Task 46, Erosion of Wind Turbine Blades

Climatic conditions driving erosion (WP2)

Sara C. Pryor
(Cornell University)

Wind turbine operations with erosion (WP3)

David C. Maniaci
(Sandia National Laboratory)

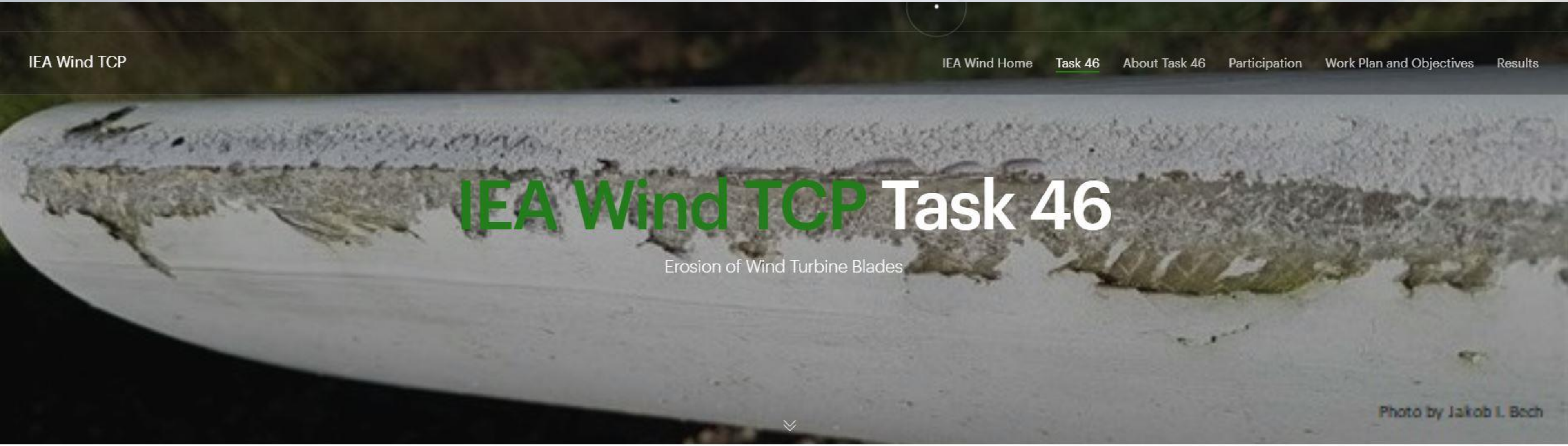
Laboratory testing of erosion (WP4)

Nicolai Frost-Jensen Johansen
(DTU)

Erosion mechanics & material properties (WP5)

Fernando Sánchez
(Univ. Cardenal Herrera CEU)

Management (WP1) Charlotte Hasager (DTU)

