4	-3.0%	-2.6%	-2.2%	-1.9%	-1.6%

Field Data Analysis

- Archival SCADA data from the turbines and nearby meteorological towers was collected in 10-minute records.
  - Measurements include windspeed, wind direction, temperature, atmospheric pressure, power production, turbine state, and nacelle direction, among other channels.
- The data is corrected by comparing multiple measurements of the same quantity when possible. Power curves are then calculated according to IEC 61400-12 [10] for each turbine over smaller time intervals.
- The power curves were then quantified by mean, standard deviation, and other metrics over windspeed bins.
  - Combining these data points across all the smaller intervals gives a multivariate time series. From this, any systematic reduction in productivity was identified.
- Specifically focusing on a pair of Class 4 level erosion wind turbines, **Turbine B** was repaired in September 2019, while its pair **Turbine A** was not repaired.
  - Comparing the power generated by each turbine at a given 10-minute time bin will allow the change in performance based on the repairs to be assessed.
  - The data to compare these turbines spans from January 2016 to June 2020, which does limit the data available post-repairs.

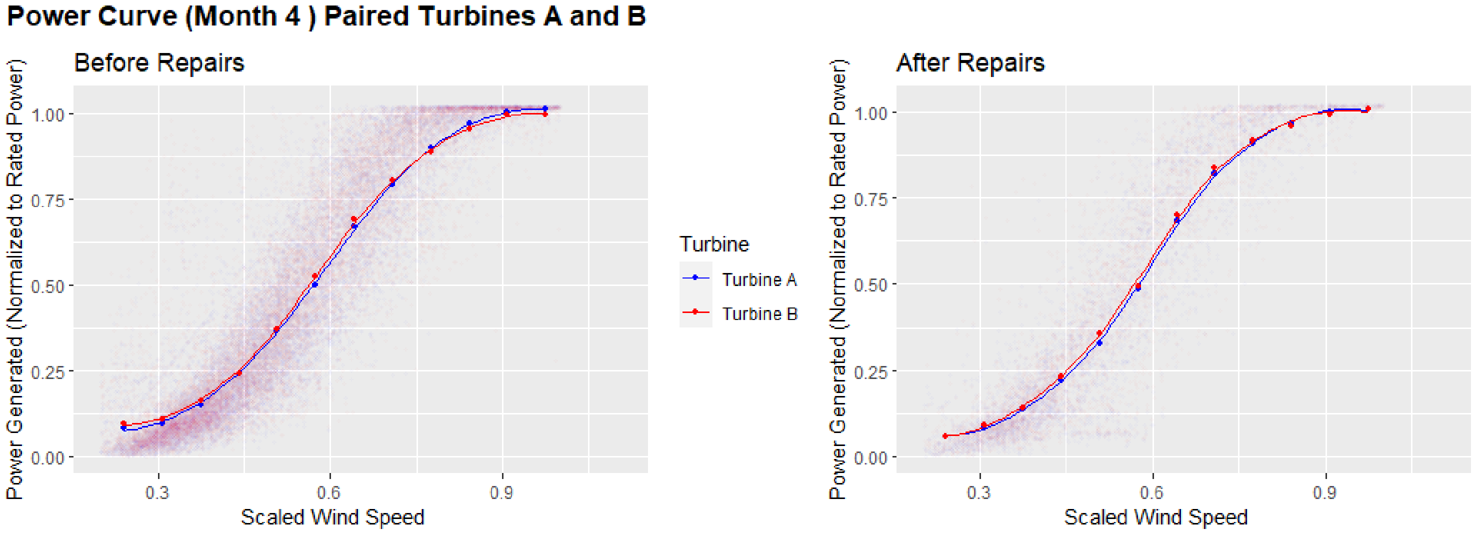
Example Cat4 Erosion

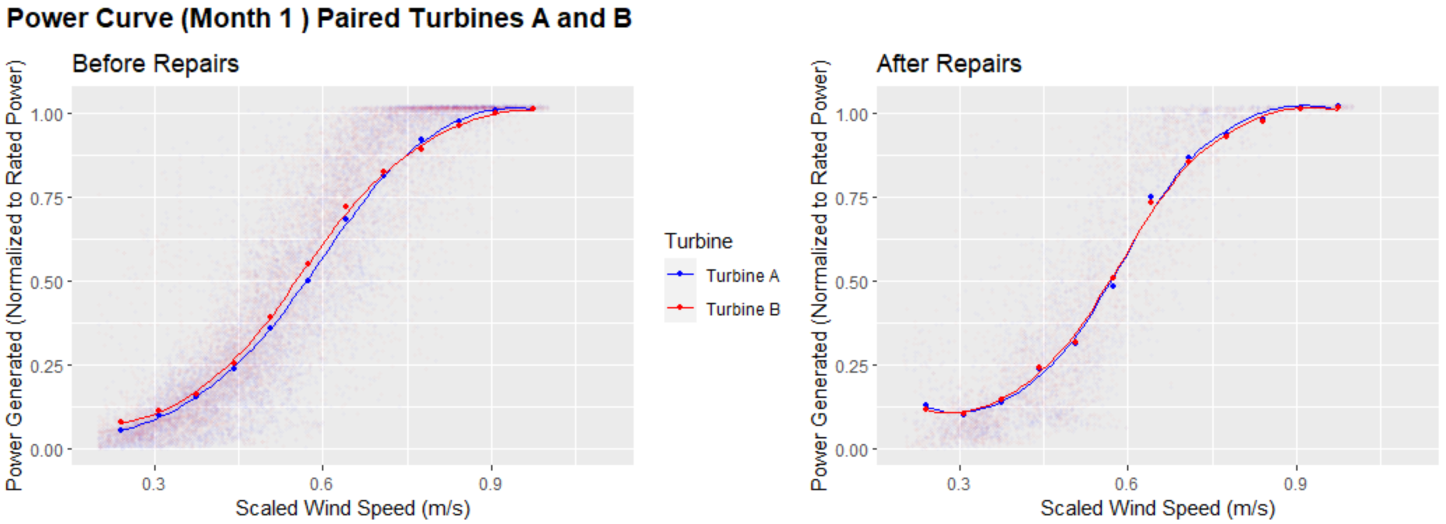


[10] IEC 61400-12-1:2017 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines, International Electrotechnical Commission, 2017.

Turbine Data Comparative Analysis

- In the exploratory analysis, power curves for matched pairs before and after repairs were made using the wind speed binning method described in IEC 61400-12 [10].
- Some months showed improvement in Turbine B1 after repairs, while some showed little change.
- Some observations showed underperformance during below freezing temperatures which affects the wind speed bin mean power output in some of the curves.

