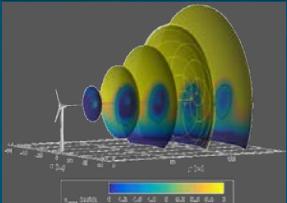




Sandia  
National  
Laboratories

SAND2020-13891C

# Effect of Leading Edge Erosion on Wind Turbine Performance from Simulation and Field Data



## PRESENTED BY

Kaitlyn R. Dowden, Joshua A. Paquette, David C. Maniaci,  
and Alan Hsieh

Sandia National Laboratories, Albuquerque, NM

AIAA 2021 SciTech Conference, January 19, 2021



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.



- Leading edge erosion (LEE) is a prominent issue for wind turbine blade reliability
- Causes 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 erosion period
  - Initial erosion labeled as category 1 or 2, up to 2% AEP loss
  - Structural damage starts at category 3 erosion, and progresses to category 4 with up to 5% AEP loss



Field measurements of erosion<sup>[4, 5]</sup>



Category 4 erosion

[4] 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.

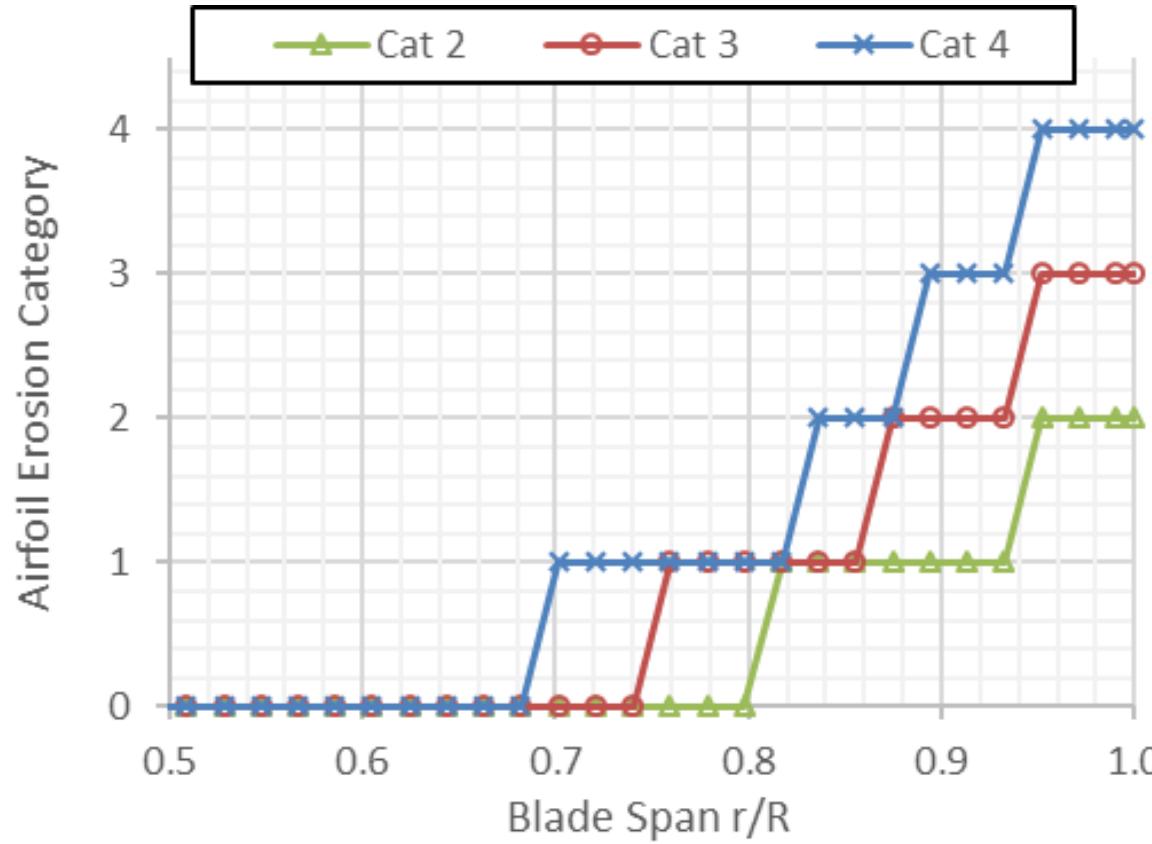
[5] Ehrmann, Robert S., and White, E. B. *Effect of Blade Roughness on Transition and Wind Turbine Performance..* United States: N. p., 2015. Preprint, Web. <https://www.osti.gov/servlets/purl/1427238>.

