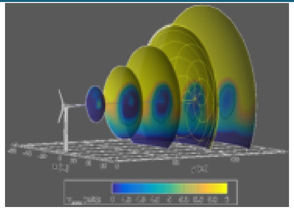
SAND2022-9797C

Sandia National Laboratories

Leading Edge Erosion: Quantifying Impacts of Performance and Reliability



PRESENTED BY

Josh Paquette

U.S. DEPARTMENT OF ENERGY NNSA

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Outline

Introduction and Erosion Trends

Aerodynamic Impact

Performance Loss Modeling

Model Validation

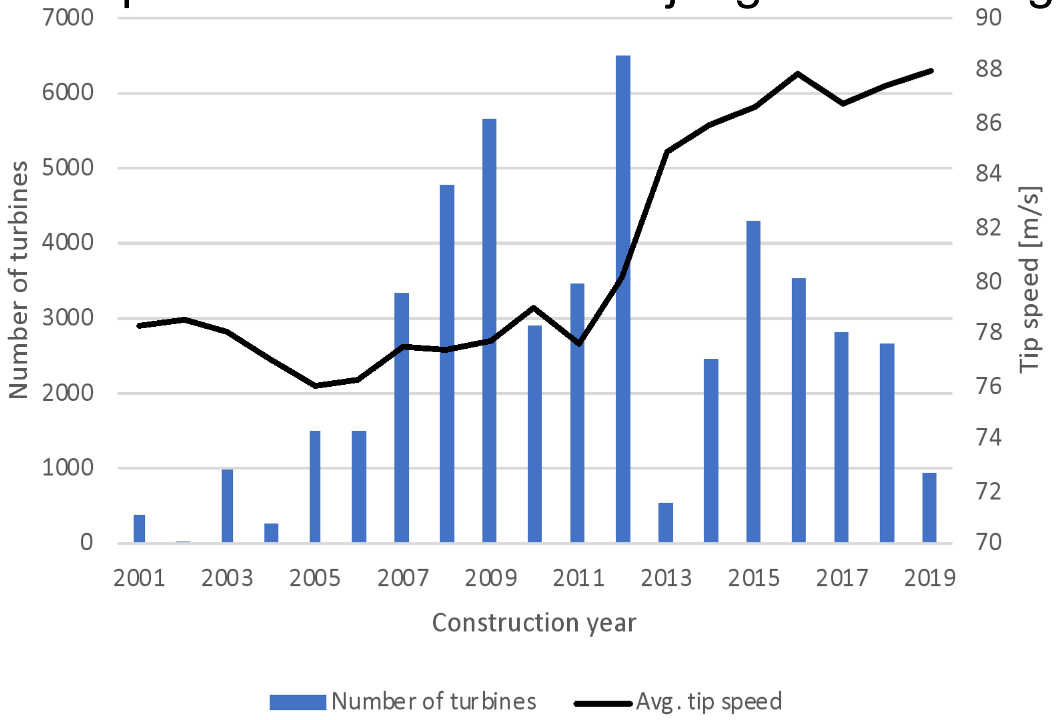
International Efforts
- IEA Task 46
- IEA Task 43

Predictive Modeling

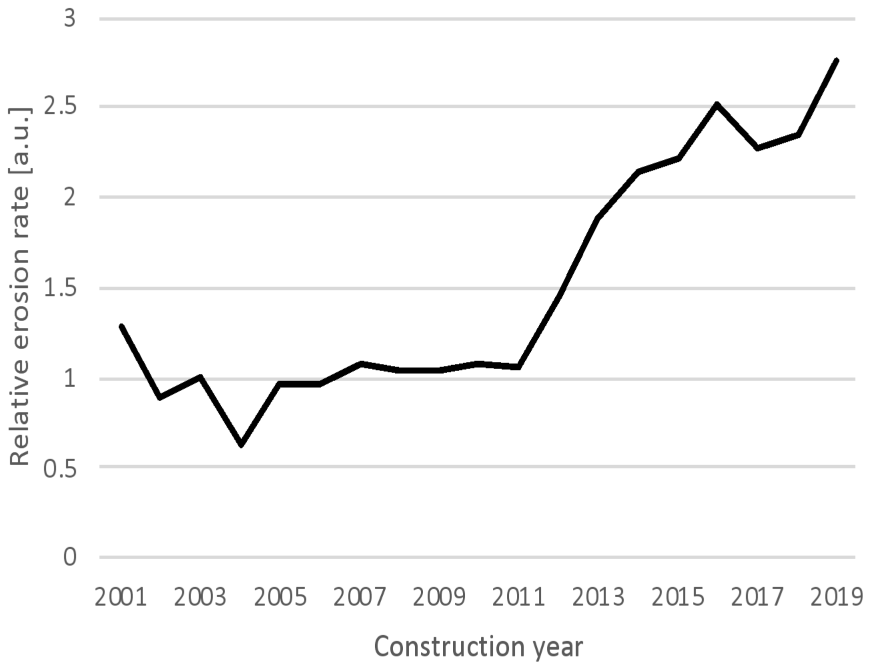
Future Needs

Introduction and Erosion Trends

- Gradual performance decrease and persistent maintenance costs
- Erosion rates can vary significantly between sites, depending on atmospheric effects, turbine design/operation
- Tip speeds have been increasing leading to an increasing relative erosion rate
- Inspections every 1-3 years, drones becoming standard practice
- Severity scale of 1 to 5, with uncertainty in application
- Repair decisions based on judgment and logistical drivers (weather, budget)