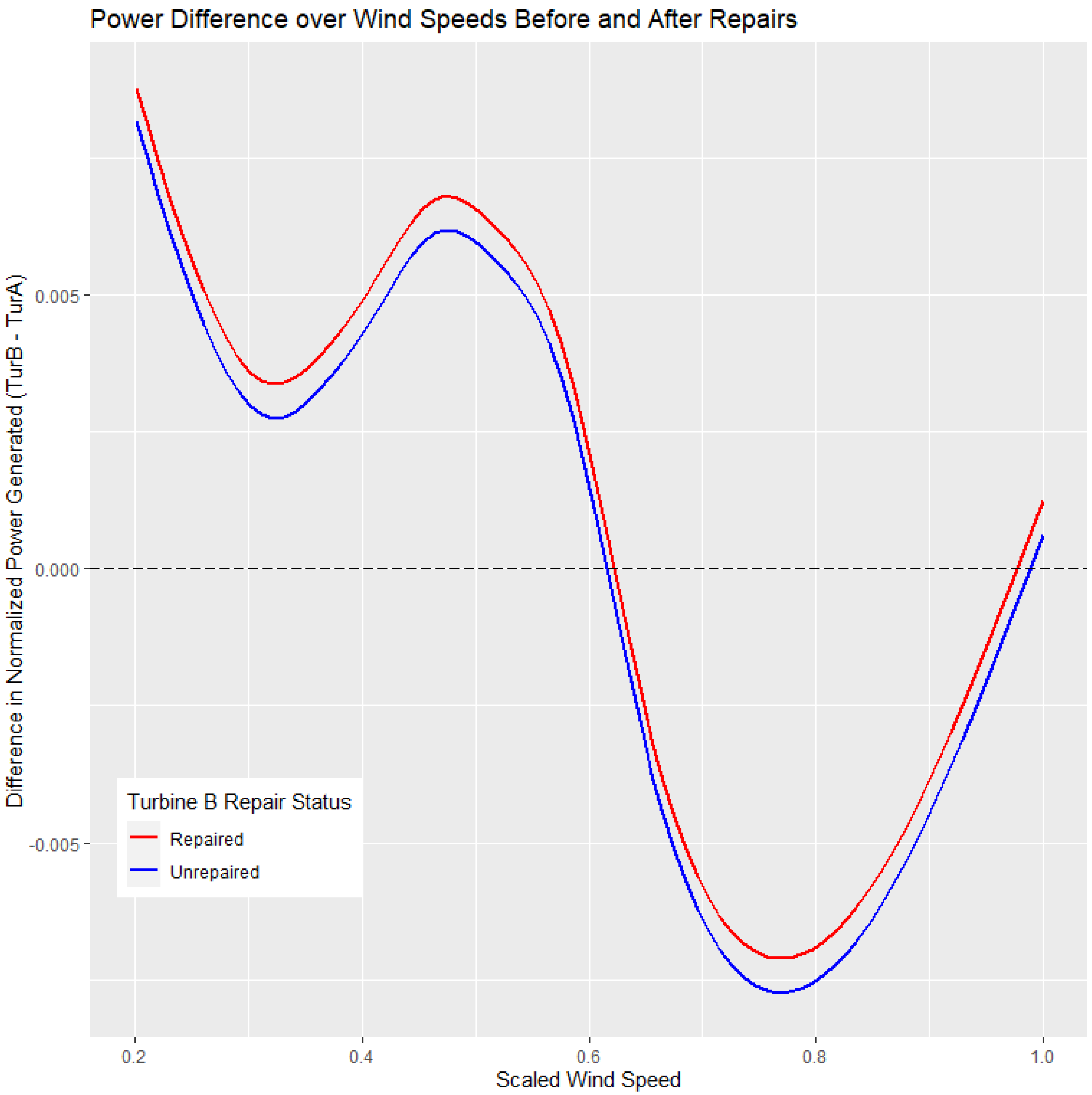




[10] IEC 61400-12-1:2017 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines, International Electrotechnical Commission, 2017.

