SAND2023-11779C

Task 46 Erosion of Wind Turbine Blades
Work Package #3: Wind turbine operation with erosion

Development of a Standard Erosion Classification System

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4th International Symposium on Leading Edge Erosion of Wind Turbine Blades

7-9 February 2023

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IEA Task 46: Erosion of Wind Turbine Blades

Work Package	Coordinating organization(s)	work package leader / co-leaders
WP2: Climatic conditions driving blade erosion	Cornell University (US), Ørsted (DK)	Sara C Pryor , Marijn Veraart
WP3: Wind turbine operation with erosion	Sandia National Laboratories (US)	David C Maniaci
WP4: Laboratory testing of erosion	DTU (DK), Hempel (DK)	Jakob Ilsted Bech, Maral Rahimi
WP5: Erosion mechanics & material properties	CEU Cardenal Herrera University (ES), University of Bergen (NO)	Fernando Sánchez López, Bodil Holst

Coordination of technical work packages

WP 3 :Wind turbine operation with erosion

This work package has three key overarching objectives:

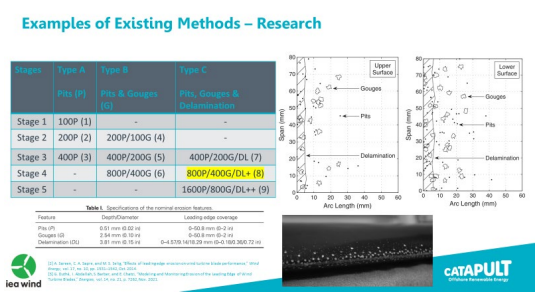
1. Promote collaborative research to mitigate erosion by means of wind turbine control, assessing the viability of erosion safe mode.
2. Improve the understanding of droplet impingement in the context of erosion.
3. Improve the understanding of wind turbine performance in the context of erosion, specifically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

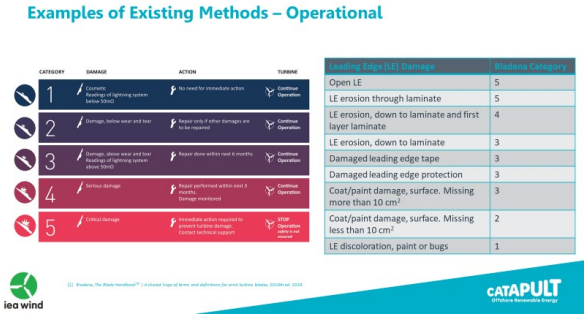
	Activity	WP code
Year 1	Model to predict annual energy production loss on blade erosion class	WP3.1
Year 1	Report on standardization of damage reports based on erosion observations	WP3.2
Year 2	Droplet impingement model for use in fatigue analysis	WP3.3
	Potential for erosion safe-mode operation	WP3.4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

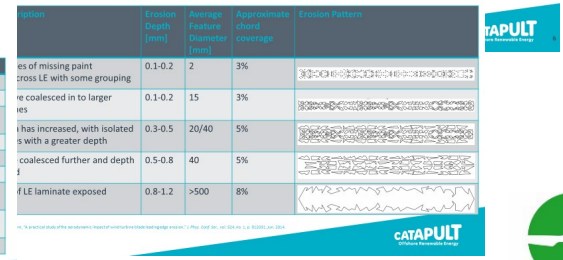
Stakeholder Scenarios for Blade Damage Classification

- There are different motivations and techniques for categorizing wind turbine blade damage.