# Categories of Erosion Along Blade



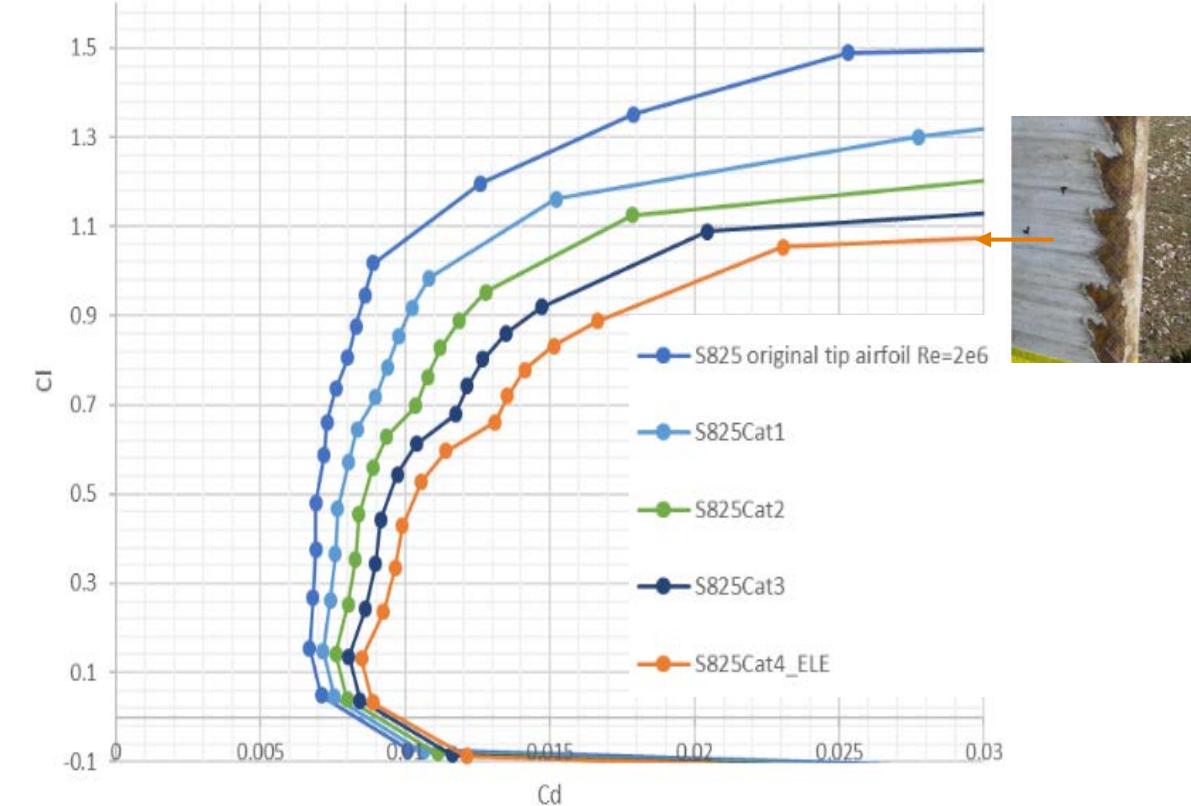
- Blade erosion rates simulated using local blade velocity to the 6.7 exponent for erosion

Erosion categories along blade span



- Airfoil performance for each erosion category based on wind tunnel testing of a similar airfoil