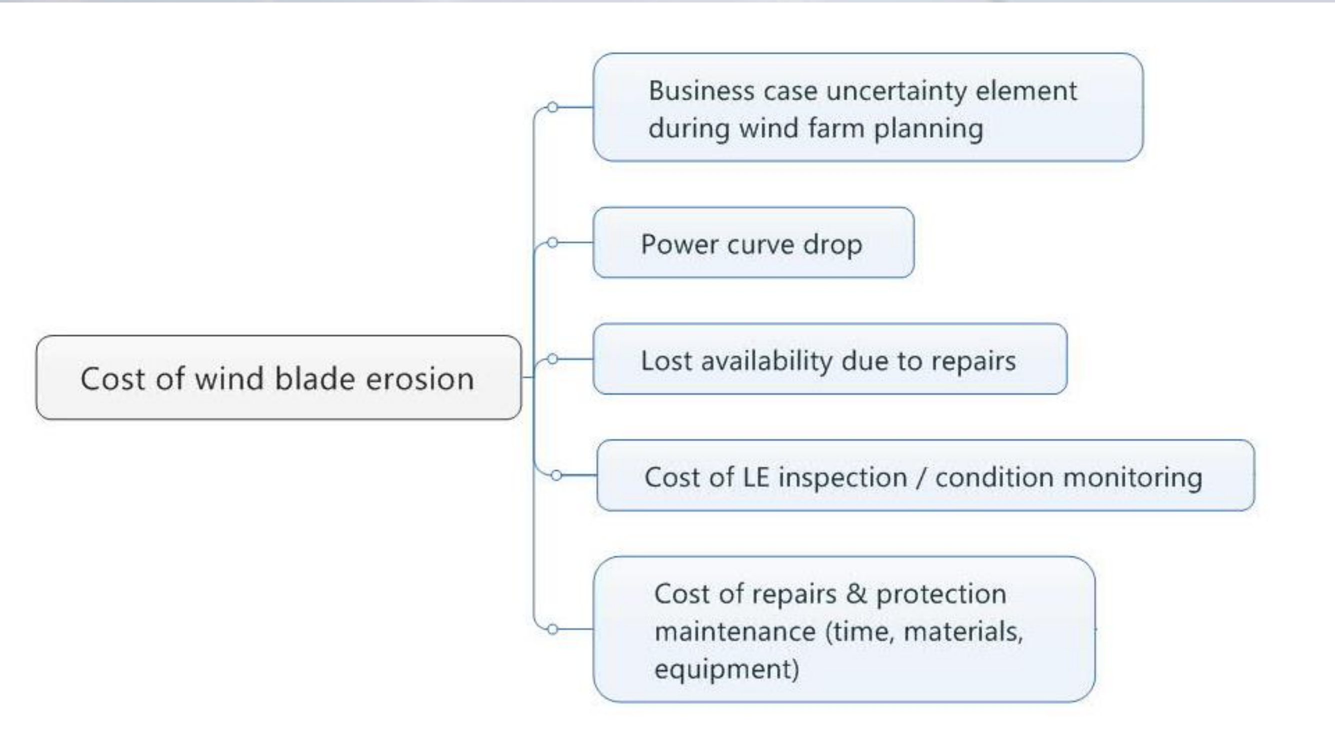


https://iea-wind.org/task46

About Task 46

Leading-edge erosion (LEE) has been identified as the main factor substantially reducing both blade lifetime and energy output over time. Field repairs are costly due to lost availability and challenging access and weather conditions. It is crucial to understand the impact of leading-edge erosion on the performance of wind plants to be able to determine the cost/benefit of proposed mitigation strategies.

Why blade erosion is relevant?



The purpose

- The purpose of IEA Wind Task 46 is to improve understanding of the erosion driving factors, develop datasets and model tools to enhance prediction of leading edge erosion likelihood, identify damage at the earliest possible stage and advance potential solutions.

Participants

- The work plan is delivered by 40 organizations from 12 countries:
  - 1 certification body
  - 5 wind turbine manufacturers
  - 6 wind farm owners
  - 8 coating manufacturers
  - 20 academic organizations

Country	Contracting Party	Participant Organization
Belgium	Belgian Ministry of Economy	Engie
Canada	Natural Resources Canada	WEICan
Denmark	Danish Energy Agency	DTU , Hempel, Ørsted
Finland	Business Finland	VTT
Germany	Federal Ministry for Economic Affairs and Energy	Fraunhofer IWES, Covestro, Emil Frei (Freilacke), Nordex Energy, DNV, Mankiewicz, RWE
Ireland	Sustainable Energy Authority of Ireland	Institute of Technology Carlow, University of Galway, University of Limerick
Japan	New Energy and Industrial Technology Development Organization	AIST, Osaka University, Tokyo Gas Co. Asahi Rubber Inc.
Netherlands	Netherlands Enterprise Agency	TU Delft, Eneco, Suzlon, TNO
Norway	Norwegian Water Resources and Energy Directorate	Equinor, University of Bergen
Spain	Centre for Energy, Environmental and Technological Research	Aerox, CENER, Nordex Energy Spain, Siemens Gamesa Renewable Energy, Universidad Cardenal Herrera - CEU
UK	Offshore Renewable Energy Catapult	ORE Catapult, University of Bristol, Lancaster University, Imperial College London, Vestas UK. Ilosta
US	US Department of Energy	Cornell University, Sandia National Laboratories, 3M

iea wind

Who can participate in Task 46?

To participate in the research activities of Task 46, researchers must reside in a country that participates in the IEA Wind Agreement AND has agreed by official letter to participate in Task 46. The participating member country of the IEA Wind TCP must designate a lead institution that agrees to the obligations of Task participation (pay the annual fee and agree to perform specified parts of the work plan).

Active researchers (performing part of the work plan) benefit from meetings and professional exchange during the term of the Task. Countries participating in the Task benefit from the information developed by the Task. The value of the research performed is many times the cost of the country participation fee or the labor contributed to carrying out the work plan.