Assessment	Primary motivation
Research	Novel insights and understanding
Testing	Replicating in-situ conditions to predict expected performance
Manufacturing	Quality control
Operational	Performance and structural integrity of wind turbine assets







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Leading Edge Erosion Categorization Considerations

Assessment Method

- Methodology
  - Drone, Rope Access, Ground Based Cameras
- Interpretation/Subjectivity
- Inspection Quality
- Technology
  - Visual
  - NDT, Other

Blade Geometry

- Blade Area
- Blade Location (Span and Chordwise)
- Blade Cross Section
- Distinguishing Different Locations of Erosion

Subsequent Action

- Damage Progression
- Intervention Decision
  - Influence of Other Forms of Damage
  - Predicted Lifetime of LEP
- Repair Categorisation

Damage Mechanism

- Material Type
  - Leading Edge Protection - Tape, Softshell, Coating, Other…
  - Unprotected Blades
- Root Cause
- Type of Failure/Damage Exhibited
  - Erosion/Degradation
  - LEP Adhesion Failure

Performance

- Mass Loss
- Roughness
- AEP
- LEP Failure
  - Adhesion
  - Degradation
- End Of Incubation Period

Structural Integrity

- Blade Feature
- Damage Cohesion
- Damage Form/Type
- Damage Extent
- Damage Depth

Assessment Type

- Research – CFD, Wind Tunnel/Rain Erosion Testing (RET)
- Operational Turbine
- Other

Additional Context

- Number of Blades Affected
- Age of Blades
  - Lifetime Extension
- Previously Known Damages
- Expected Erosion Conditions

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Erosion Classification System Example

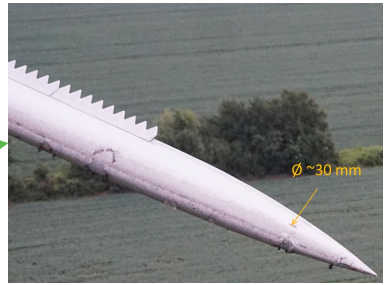
- Participants were asked to test the draft classification system on a sample of images.

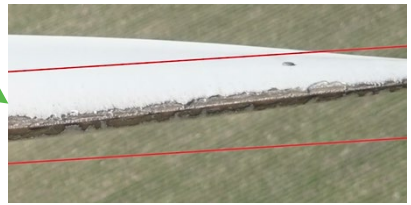
Information to Categorize	Erosion Class	Note
Visual data definition	4	Large exposed surfaces of fiberglass. Signs of damage to the underlying fiberglass.
Mass-loss or Depth	4	
Aerodynamics/Performance	4	
Structural	3	

Parameter (Specified by Service Provider)	Value
Material	Laminate
Blade Length	37 m
Distance from Root	37.3 m
Length of damage	4.1 m
Width of damage	0.15 m

Erosion Classification System Test

	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





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Initial Feedback – Key Themes

- Large variance in some assessments from Erosion Classification Task submissions
- Different perspectives from different types of organisations
  - RTO, O/O, Academia, Turbine OEM
- Difficult to assess all evaluation criteria based on visual imagery
- Variables associated with assessment (materials, turbine, location)
- Consideration of LEP/No LEP separately for Visual Condition

	Organisation Type	RTO	Owner/Operator	University	Turbine OEM	University	RTO	University	RTO	Owner/Operator	Turbine OEM	Median	Variance
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	Aerodynamics/Performance	1	1		1	1	1		1	1	0	1	0.13
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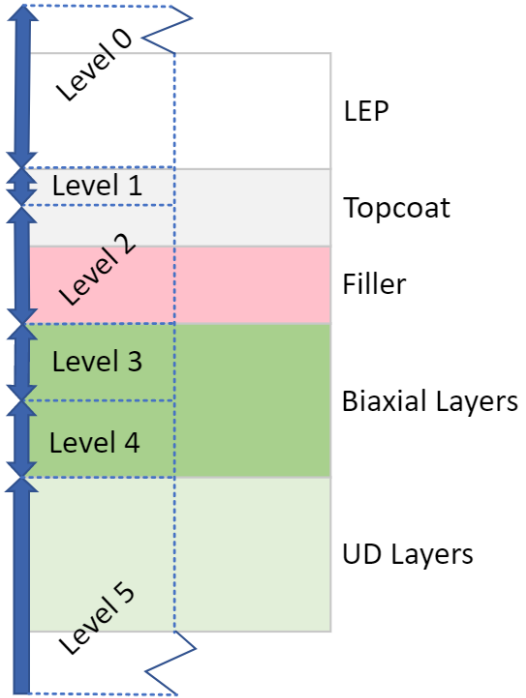
Severity Level definitions and thresholds