Turbine Installations and Tip Speed

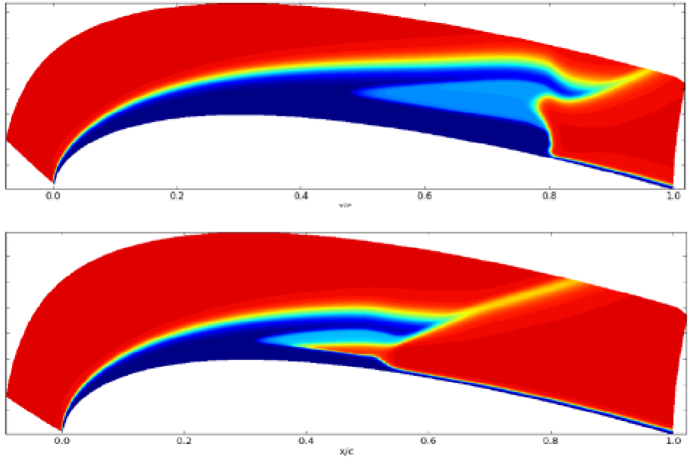


Predicted Relative Erosion Rate

Aerodynamic Impact

Measure Erosion Profiles

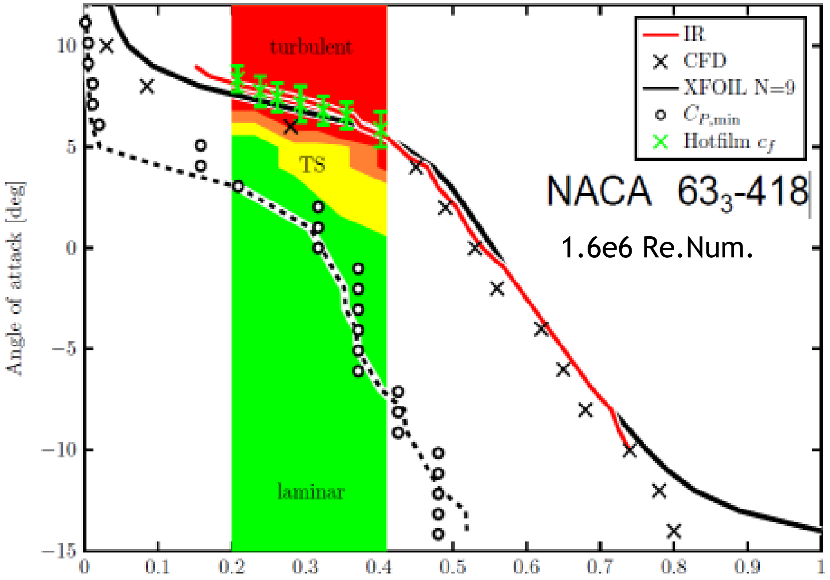
Develop Wind Tunnel Models



No Roughness

k_s = 350 μm

CFD Analysis



Airfoil Performance

[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.

