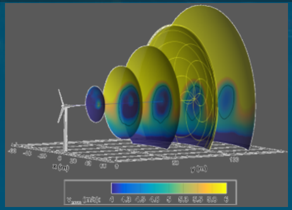
SAND2023-03973C

Sandia National Laboratories

Additively Manufactured, System Integrated Tips (AMSIT) for Wind Turbine Blades



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WETZEL WIND

Brent C. Houchens, Daniel R. Houck, Helio Lopez, David C. Maniaci, Graham Monroe, Joshua A. Paquette, Sal Rodriguez, Evan G. Sproul,
Julia N. Tilles, Nathaniel B. deVelder, Michelle Williams

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James A. Payant, Kyle K. Wetzel

WESC 2023, Glasgow, Scotland, UK

U.S. DEPARTMENT OF ENERGY NNSA

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Team

Sandia Core Research Team

- James Cutler, Aerodynamic design tools
- Nathaniel B. deVelder, OLAF/OpenFAST Simulations
- Daniel R. Houck, Field experiment design
- Helio Lopez, Materials selection
- David C. Maniaci, Aerodynamics design
- Joshua A. Paquette, Loads analysis, Stakeholder lead
- Salvador B. Rodriguez, Computational fluid dynamics
- Evan G. Sproul, Technoeconomic analysis
- Julia N. Tilles, Electrostatics and lightning
- Carsten Westergaard, SME Advisor, Industrial perspective
- Michelle Williams, Materials test lead (lightning and mechanical)
- Brent C. Houchens, PI

Sandia SWiFT Team

- Paolo Caserta, Miguel Hernandez, and Lee Wilks, Blade cutting and modifications
- Johnny Luevano - Field site logistics

Sandia Analysis and Design Support Team

- Chris Kelley, Proposal developer, blade measurement SME
- Amy Chen, Meshing
- Neal P. Grieb, Meshing
- Graham Monroe, CFD
- Paul Clem, Lightning SME

Sandia Analysis and Design Support Team

- Henry Lorenzo and Casey Sanchez, 3D blade scanning

Stratasys Team

- Jalel Nadji, Dave Phillips - Aerospace AM consultants
- (formerly Trey McIntosh)

Wetzel Wind

- Kyle Wetzel, Jim Payant - Wind blade design experts

Team Summary

20+ Sandians, 5+ External partners, 10+ Stakeholder Advisors

Objective, Motivation and Technologies Considered

US Department of Energy AMO Sponsored project with the Objective to:

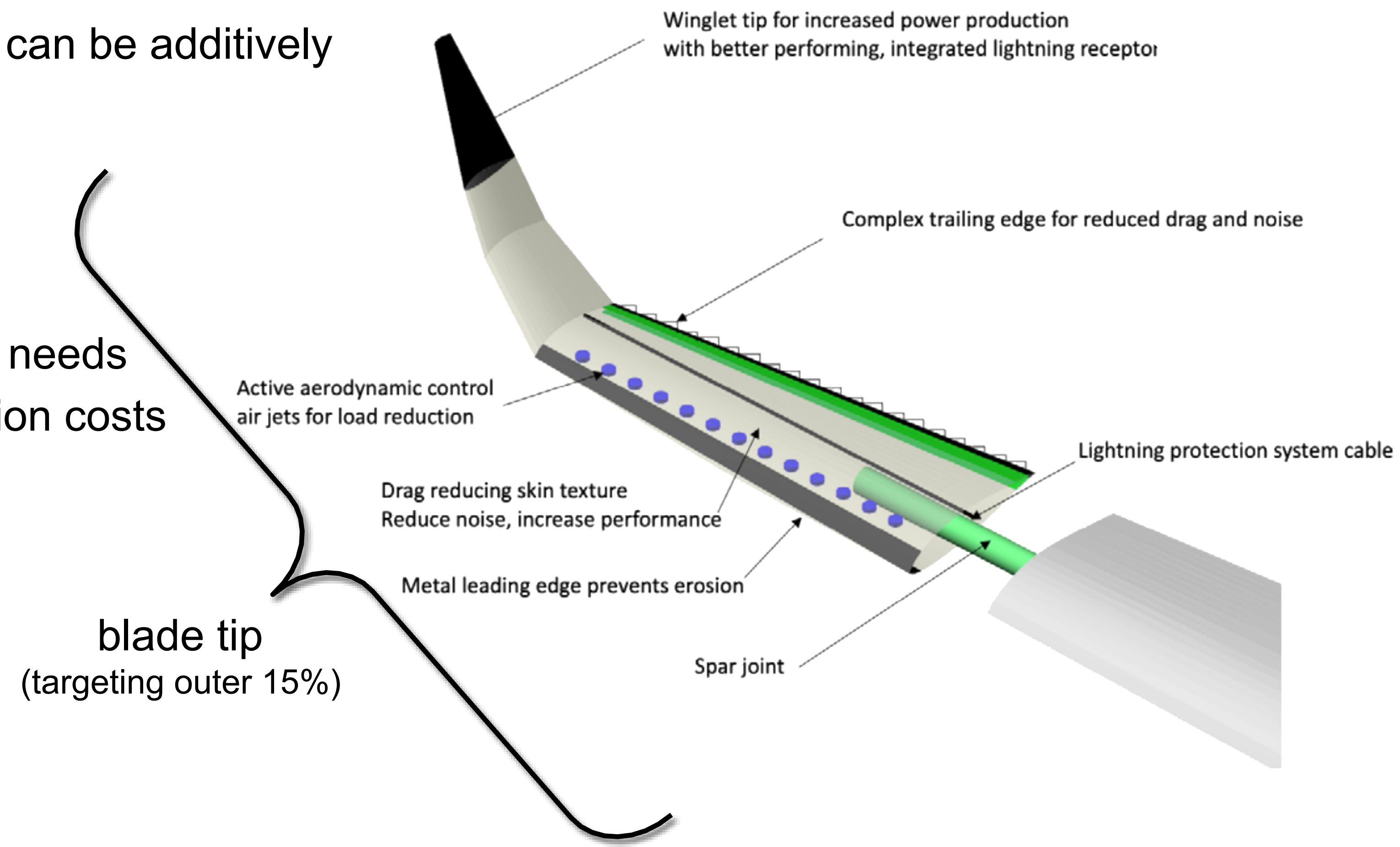
- Demonstrate that a wind turbine blade tip can be additively manufactured

Motivation

- replace or repair damaged tips
- explore design modularity for site specific needs
- blade segmentation to reduce transportation costs
- integrate technologies to reduce LCOE

Technologies considered

- surface texturing for drag and aero-acoustic improvements
- integrated lightning protection
- winglet for increased rotor efficiency
- improved erosion protection



Parallel Design Paths for kW and MW-scales

Primary Project Objective:

- **print new tips for kW-scale blades and complete a flight test**
  - **prove that AM is viable for wind blades**
  - **measure a power increase (hopefully)**

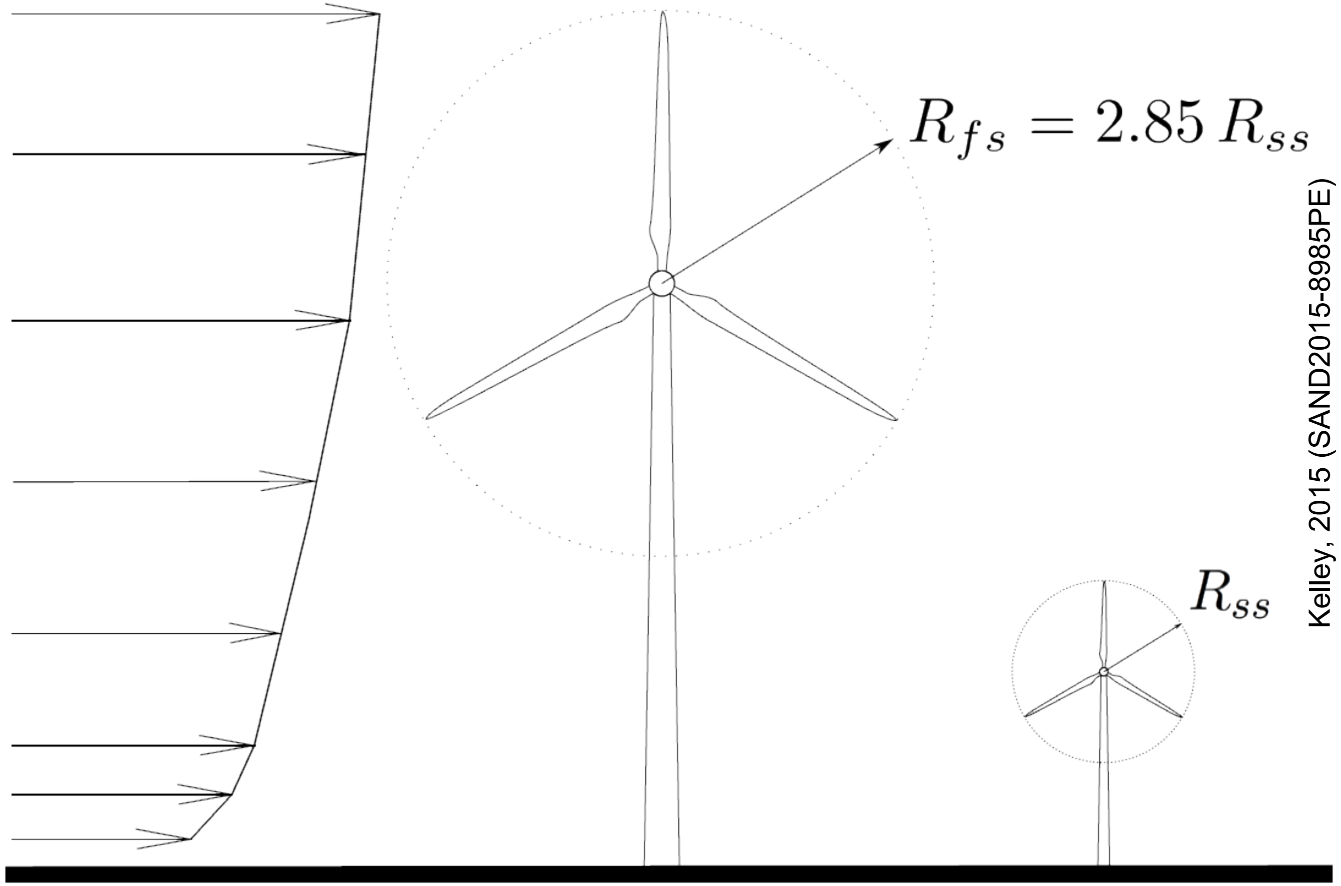
Secondary Objectives:

- consider design questions for modern MW-scale blades of more impact to wind industry

“R&D SWiFT-scale” vs MW-scale parallel path

- MW-scale is a paper-only design
  - interesting additional considerations due to flexibility of MW scale blades, but also more potential impact (potential solution for reduced CapEx and OpEx of 100 m+ blades)

Example: GE37c versus kW-scale blade



Kelley, 2015 (SAND2015-8985PE)

Field-test Opportunity at SWiFT Site

~3 month flight test

- 3 modified blades
- regular inspections of tip joints
- ideal configuration is side-by-side test
  - a1 turbine flying original blades and b1 turbine flying the AMSIT blades

Target measurements

- power production
- blade noise
- post-test assessment of material and joints

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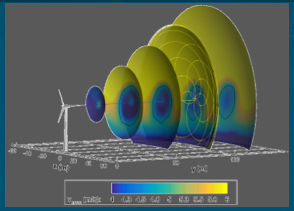
AMSIT Technoeconomic Analysis



WORK BY

Evan Sproul

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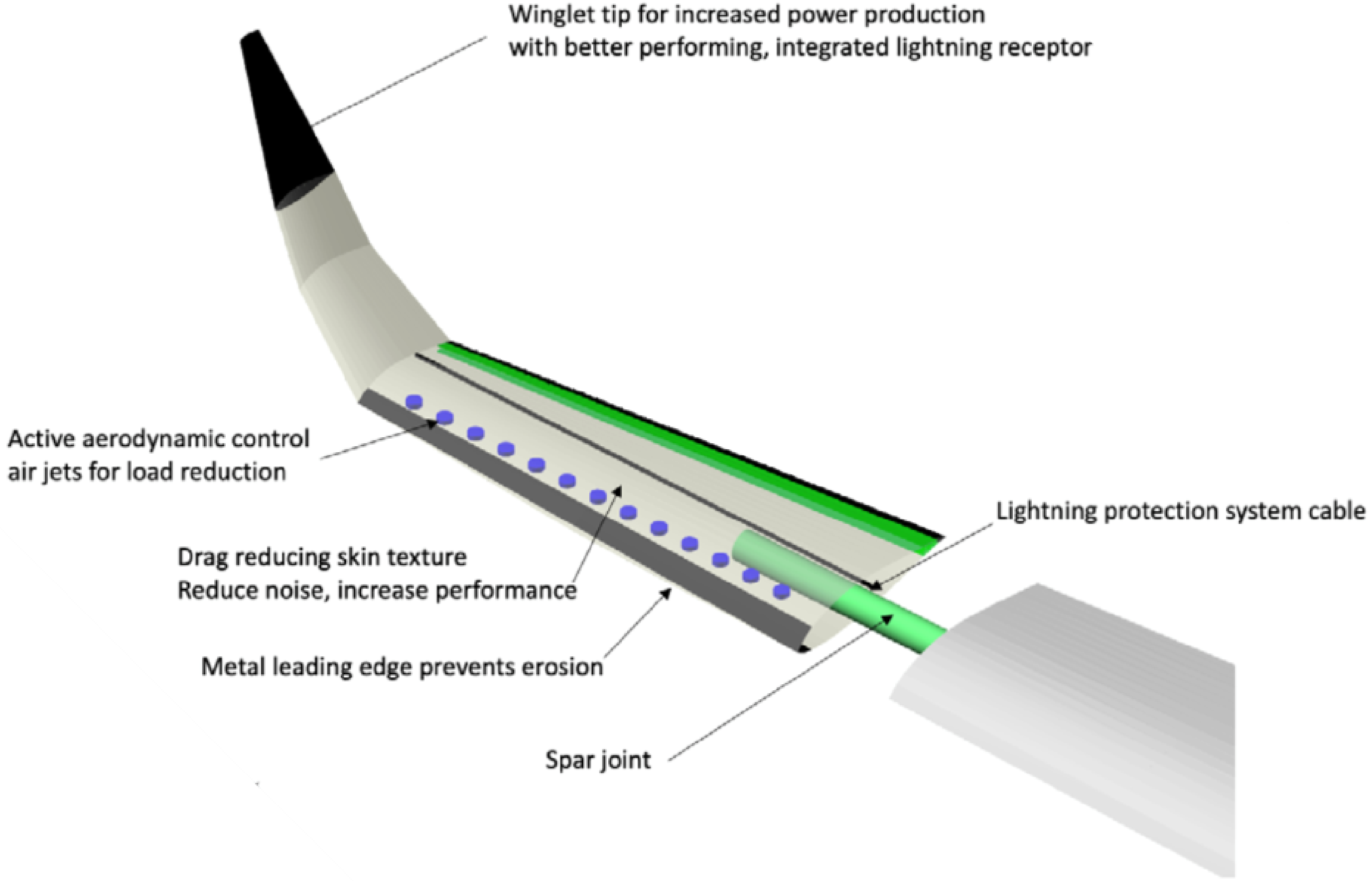
Scope of TEA

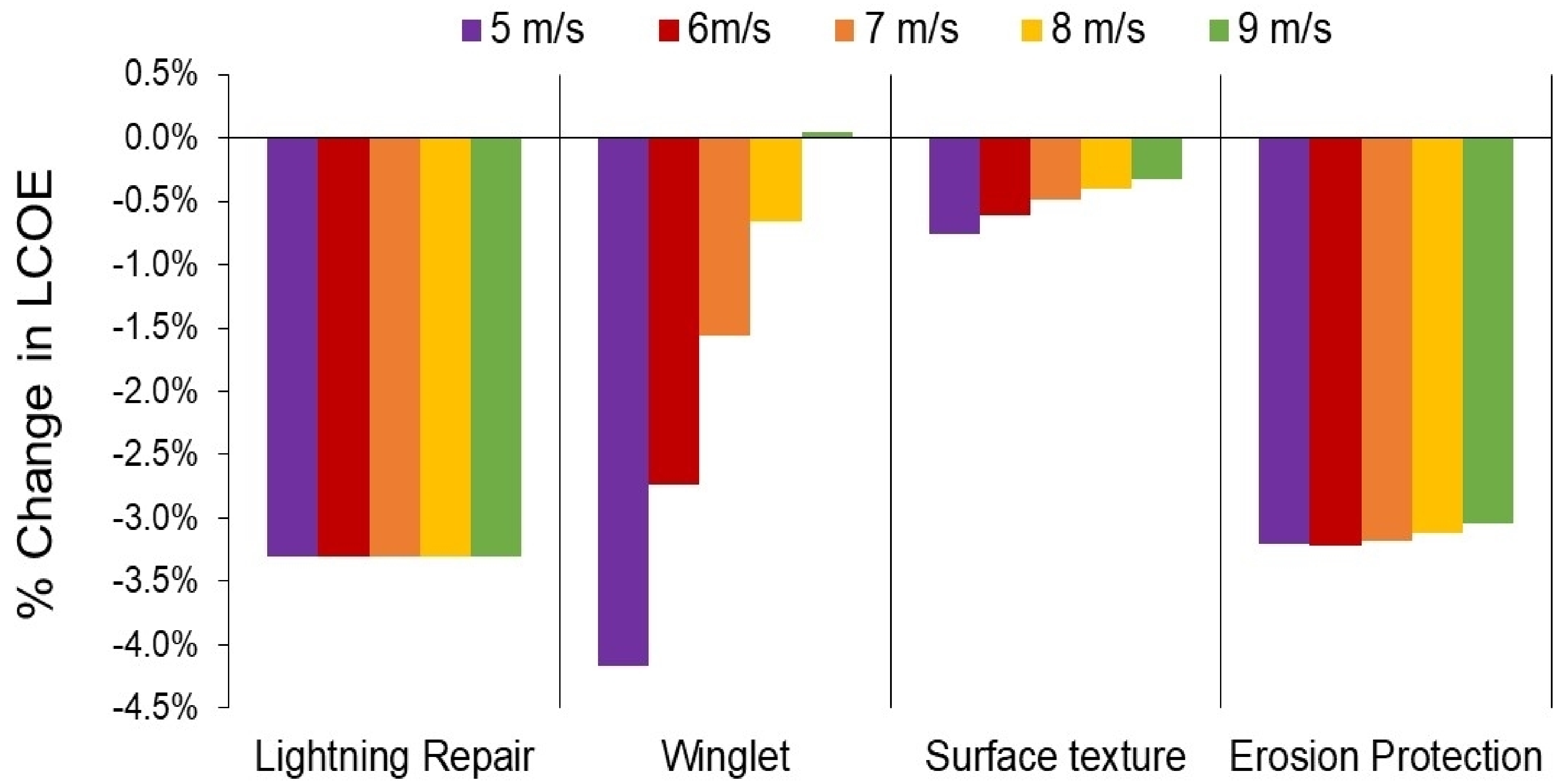
Objective: Assess different technology impacts on LCOE