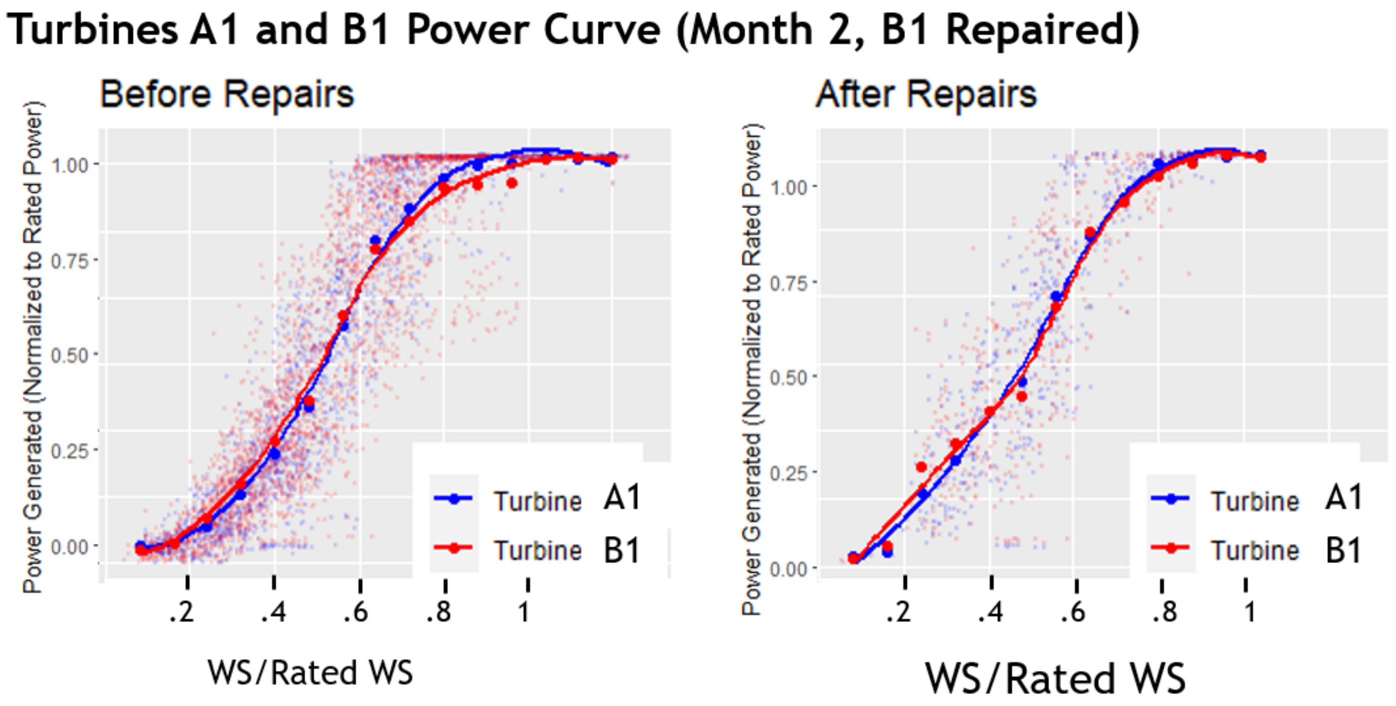
Turbine Data Comparative Analysis

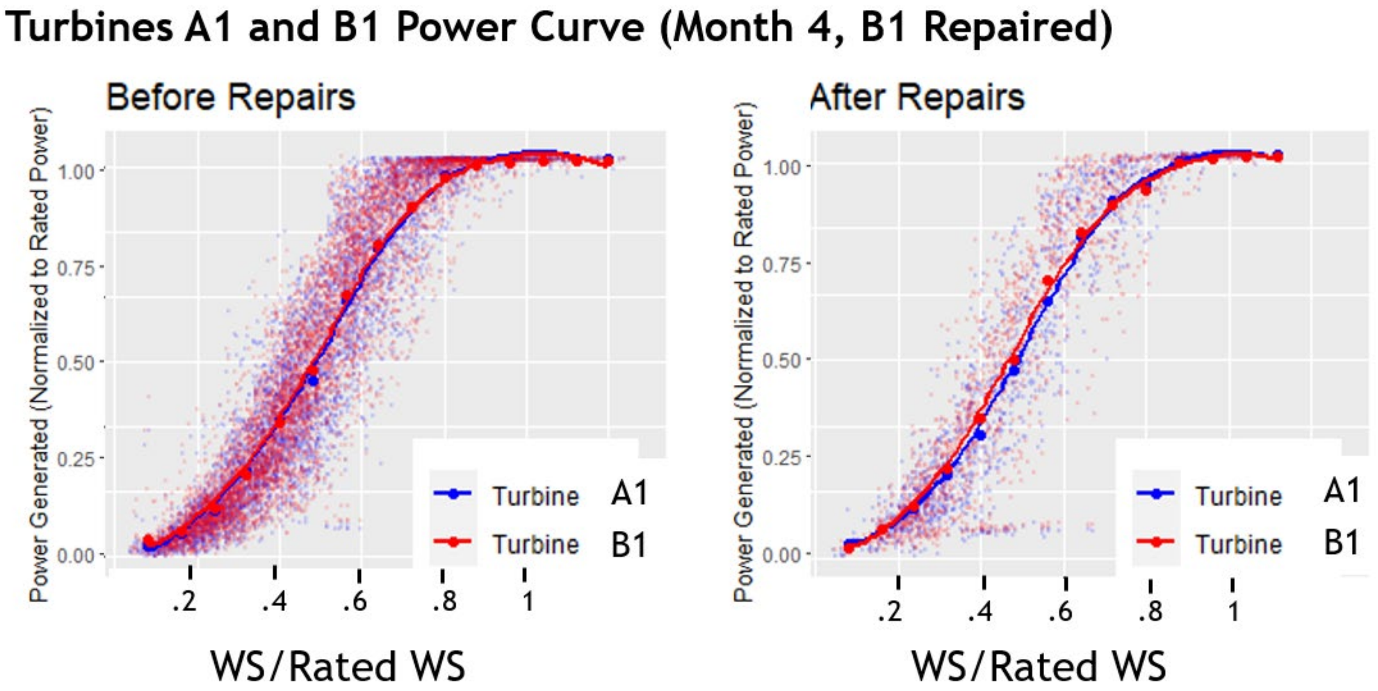
- The model shows an increase in Turbine B1's power generated compared to Turbine A1, after Turbine B1 was repaired.
- The final model included the following predictors:
  - Indicator of Turbine B1 having been repaired
  - Air Temperature
  - Wind Speed
  - Power Generated by Turbine A1
  - Difference in set and actual Torque Value for both turbines
  - Torque for both turbines
  - Month
  - Two artificial variables related to air density