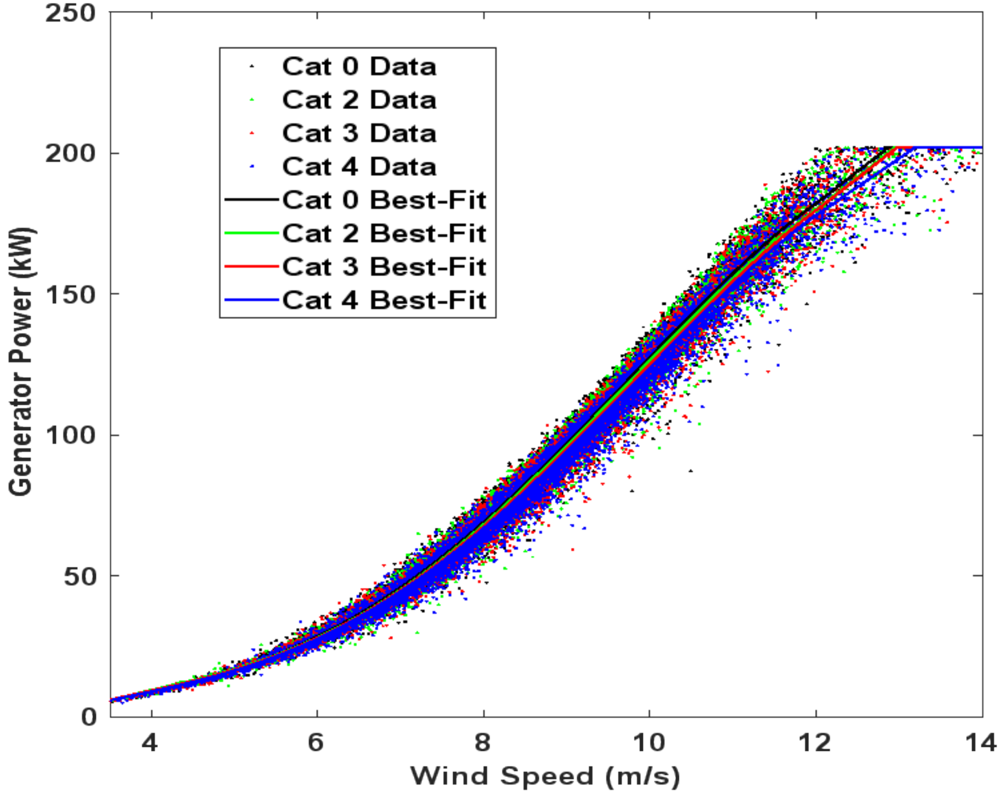
Performance Loss Model

Monte Carlo sampling was conducted to randomly sample 10,000 simulations, each 10 minutes long, for each of the four erosion categories

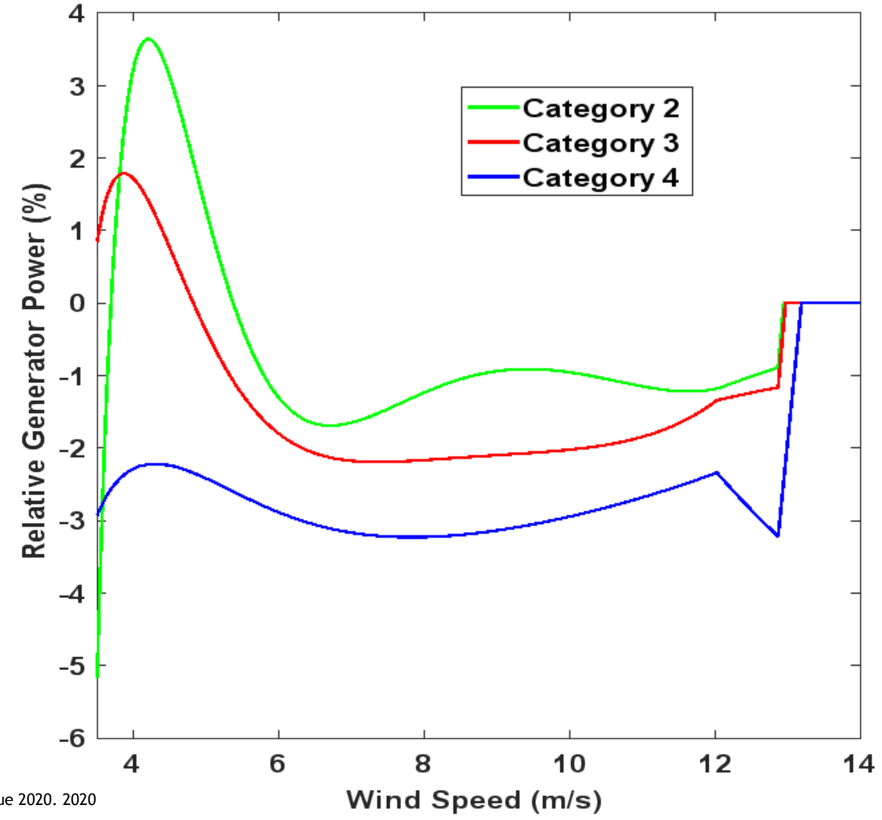
Uncertain aleatoric parameters: hub-height wind speed, turbulence intensity, shear exponent, air density, yaw offset, collective blade pitch

- Power increase at low wind speeds due to small number of samples relative to inflow variance

Power curve cloud



Change in power curve fit



[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
[14] NWTC Information Portal (OpenFAST)," ed. https://nwtc.nrel.gov/OpenFAST. Last modified 14-June-2016; Accessed 05-December-2019
[17] 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.

Performance Loss Model

- 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.