Four technology impacts considered

1. Winglet aerodynamics
2. Surface texturing
3. Lightning protection and repair
4. Leading edge erosion protection



Guiding kW-scale Results

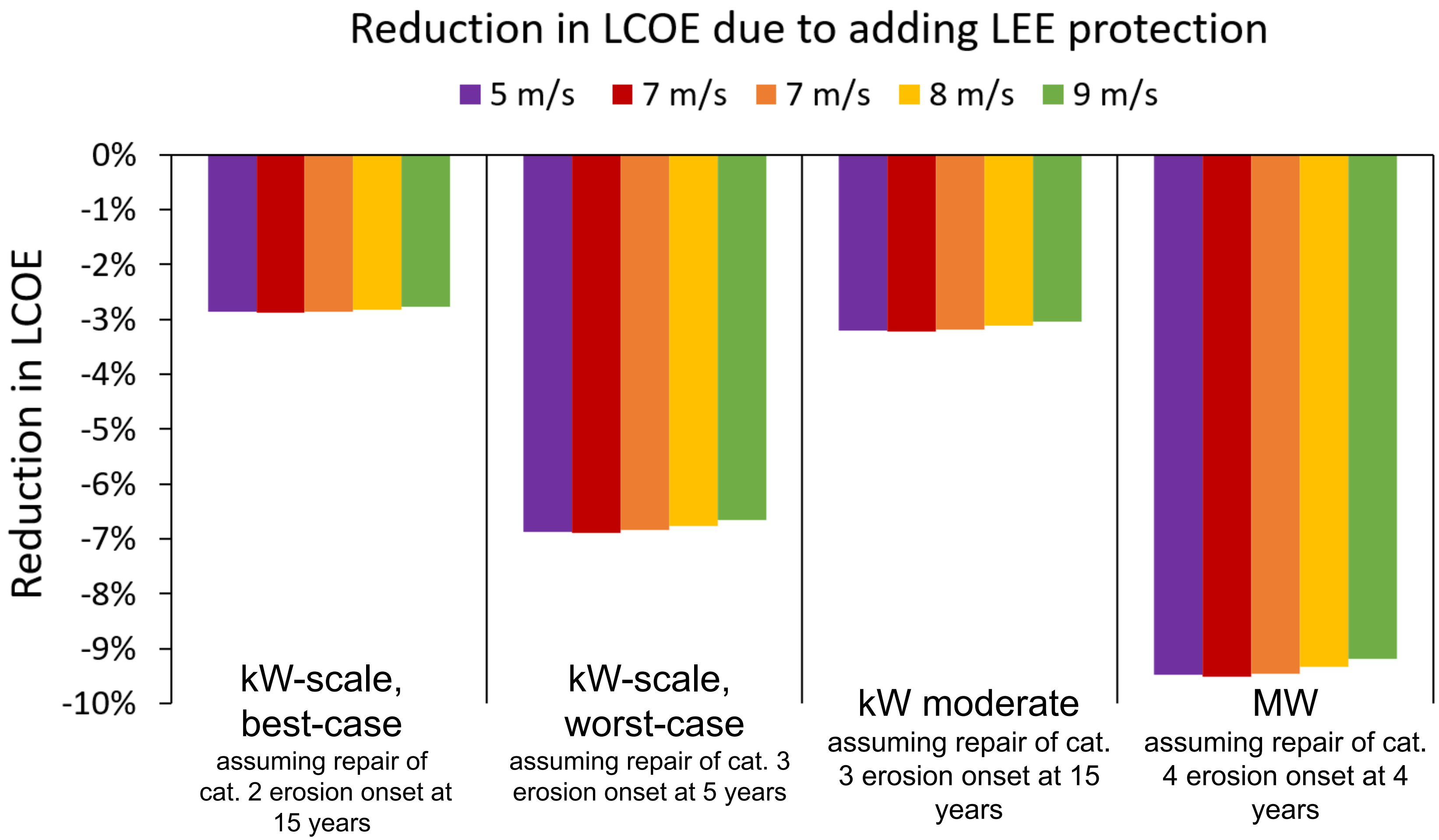


⇒ expecting at least a 4% LCOE reduction for kW-scale machines with the integrated AMSIT solution

Erosion Reanalysis with Separate kW and MW-Scale Considerations

Sensitivity to various erosion rates considered for different scale machines

- input from SWiFT staff
  - no known erosion repairs for kW-scale machines at SWiFT, though run time is low



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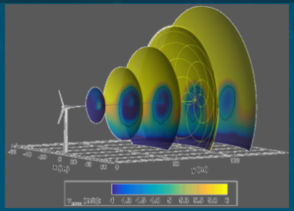
AMSIT Aerodynamic Design



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WORK BY

David Maniaci, Sal Rodriguez and Team

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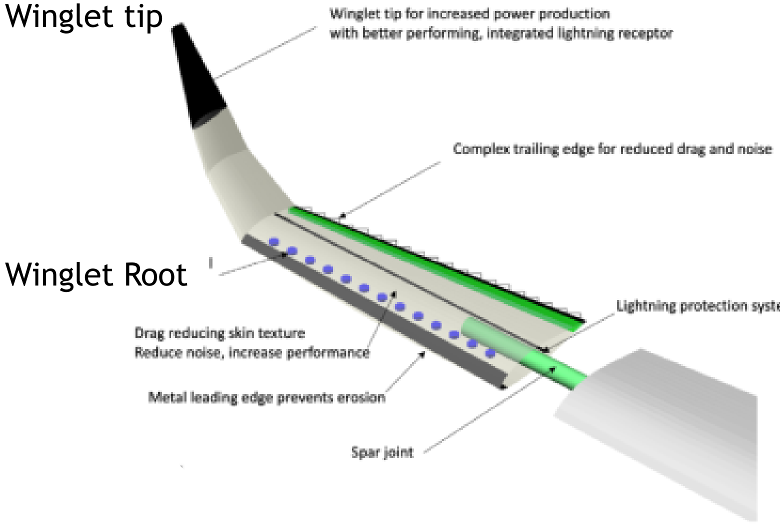
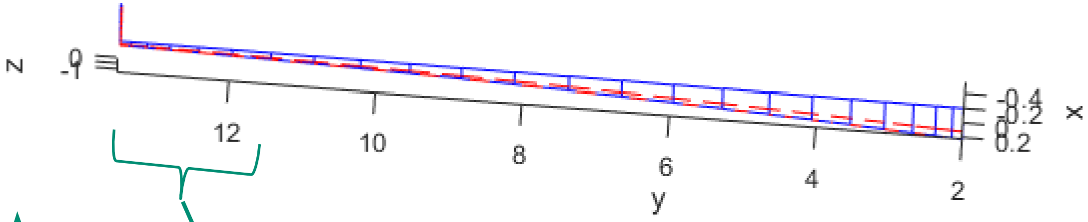
Winglet Concept and Modeling for AMSIT



blade tip

Blade model with winglet using lifting line model of circulation.



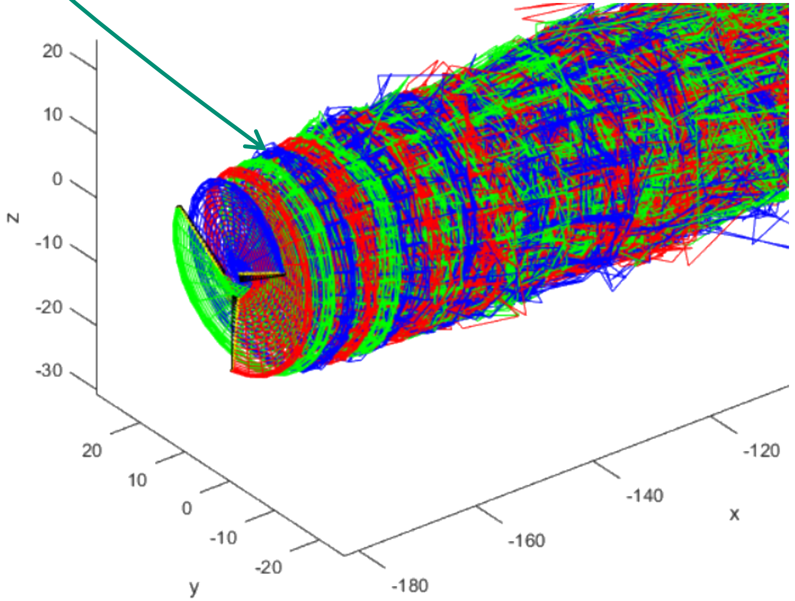
Concept

Design + Model

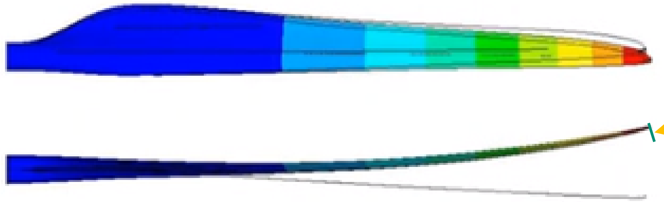
Aerodynamic Analysis

Loads Analysis

Free-vortex wake method model of the wake and rotor interaction.



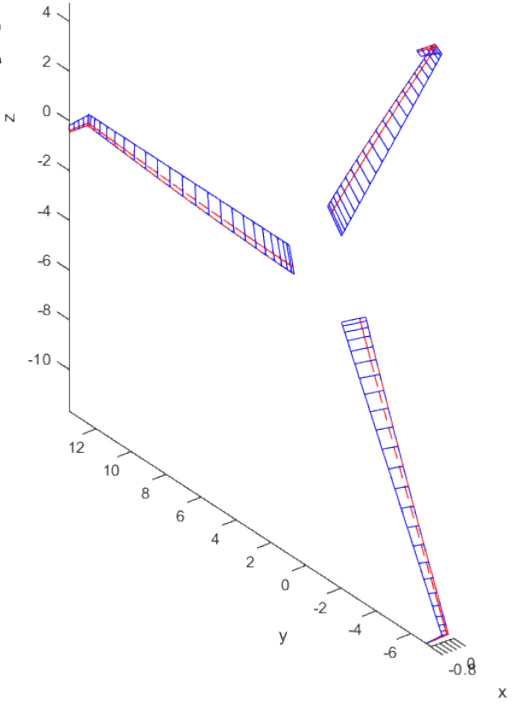
NRT deformation with closest approach loading.
Note: winglet must face upstream to avoid tower impact

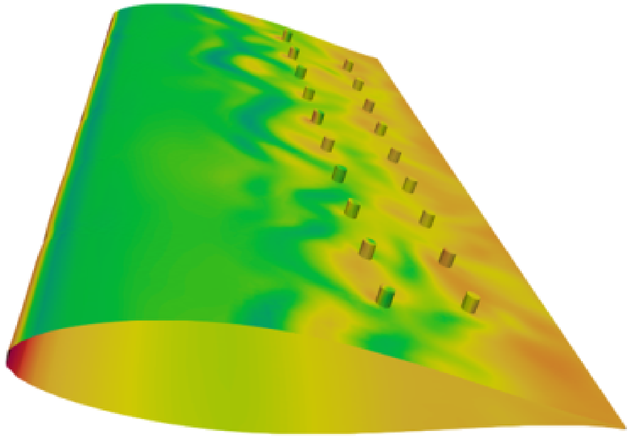


Upwind winglet

Figure 1. Deformed Shape of Blade Under Tower Closest Approach Loading

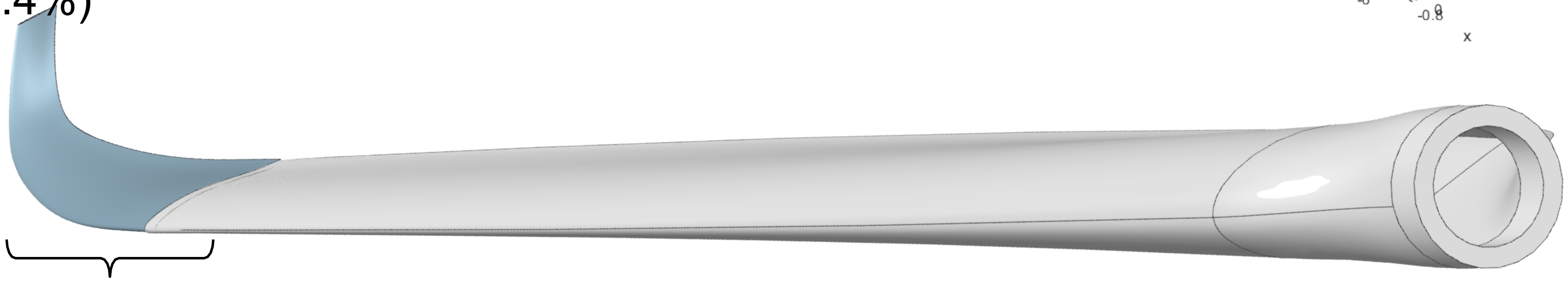
kW-Scale Basic Upwind Winglet





Initial kW-scale winglet design*

- winglet height = 4% of rotor radius in upwind direction (height = 0.54m)
- Starts at 100% of original blade span, ends 100.3% span, slightly less than 90 degree cant angle, slight swept back
- 3.6% power increase vs. baseline, thrust increase (~2.4%)

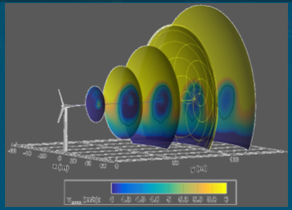


More recent advanced design is half the size and shows 4.4% region 2 power increase for no increase in peak root out of plane bending moment

- selected for flight test to balance safety and performance

*Maniaci, D.M., Houck, D.R., Cutler, J.J. and Houchens, B.C., Winglet Design for a Wind Turbine with an Additively Manufactured Blade Tip. *Proc. of 2023 AIAA*

Additive Manufacturing



WORK BY

Josh Paquette, Helio Lopez,

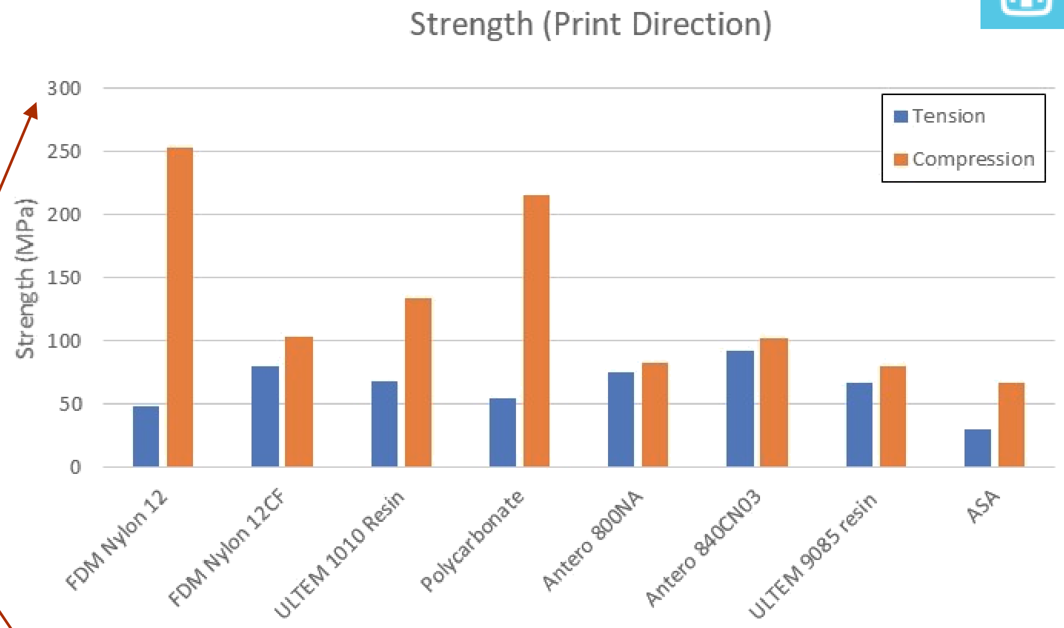
Michelle Williams and Jim

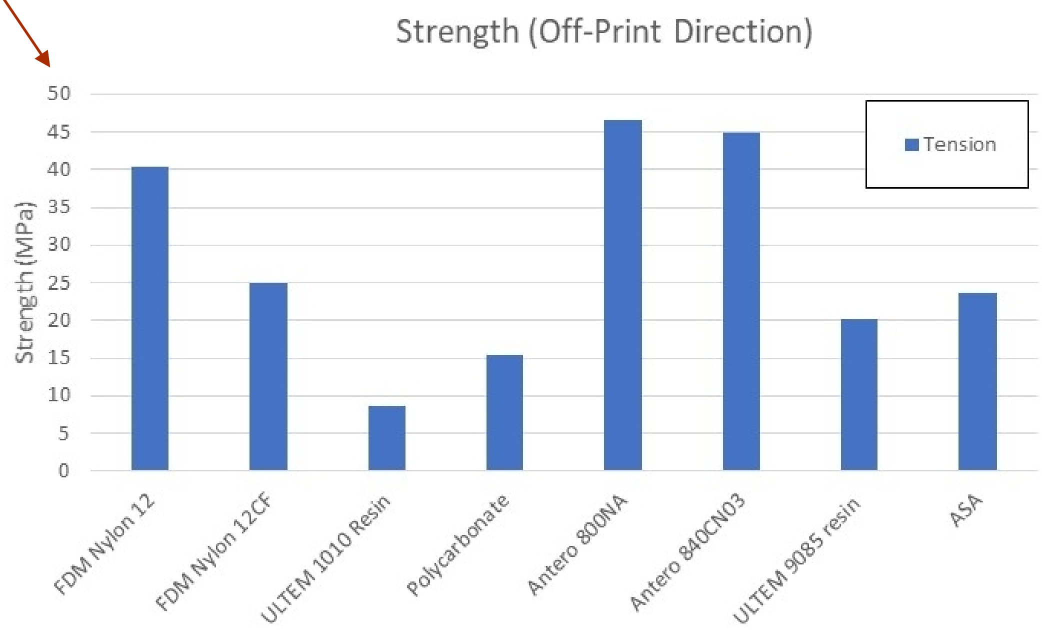
Payant

Material Considerations

- Strength considerations drove down-select to 4 potential materials
  - considered strength, stiffness, toughness (proxy for fatigue), thermal expansion and T_g effects
  - selected
    - two electrical insulators
    - two with conductive fibers (not continuous - not a true conductor)
- Print direction is a critical consideration
  - factors of 2-3x difference in tensile strength are common
- Additional down-select to be made by
  - print quality
  - lightning tests
  - strength and fatigue tests