Turbine A1 & B1 by Month

- Additional data processing has been applied at lower wind speeds.
- New Filters make the Power Curves adhere closer to expectations.
- The Data was also filtered to remove temperatures below -10 degree F.
- We can still see some improvement in Turbine B1 compared to Turbine A1 after repairs.

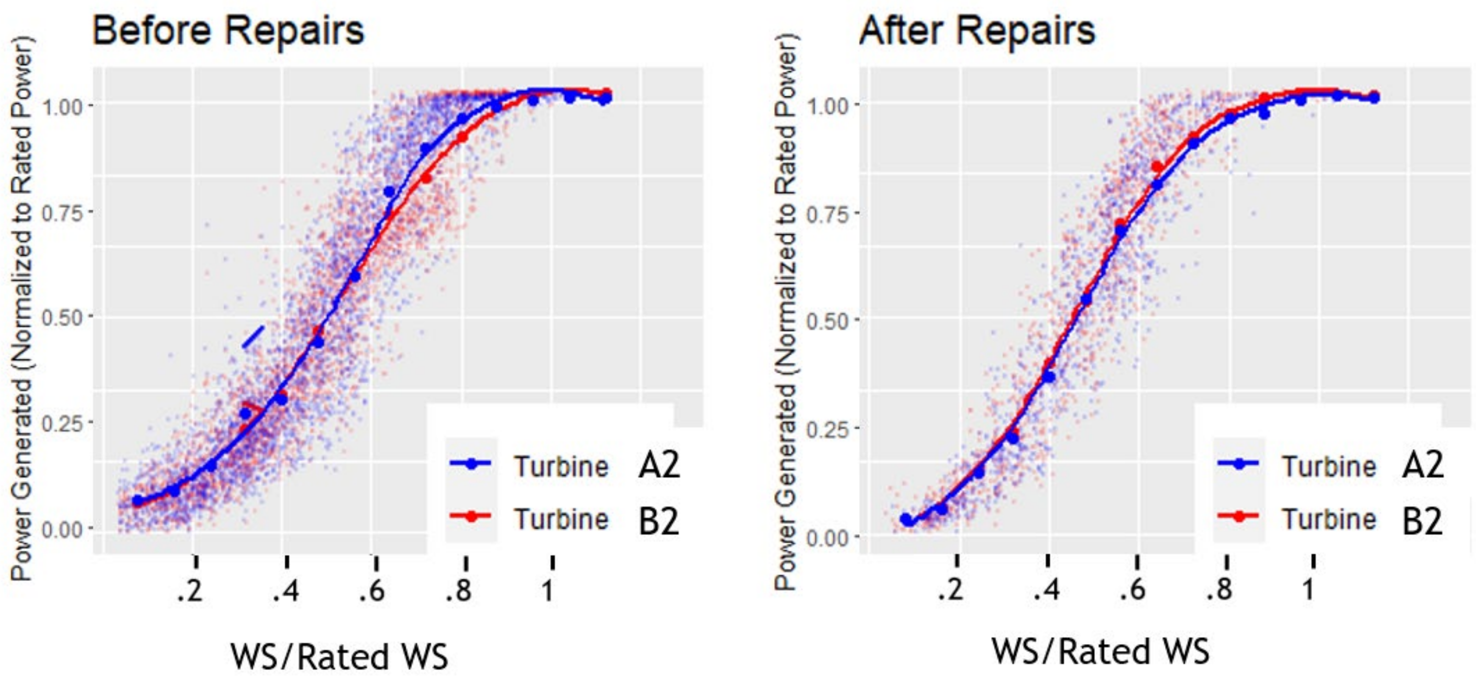