ΔAEP	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%

Model Validation

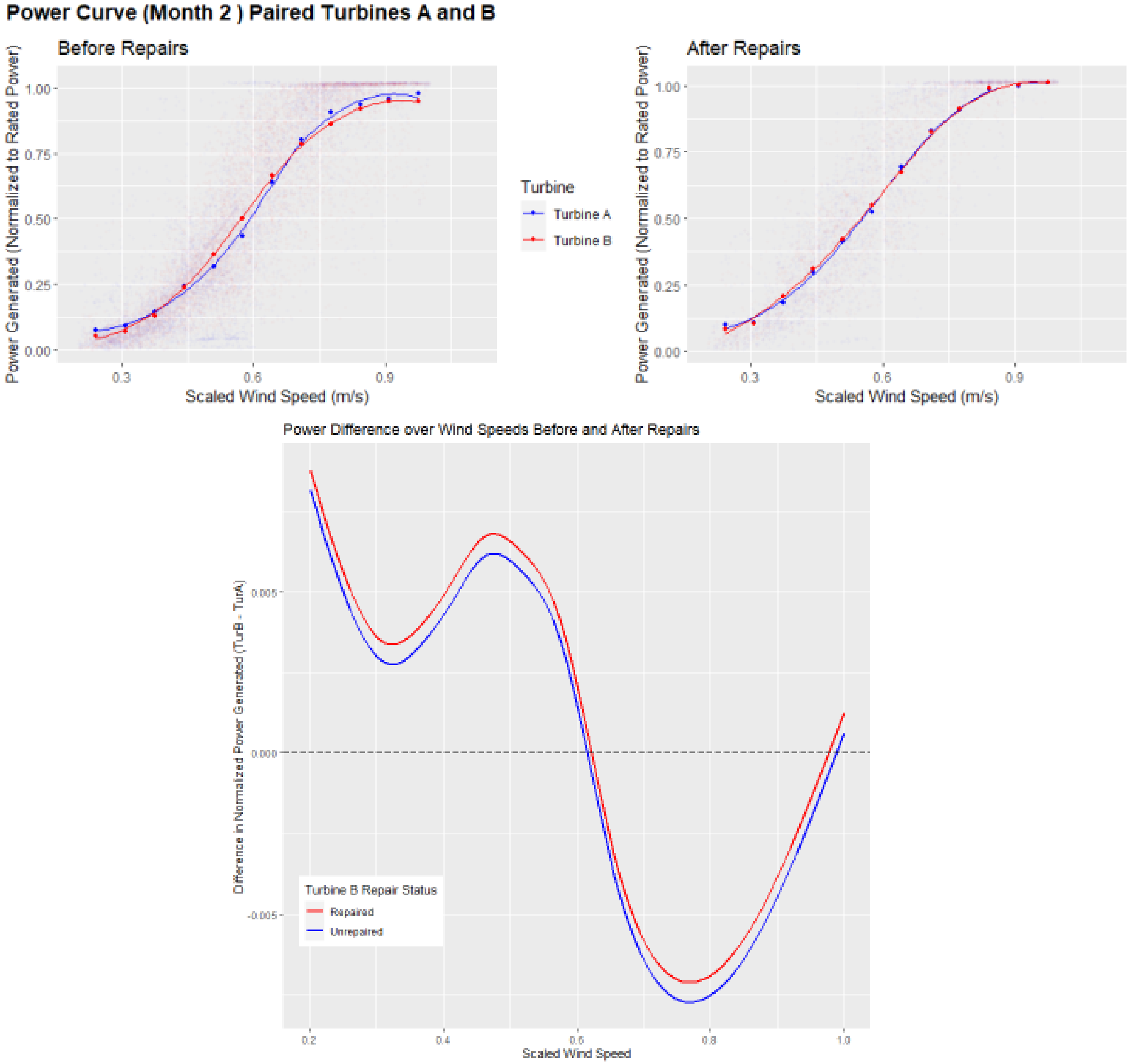
Archival SCADA data from the turbines and nearby meteorological towers was collected in 10-minute records.

- windspeed
- wind direction
- temperature
- atmospheric pressure
- power production
- turbine state
- nacelle direction

Data is corrected by comparing multiple measurements of the same quantity when possible.

Power curves are then calculated according to IEC 61400-12 for each turbine over smaller time intervals.

Class 2, 3, and 4 turbine pairs compared before and after repair.



IEA Task 46: Erosion of Wind Turbine Blades

Climatic Conditions

- Leading-edge erosion atlas
- Best practice for measurements of LEE drivers

Wind turbine Operation & Maintenance with Erosion

- Potential for safe-mode (de-rating) operation
- Model to predict annual energy production loss based on blade erosion class
- Standardization of damage reports based on erosion observations