For more information, contact the Operating Agent Charlotte Bay Hasager or the IEA Wind Secretariat.

https://iea-wind.org/task46

iea wind

Task 46 - Erosion of wind turbine blades: WP#2 Climatic conditions

Purpose of WP2:

Improve description of the atmospheric properties believed to be drivers of LEE.

Sara C Pryor
sp2279@cornell.edu

1. Priority areas for mapping LEE potential – focus on hydrometeors
2. Identify (other) crucial parameters (e.g. dust, freezing rain, sea-spray, UV, temperature variation (diurnal & seasonal))
3. Lit rev: Hail, rain & dust in priority areas
4. Lit. rev. Hydrometeor size dist. As f(climate)
5. Data quality/availability update
6. Roadmap for LEE atlas
7. Recommended Practice for measurement of LEE drivers
8. Methods to perform model V&V on LEE drivers

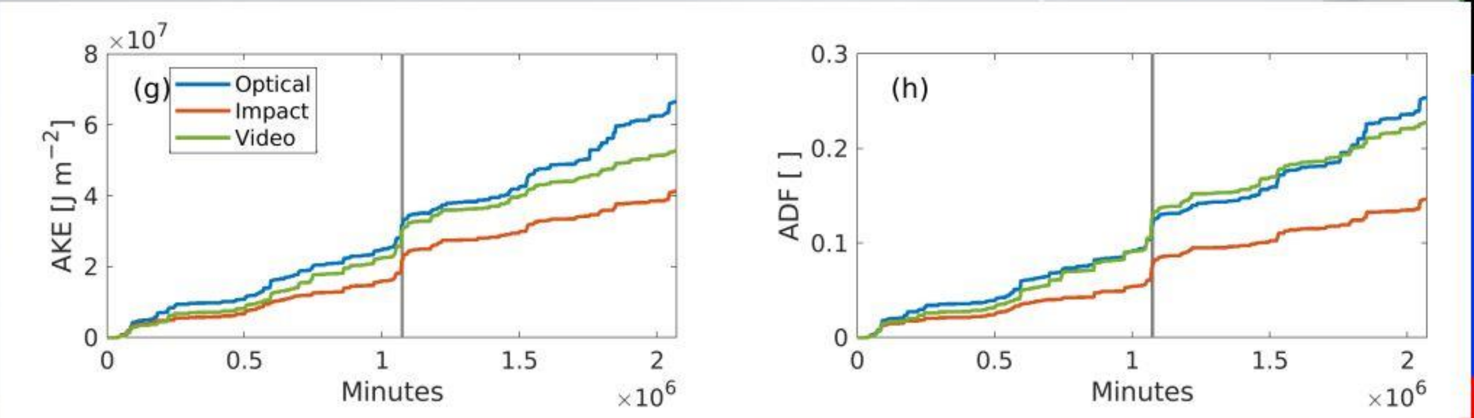
Task 46 - Erosion of wind turbine blades: WP#2 Climatic conditions

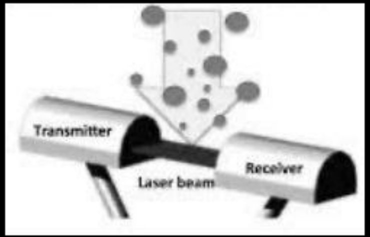
What did we 'discover' in actions 1-5?:

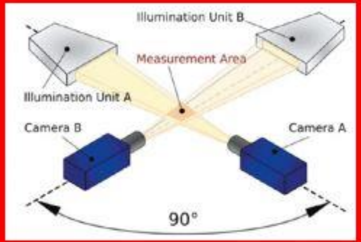
- That the instrumentation used to measure rainfall rates, and hydrometeor size & phase CRITICALLY dictate the inferred rate of LEE (e.g. estimated by Springer model).
- That there is NOT best practice available for data collection OR processing
- That commonly used size distributions for hydrometeors DO NOT represent observations

Current work: Recommended Practice for measurement of LEE drivers

- Example of influence of measurement technology on 'LEE estimates'
    - AKE = Accumulated Kinetic Energy of impact
    - ADF = Accumulated Distance to Failure (from Springer).