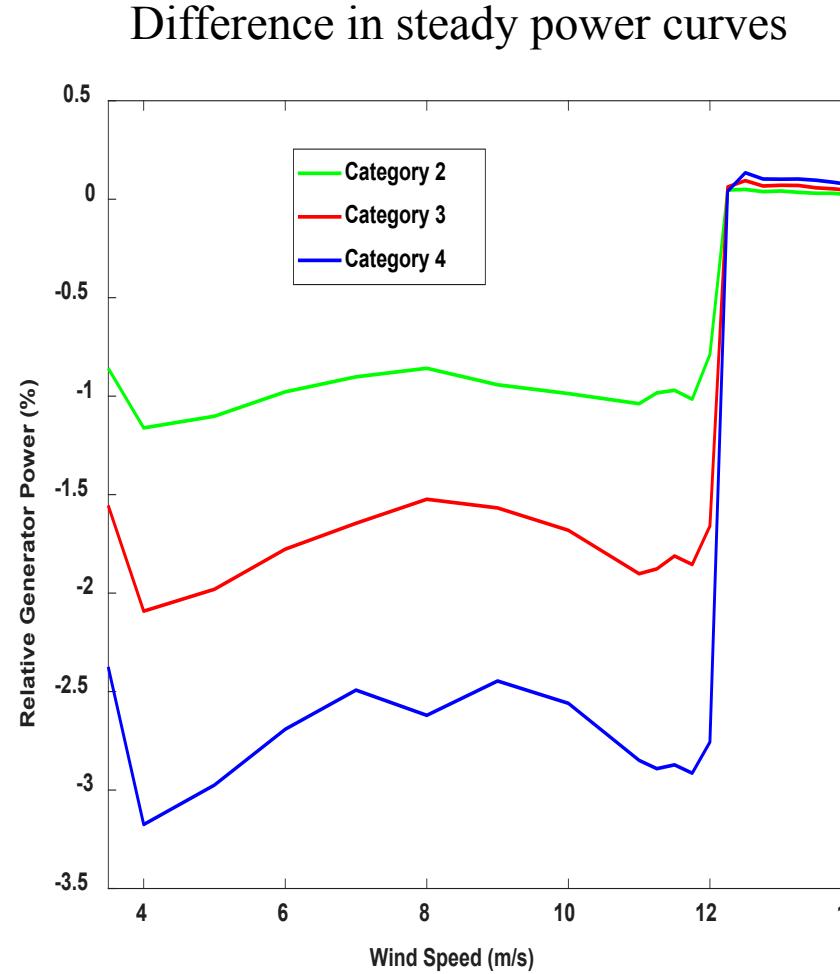
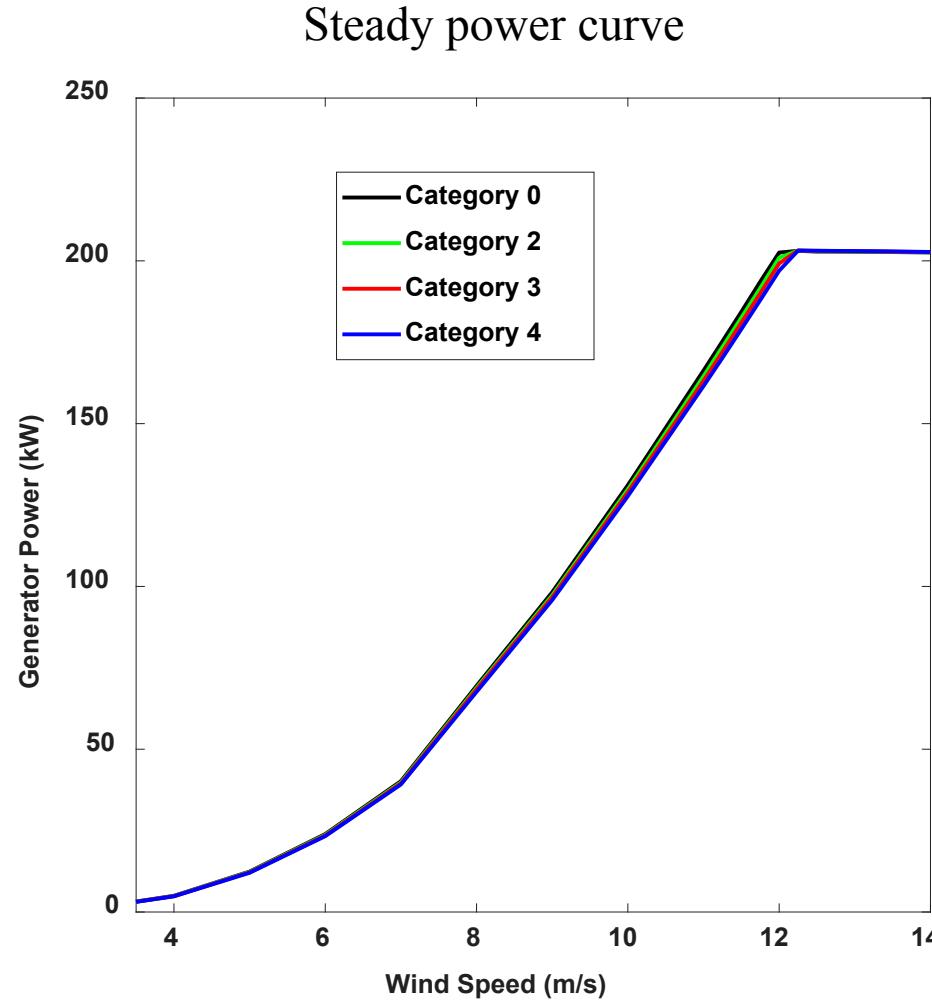
Airfoil performance for each erosion category