Structural Integrity

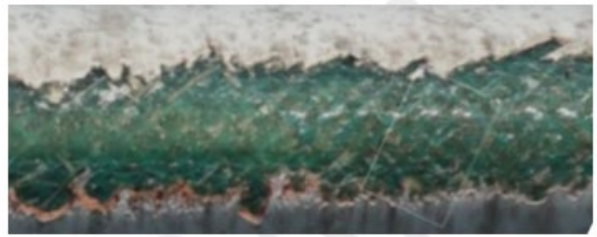


Visual Condition

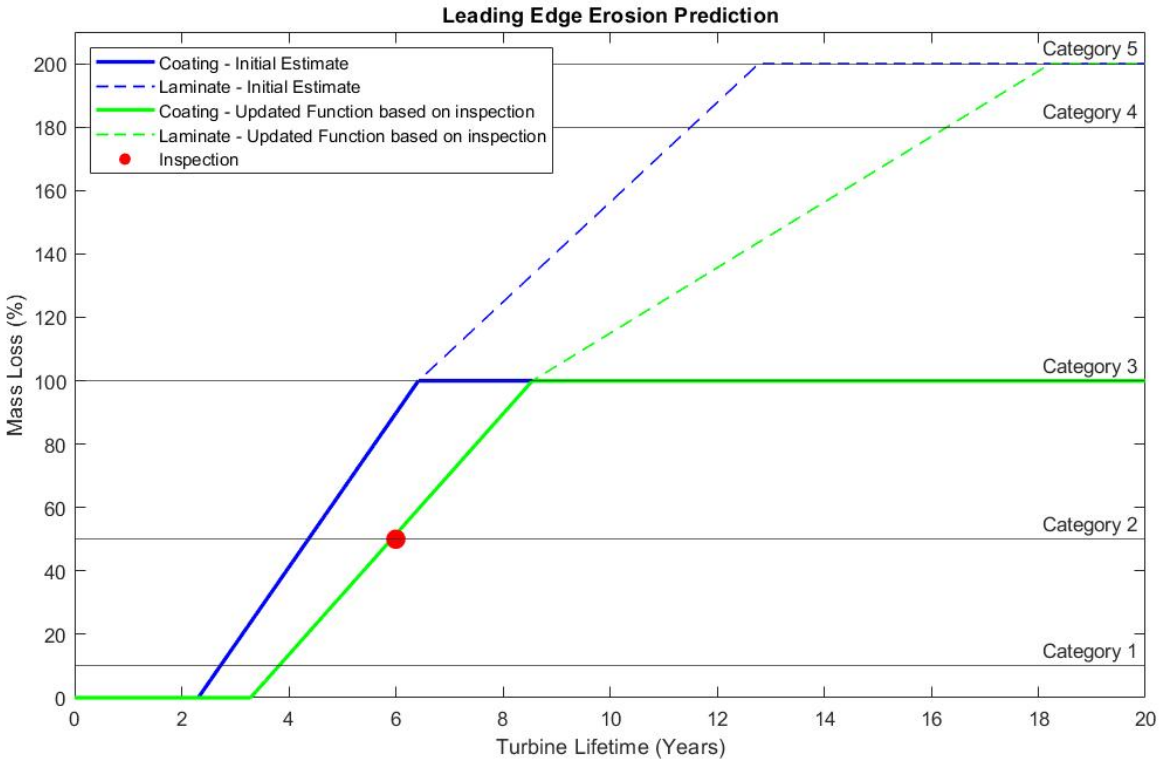
***Level 4** – "Erosion of topcoat with immediate layer underneath visible and exposed"*

Damage threshold: erosion of topcoat ≥10cm²; erosion of laminate ≤1cm²

- Erosion has worn away to the laminate such that the filler layer or immediate laminate is observable over an area greater than 10cm²
- Damage to the substrate is either not entirely obvious or sufficiently small/minor.