Letson & Pryor (2023): *Energies*. **16,** 3906; doi: 10.3390/en16093906

Current work: Roadmap for LEE atlas (w/WP5)

Best practice to convert our measurements (DSD, v_f from disdrometers and WS at hub-height from e.g. lidars) to ESTIMATE blade lifetimes. Questions we are considering:

a. Which reference wind turbine: 3 MW NREL? Or 15 MW IEA? (RPM, tip speed)
b. Mapping DSD & closing velocity to damage: Which model?
    - Kinetic energy of impact: No assumptions about materials BUT not a lifetime
    - Springer + Miner's rule: Accumulated distance to failure. BUT large uncertainties on coefficients & not mechanistic
    - More mechanistic models = more computational demanding, can we build emulators?
c. *How best to model co-stressors:*
    - *Thermal variability*
    - *Ultraviolet radiation (embrittlement models?)*
    - *Lightning strikes*
    - *Icing on blades*
    - *Blade strain*
d. *Should we focus on time to incubation or time to repair due to erosion, i.e. operators decision point?*

Task 46 Erosion of Wind Turbine Blades

Work Package #3: Wind turbine operation with erosion

Operation with Erosion, Aerodynamic Benchmarking Updates and Next Steps

David Maniaci (Sandia National Laboratories)

dcmania@sandia.gov

Public Webinar - 4 December 2023

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.

SAND2023-14448PE

WP 3 : Wind turbine operation with erosion

David C. Maniaci
dcmania@sandia.gov
Sandia National Laboratories (U.S.)

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
WP3.1: Model to predict annual energy production loss on blade erosion class Common model of performance loss due to leading edge roughness and erosion standardized classes.	WP3.1
WP3.2: Report on standardization of damage reports based on erosion observations Erosion classification report released February 2023 (https://iea-wind.org/task46/t46-results/)	WP3.2
WP3.3: Droplet impingement model for use in fatigue analysis Develop a standard model for droplet impingement, validated with wind tunnel experimental data.	WP3.3
WP3.4: Potential for erosion safe-mode operation Report describing potential for leading edge erosion safe mode operation.	WP3.4
WP3.5: Accuracy of LEE performance loss model based on field observations (validation) Iterative aerodynamic loss benchmarks. Validation of performance loss model using probabilistic analysis of field observations.	WP3.5

Project end: 14 March 2025

Year/År	2021											
Work packages			3	4	5	6	7	8	9	10	11	12
Running month during project			1	2	3	4	5	6	7	8	9	10
WP3 Wind turbine operation with erosion												
WP3.1 Model to predict annual energy												
WP3.2 RP on standardization of damage report												
WP3.3 Droplet impingment model for fatigue												
WP3.4 Potential for erosion safe mode												
WP3.5 LEE performance model validation												

Year/År	2022											
Work packages	1	2	3	4	5	6	7	8	9	10	11	12
Running month during project	11	12	13	14	15	16	17	18	19	20	21	22
WP3 Wind turbine operation with erosion												
WP3.1 Model to predict annual energy												
WP3.2 RP on standardization of damage report												
WP3.3 Droplet impingment model for fatigue												
WP3.4 Potential for erosion safe mode												
WP3.5 LEE performance model validation												

Year/År	2023											
Work packages	1	2	3	4	5	6	7	8	9	10	11	12
Running month during project	23	24	25	26	27	28	29	30	31	32	33	34
WP3 Wind turbine operation with erosion												
WP3.1 Model to predict annual energy								D3.1				
WP3.2 RP on standardization of damage report	D3.2											
WP3.3 Droplet impingment model for fatigue											D3.3	
WP3.4 Potential for erosion safe mode												
WP3.5 LEE performance model validation												

Year/År	2024											
Work packages	1	2	3	4	5	6	7	8	9	10	11	12
Running month during project	35	36	37	38	39	40	41	42	43	44	45	46
WP3 Wind turbine operation with erosion												
WP3.1 Model to predict annual energy												
WP3.2 RP on standardization of damage report												
WP3.3 Droplet impingment model for fatigue												
WP3.4 Potential for erosion safe mode			D3.4									
WP3.5 LEE performance model validation												

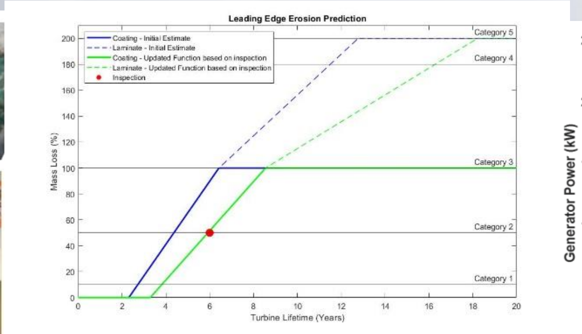
Year/År	2025		
Work packages	1	2	3
Running month during project	47	48	
WP3 Wind turbine operation with erosion			
WP3.1 Model to predict annual energy			
WP3.2 RP on standardization of damage report			
WP3.3 Droplet impingment model for fatigue			
WP3.4 Potential for erosion safe mode			
WP3.5 LEE performance model validation	D3.5		