# Steady State Power Curve Erosion Effect



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

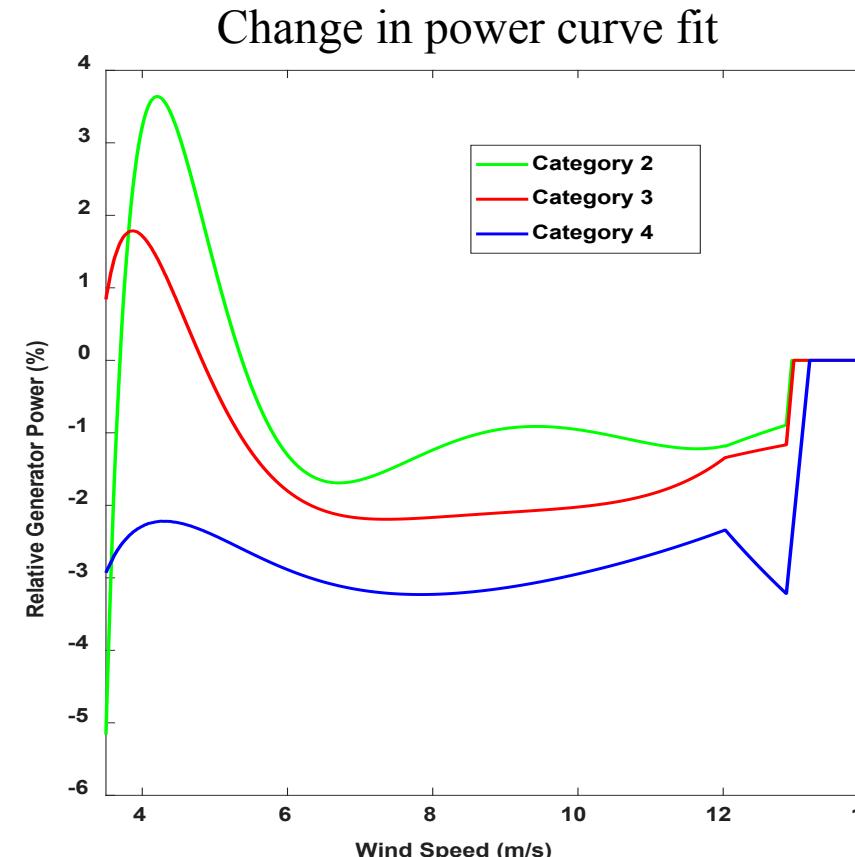
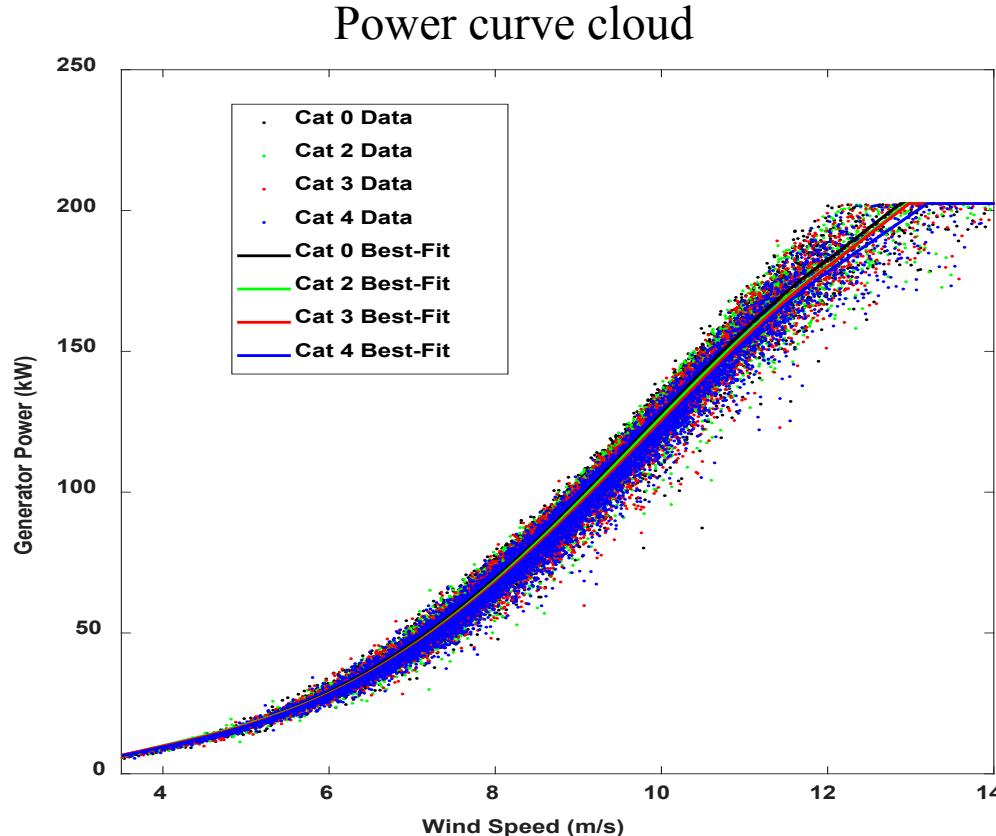


# Probabilistic Power Curve Uncertainty Analysis

5



- Monte Carlo sampling was conducted to randomly sample 10,000 simulations, each 10 minutes long, for each of the four erosion categories
- Dakota used for UQ analysis, with TurbSim for inflow and OpenFAST 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



## 6 Field Data Analysis



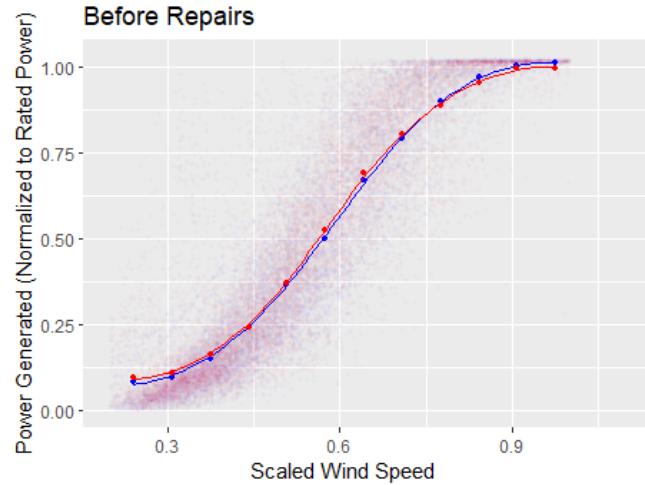
- Archival SCADA data from the turbines and nearby meteorological towers was collected in 10-minute records.
  - Measurements include windspeed, wind direction, temperature, atmospheric pressure, power production, turbine state, and nacelle direction, among other channels.
- The data is corrected by 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.
  - The data to compare these turbines spans from January 2016 to June 2020, which does limit the data available post-repairs.