Laboratory testing of erosion

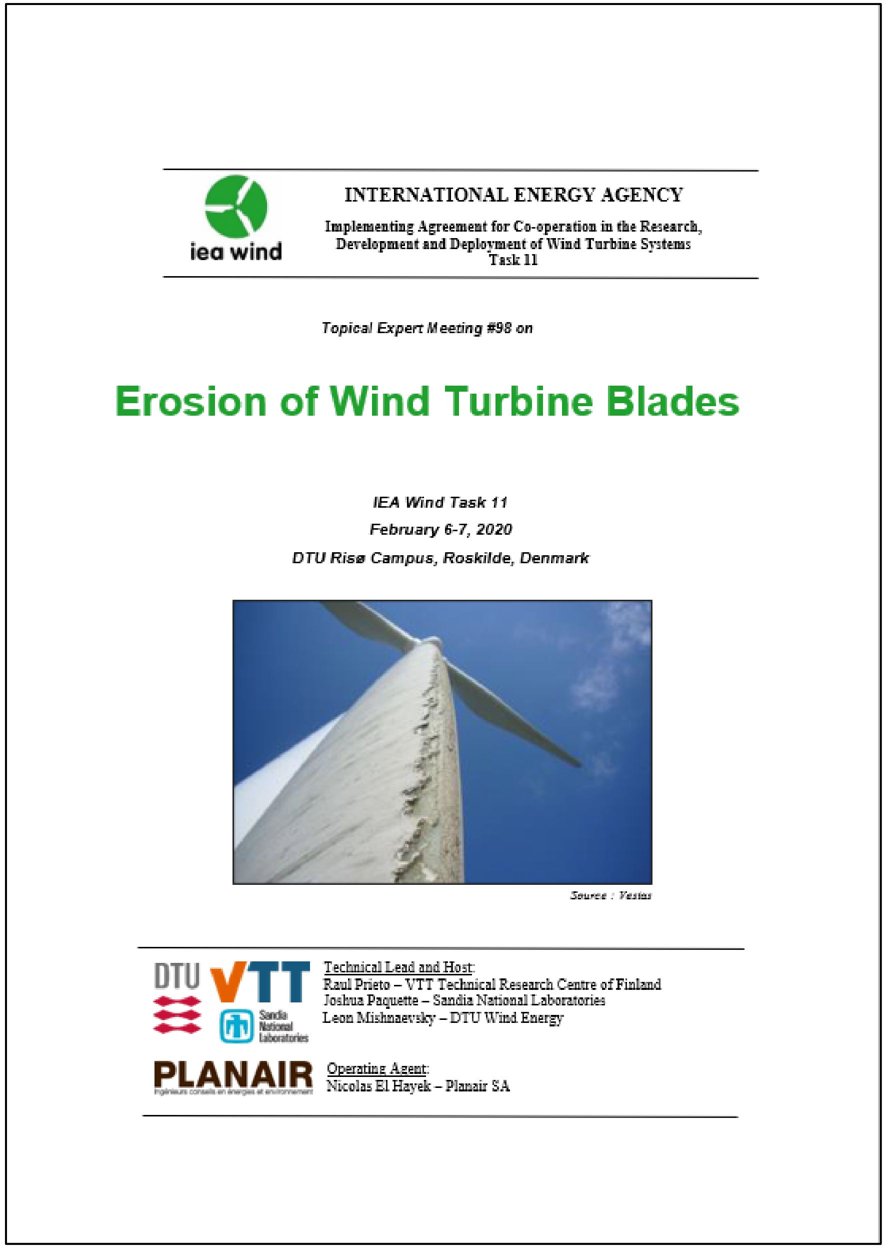
- Standardization of test substrates for rain erosion testing

Erosion mechanics

- Droplet impingement model for use in fatigue analysis

Material properties, microstructure & innovations

- State of the art in polymers and additives
- Test data for materials relevant to the erosion process


INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

Topical Expert Meeting #98 on

Erosion of Wind Turbine Blades

IEA Wind Task 11

February 6-7, 2020

DTU Risø Campus, Roskilde, Denmark

Source : Vestas

Technical Lead and Host:
Raul Prieto – VTT Technical Research Centre of Finland
Joshua Paquette – Sandia National Laboratories
Leon Mishnaevsky – DTU Wind Energy

Operating Agent:
Nicolas El Hayek – Planair SA

IEA Task 46: Erosion of Wind Turbine Blades

This work package has three key overarching objectives:

1. Promote collaborative research to mitigate erosion by means of wind turbine control, assessing the viability of erosion safe mode.
2. Improve the understanding of droplet impingement in the context of erosion.
3. Improve the understanding of wind turbine performance in the context of erosion, specifically the effect of LEE surface roughness on aerodynamics.

	Activity	WP code
Year 1	Model to predict annual energy production loss on blade erosion class	WP3.1
Year 1	Report on standardization of damage reports based on erosion observations	WP3.2
Year 2	Droplet impingement model for use in fatigue analysis	WP3.3
	Potential for erosion safe-mode operation	WP3.4
	Accuracy of LEE performance loss model based on field observations (validation)	WP3.5

Please reach out if interested in collaborating!