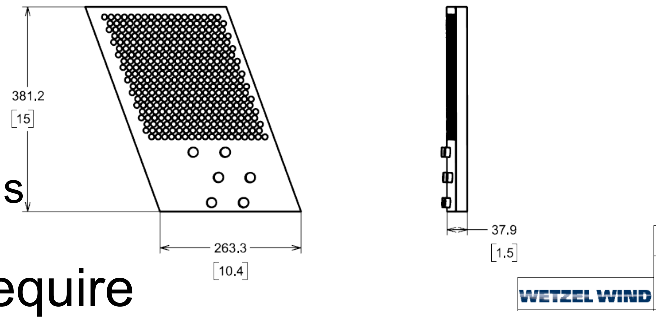
note scales

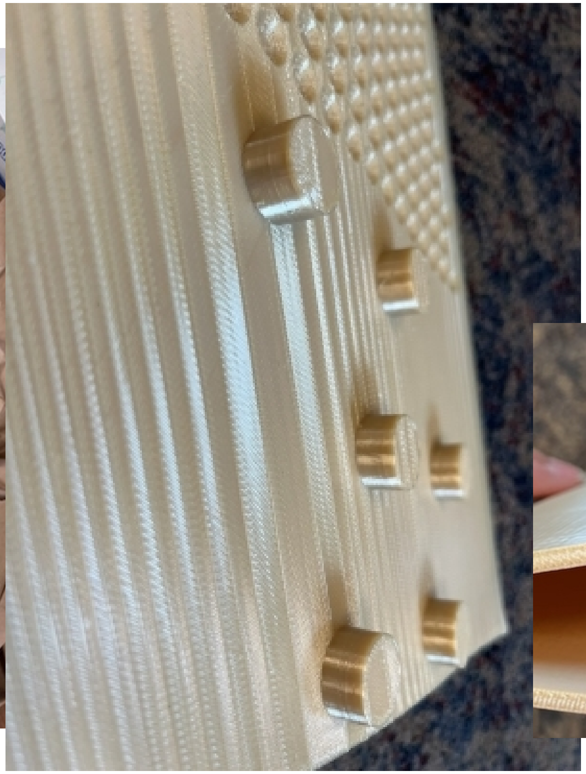


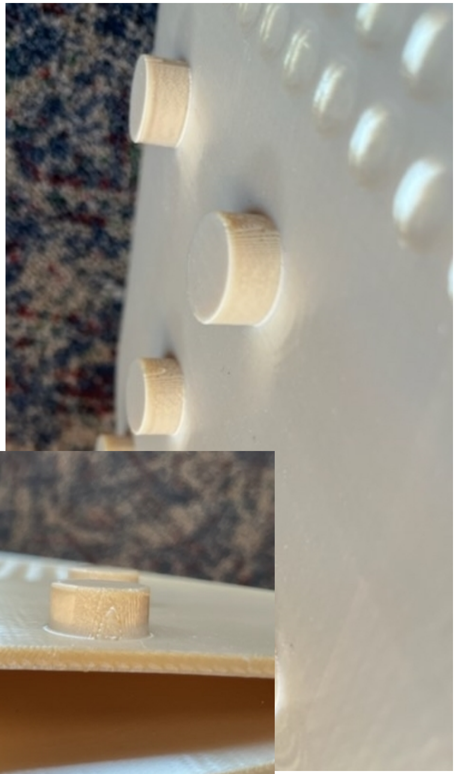


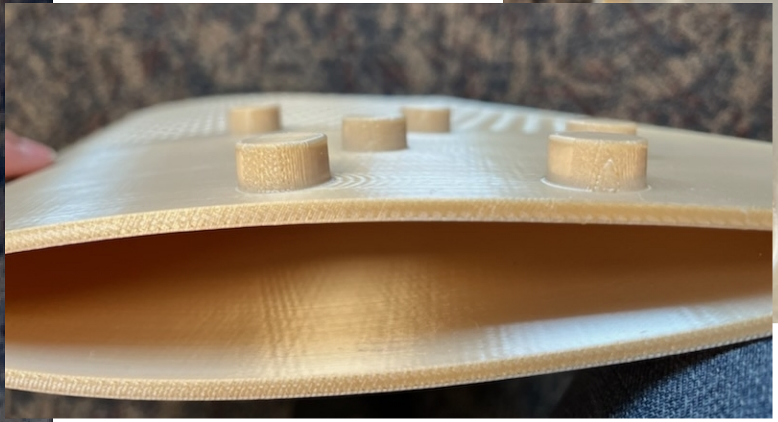
Test Prints for Surface Quality and Rigidity

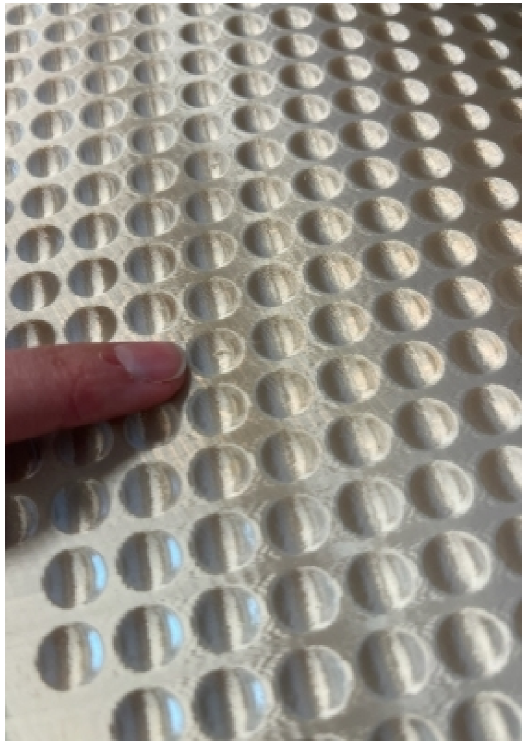
- First test prints in Ultem from Stratasys
  - 1 material in 2 thicknesses, each in 2 print orientations
- Most favorable strength direction would require secondary finishing at least on low pressure side



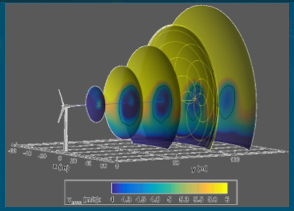








Lightning Tests



WORK BY

Michelle Williams, Brent Houchens and Julia Tilles

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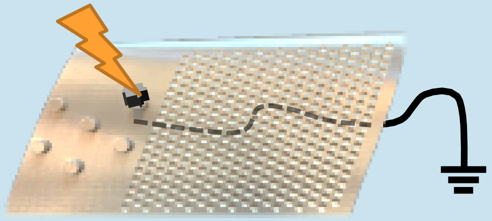
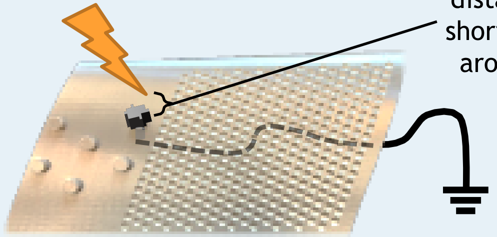
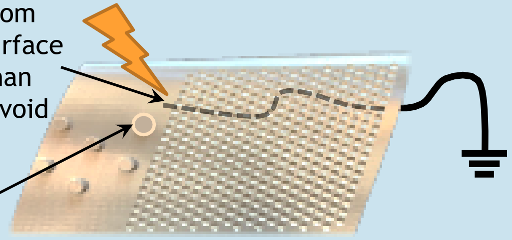
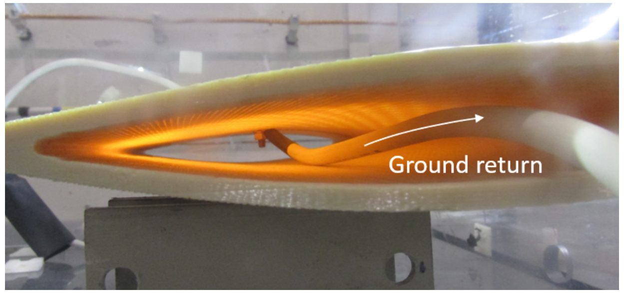
Lightning Test Concepts

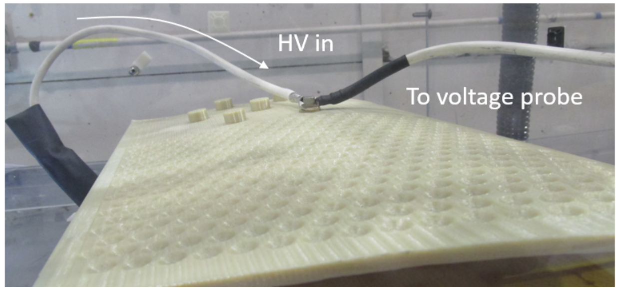
- testing both a non-conductive and mixed (conductive fibers, non-conductive

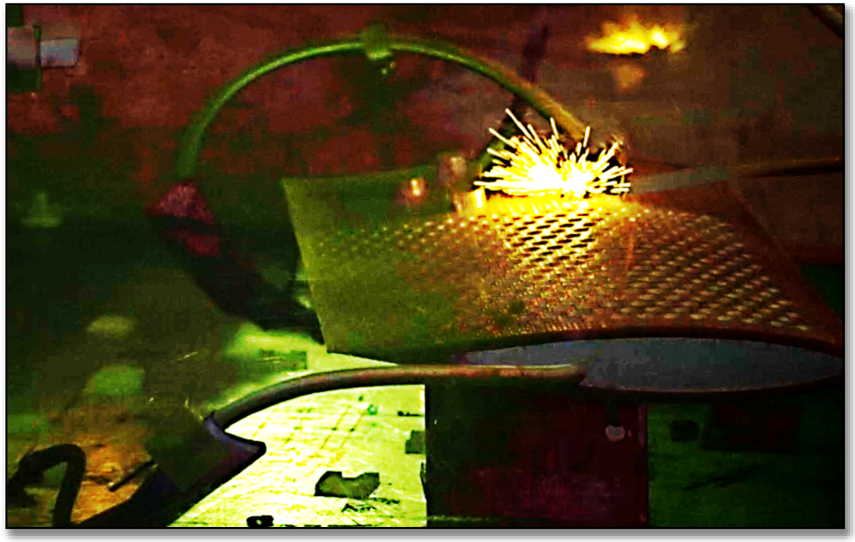
Lightning Test Concepts	Configuration
Initiation at LPS: Strike (outside surface) which is grounded by a bolt (exterior) and nut (interior) and ground wire passing through interior open space.	
Initiation "near" LPS: Same grounding as above, through the interior open space. When strike "close" to LPS (relative to breakdown potential), expect surface tracking across top to bolt. At some farther distances, current may pass through material instead.	
LPS Removed, Dielectric breakdown test: No LPS, so voltage is increased until current is forced through AM material	

Initial Practice Strikes

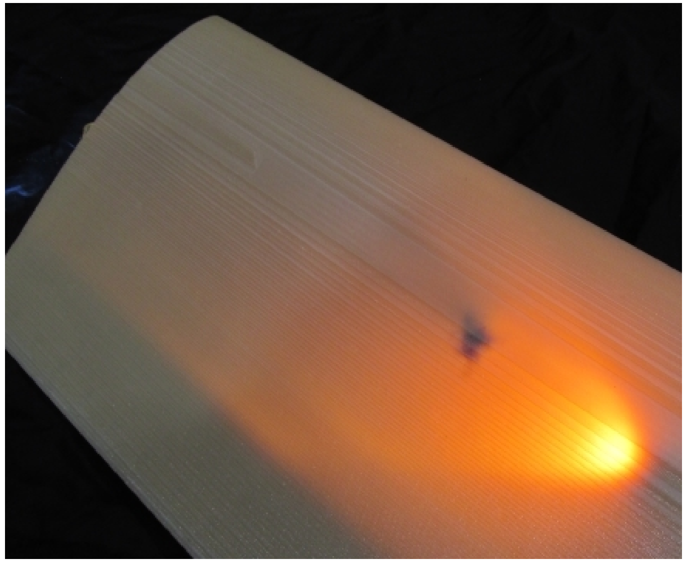
- Setup for LPS functioning
  - sparking at contact point, but good down conduction
    - no visible damage

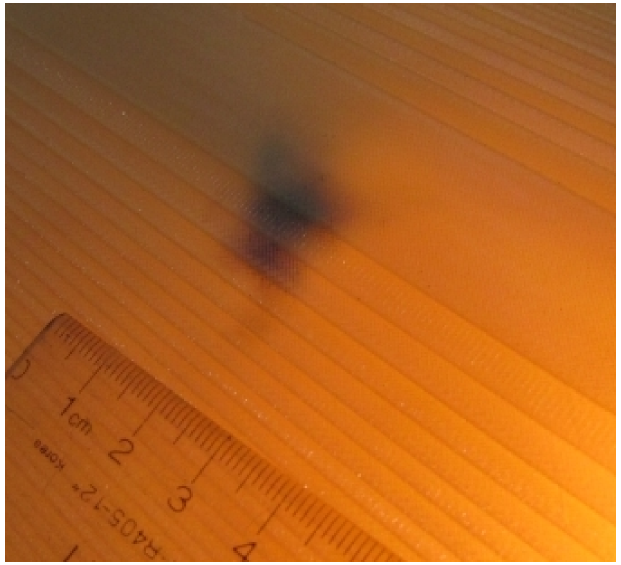






- Dielectric breakdown through material
  - modest damage with high voltage (kV) and milliamp current
  - switching to kA scale current in next tests





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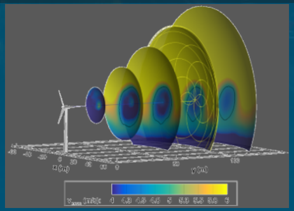
Current Work: Prep for Field Tests



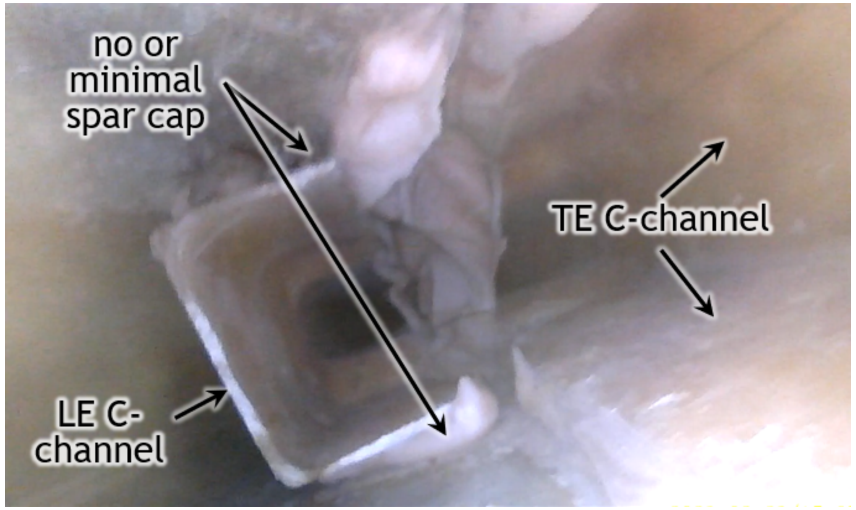
WORK BY

SWiFT Team including Paolo Caserta, Miguel Hernandez, and Lee Wilks and Brent Houchens

Blade-cut Strategy

- Skin-cut with retention of internal structure deemed best option from PIRT-like analysis
  - blades have significant internal structure for a bolt-on design
  - adds a new capability for testing novel tip designs

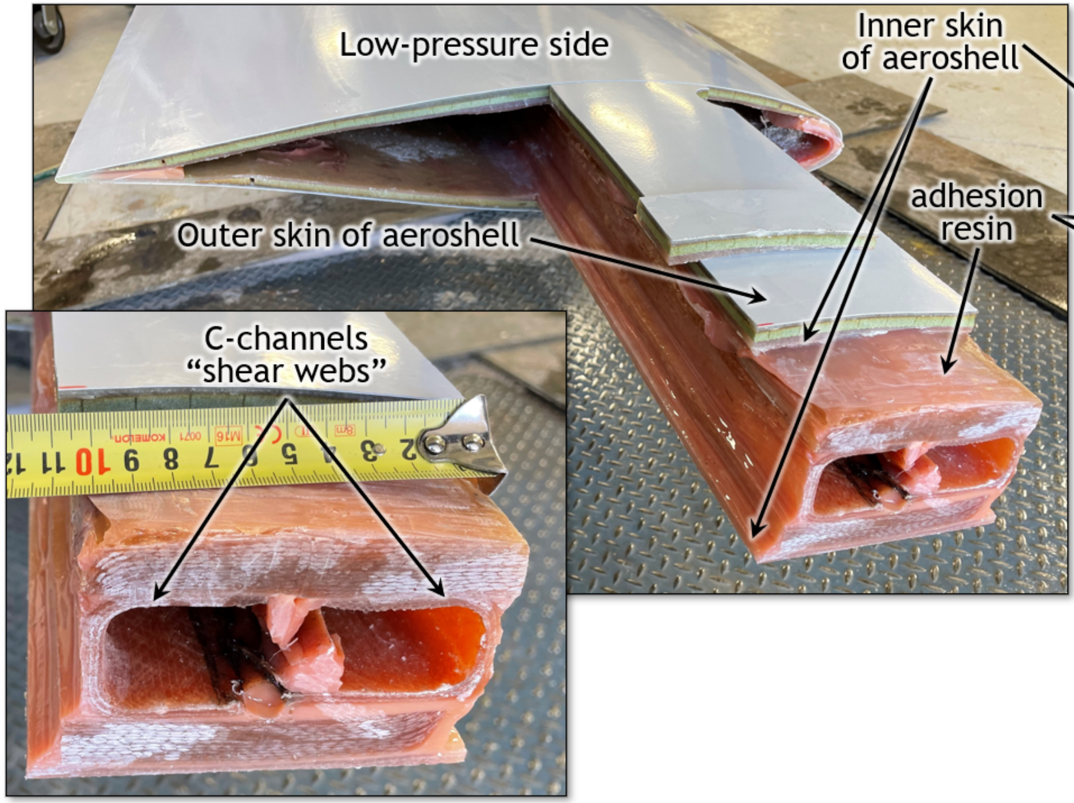
- Borescope verified internals on all three blades are similar

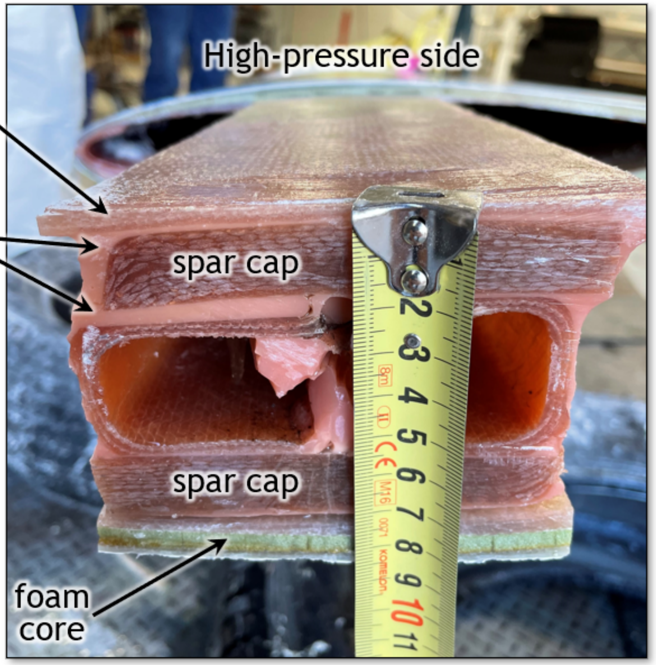


- Targeting cut of one b1 blade this spring, and verification of design of bolt-on tip this summer
  - cut remaining blades once design is verified
  - field testing late 2023 to early 2024

First blade cut

- Cut one 13 m blade to determine mounting options
  - targeting a bolt-on, interchangeable tip
    - could allow multiple tip design tests for future





Merging Designs for Final Down-select

- High current lightning tests currently underway
  - one nonconductive material and one conductive material
    - goal is to down-select one material based on observed damage