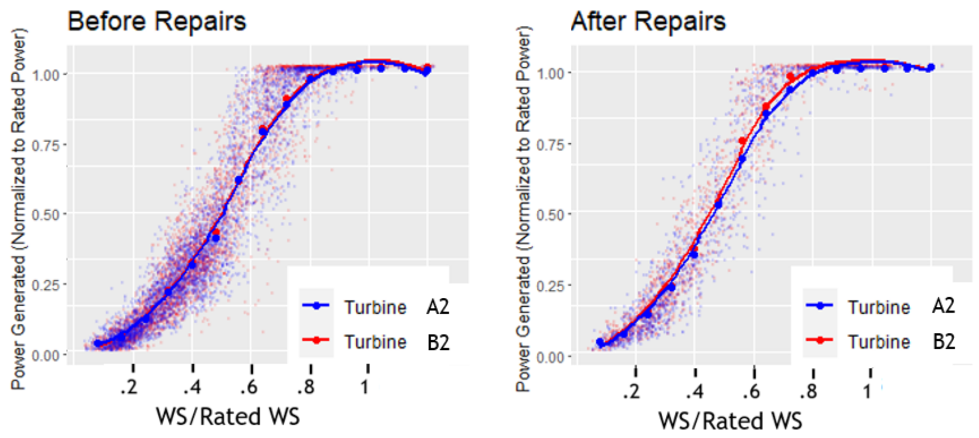
Turbine A2 & B2 by Month

- We can see some improvements in Turbine B2 compared to Turbine A2 after Turbine B2 is repaired.
- There are some areas that need more investigation and filtering, such as Month 10 Turbine A2 before repairs and Month 5 before repairs.

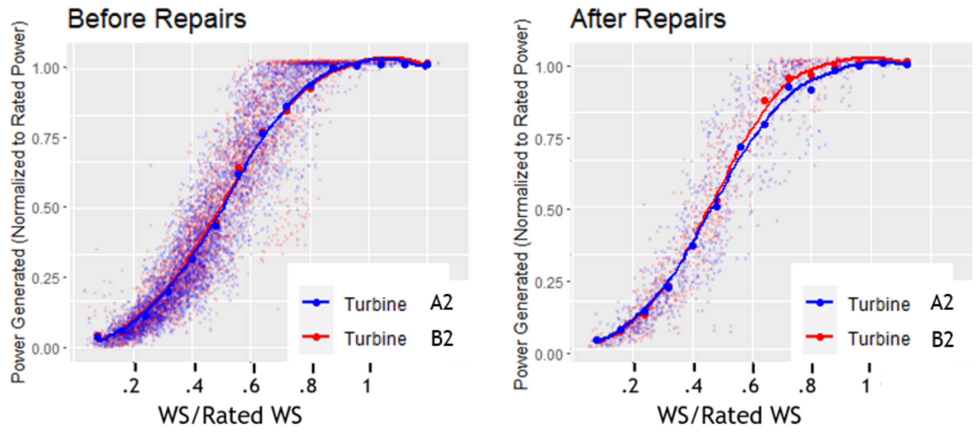
Turbines A2 and B2 Power Curve (Month 10, B2 Repaired)