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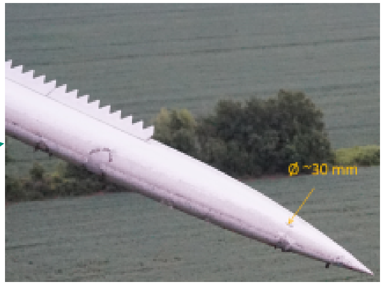
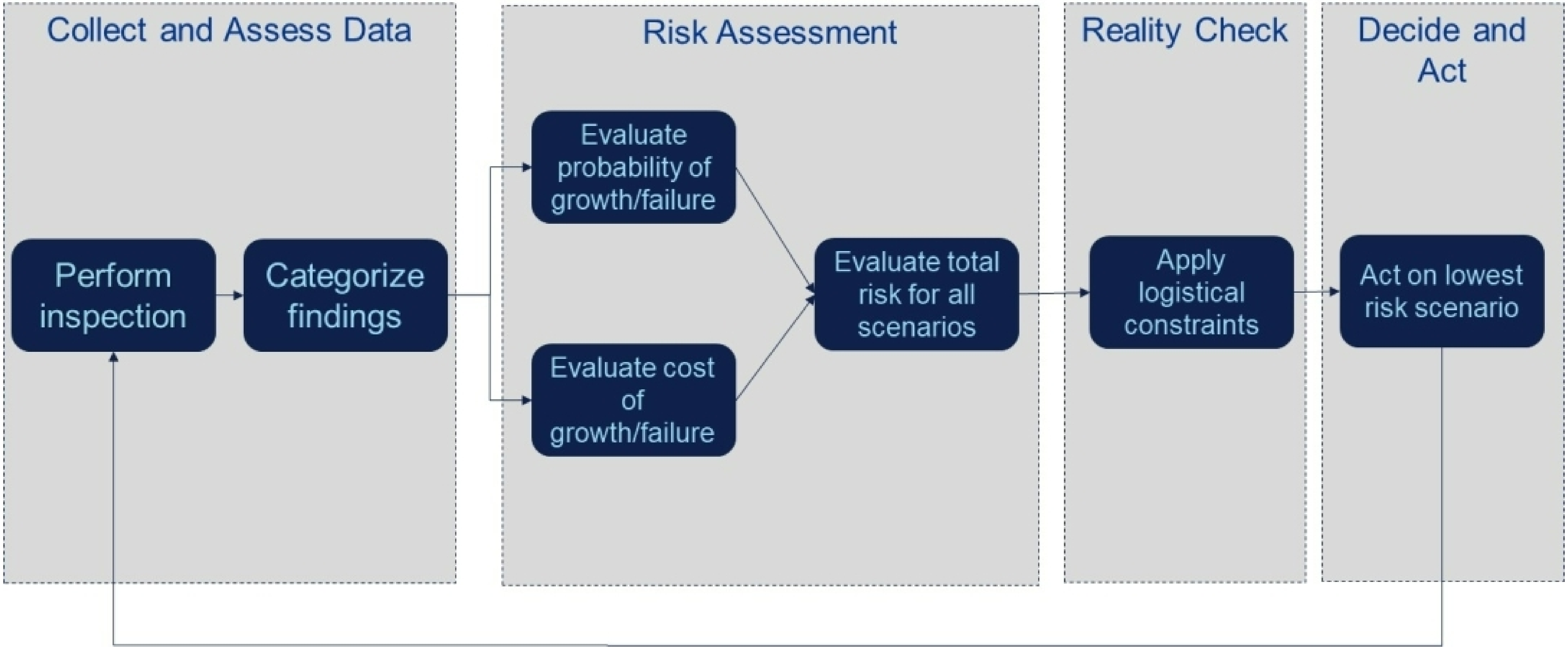
IEA Task 46: Erosion of Wind Turbine Blades