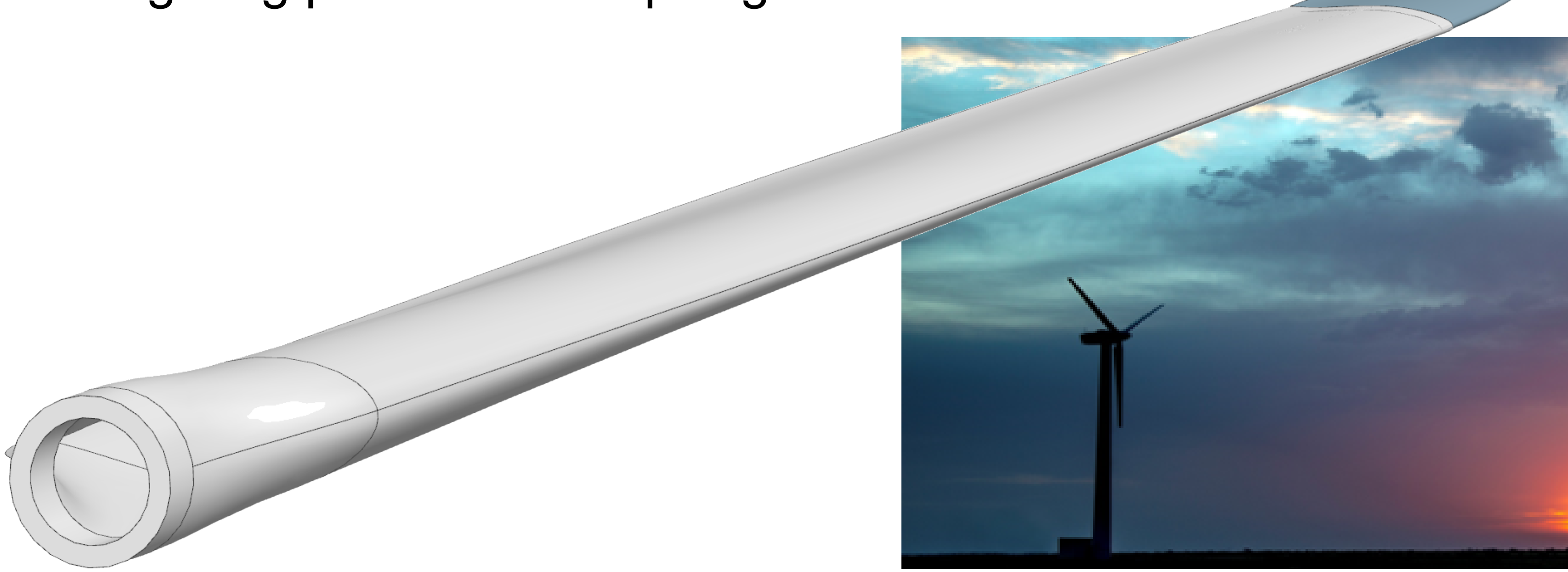
- Porting final aero-design to structural analysis codes
  - investigating loads envelop
  - designing turbine controls

- Investigating leading edge protection options
  - combining traditional sheet metal manufacturing and AM provides promising solutions

- Structural mounting design by Wetzel Wind
  - determines feasibility of a hardware-based connection (as opposed to adhesives)
  - goal is to allow interchangeable tips (base blades can be recovered after AMSIT)

Take-aways to Date

- AM has advanced to the brink of major impact on the wind industry
    - better and broader material properties, consistency and increased scale
- over a 30-year lifetime, improvements in lightning protection, leading edge erosion protection, and aerodynamic gains from winglets and surface texturing show a potential for
    - at least 4% LCOE reduction for kW-scale machines
    - 11% LCOE reduction for MW-scale machines
- targeting proof-of-concept flight in next 12 months



Backup slides

Overview

Project Concept
- Objectives, motivation and technologies considered
- kW-scale test blade vs. modern MW-scale duality
- SWiFT test site

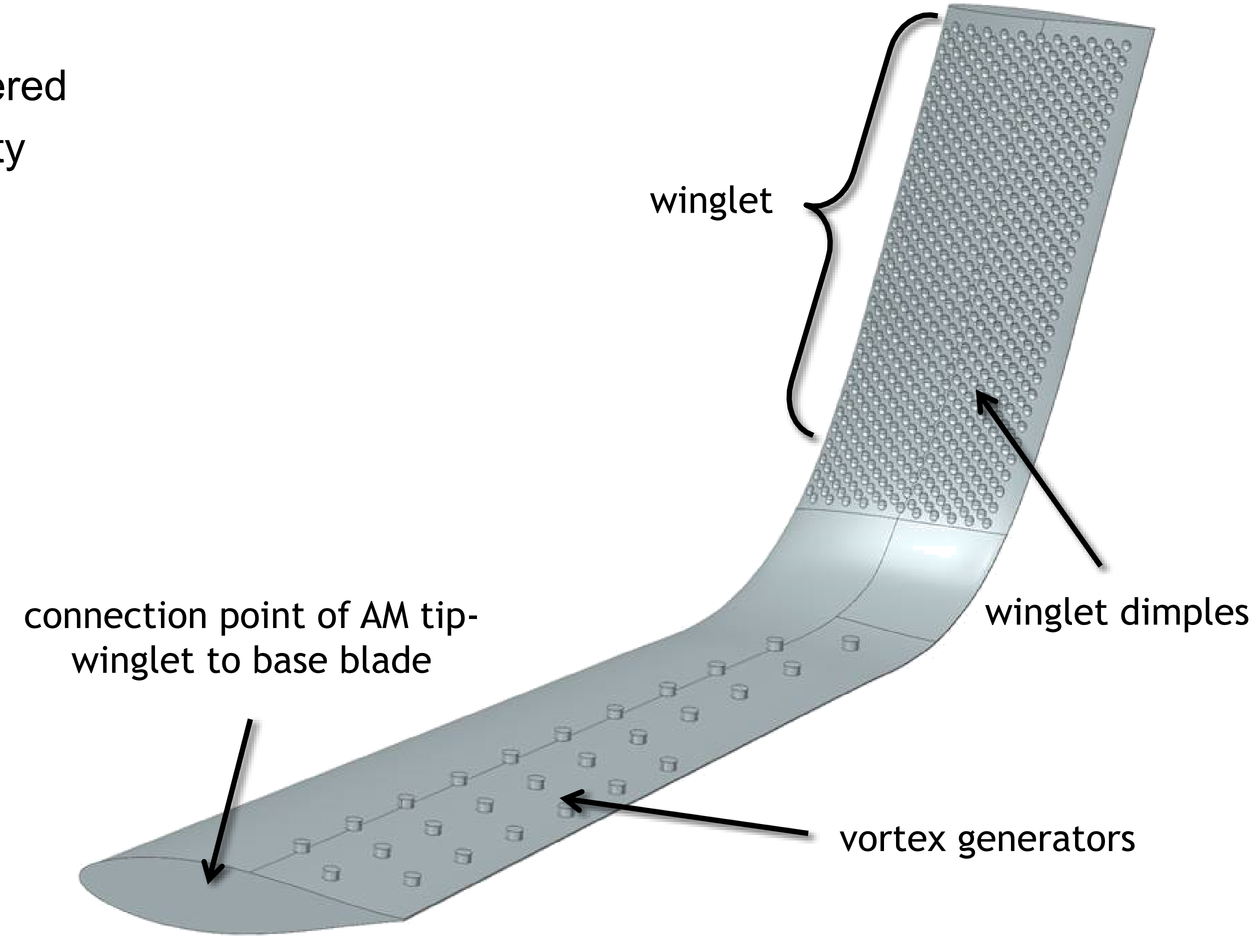
Technoeconomic Analysis
- Design drivers

Aerodynamic Design
- Winglet with surface texturing

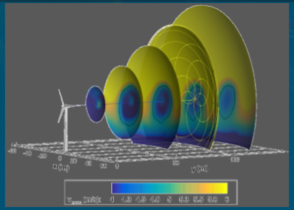
Additive Manufactured (AM)
- Material considerations
- Test prints

Lightning Tests
- Survival considerations

Prep for Field Tests



AMSIT Leading Edge Erosion



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Introduction to Leading Edge Erosion

- 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
  - ge starts at category 3 erosion, and progresses to category 4 with up to 5%

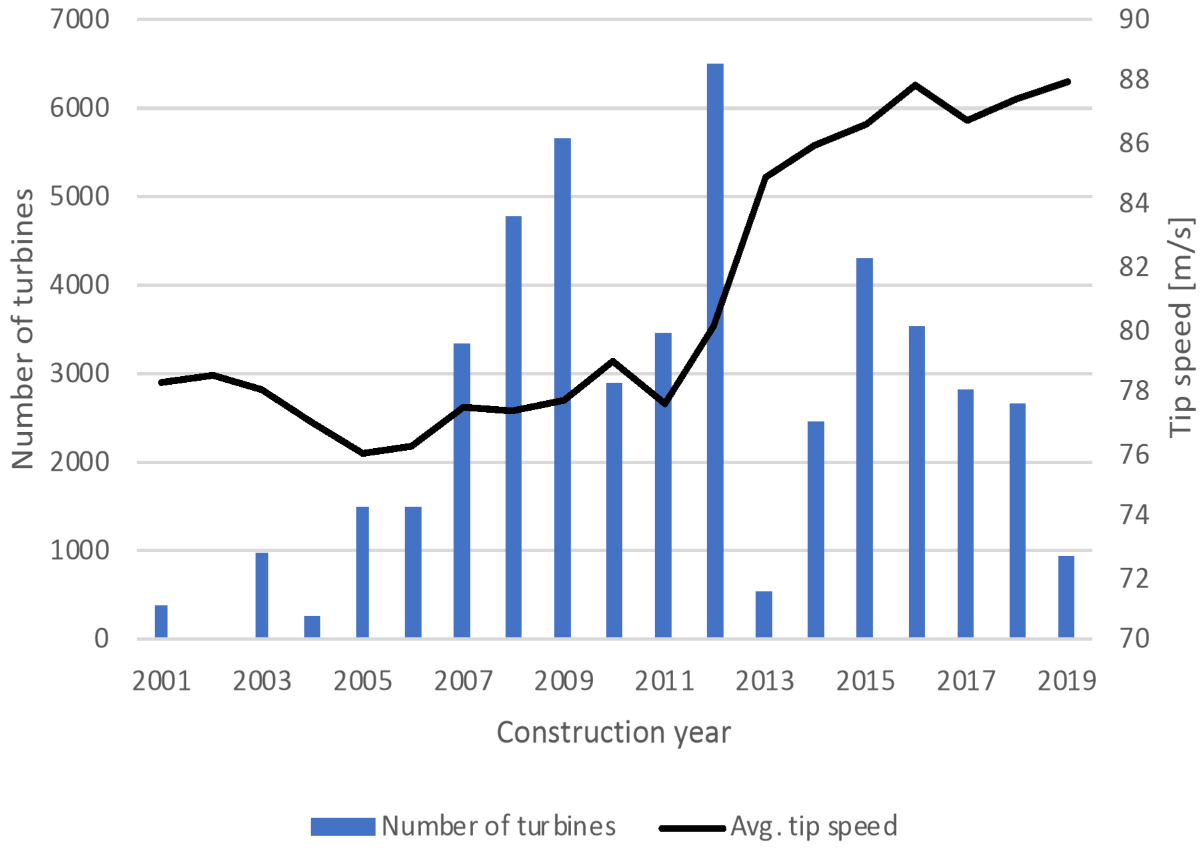
Erosion observation in field.

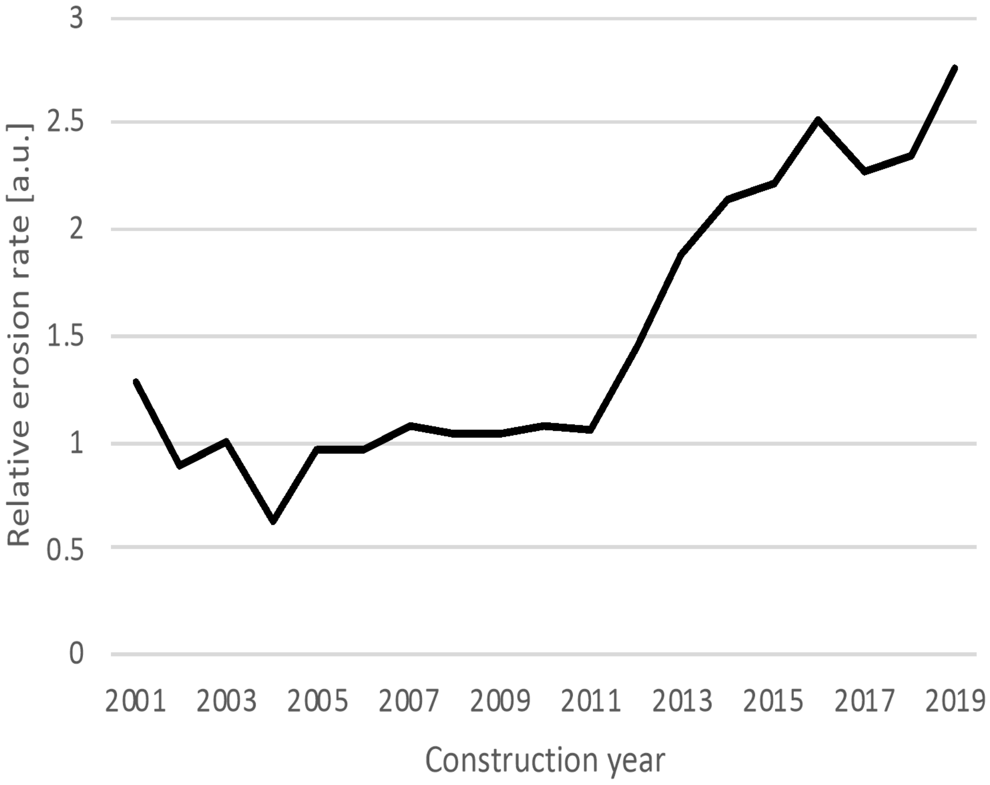
Field measurements of erosion.[1]

Category 4 erosion

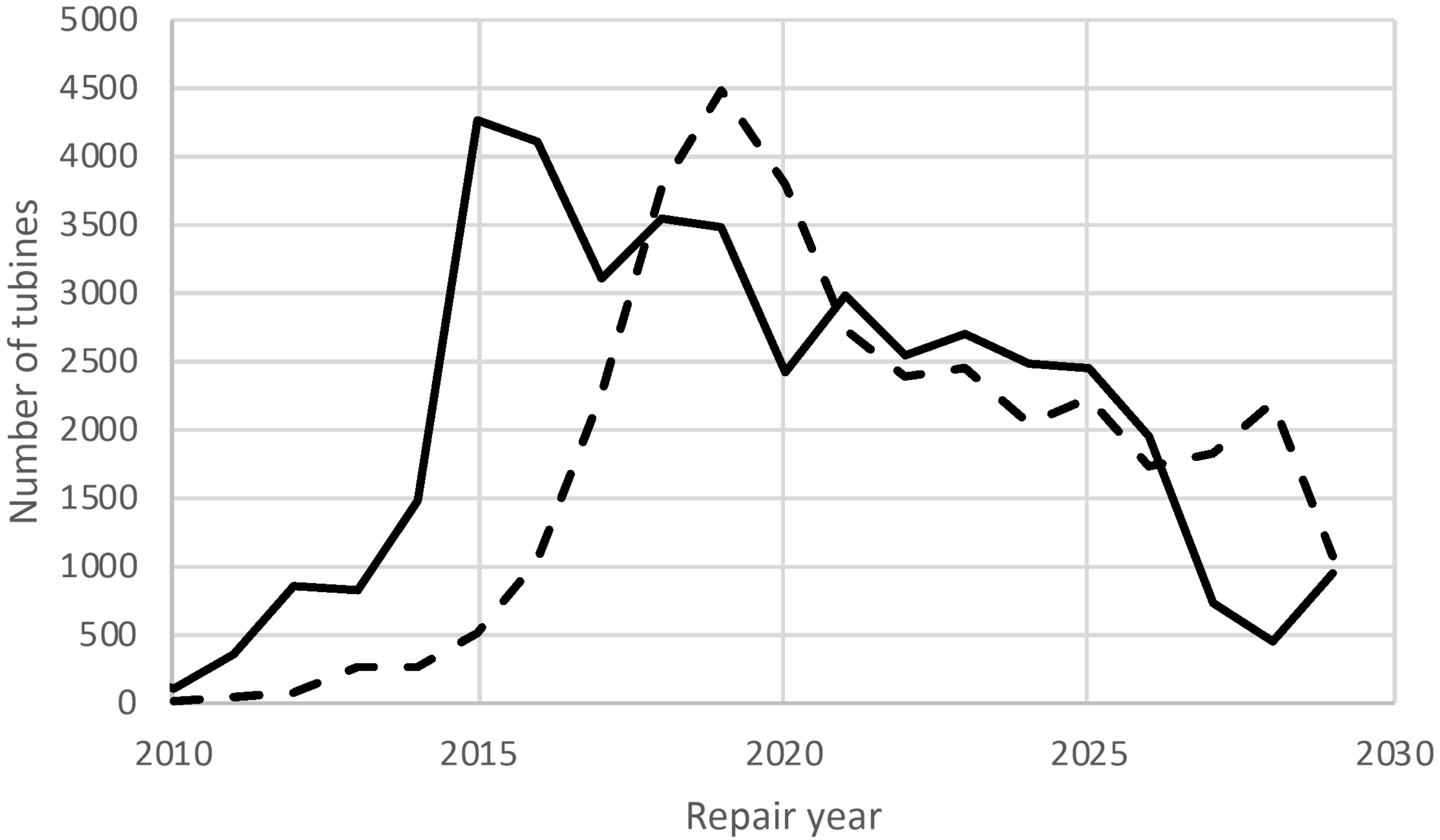
Industry-level Erosion Analysis

- Erosion rates can vary significantly between sites, depending on local atmospheric effects as well as turbine design and operation
- In general, tip speeds have been increasing leading to an increasing relative erosion rate





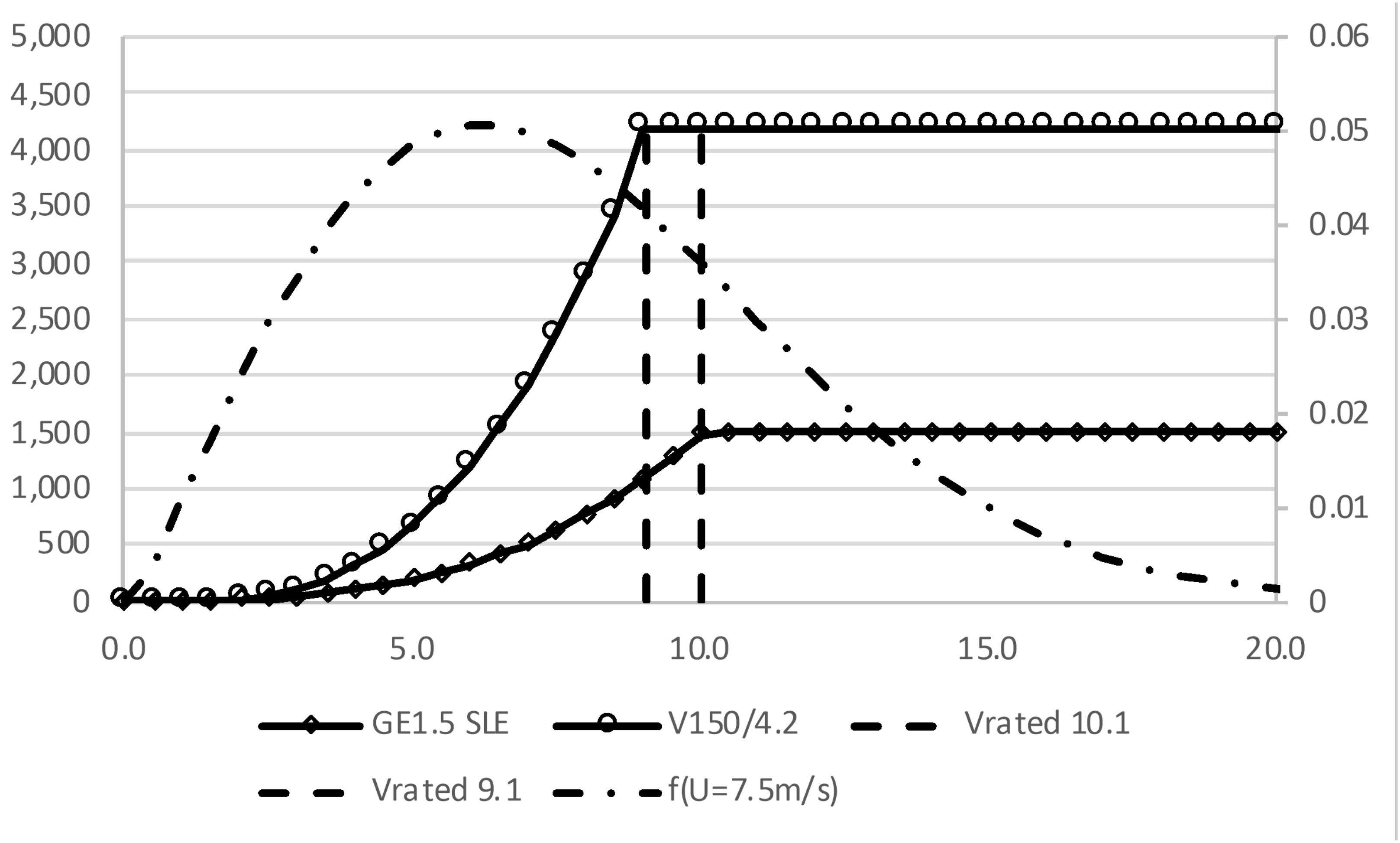
Number of Turbines Needing LEE Repair



- Number of turbines in the existing US fleet needing LEE repair, assuming 10 (solid) to 15 years (dash) offset time to repair.
  - The number of repairs tapers off because future turbine construction is unknown and thus not added.
- If the trigger point for repair is significant LEE detected by visual inspection, the associated annual energy losses are significant and increasing

Effect of Modern High Capacity Factor Turbine

- Ideal power curves of a typical turbine constructed in year 2004 to 2011 and an example of a new high capacity factor IEC class III new turbine, which has not entered the market yet, shown with a Rayleigh distribution Uavg=7.5m/s.