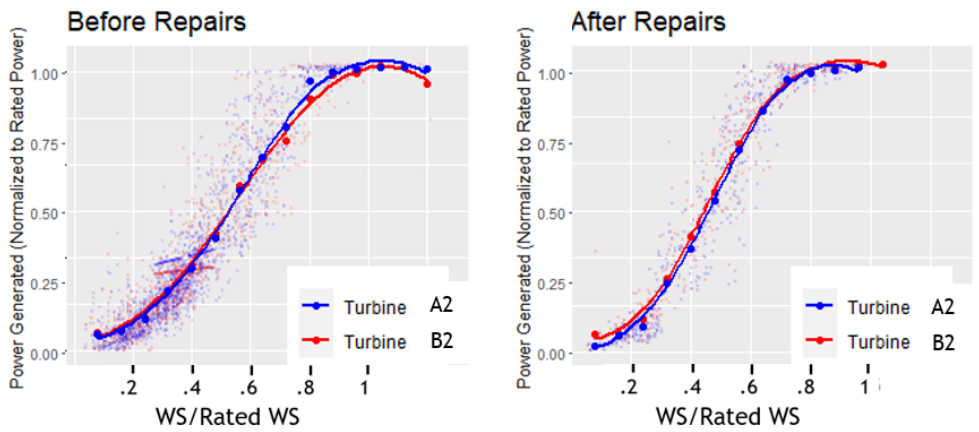
Turbines A2 and B2 Power Curve (Month 3, B2 Repaired)



Turbines A2 and B2 Power Curve (Month 4, B2 Repaired)