Accomplishments in Work Package 3: Erosion Classification System

Visual Condition

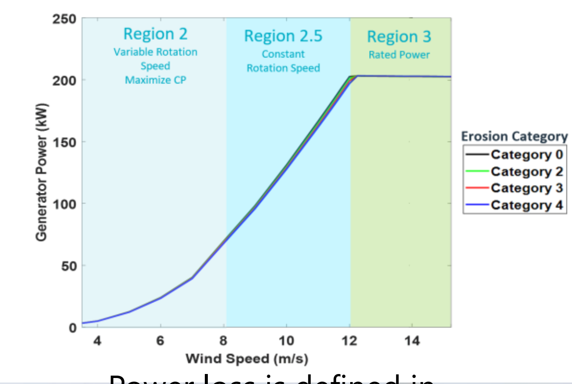
Report contains many visual examples of categories of blade and LEP damage.

Mass Loss



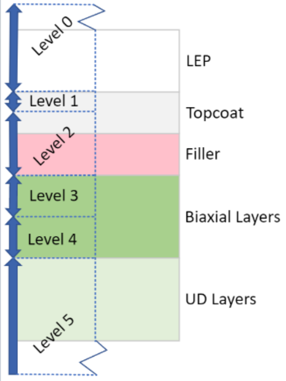
Prediction of future erosion level progression.

Aerodynamic Performance



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

Structural Integrity



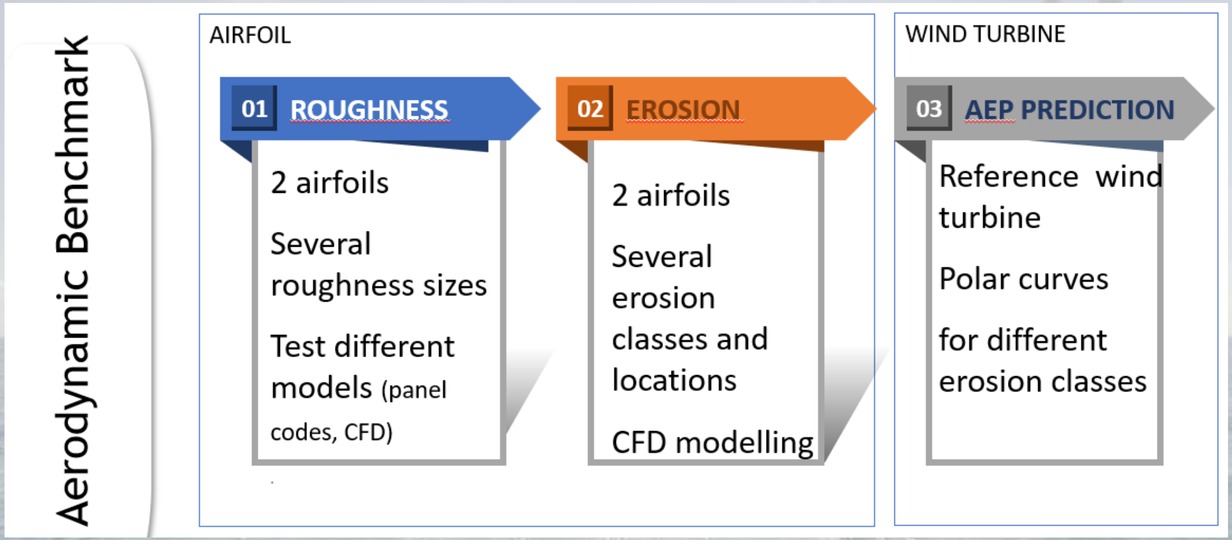
Detailed description of severity level definitions and thresholds.

	Severity Level					
Evaluation Criteria	**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

WP3: Aerodynamic Benchmark

- Aerodynamic benchmark kicked off in Fall 2022, coordinated by Beatriz Mendez at CENER.
  - Focused on NACA 63_3-418 and S814 airfoils
- Results from six participants; includes national labs, academia, and OEMs.