AEP Impact from Power Curve Uncertainty 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.

	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%

[1] "Uncertainty Quantification of Leading Edge Erosion Impacts on Wind Turbine Performance"; Maniaci, David (SNL); Westergaard, Carsten (SNL); Hsieh, Alan (SNL); Paquette, Joshua (SNL); Torque2020 Conference; September 2020. IOP Journal of Science Conf. Series, 1618(5):052082. https://doi.org/10.1088/1742-6596/1618/5/052082

Leading Edge Protection

Conventional Leading Edge Protection (LEP) relies on a flexible coating (urethane tape is most common). The flexibility of the tape lowers the shear stress from rain drop impacts on the material surface, reducing the erosion damage rate. The material needs to be replaced at regular intervals that depend on the site conditions.

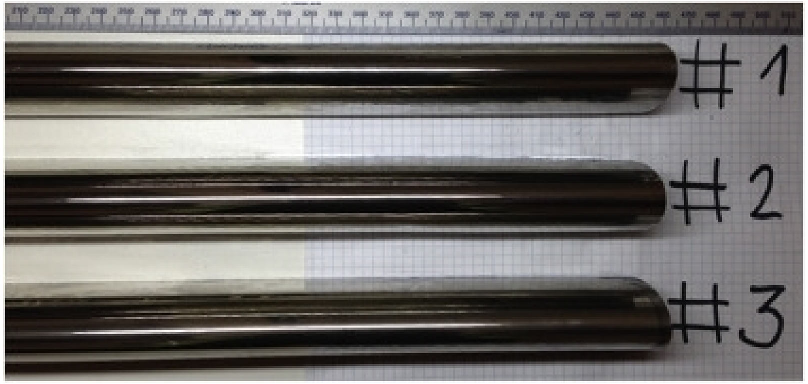
Conventional leading edge erosion protection tape

An alternative technology is a hardened leading edge, metal is common in the rotorcraft industry. The hard material increases the stress from the rain drop, but the material is more resistant to the stress.

A Nickel-cobalt leading edge material was tested in lab and showed a 30+ year lifetime. Main issue: how to attach it reliably to the blade material for clear value of the turbine lifetime.

The metal leading edge can reduce lifetime O&M costs and increase lifetime power production.

Nickel alloy leading edge erosion protection



Nickel alloy sample showed no degradation in testing, extrapolated to a 30+ year life with potential for 32% reduction in LCOE.

Robbie Herring, Kirsten Dyer, Ffion Martin, Carwyn Ward, "The increasing importance of leading edge erosion and a review of existing protection solutions," Renewable and Sustainable Energy Reviews, Volume 115, 2019, 109382.

Limitations and Future Work

Significant existing limitations in analysis:

- Uncertainty in material and installation costs of tip
- Lack of available lightning/erosion repair cost data

Future work:

- Reduce uncertainty in material costs as design is finalized
- Incorporate results of updated/improved aerodynamics modeling
- Analyze a broader range of optimistic and conservative operating scenarios

Wing Turbine Blade Tip Aerodynamic Opportunities

- Many tradeoffs are made in the design of a wind turbine blade tip
  - Material limits and manufacturing processes limitations influence tip design
  - Transportation limit the height and length of a blade
  - Installation consideration drives toward simpler, single unit design
  - Lightning receptors protrude from the blade surface (drag)
  - Trailing edge is designed for manufacturing and handling (drag)

- These limitations provide some opportunities for improvement through new materials and rapid testing of new concepts
  - Reduced drag through thinner trailing edge
  - Improved siting process and spacing through integrated noise reduction
  - Robust performance improvement through advanced surface texturing
  - Power improvement across operating conditions through non-planar complex tip design
  - Increased power and reduced O&M through advanced, integrated leading edge protection
  - Improved reliability through advanced, integrated lightning protection

- **Rapid Testing of Innovation**: Additive manufacturing allows for enhanced testing of risky configurations, getting test data as fast or faster than we can from high fidelity computational models.

Tip Design Considerations

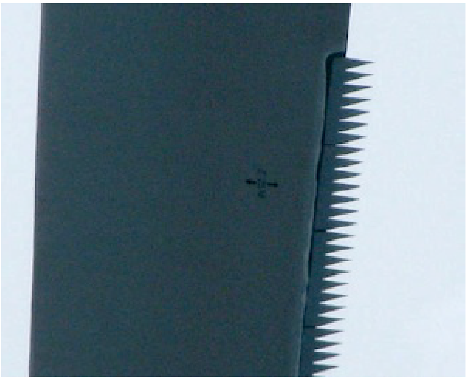
Noise: We proposed serrated trailing edges, but experimental data is mixed, they help for some frequencies and not much for others.

Lightning: Coating or paint over surface, copper mesh in the carbon fiber, conductors to take charge from carbon fiber. What is influence of tip shape and a non-planar wing tip?

Leading Edge Erosion: Nickel-cobalt leading edge material was tested in lab and showed a 30+ year lifetime. Main issue is how to attach it reliably to the blade material. Urethane tape with significant thickness is standard now.

Vortex Generators (Dimples): Potential for reduction in skin friction drag. Hasn't been tested on a wind turbine or winglet airfoil. Would ideally want wind tunnel testing, (clean and with erosion).

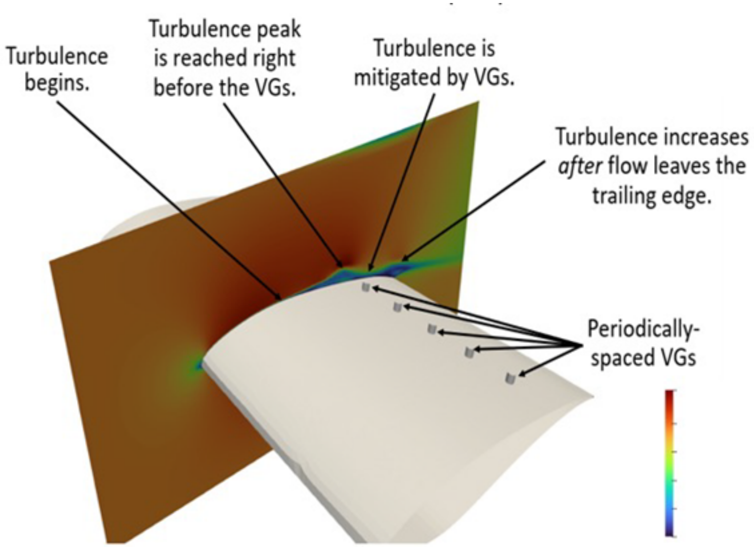
Non-planar wing tip (winglet): Increased power with less structural impact as a tip extension, but pushes the state of the art in design process and modeling tools



Trailing edge serrations for noise reduction.

Acoustic Ecology Institute, Wind Farm Noise, 11/17/2012, acousticecology.org/wind

Leading edge erosion example with a conventional lightning receptor.

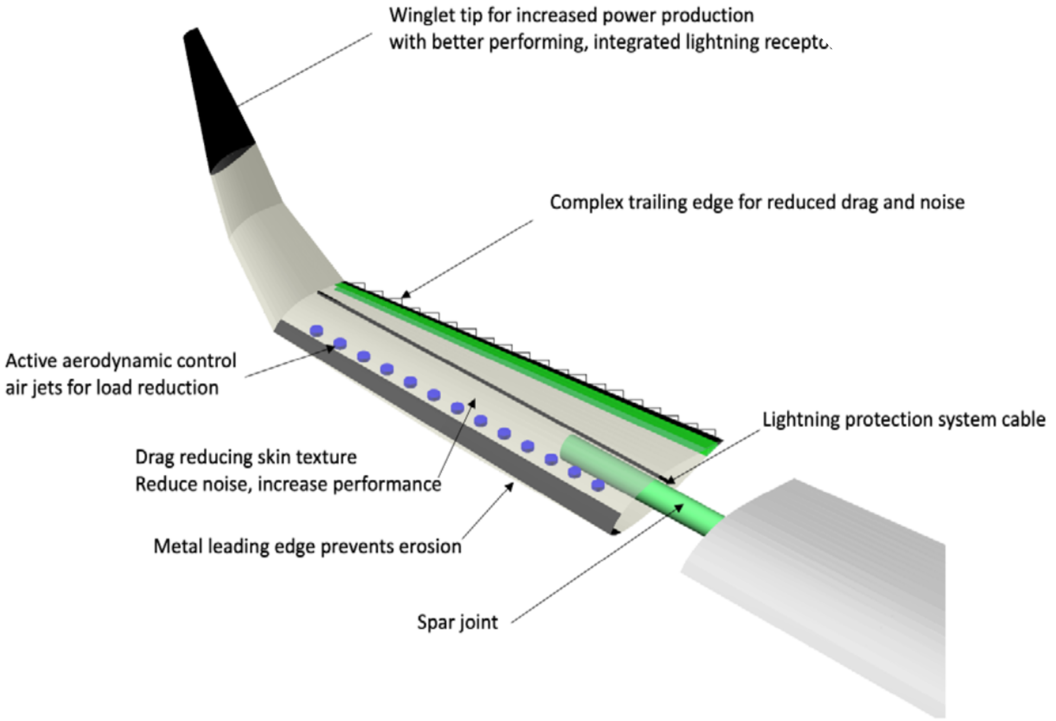


CFD simulation of the flow over a wind turbine blade with cylindrical vortex generators. Design and simulation led by Sal Rodriguez.

Backup slides

Next Steps and Questions

- Complete loads analysis of advanced non-planar tip design with upwind winglet
- Develop mechanical design of hardened leading edge erosion protection system
- Apply trailing edge chevrons for noise reduction
- Apply dimpling and CVG's to final tip shape
- Fully integrate design of aerodynamic aspects with other systems
- As component designs mature, revisit the techno-economic analysis



Thank you. Questions?

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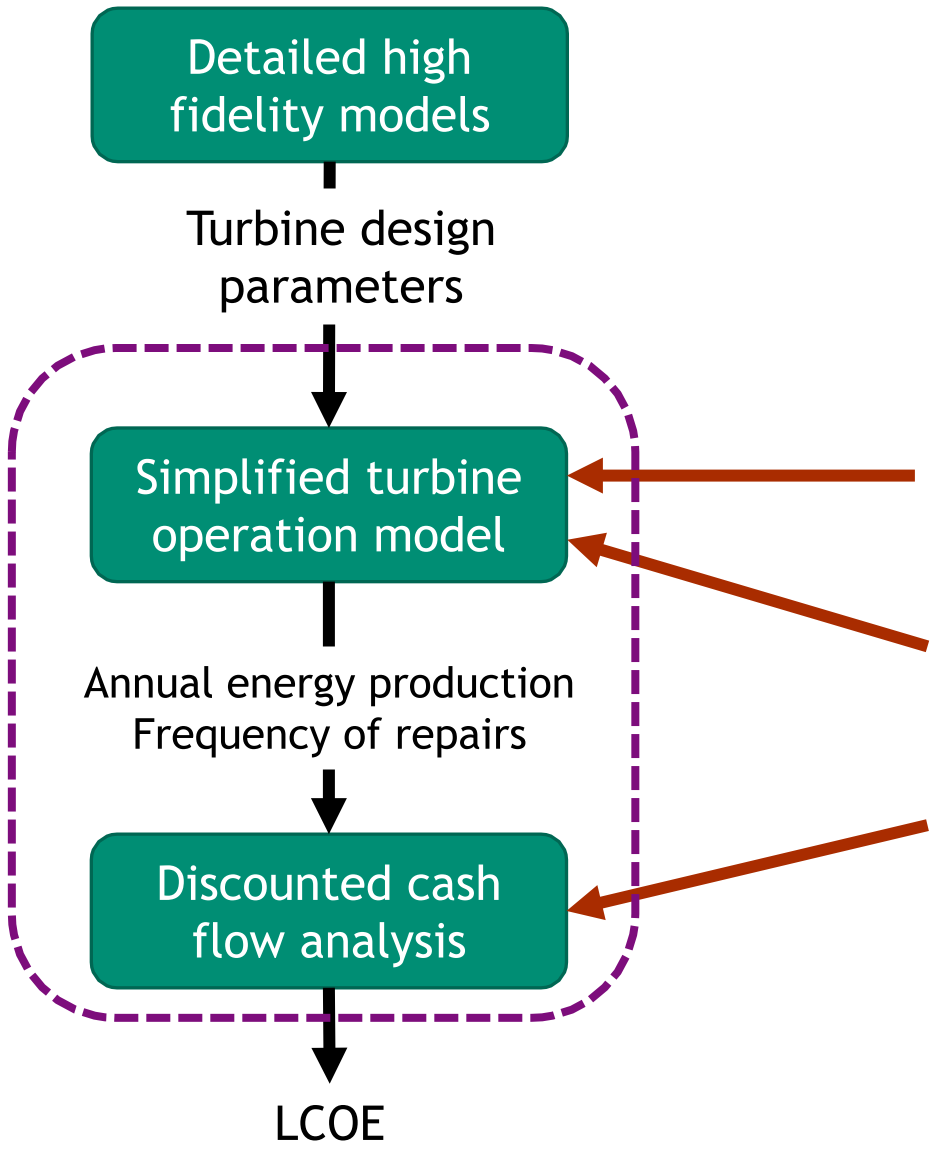
Approach



Important inputs:

Erosion Rate
Estimated via previous observed and modeled data

Frequency of Lightning Strikes
Calculated based on IEC 61400-24

Economic Parameters
Sourced from NREL Cost of Wind Energy Report
Stehly, T.; Duffy, P. *2020 Cost of Wind Energy Review*; NREL/TP-5000-81209; National Renewable Energy Laboratory: Golden, CO, 2021.

Scenarios

Baseline	96% of strikes - no damage 4% of strikes - blade replacement	No winglet	No texture	No protection
Lightning Repair	96% of strikes - no damage 2% of strikes - blade replacement 2% of strikes - tip replacement	No winglet	No texture	No protection
Winglet	96% of strikes - no damage 2% of strikes - blade replacement 2% of strikes - tip replacement	Winglet included	No texture	No protection
Surface Texture	96% of strikes - no damage 2% of strikes - blade replacement 2% of strikes - tip replacement	No winglet	Texture included	No protection
Erosion Protection	96% of strikes - no damage 2% of strikes - blade replacement 2% of strikes - tip replacement	No winglet	No texture	Protection included

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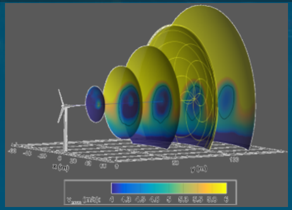
Simulation for AMSIT Field Experiment Planning



Dan Houck

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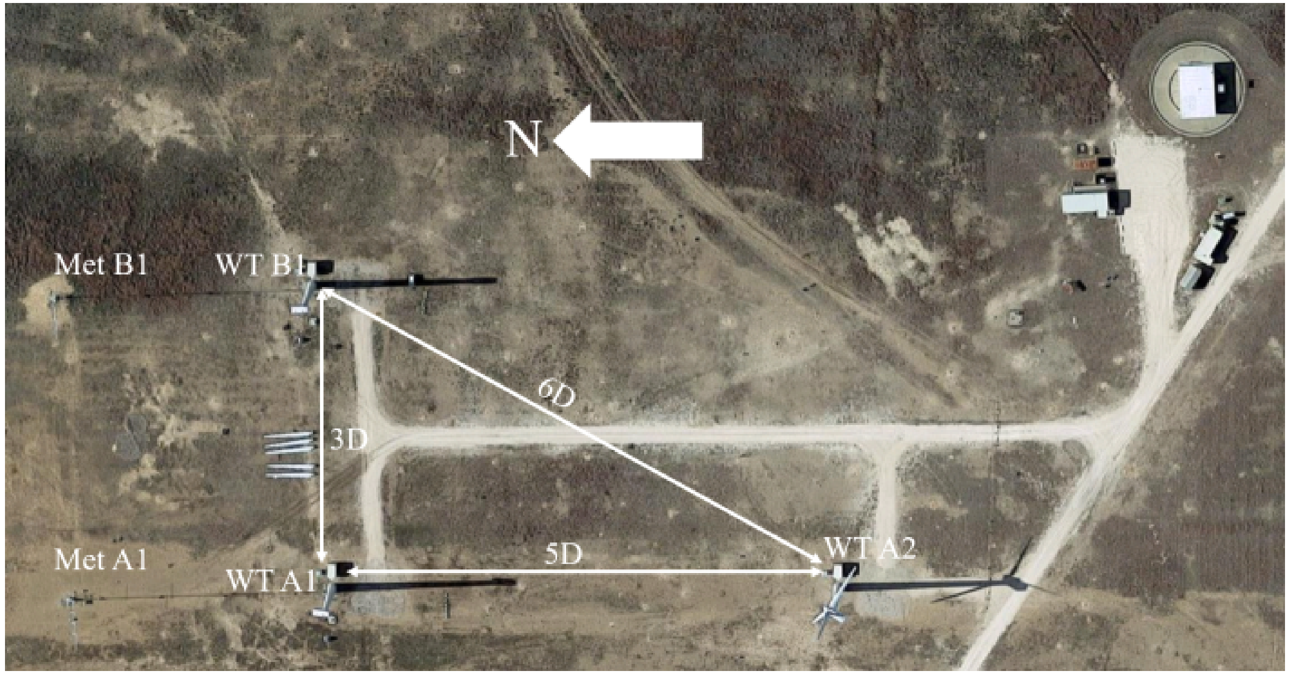
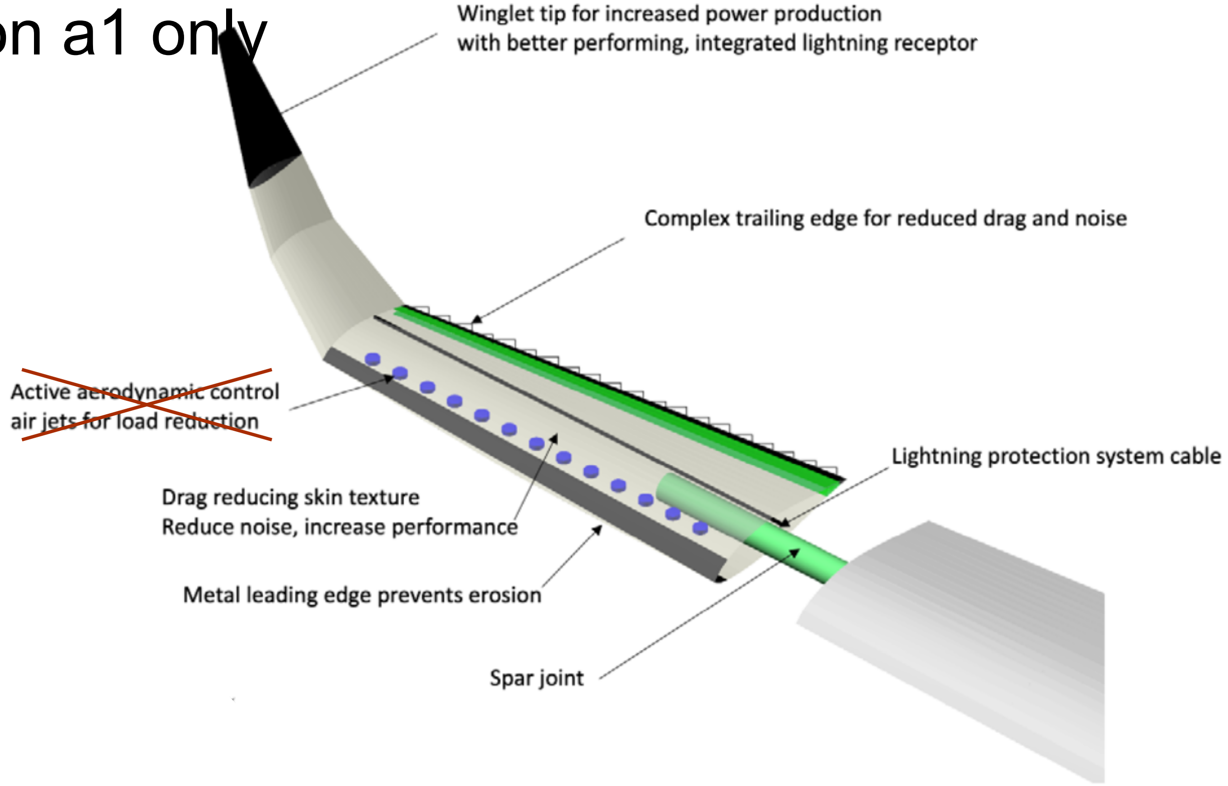
U.S. DEPARTMENT OF ENERGY NNSA