# Turbine Data Comparative Analysis

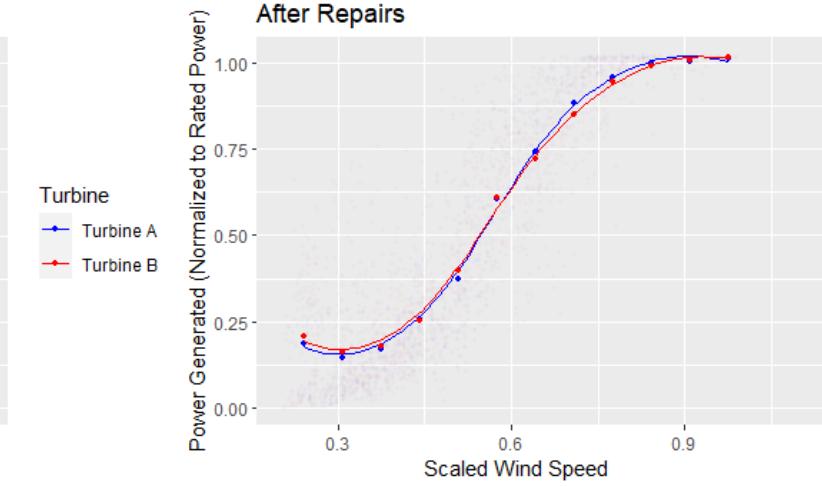


- In the exploratory analysis, power curves for matched pairs before and after repairs were made using the wind speed binning method described in IEC 61400-12 [10]
- Some months showed improvement in Turbine B after repairs, while some showed little change.

**Power Curve (Month 4 ) Paired Turbines A and B**



**Power Curve (Month 5 ) Paired Turbines A and B**

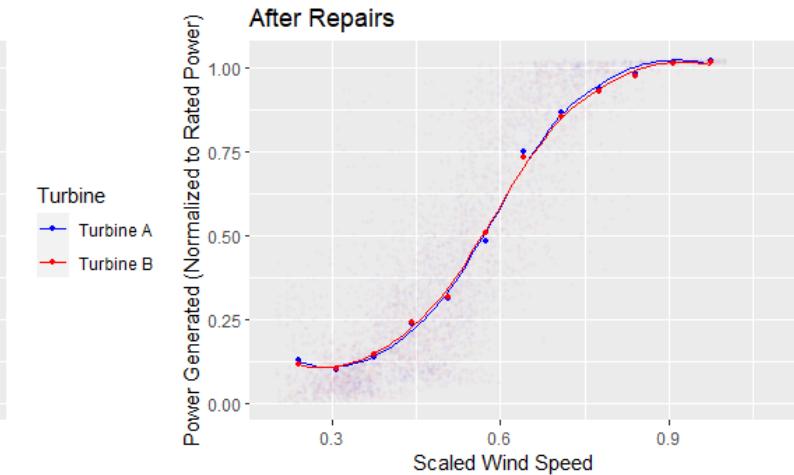
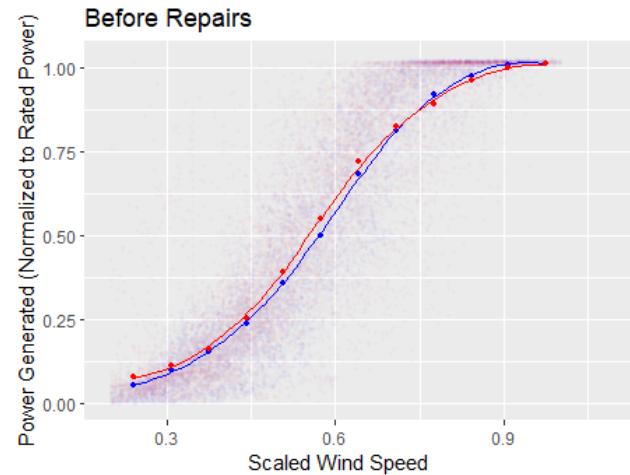


# Turbine Data Comparative Analysis

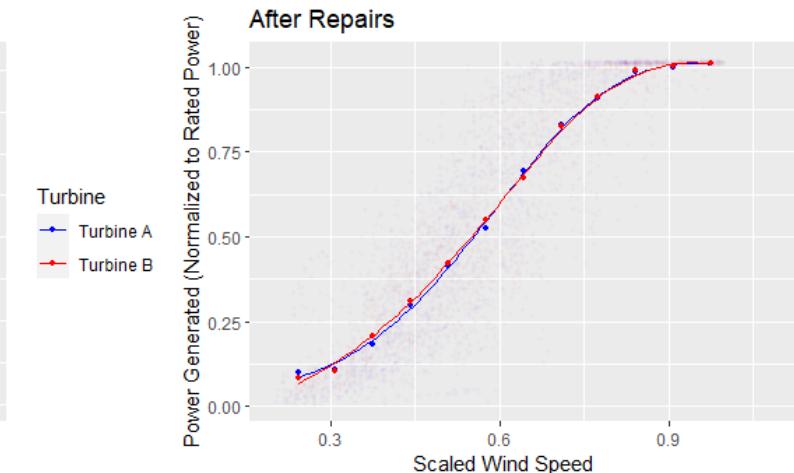
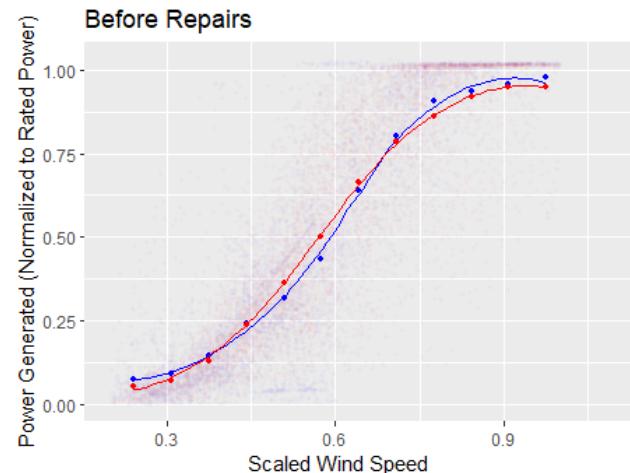


- Some observations showed below expected performance during below freezing temperatures which affects the wind speed bin mean power output in some of the curves.
- This data was kept in the analysis since air temperature was also used within a predictor variable in the model.
- Additional data processing is being developed for lower wind speeds.