- There is a wide spread in the results for some cases, so comparing model parameters
- Also comparing coordinates of the airfoils for the different wind tunnel tests



Next Steps in Work Package 3

- **Aerodynamic benchmarks**, publication of phase 1 results and phase 2 to commence in spring 2024
- 3.1 **AEP loss model**. Work will progress through the aero. benchmarking group for detailed modeling.
  - Will also pursue simpler model, likely based on DTU or SNL simple performance models
  - Develop detailed turbine models for performance loss, onshore and offshore (1.5MW-22MW)
- 3.3 **Impingement model**: via aerodynamic benchmark group
  - WP3: Model the aero. impact of the geom. Change (lwift/drag curves, then used for power and AEP change). WP5: Damage progression modeling of the eroded shape, quantify damage evolution
- 3.4 **Erosion Safe Mode**: demonstrated by able participants on the reference turbine model(s)
- 3.5 **Validation with field data**: ongoing work by multiple participants
  - Goal is to align with reference turbine models

Project end: 14 March 2025

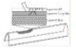
Year/År	2021												2022											
Work packages			3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Running month during project			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
WP3 Wind turbine operation with erosion																								
WP3.1 Model to predict annual energy																								
WP3.2 RP on standardization of damage report																								
WP3.3 Droplet impingment model for fatigue																								
WP3.4 Potential for erosion safe mode																								
WP3.5 LEE performance model validation																								

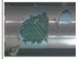
Year/År	2023												2024												2025		
Work packages	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
Running month during project	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	
WP3 Wind turbine operation with erosion																											
WP3.1 Model to predict annual energy								D3.1																			
WP3.2 RP on standardization of damage report	D3.2																										
WP3.3 Droplet impingment model for fatigue											D3.3																
WP3.4 Potential for erosion safe mode															D3.4												
WP3.5 LEE performance model validation																									D3.5		

WP4 – Laboratory testing of erosion

3.4 failure before incubation - failure at n to n-1 layer interface

Description						Defect Appearance					
This failure mode covers adhesive failure between layers in the coating system this can be between LEP and topcoat; or LEP to porefiller. Also seen on tape/shell solution as failure of the adhesive to n layer interface. This can also result from a local defect, on cohesively strong coatings. When the coatings tensile strength exceeds the adhesive strength at the interface pealing can occur						Typically presents as peeling of the coating Underlying layer relatively undamaged					
						Interchangeable defects					
Affecting layers						Point erosion can be due to this type of failure					
Example of coating specific layer name	LEP	Coating	Filler	Surface laminate	Laminate						
Layer number	n	n-1	n-2	0	-1	Approximate IEA erosion severity Level:					
Affecting layers	x	x	(x)			0:	1:	2:4 2%	3:14	4:2 9 %	5: 14%
Example images											
Illustration		1				2					

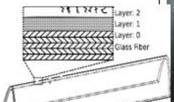




- D4.2 – Johansen, N. F.-J., Erosion failure modes in leading edge systems (06/2023)

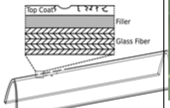
3.1 Pre incubation - Homogeneous roughening

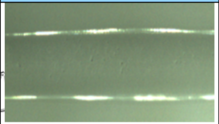
Description						Defect Appearance					
The defect type is characterized by morphology change with little to none material removal. Typically seen on homogeneous materials. It is usually the first defect appearing during a RET. As can be seen on the illustration, the rough/matt appearance occur because of crack formation in the n layer (LEP). These cracks results in reflected light being diffused giving rise to the matt appearance						The appearance is very dependent on the material, on metallic surfaces it is seen as a loss of gloss. On Clear coatings it can be seen as cracks normal to the surface as illustrated					
						Interchangeable defects					
Affecting layers						This type of defect is similar to initial material removal. Can also look like point erosion.					
Coating specific layer name	LEP	Coating	Filler	Surface laminate	Laminate						
Layer number	n	n-1	n-2	0	-1	Approximate IEA erosion severity Level:					
Affecting layers	x					0: 28%	1:29%	2	3	4:29%	5: 15%
Example images											
Illustration		1				2					