Field testing AMSIT

- In ~1 year, we will field test a V27 rotor with an AMSIT and compare to a baseline V27 rotor
- We hope to test them **simultaneously** on a1 and b1, but…
- We may have to test them **sequentially** on a1 only



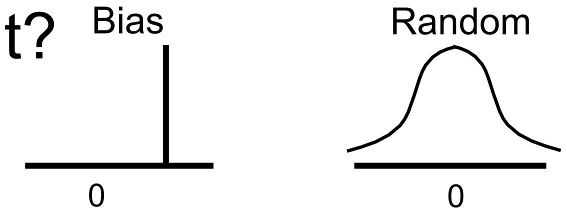


Field testing is hard

- Field testing can have high uncertainties due to many sources of error, both random and bias
- We will likely be looking for small differences between the two rotors, e.g., an increase in power of ~4%
- But the uncertainty of differences is larger than the uncertainty of individual measurements…

Quick Refresher on Uncertainties

What determines the uncertainty of a measurement?



Uncertainty comes from bias and random errors. In context…

Bias errors will probably be from differences in inflows if measurements are not simultaneous and more or less co-located and from any differences in the turbines if we use two. Bias errors may be mitigated by binning data to compare similar conditions.

If you can say the "same" experiment was done for the control and treatment, then bias errors are equal and subtract to a negligible magnitude when looking at differences.

Random errors will primarily come from the inflow.

They can be quantified using a bootstrap technique and can be minimized by ensuring the data set is long (in time not number of points) enough.

	Sequential testing	**Simultaneous testing**
Bias errors	Potentially large differences in inflows	Probably small differences in turbines and inflow
Random errors	From inflow, but not same	From inflow, but probably same

Uncertainty in Control and Treatment

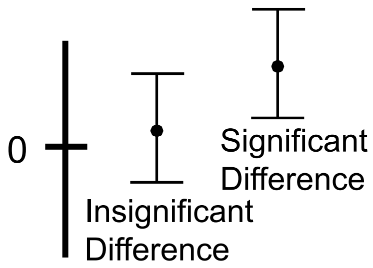
Let P_1 and P_2 be the powers produced by two rotors and the expected difference between them be

$$D = P_1 - P_2.$$

The uncertainties in measuring P_1 and P_2 are δP_1 and δP_2, respectively, then the uncertainty in D is

$$\delta D = \sqrt{\delta P_1^2 + \delta P_2^2}$$

using the root-sum-square the combine the individual uncertainties.



To simplify, assume that $\delta P_1 = \delta P_2$, then

$$\delta D = \sqrt{2}\delta P_1 \approx 1.4\delta P_1.$$

Finally, $D \pm \delta D$ does not contain zero in its interval, then the result is significant.

In words, it's more difficult to measure the difference between two measurements because their individual uncertainties produce an uncertainty in the difference that is 40% larger.

For example, if we expect $P_1 = 1.04P_2$, then $D = 0.0385P_1$, which means that $\delta D < 0.0385P_1$ for the result to be significant. This in turn means that $\delta P_1 < 0.0272P_1$, which is probably a difficult level of accuracy to achieve.

Questions we need to answer…

- What QoI do we care about most?
  - Power, thrust, root bending moment
- What size difference do we expect in those QoI between the two rotors?
  - TBD, but all small
- What uncertainty do we expect in the measurement of those QoI?
  - TBD and depends on method, but possibly large
- How does the amount of data affect the uncertainty?
  - Will definitely reduce random error and more data will allow for finer binning to reduce bias error
- How does this ultimately influence how we should conduct the field test to achieve significant differences in the QoI?
  - May tell us how long to test and/or that it would be better to focus on certain conditions

Proposed Simulations To Help

- Use TurbSim/OpenFAST
- Realistic ranges of conditions at SWiFT (wind speed, TI, shear, veer)
- Baseline V27, AMSIT V27, and one more with larger expected differences

Setting Up TurbSim

- TurbSim needs hub height wind speed, TI, shear exponent, and veer as inputs

- Met data resources:
  - ~1.5 years of TTU met tower data,
  - lots of a1 met tower data, and
  - some b1 met tower data

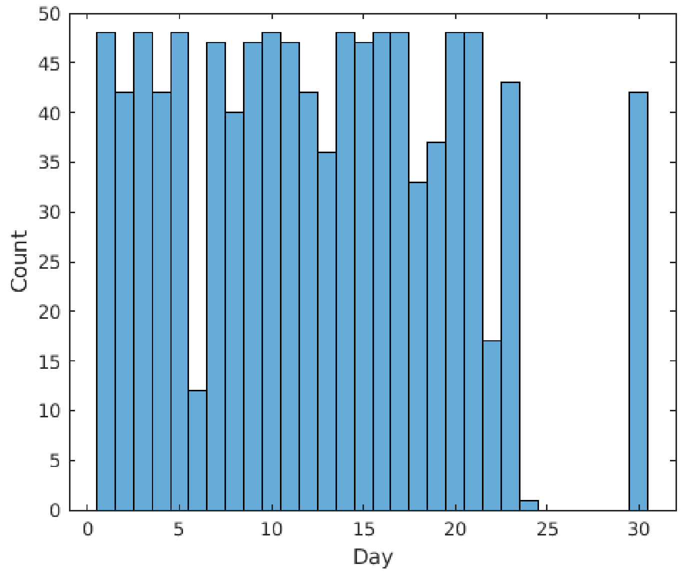
- Need to represent three inflows:
  - Baseline inflow to a1
    - ✓, September, 2021
  - Simultaneous inflow to b1
    - Not enough data from b1 for this, so we'll have to explore other options
  - Later inflow to a1
    - ✓, October, 2021

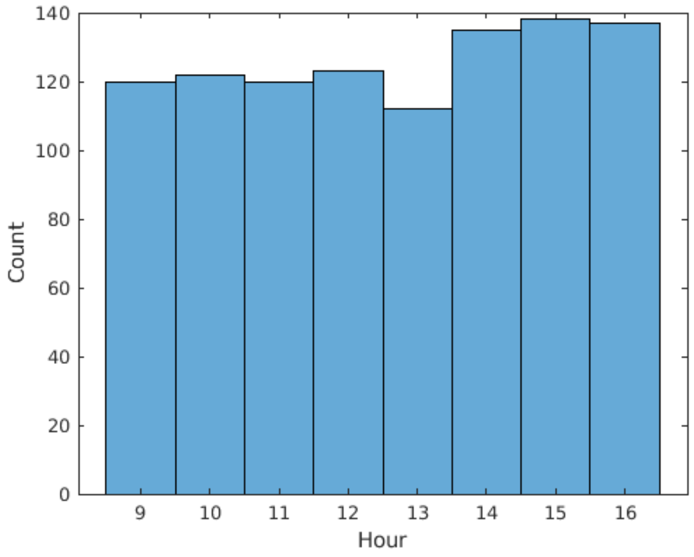
Steps To Set Up TurbSim Inputs

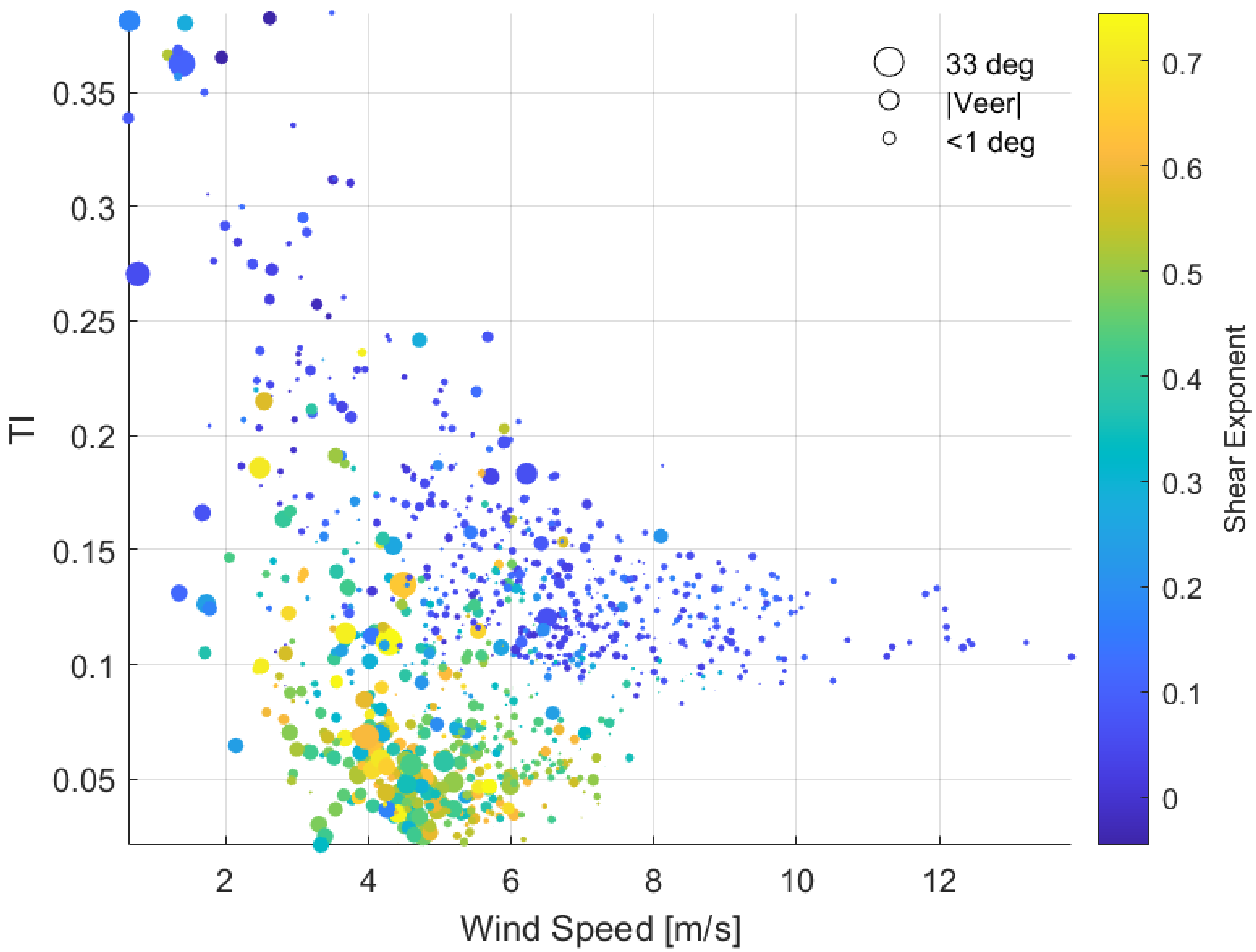
- Could produce TurbSim inputs from assumed distributions, but we have real data

- Gather data from meta1 (just 2021) and metb1 (2019-2021) from September and October (expected testing months)
  - Check that bins are not correlated to ensure independence of inputs
  - High level filtering of data
  - Put into bins and pull out average hub height wind speed, TI, shear, and veer

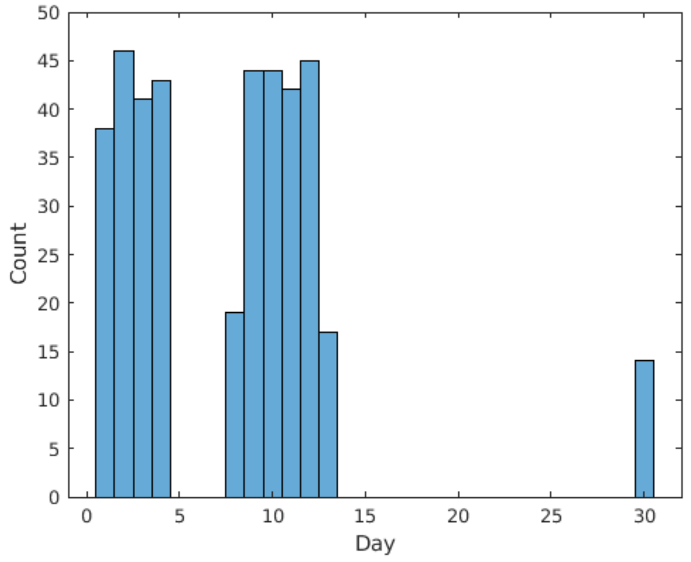
Example of Result – September, a1

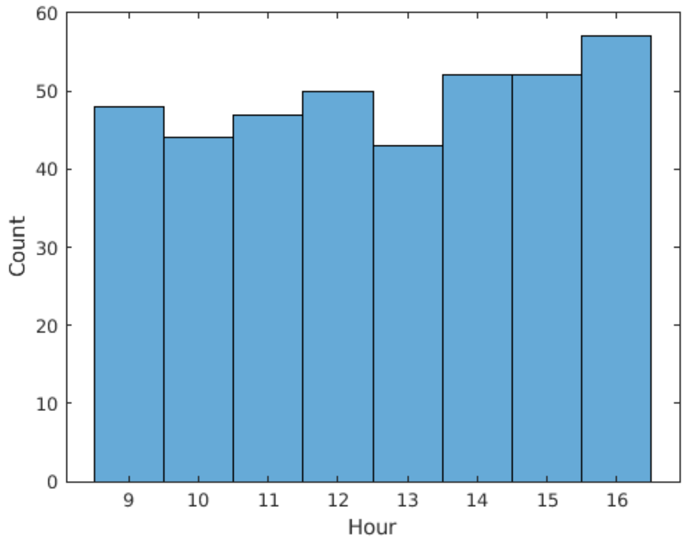


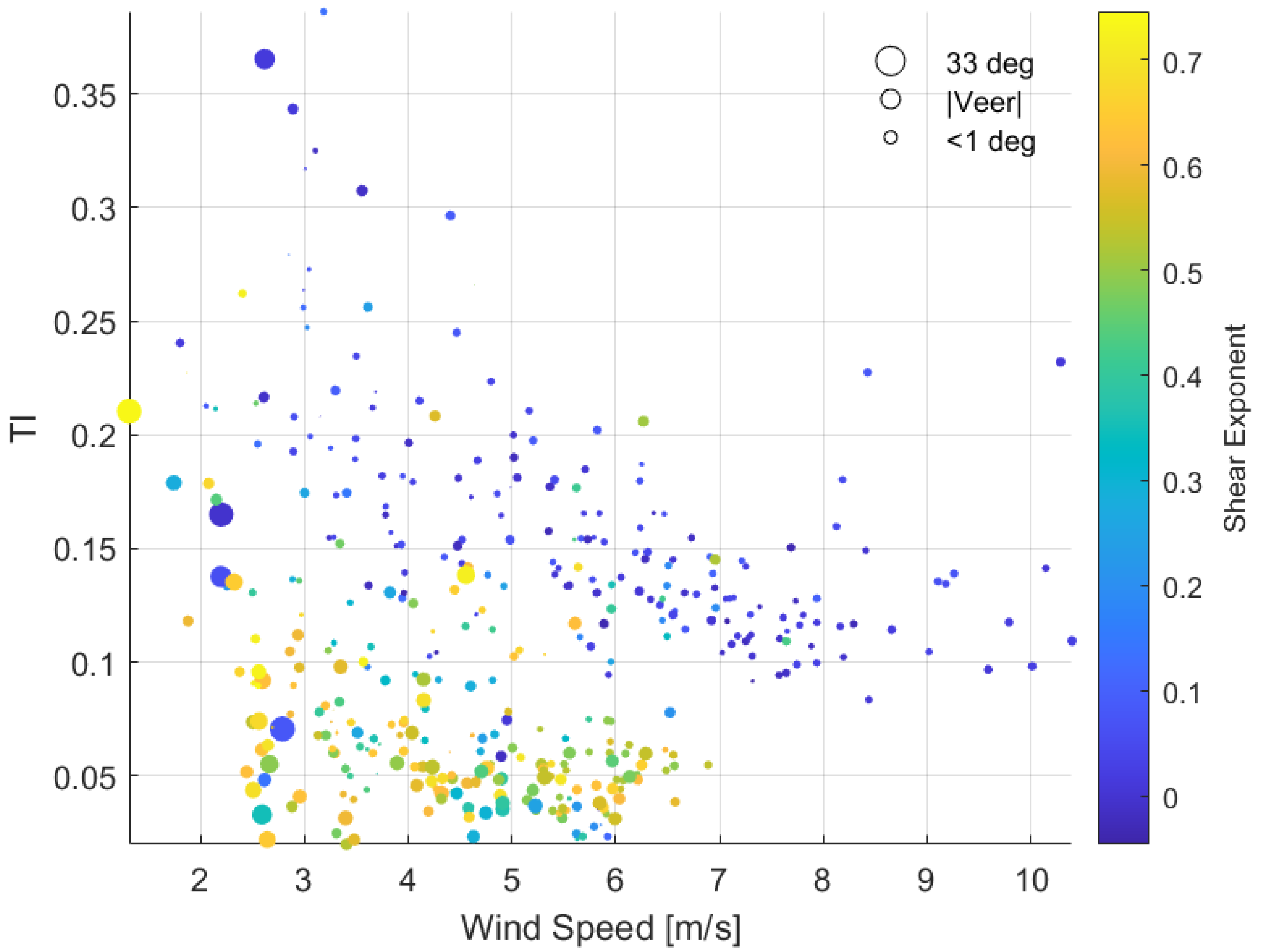




Example of Result – September, b1







TurbSim Inputs

Number of TurbSim Inputs Acquired

	September	October
meta 1	1007	1269
metb 1	400	395*

*Not technically needed

Questions to answer about TurbSim

- How will we back-calculate from TurbSim/OpenFAST results how much field data is needed to get the equivalent in binned data?
  - Each TurbSim/OpenFAST simulation is implicitly a bin. We'll also run them a long time to allow for further binning. Then repeat binning with met data to determine field time needed.
- How long should the TurbSim/OpenFAST simulations be, i.e., how much data do we need in a bin?
  - TurbSim drives velocity distribution toward Gaussian. Reaches $R^2 = 0.99$ after 1 hr.
- Does TI affect convergence time?
  - It does not appear to affect it.
- What is more important: total points or total time?
  - Total time is more important to fill out tails than the total number of point, so lower sample rate is acceptable to reduce processing time.
- How does six seeds, 10 minutes each compare to one seed for 60 minutes?
  - Longer sims have higher standard deviations because they capture more in the tails.