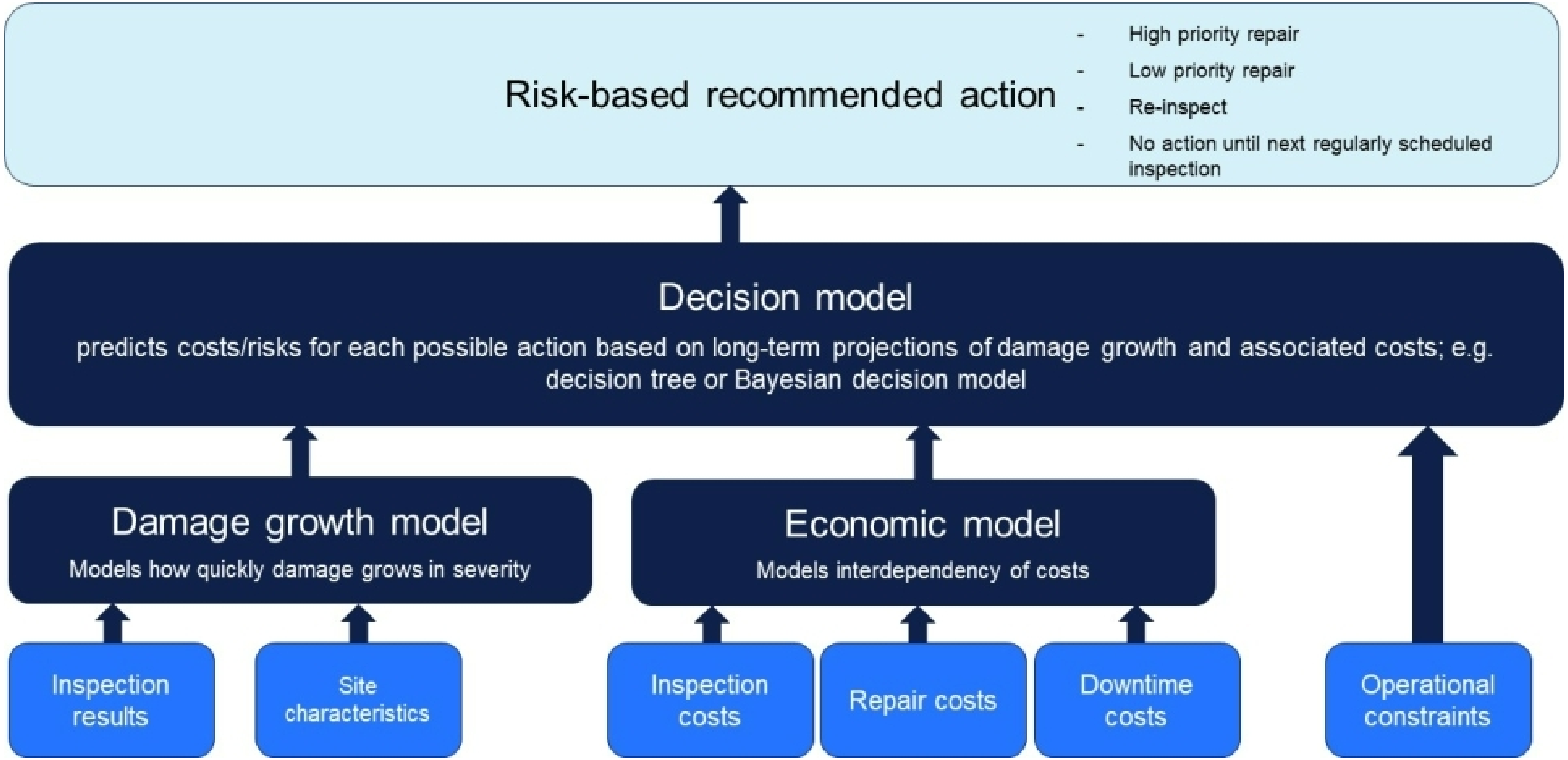
Organisation Type		RTO	Owner/Operator	University	Turbine OEM	University	RTO	University	RTO	Owner/Operator	Turbine OEM	Median	Variance
Image 1	Visual data definition	2	1		2	0	2.5	2		2	3	2	0.85
	Mass-loss or Depth	1	1			2	1			1	4	1	1.47
	Aerodynamics/Performance	2	1	5	2.5	2	2		2	1	3	2	1.44
	Structural	1	1			0	2.5		2	2	3	2	1.06
Image 2	Visual data definition	4	4		4	3	4	5	4	4	5	4	0.36
	Mass-loss or Depth	4	4			3	3			3	5	3.5	0.67
	Aerodynamics/Performance	4	4	5	4.5	3	3.5		4	3	5	4	0.56
	Structural	4	3			0	4		3	4	5	4	2.57
Image 3	Visual data definition	1	2		2	1	2		2	1	2	2	0.27
	Mass-loss or Depth	1	1			0	1			1	1	1	0.17
	Aerodynamics/Performance	1	1		2	1	2		2	1	3	1.5	0.55
	Structural	2	1			0	2		3	1	2	2	0.95
Image 4 - Part 1	Visual data definition	3	1		2	1	2	1	2	1	2	2	0.50
	Mass-loss or Depth	2	1			1	1			1	4	1	1.47
	Aerodynamics/Performance	3	1	3	2	1	1.5		2	1	2	2	0.63
	Structural	2	1			0	2		3	2	3	2	1.14
Image 4 - Part 2	Visual data definition	2	2		1	1	2.5	1	2	1	1	1	0.38
	Mass-loss or Depth	1	2			1	1.5			1	1	1	0.18
	Aerodynamics/Performance	2	1	2	1	1	1.5		2	1	2	1.5	0.25
	Structural	2	1			0	2		3	2	1	2	0.95
Image 5	Visual data definition	1	1		1	0	0.5	2		1	0	1	0.42
	Mass-loss or Depth	1	1			0	0			1	1	1	0.27
	Aerodynamics/Performance	2	1	2	2.5	2	1		1	2	2	2	0.32
	Structural	1	1			0	1			1	0	1	0.27
Image 6	Visual data definition	1	1		1	1	1.5	1	1	1	1	1	0.03
	Mass-loss or Depth	1	1			1	1			1	1	1	0.00
	Aerodynamics/Performance	1	1		1	1	1		1	1	0	1	0.13
	Structural	2	1			0	2		2	1	1	1	0.57
Image 7	Visual data definition	2	1		1.5	0	1	1	1	1	3	1	0.69
	Mass-loss or Depth	1	1			1	0			1	2	1	0.40
	Aerodynamics/Performance	2	1		3	2	1		2	2	4	2	0.98
	Structural	1	1			0	1		2	1	1	1	0.33