Power Curve (Month 1 ) Paired Turbines A and B



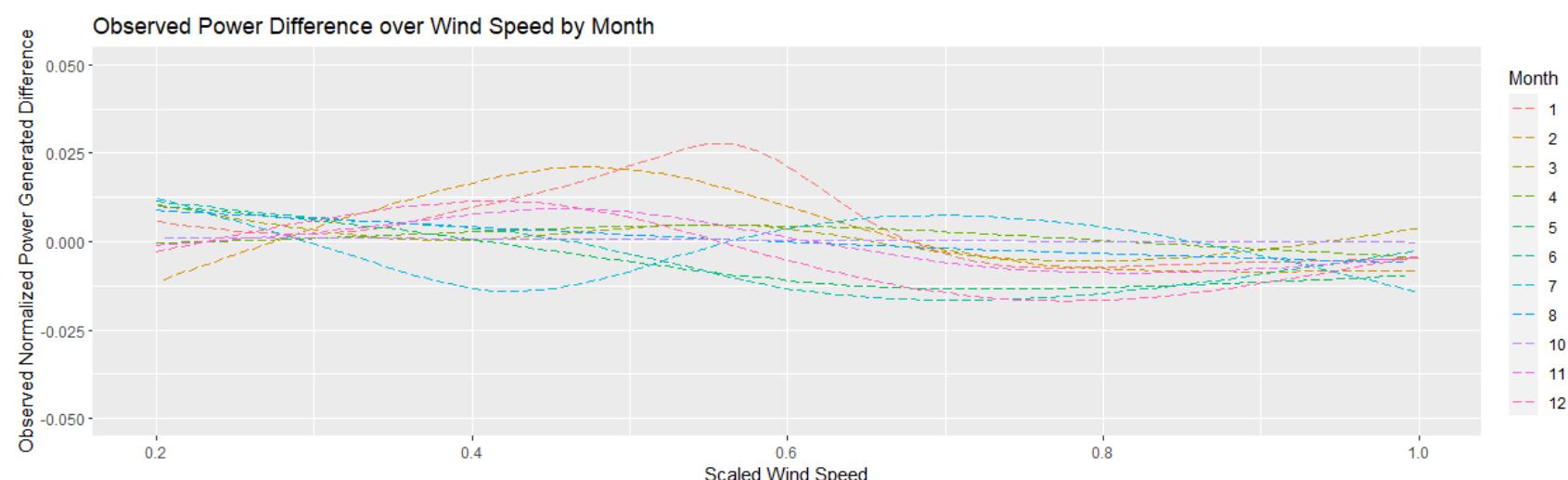
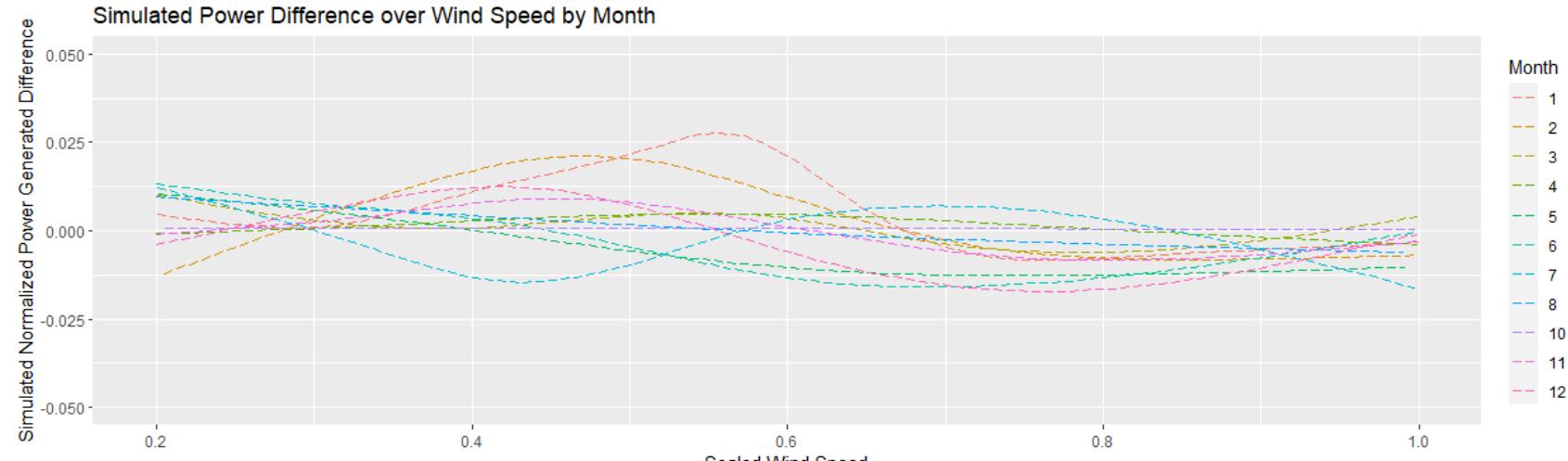
Power Curve (Month 2 ) Paired Turbines A and B