What about the rotors?

- Three rotors:
  - Baseline V27 ✓
  - AMSIT rotor – in progress
    - Small expected changes in QoI
    - Working on verifying OpenFAST model of winglet
    - Will alter polars to reflect changes in lift/drag due to surface texturing
    - May need to update weight distribution and dimensions
  - A third one – TBD, maybe just bigger?
    - Want one with a higher expected change in QoI
    - Academic interest in parameterizing how what can be significantly measured changes with more/better data

Next Steps and Questions

- Finish OpenFAST model of AMSIT rotor
  - Validate winglet design in OpenFAST against results from WindDVE
  - Modify polars and test
- Design a third rotor
  - A “V28.3” (28.3 m diameter V27) would produce ~10% more power
  - An AMSIT rotor with relaxed loading constraints

Thanks and Questions?

Team

Sandia

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Evan Sproul
technoeconomic analysis

Carsten Westergaard
economics modeling

Stratasys

- Jalel Nadji, Dave Phillips - aerospace AM consultants
- (formerly Trey McIntosh)

Wetzel Wind

- Kyle Wetzel, Jim Payant - wind blade design experts

Questions we have

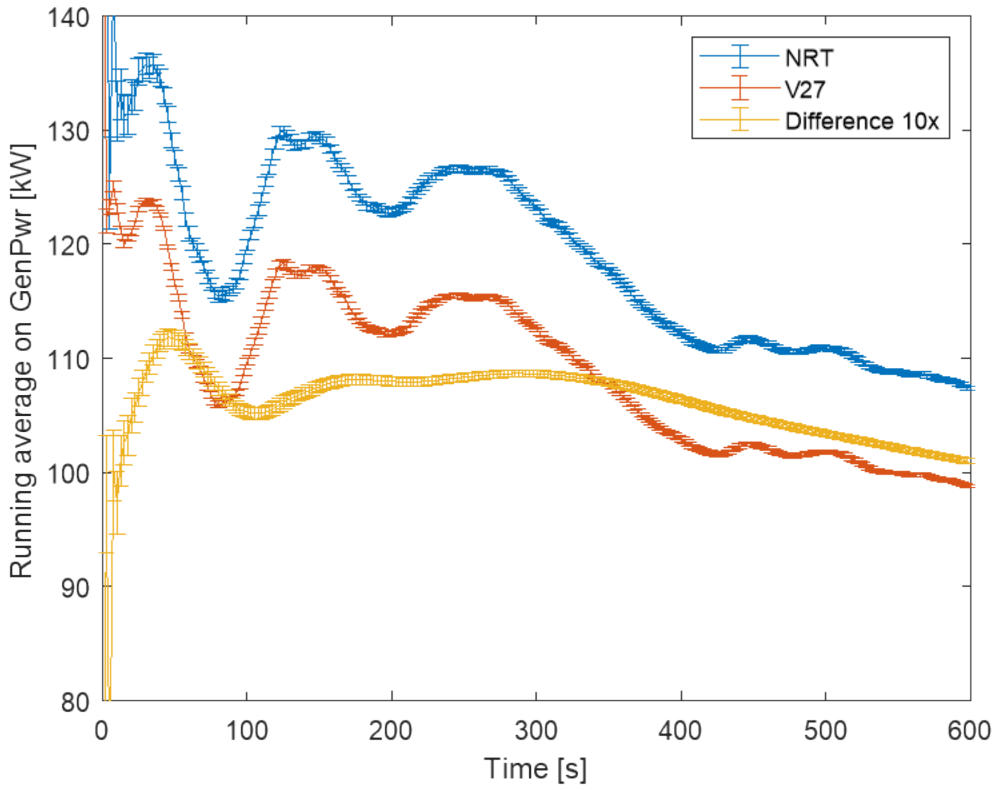
- How good do our turbine/rotor models need to be?
  - OK if discrepancies from “true” are constant offsets since we only care about differences
- How will the discrepancy in the number of a1 vs b1 simulations affect results?
  - Could randomly select inputs from a1 to match number available from b1
  - Or use 5 minute samples from b1 to get twice as many inputs out of it
- How valuable would actual simultaneous data from a1 and b1 be?
  - Should we find a case study for a month when both were recording?
- Will this be an unwieldy amount of data to process?
  - Don’t necessarily need to output at a high rate

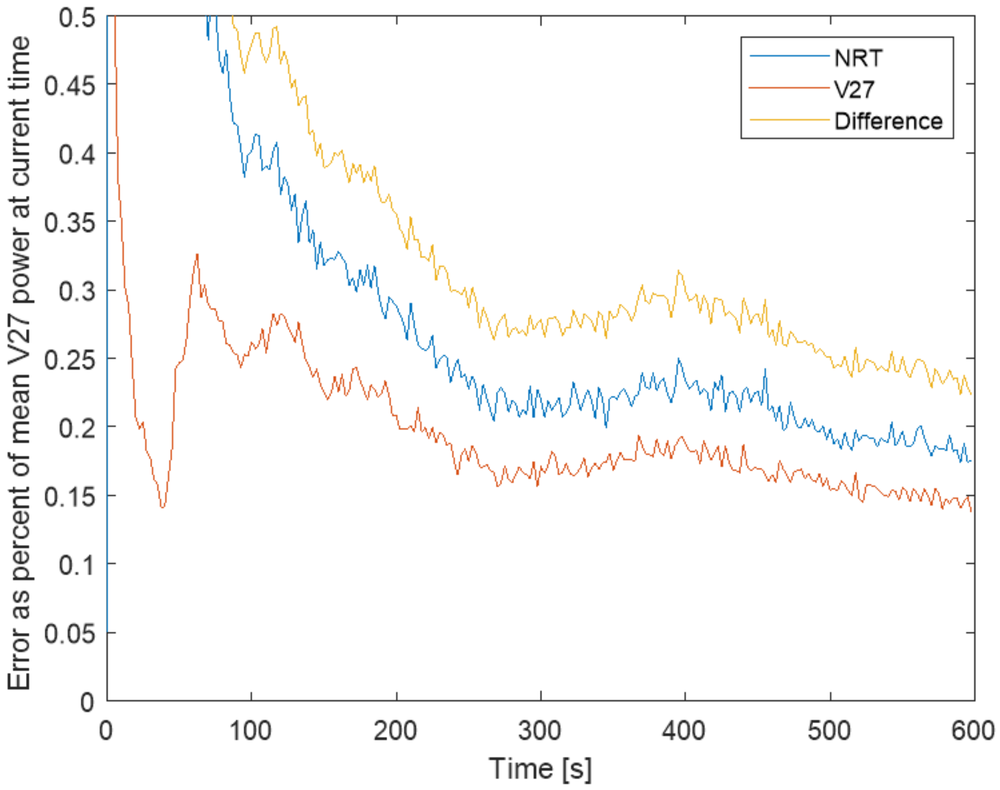
Simulated Simultaneous Testing

10 minute OpenFAST BEMT simulation with TurbSim inflow of NRT and V27

Identical inflows, so similar to simultaneous testing, but ONLY one 10 minute dataset.

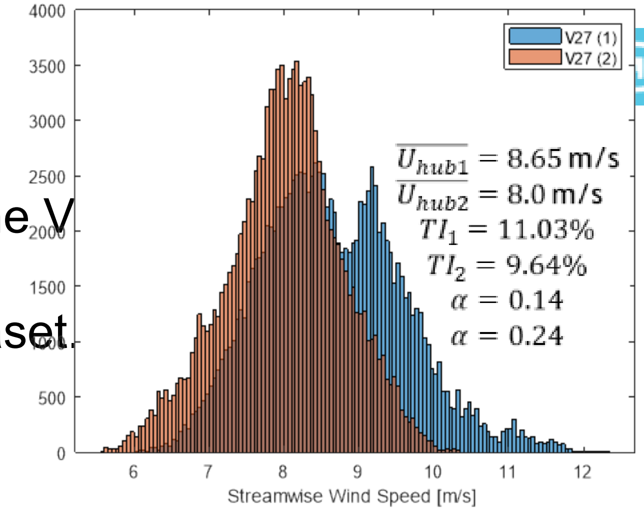
Errorbars calculated with a running bootstrap





Results improve with time and uncertainty in the difference is always higher than the individual uncertainties.

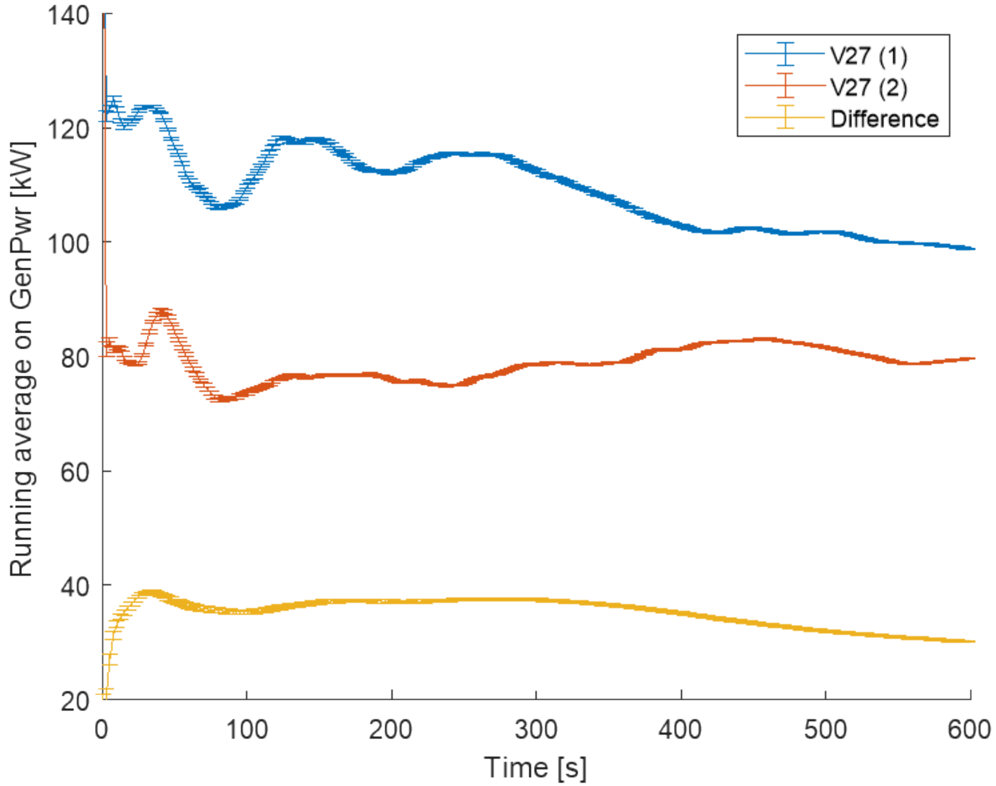
Simulated Sequential Testing

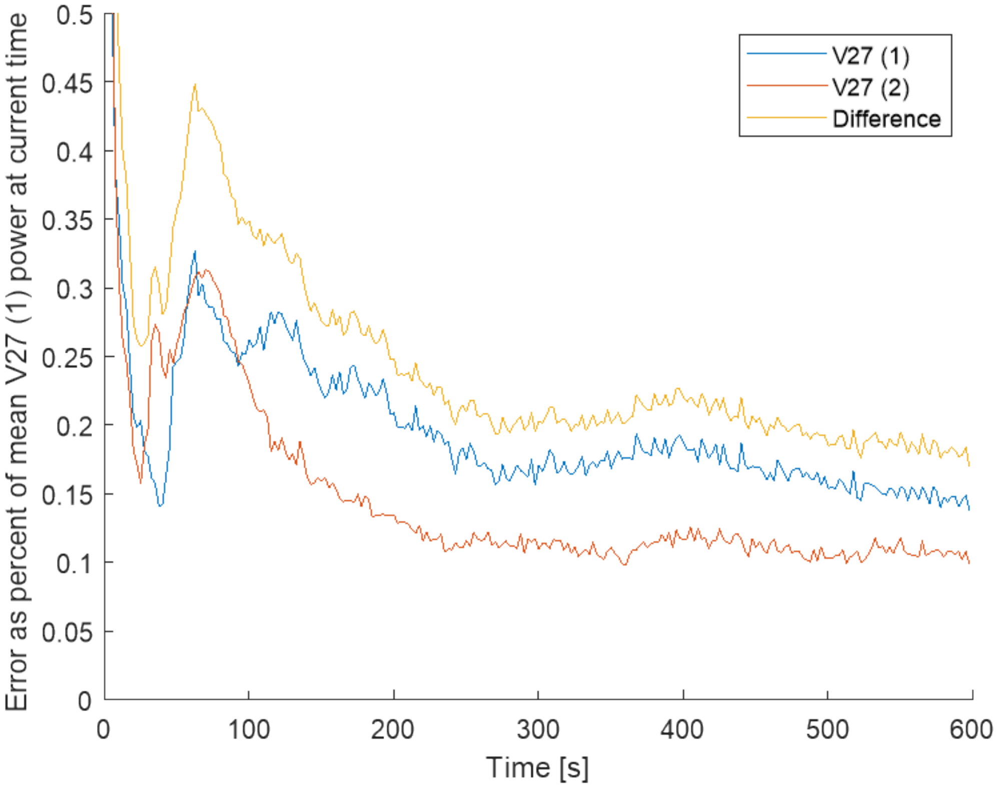


10 minute OpenFAST BEMT simulation with two different TurbSim inflows of the V

Different inflows, so similar to sequential testing, but ONLY one 10 minute dataset.

Errorbars calculated with a running bootstrap





Results improve with time and uncertainty in the difference is always higher than the individual uncertainties.

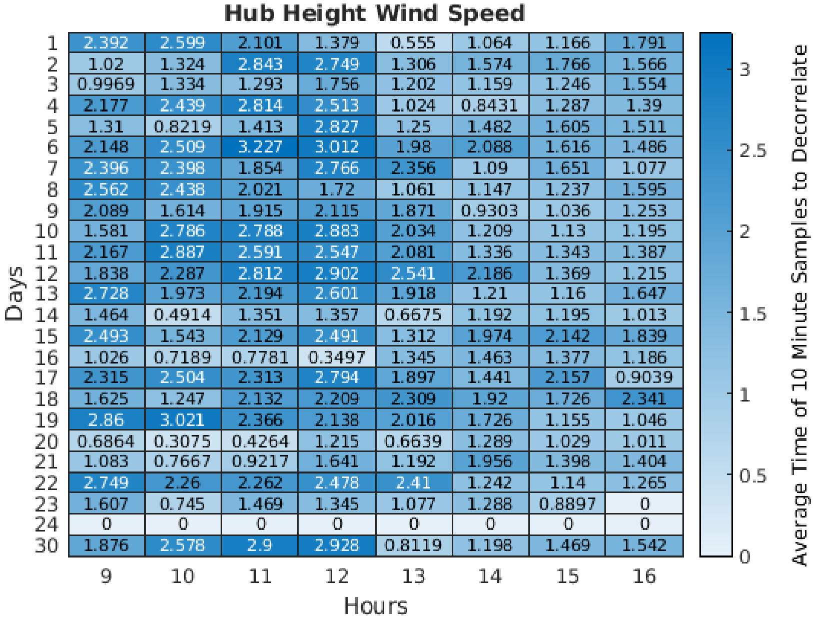
What is bootstrapping?

- So you've done an experiment and have a dataset and want to estimate statistics,
- But the distribution of the data is complicated or unknown,
- And it'd be real hard to repeat the experiment a bunch to get the data you really need,
- Then bootstrap it!
- That is, resample the dataset with replacement to create at least 100 "new" datasets and calculate your statistics of interest on each of those and average the results.
- There. It's like you just repeated your experiment.
- No, this isn't cheating if you do it right.