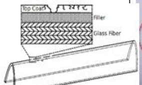

3.2 End of Incubation - Initial material removal

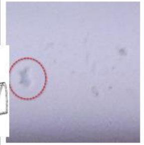
Description						Defect Appearance					
The defect is characterized by local material loss and is usually the starting point of erosion development. The damage is within a confined area without connecting to preexisting erosion, limited to the top coating within a single layer.						Defect size is equal to coating thickness squared or smaller. The damage is entirely confined to the outer n layer with no penetration					
						Interchangeable defects					
Affecting layers						• Homogeneous roughening – distinct spots with clear difference from the neighboring area • Local erosion – Limited to single layer					
Example of coating specific layer name	LEP	Coating	Filler	Surface laminate	Laminate						
Layer number	n	n-1	n-2	0	-1	Approximate IEA erosion severity Level:					
Affecting layers	x					0: 29%	1: 14%	2: 14%	3	4:28 %	5:14%
Example images											
Illustration		1				2					






Description						Defect Appearance					
The defect is characterized by local material loss exposing an underlying layer. This is usually the starting point of erosion development. The damage is within a confined area without connecting to preexisting erosion. Within this area, the defect can propagate to the underlying area.						Defect size is equal to coating thickness squared or larger. The damage has removed part of the n layer exposing the n-1 layer. Typically, underlying layers have different colors to the top coating. This makes this type of damage, relatively easy to identify. And					
						Interchangeable defects					
Affecting layers						• Initial material removal • Homogeneous roughening					
Example of coating specific layer name	LEP	Coating	Filler	Surface laminate	Laminate						
Layer number	n	n-1	n-2	0	-1	Approximate IEA erosion severity Level:					
Affecting layers	x	x	(x)			0:	1:29%	2:14%	3:14%	4:29%	5: 14%
Example images											
Illustration		1				2					






Classification system to better indetify incubation damages. And seperate RET failure modes

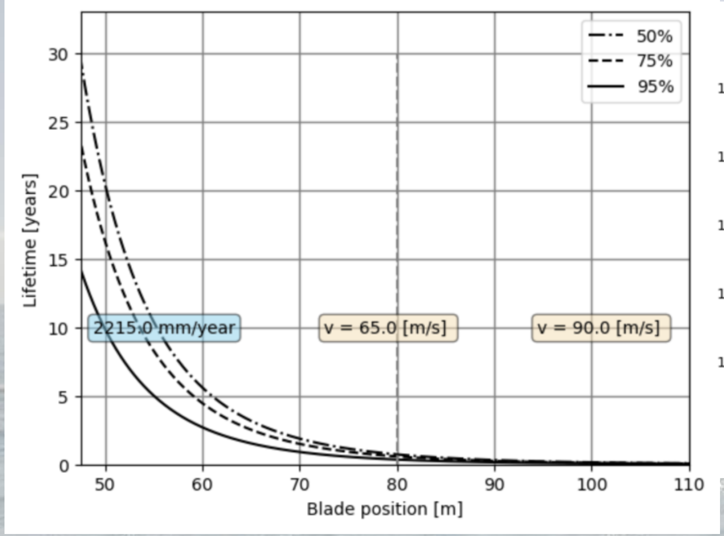
iea wind

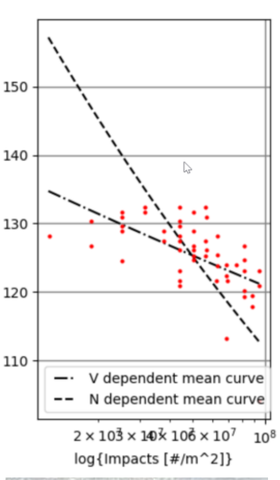
WP 4 Devlivery 4.3

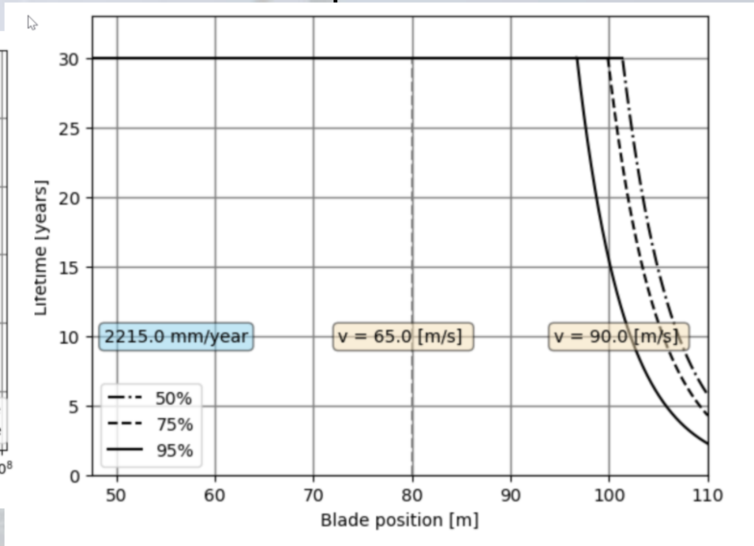
- Python-Jupityr notebook implementation of DNV-GL 0573
  - Improved regression analysis
    - High Impact on predicted lifetimes