Mass Loss Model



- Mass loss model has the potential to improve its prediction of future erosion level progression through incorporation of inspection data.
- When correlated with the other erosion categories, allows for prediction of expected future performance loss.
- This model is currently under development and will need to be validated against wind plant inspection and operational data, a process that is currently underway.

Example plot of leading-edge erosion prediction of a wind blade airfoil section where initial model estimates are updated to better fit inspection data from the field.

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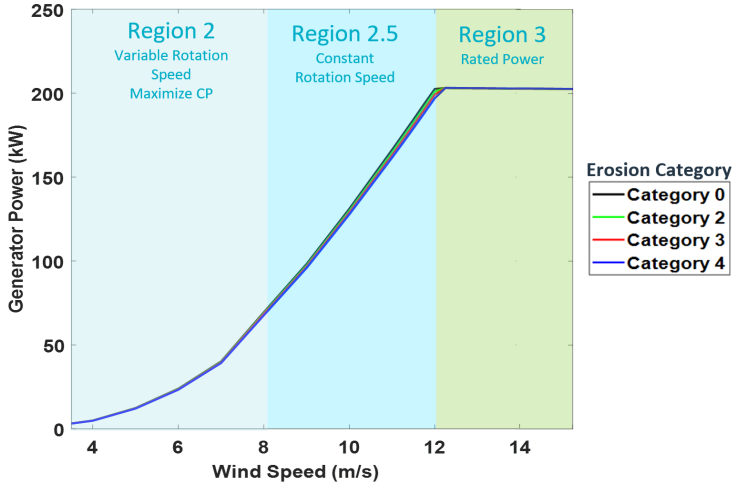
Aerodynamic Performance Categorization

- **Category 0**: Flow not disturbed. Roughness effects are damped by the viscosity of the flow.
- **Category 1**: Region 2 Power loss <1%. The transition point is moved forward toward the leading edge.
- **Category 2**: Region 2 Power loss 1%, Moderate loss to L/D and CL_max, (-20% and -5%). The transition point is moved forward to the leading edge.
- **Category 3**: Noticeable loss to L/D and CL_max (-30% and -5-10%). The flow is fully turbulent downstream of the roughness elements in eroded regions of the blade span.
- **Category 4**: Significant loss to L/D (> -40%) and CL_max (> -10%). The flow separates in downstream locations due to the boundary layer weaknesses against adverse pressure gradients given by airfoil geometry.
- **Category 5**: Severe loss to L/D and CL_max due to flow separation and a lack of laminar flow.

- Region 2 power loss from the erosion severity categories can be mapped to the annual energy production (AEP) loss.

Power loss is defined in Region 2 of the power curve.



AEP loss due to erosion.

Erosion Category	Mean Wind Speed (m/s)				
	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%

Figures modified from: Maniaci, D. C., Westergaard, C., Hsieh, A., & Paquette, J. A. (2020). Uncertainty Quantification of Leading Edge Erosion Impacts on Wind Turbine Performance. *Journal of Physics: Conference Series*, *1618*(5), 052082. https://doi.org/10.1088/1742-6596/1618/5/052082

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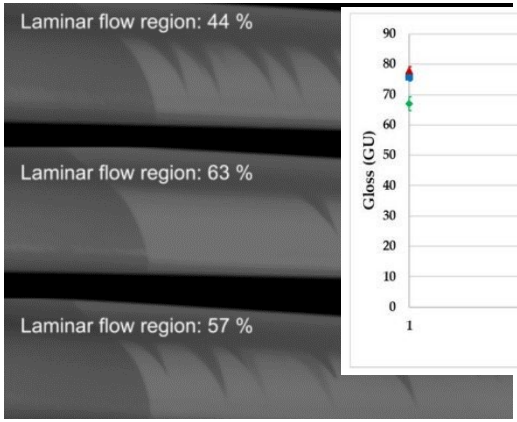
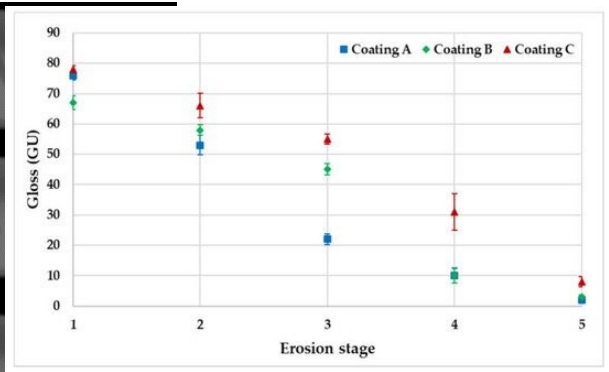
Updated Classification System