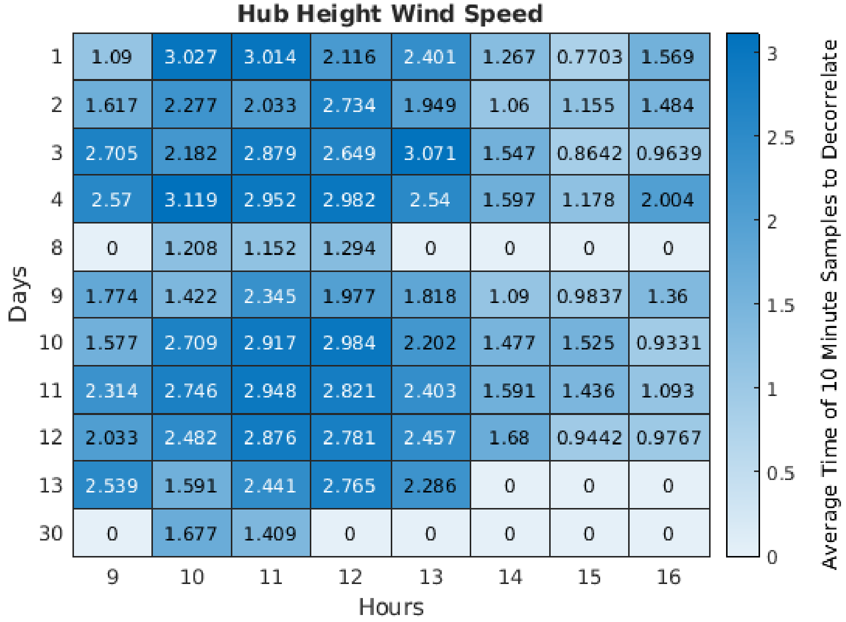
Checking for Correlations

- If any TurbSim variables remain correlated for over 10 minutes, then they do not represent independent 10 minute samples of the inflow
- meta1 and metb1 data from September and October were filtered for working hours, 9 AM-4 PM
- Autocorrelation times were calculated as the time to the first zero-crossing for each 10 minute bin and then averaged for each hour

September meta1



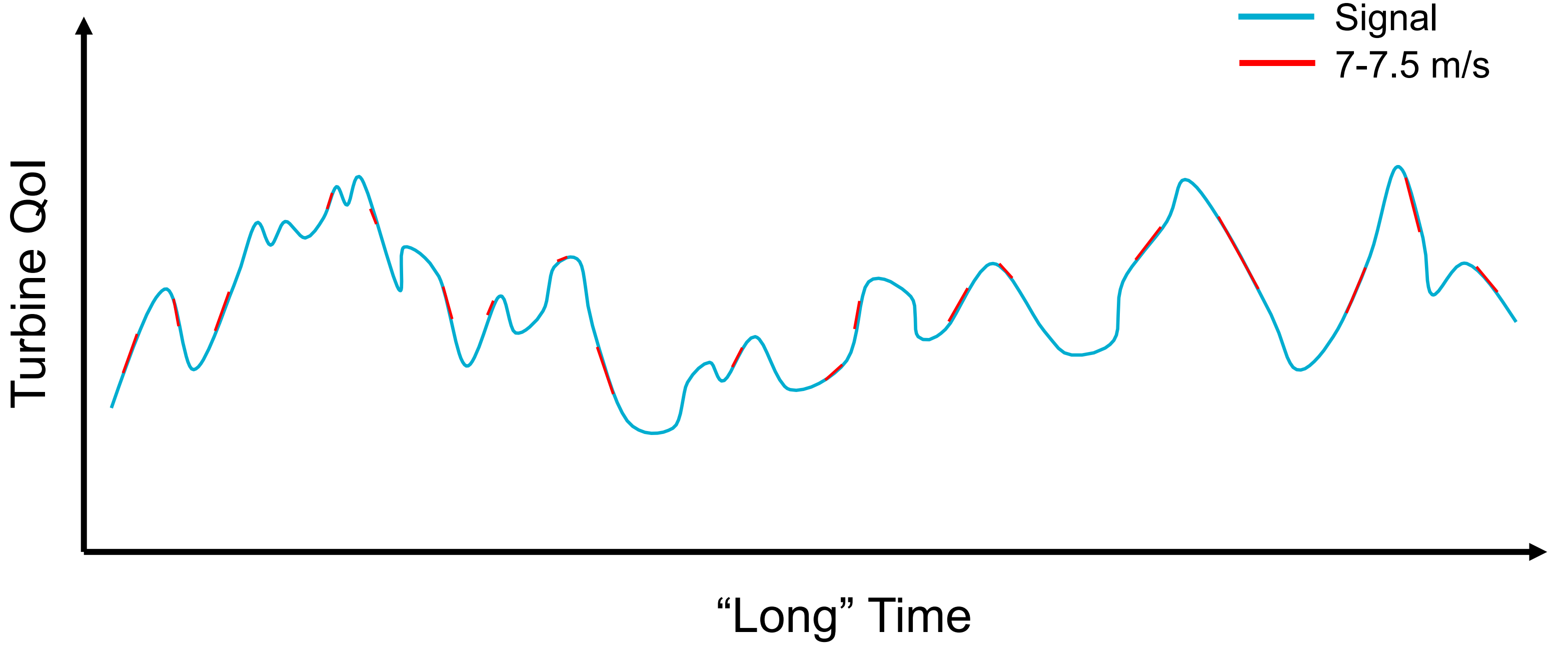
September metb1

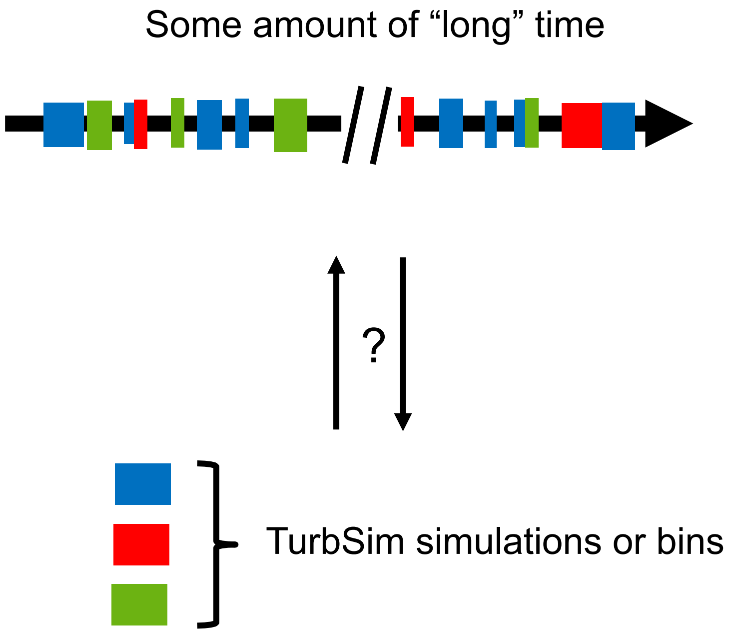


High Level Data Filtering

- Used the already QA/QC'd TTU met data to produce acceptable ranges of values
- Considering September-October and 9 AM-4 PM, calculated the 95% interval for TI, shear exponent, and veer
  - Hub height wind speed: "Visual" filtering, sonics are very reliable and no calculations are needed
  - 0 < TI < 0.4
  - -0.5 < shear exponent < 0.75
  - -35 < veer < 35

Going Between Simulation and Field Data



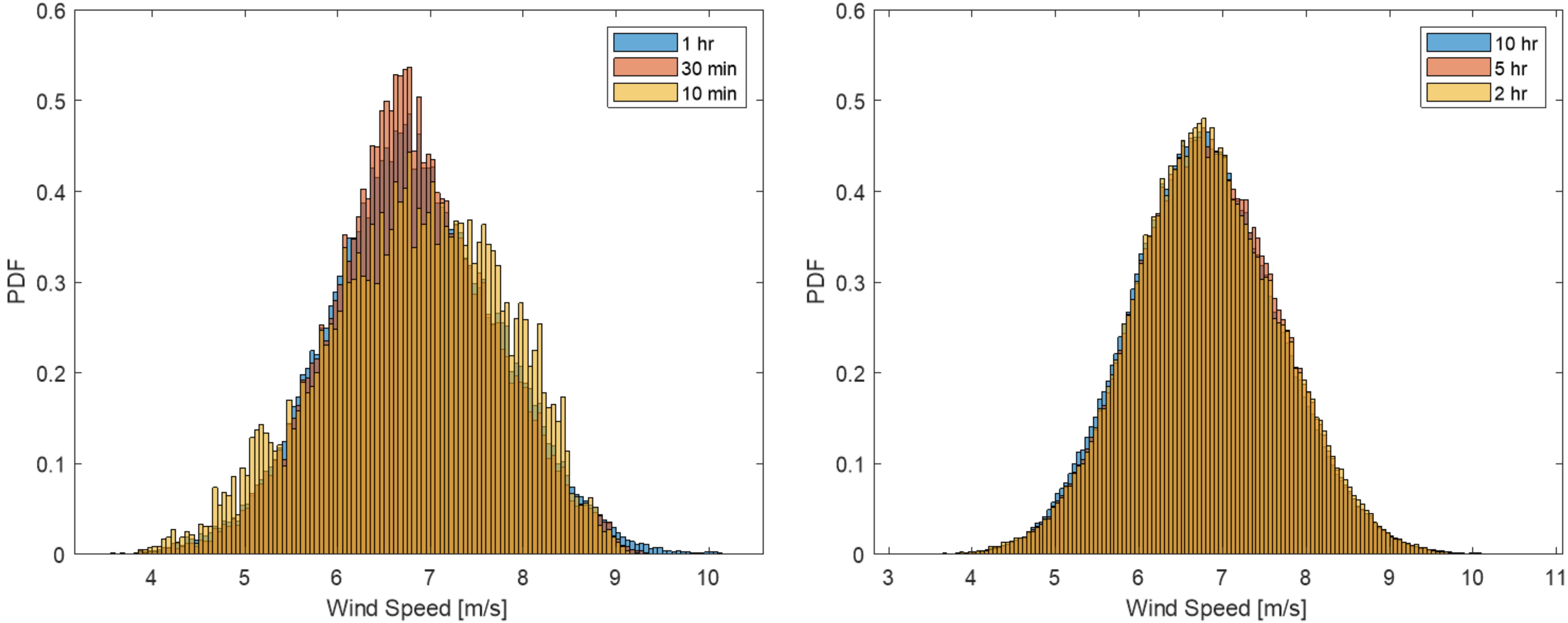


- TurbSim is implicitly binned because inputs are averages
- Raises many questions…

How long should TurbSim/OpenFAST run?

- Standard is 10 minutes
- But our goal is to know how much data we need, so more is better
- And we'll only use one seed since that's a better match to field data

Histograms of *U*

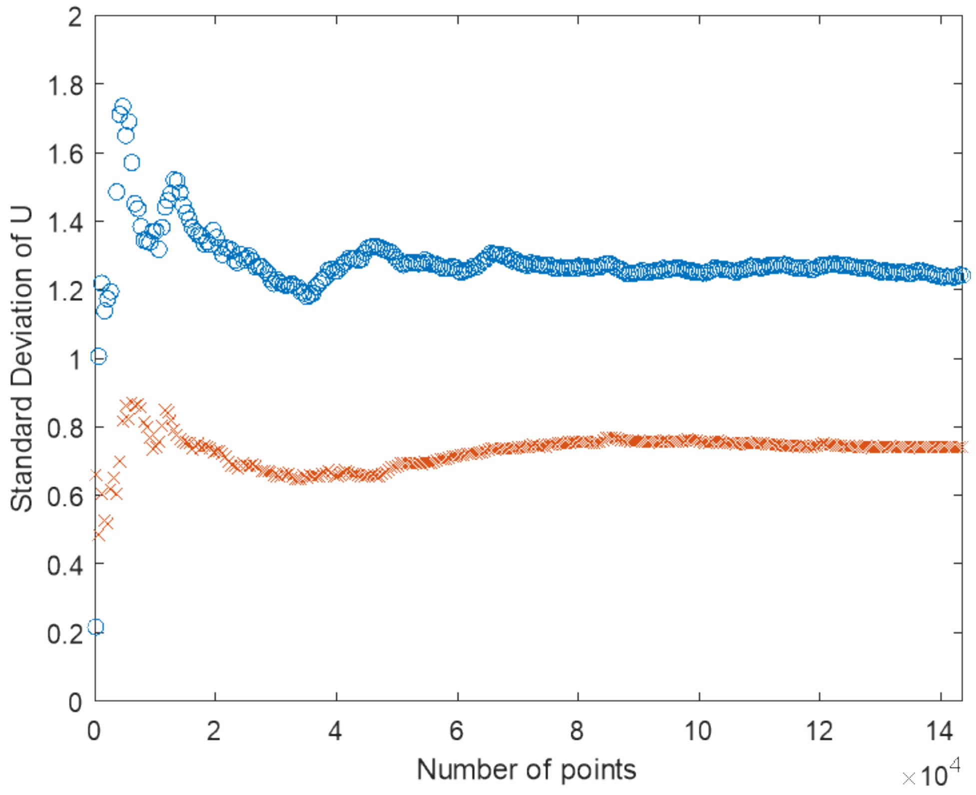


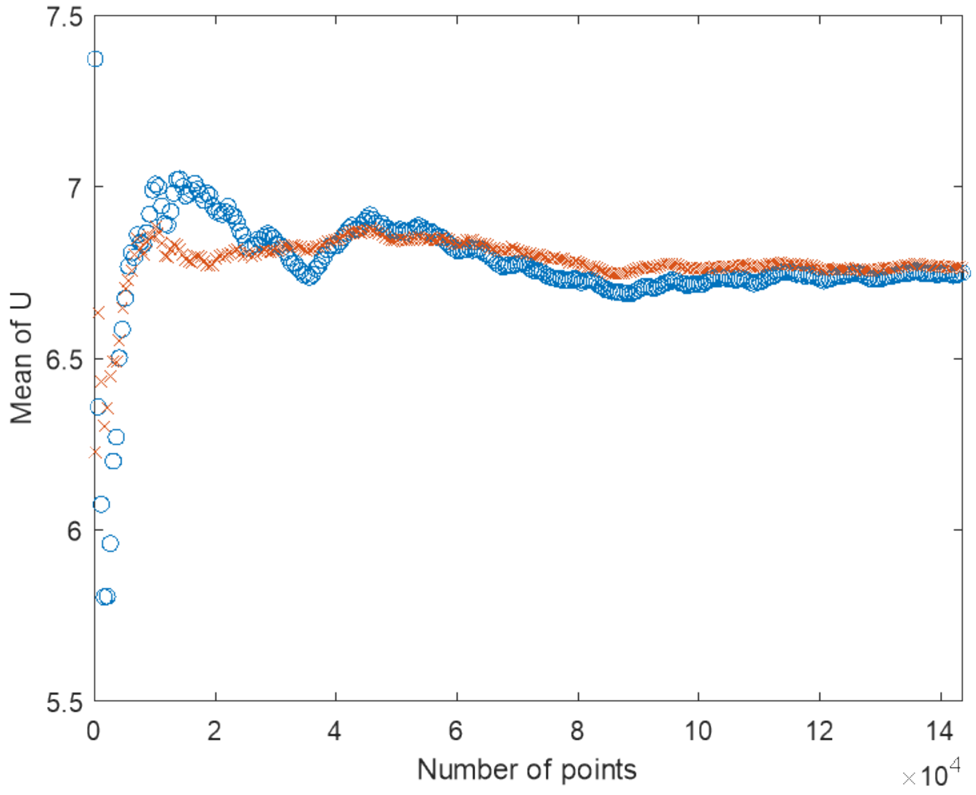
TurbSim prescribed distribution is Gaussian

From TurbSim/OpenFAST to Field Data

- Though simulations from TurbSim/OpenFAST are each implicitly a “bin”, we’ll do enough long simulations that we can aggregate the data – we don’t care about time series
- Then we can rebin on different parameters
  - Wind speed
  - TI
  - Shear
  - Stability?
- Quantify how the binning affects the uncertainty of the QoI
- Given best binning procedure, repeat it with met data to determine how much field data we need to get the same bins (in definition and amount of data in each)

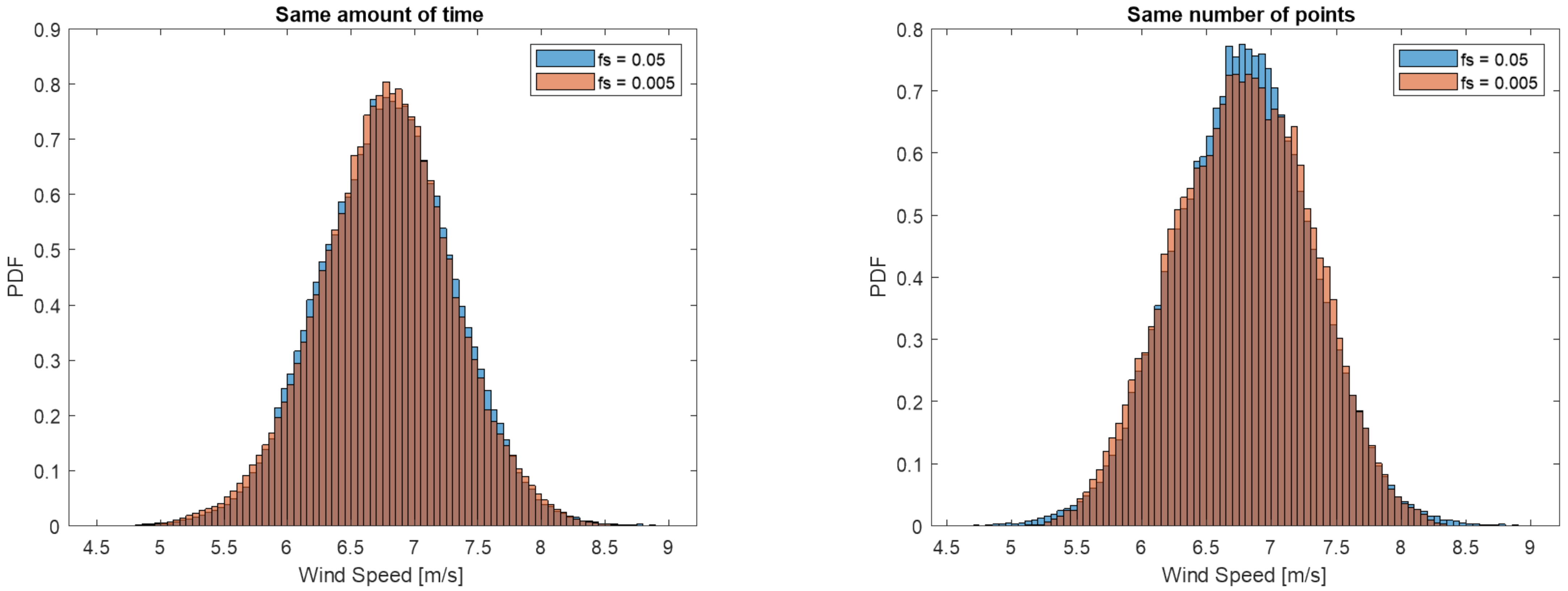
Convergence of different TI levels





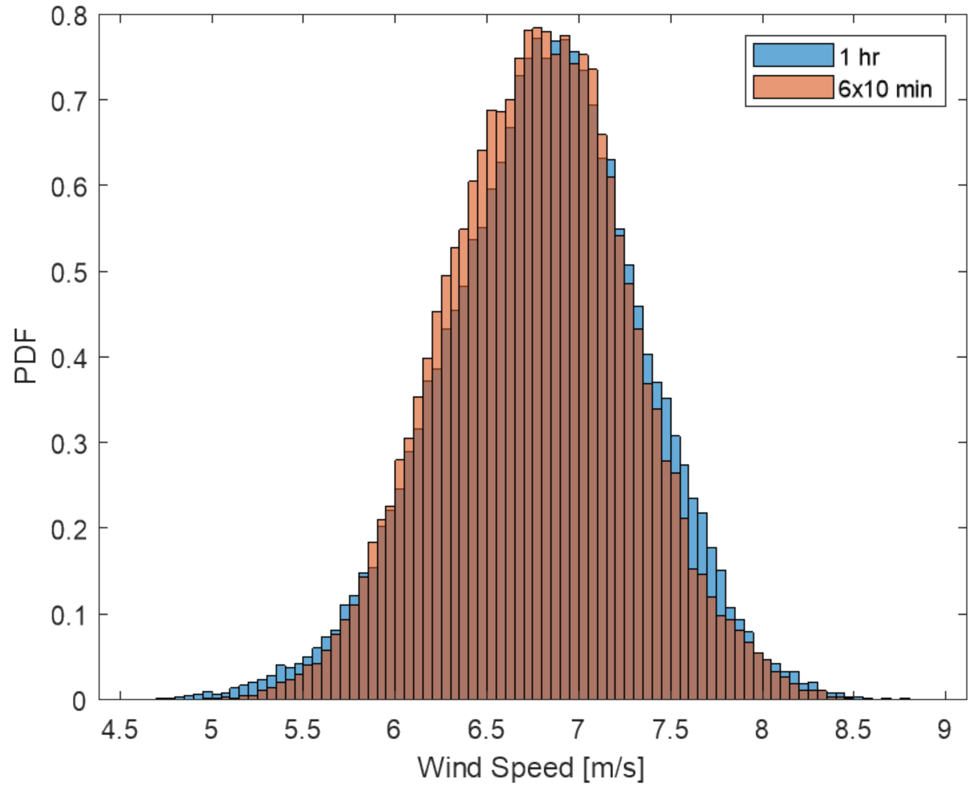
Visually, it looks like the high (blue) and low (red) TIs converge at the same rate, all else being equal.

Comparing different sample rates



Looks like they approach more similar distributions with the same amount of time and not number of points. Note, the lower sample rate has more data in its tails than the high sample rate when they have the same number of points.

1 hr compared to 6x10 mins



	Mean	Std. Dev
6 – 10 min	6.7554	0.7171
1 hr	6.8022	0.7466
2 hr	6.7641	0.7413

The increase in standard deviation between the six 10 min sims and the 1 and 2 hr ones suggests that the aggregate of the six 10 min sims is missing some data in the tails.