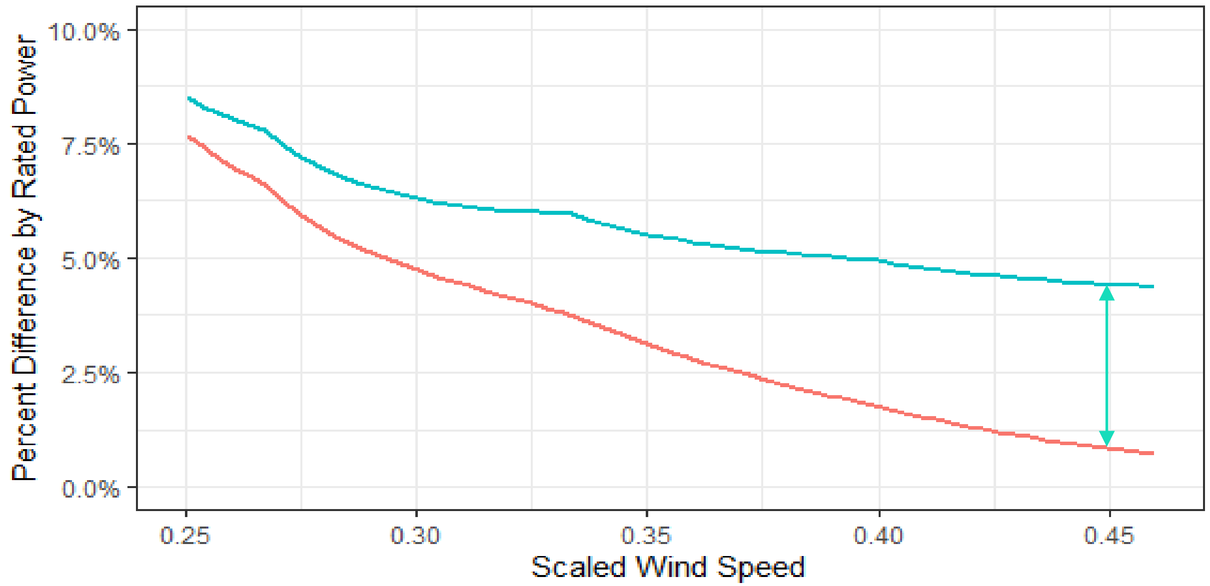


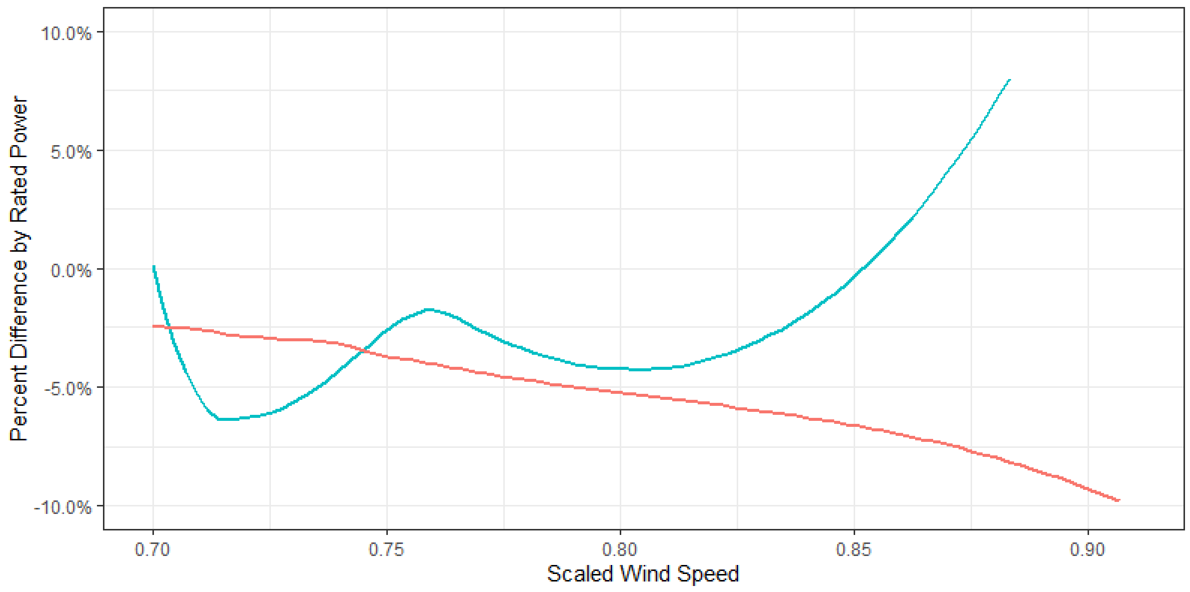
Turbines A2 and B2 Power Curve (Month 5, B2 Repaired)



Low and High Wind Speed Turbine B1 Minus Turbine A1 Power Difference

- Using Simulated Data based on a regression model which takes the average value for predictors for each Wind Speed Bin (size 1 m/s) and for each month, we predict the difference for both repaired (B1) and unrepaired Turbine (A1).





- The low wind speeds were further filtered to have average blade angle at least 0.

- Alternate regression methods are being investigated.

- Additional pairs of turbines with a range of erosion categories will be investigated.

Results Interpretation

- In region 2 operation, the computational model predicted ~1% power loss in power for category 2 erosion, 2% for category 3, and 3% for category 4.
- The model predicted relatively constant percentage power loss across region 2, quickly dropping to zero loss as rated power was reached.
- The comparative turbine field data analysis showed a peak power loss similar to the model predictions in repaired versus unrepaired power at lower wind speeds.
- The disagreement in the magnitude of power loss at higher wind speeds due to erosion indicate improvements are needed in the computational model and the field data analysis, which are currently underway.
  - Additionally, more field data is anticipated.

Conclusions

- Field data of two turbines was compared to assess the change in performance before and after leading edge erosion repairs.
- A statistical analysis was performed to assess whether the measured performance difference was plausible, and the analysis showed that there was an improvement in power with the repairs that was statistically significant, but less than the erosion model predictions.
- Despite the differences between the trend of power loss with wind speed due to LEE from the model predictions and the field data analysis, the observation that both data sets show similar peak power loss in region 2 is encouraging toward future model improvements and data analysis.

Future Work

- Future work will include continued analysis over a longer time period and using more turbines with a range of erosion categories.
- A predictive computational model will be developed that more directly represents the turbines specific to this site.
- A probabilistic simulation of the specific site conditions over the test period will also be deployed to better represent observed variability, measurement uncertainty, and turbine condition uncertainty for comparison to the field data.
- An uncertainty analysis of the field data and modeling data will allow for a direct comparative analysis, allowing for validation of the computational model.

Thank you

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