# Turbine Data Comparative Analysis



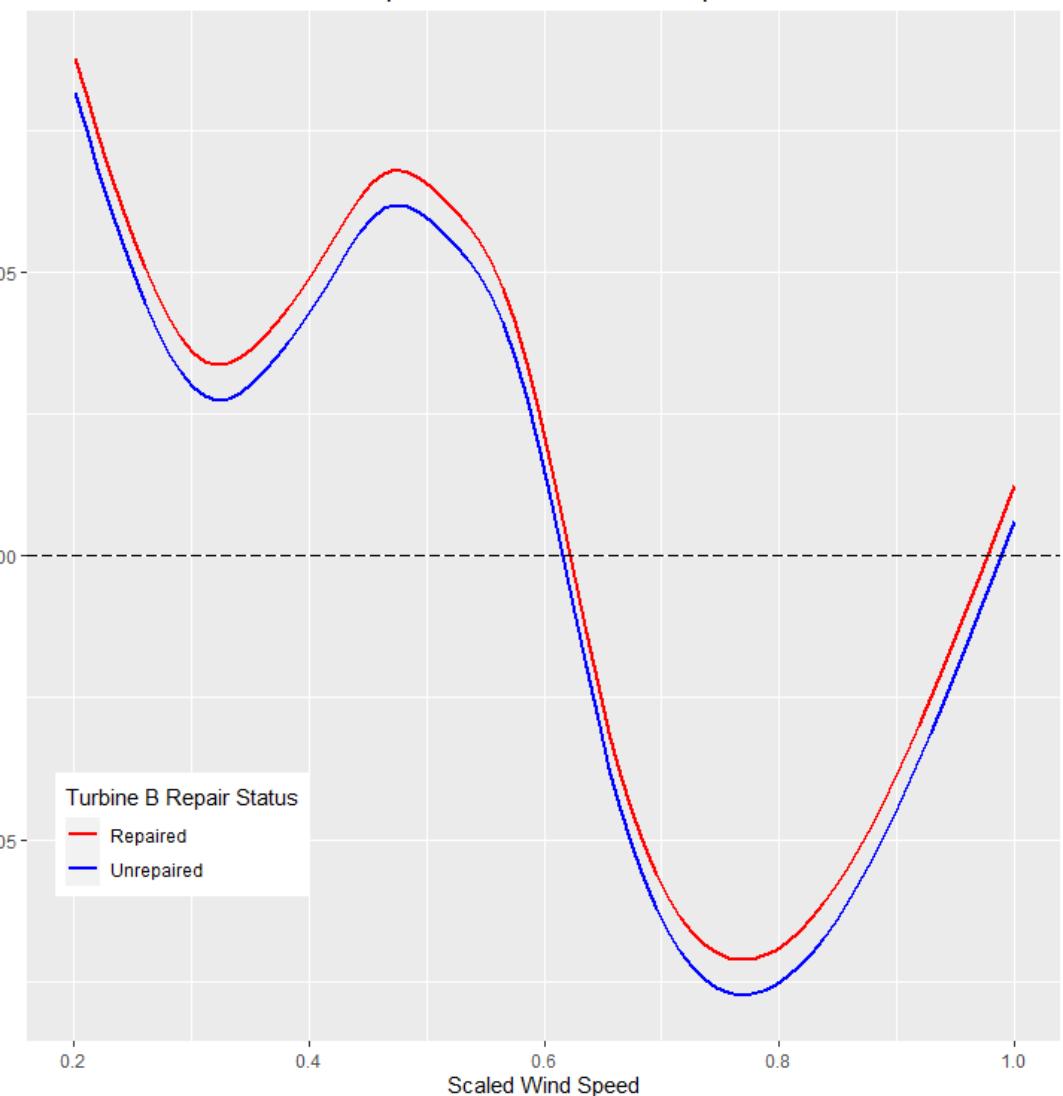
- Once a model was fitted and assumptions were checked, the model was validated by comparing simulated data from the model to the observed data