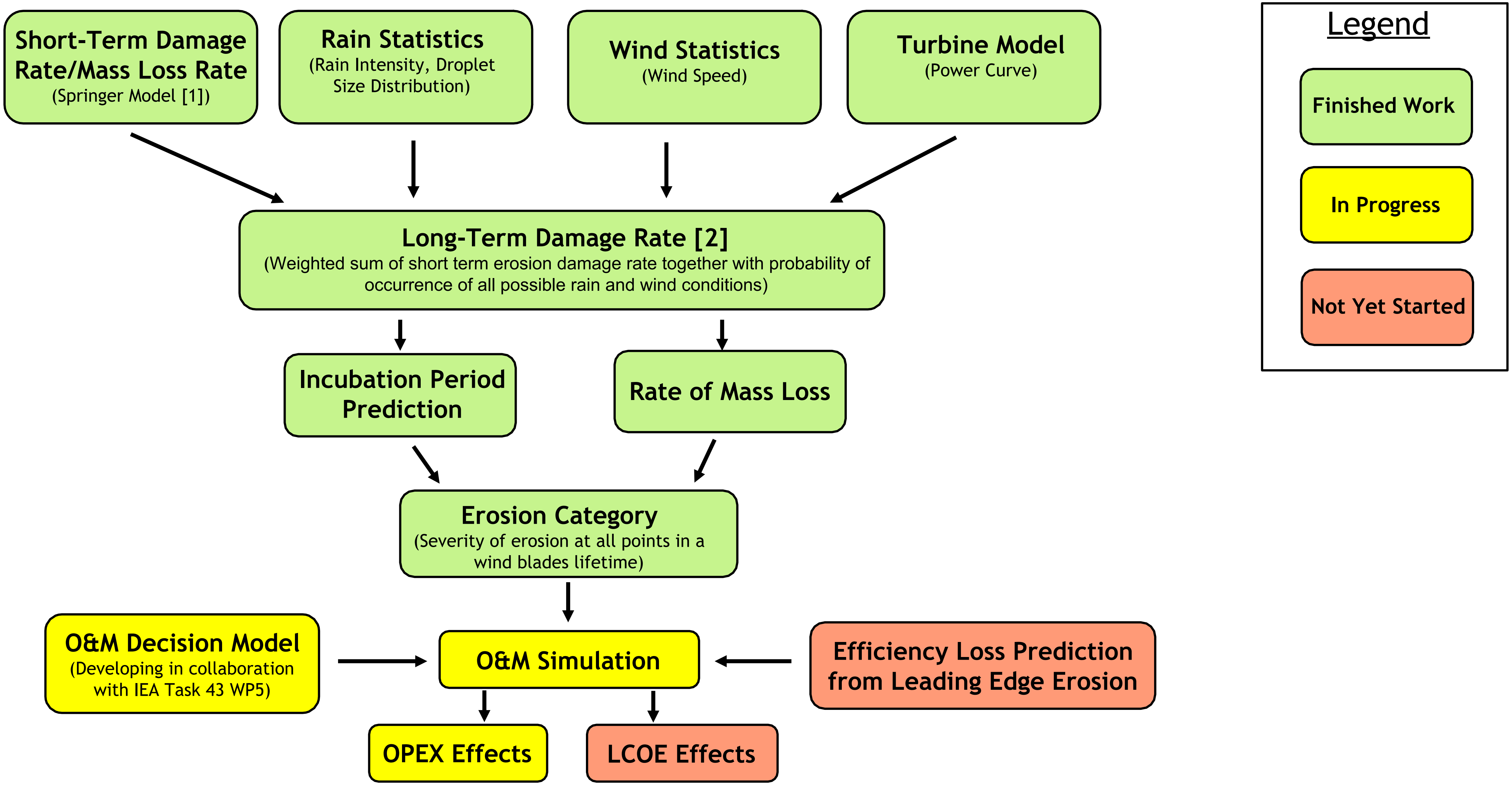
IEA Task 43: Wind Energy Digitalization, O&M Work Package



IEA Task 43: Wind Energy Digitalization, O&M Work Package



Predictive Modeling



Predictive Modeling

- Probabilistic damage growth model and approach taken from Verma et al [2]. Extended to include:
  - Mass loss rate after incubation period.
  - Attempt to relate percent mass loss to erosion category.
  - Erosion of coated materials instead of assuming homogeneous monolithic material [1].

- The model is flexible and tailorable:
  - Through the Turbine model coarse characteristics of different turbine sizes and high level control strategy effects are captured.
  - Accounting for Rain and Wind Statistics allows the model to be tailored to specific wind plant sites.
  - Using the Springer model allows for comparisons of different materials. As well as accounting for the statistical variation in material properties through stochastic simulations.

- Future work includes:
  - Adding a decision model to pair with the damage growth model.
  - Incorporating the ability to account for wind turbine efficiency loss due to leading edge erosion.

[1] GS Springer, CL Yang; PS Larsen, "Analysis of Rain Erosion of Coated Materials," *Journal of Composite Materials*, vol. 8, pp. 229-252, 1974.
[2] A. Shankar Verma *et al.*, "A probabilistic long-term framework for site-specific erosion analysis of wind turbine blades: A case study of 31 Dutch sites," *Wind Energy*, vol. 24, no. 11, pp. 1315-1336, 2021, doi: 10.1002/we.2634.

Achieving Higher Reliability

Understanding the erosive potential of the turbine and site

Standards for blade design with erosion

Predictive models for erosion progression

Decision models for repair

Better erosion protection materials and methods

Thank you