Evaluation Criteria	Severity Level 0	1	2	3	4	5
Visual Condition (LEP)	Initial factory condition	Lightly worn external coating/LEP Instances of reduced LEP adhesion	Notable areas of localized damage on external coating/LEP Individual Instances of LEP adhesive failure.	LEP is largely compromised over a large area and no longer providing protection to underlying layers	Delamination of topcoat with immediate layer underneath clearly visible and exposed	Notable damage to substrate
Visual Condition (No LEP)		Erosion barely visible or pinholes	Localized pitting	Widespread or coherent pits, some gouges		
Mass-loss		Coating <10% Laminate 0%	Coating 10-50%, Laminate 0%	Coating 50-100%, Laminate <10%	Coating 100% Laminate 10-100%	Coating 100%, Laminate 100%
Aerodynamic Performance		Normal surface roughness Region 2 Power loss 0 -1%	Region 2 Power loss 1%-2%	Region 2 Power loss 2%-3%	Region 2 Power loss 3-4%	Region 2 Power loss >4%
Blade Integrity		Initial erosion of topcoat	Erosion through topcoat	Initial exposure of immediate laminate layers	Erosion through immediate laminate layers	Exposure of structural laminate layers

Future Considerations/Research

- New Assessment Technologies
  - Non-Destructive Technologies (NDT)
  - Sensors
- Advancements in Blade Technology
  - Blade Materials and Design
  - LEP
- Advancements in Modelling
  - Leading edge erosion mechanisms
  - Aerodynamic effects
- Remedial action
  - Structural Integrity similar to typical recommendations
  - Potential control changes





Leishman G, Nash D, Yang L, Dyer K. A Novel Approach for Wind Turbine Blade Erosion Characterization: An Investigation Using Surface Gloss Measurement. *Coatings*. 2022; 12(7):928. https://doi.org/10.3390/coatings12070928

Report available: https://iea-wind.org/task46/
Please trial the classification system!
Example images available in the Appendix.

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Thank you!

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IEA TEM on LEE

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Work Package 3 Activities

WP3.1: Model to predict annual energy production loss on blade erosion class

- Develop a common model of aerodynamic performance loss due to leading edge roughness and erosion standardized classes.

WP3.2: Report on standardization of damage reports based on erosion observations

- Standardization of damage reports for validation of any erosion potential assessment and to allow effective integration of data from operators with laboratory derived estimates.

WP3.3: Droplet impingement model for use in fatigue analysis

- Develop a standard model for droplet impingement, validated with wind tunnel experimental data.

WP3.4: Potential for erosion safe-mode operation

- Report describing potential for leading edge erosion safe mode operation. This report will be used for seeking participation from industry and research funders towards a coordinated project designed to assess viability and cost-benefit of leading edge erosion safe mode operation.

WP3.5: Accuracy of LEE performance loss model based on field observations (validation)

- Carry out iterative aerodynamic loss benchmarks with model development and new wind tunnel testing for calibration and validation. Validation of complete performance loss model using probabilistic analysis of field observations.

Work Package 3 Near-term Plans

Year 2 focus areas:

- Aerodynamic benchmarks, detailed aerodynamic studies on common datasets
  - Compare AEP predictions to pre aero-benchmarks. Have the AEP models changed significantly?
- Droplet impingement model for use in fatigue analysis: Develop a standard model for droplet impingement, validated with wind tunnel experimental data.
  - Characterization of aerodynamics for droplet impingement probability.