## Turbine Data Comparative Analysis

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

Power Difference over Wind Speeds Before and After Repairs



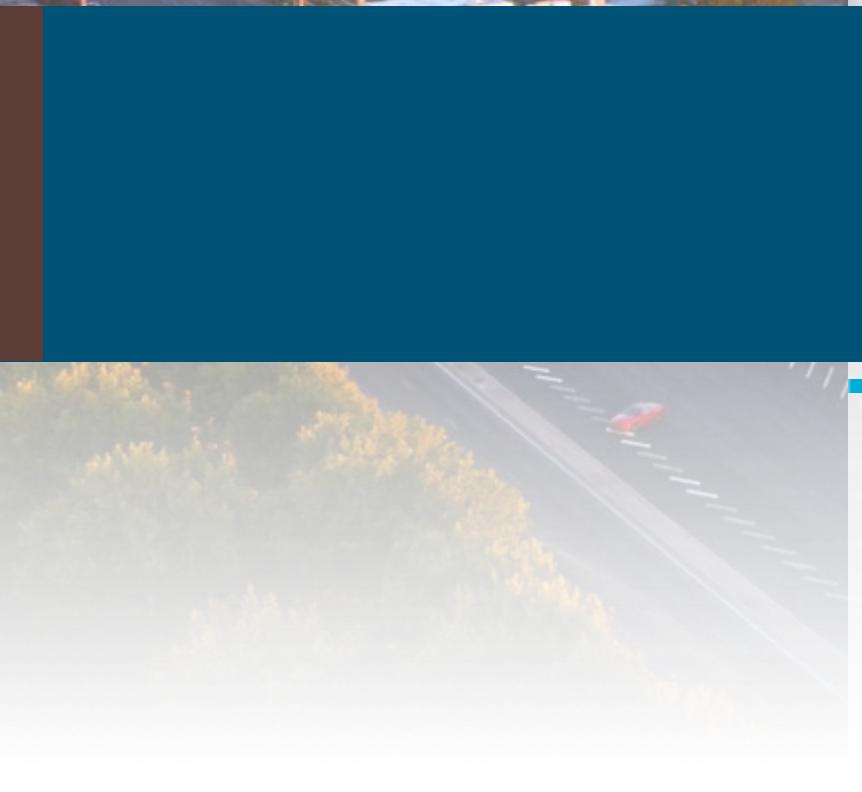
## Results Interpretation



- 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 analysis of the field data showed relatively constant dimensional power loss across region 2 operation, gradually decreasing as rated power is approached.
- The field data analysis showed a peak power loss much lower than the model predictions in repaired versus unrepairs power at lower wind speeds.
- The disagreement in the magnitude of power loss 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 believable, and the analysis showed both that there was an improvement in power with the repairs that was statistically significant.
- Despite the differences between the magnitude of power loss due to LEE from the model predictions and the field data analysis, the observation that both data sets show power loss in region 2 is encouraging toward future model improvements.
- Future work will include continued analysis over a longer time period and using more turbines.
- 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

Sandia National Laboratories is a multimission laboratory  
managed and operated by National Technology & Engineering Solutions  
of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc.,  
for the U.S. Department of Energy's National Nuclear Security Administration  
under contract DE-NA0003525.



© 2020

# References



- [1] Bech, Jakob & Hasager, C. & Bak, Christian. (2018). Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science*. 3. 729-748. 10.5194/wes-3-729-2018.
- [2] Keegan, Mark & Nash, David & Stack, Margaret. (2013). On erosion issues associated with the leading edge of wind turbine blades. *Journal of Physics D: Applied Physics*. 46. 383001. 10.1088/0022-3727/46/38/383001.
- [3] Sareen, Agrim & Sapre, Chinmay & Selig, Michael. (2014). Effects of leading edge erosion on wind turbine blade performance. *Wind Energy*. 17. 10.1002/we.1649.
- [4] 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. *Torque from Wind 2016*, IOP Journal of Science Conference Series. N. p., 2017. Web. doi:10.1088/1742-6596/753/2/022013.
- [5] 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>.
- [6] Ehrmann, R.S., et al., Realistic Leading-Edge Roughness Effects on Airfoil Performance, in 31st AIAA Applied Aerodynamics Conference. 2013, American Institute of Aeronautics and Astronautics.
- [7] Ehrmann, R.S., et al., Effect of Surface Roughness on Wind Turbine Performance. 2017, Sandia National Laboratories: Albuquerque, NM. p. 114. SAND2017-10669.
- [8] Ehrmann, R.S. and E.B. White, Influence of 2D Steps and Distributed Roughness on Transition on a NACA 63(3)-418, in 32nd ASME Wind Energy Symposium. 2014, American Institute of Aeronautics and Astronautics.
- [9] 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.
- [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
- [11] Kelley, Christopher Lee. Aerodynamic design of the National Rotor Testbed. 2015. SAND-2015-8989.
- [12] Eisenberg, D., Laustsen, S., Stege, J, Leading Edge Protection Lifetime Prediction Model Creation and Validation, Wind Europe, Hamburg, 27 to 29 September, 2016, PO.078g
- [13] Wilcox, B. and E. White, Computational analysis of insect impingement patterns on wind turbine blades. *Wind Energy*, 2016. 19(3): p. 483-495.
- [14] "NWTC Information Portal (OpenFAST)," ed. <https://nwtc.nrel.gov/OpenFAST>. Last modified 14-June-2016; Accessed 05-December-2019
- [15] "NWTC Information Portal (TurbSim)," ed. <https://nwtc.nrel.gov/TurbSim>. Last modified 5-Jan-2018; Accessed 04-December-2019
- [16] J. Berg et al., Scaled Wind Farm Technology Facility Overview, in AIAA SciTech 32nd Wind Energy Symposium, 2014.
- [17] Adams, B.M., Bauman, L.E., Bohnho, W.J., Dalbey, K.R., Ebeida, M.S., Eddy, J.P., Eldred, M.S., Geraci, G., Hooper, R.W., Hough, P.D., Hu, K.T., Jakeman, J.D., Maupin, K.A., Monschke, J.A., Rushdi, A., Swiler, L.P., Vigil, D.M, and Wildey, T.M., 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. Updated November 2016 (Version 6.5).