- N-dependent

V-dependent







4.3 Plan for 2024

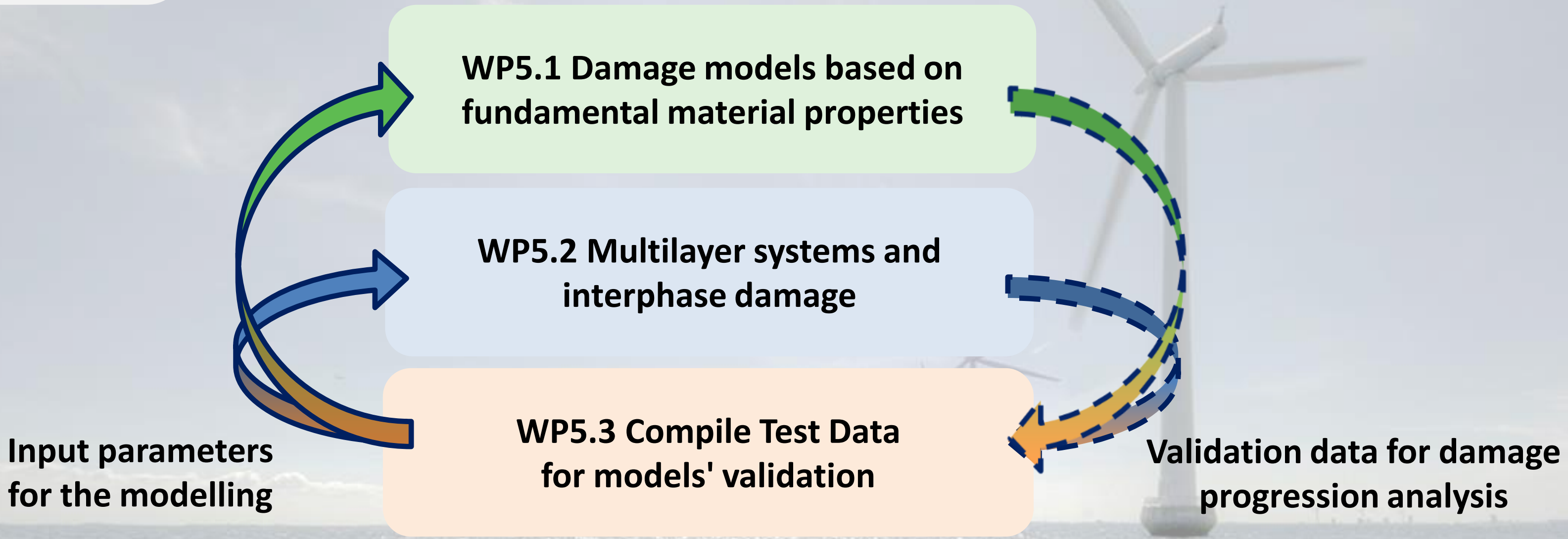
1. **Objective Overview**
    1. Test the Beta version of the code published on the sharpoint using the shared dataset from WP 4 participants.
    2. Incorporate uncertainty budget from the RET, focusing on variables such as drop size and fall velocity, into the lifetime calculation.
2. **Key Tasks**
    1. Propagate known uncertainties (e.g., drop size, fall velocity) forward to enhance the accuracy of lifetime calculations.
    2. Engage WP4 participants in testing the Beta version of the code to validate its functionality and effectiveness.
3. **Implementation of New Models**
    1. Integrate the impingement lifetime model based on the study by Bech et al. (2022), which investigates the impact of drop size on rain erosion tests and lifetime prediction of wind turbine blades.
4. **Collaborative Testing and Feedback**
    1. Have WP4 participants actively test out the code, ensuring it meets project requirements and gathers comprehensive feedback for improvements.
5. **Research and Publication**
    1. Collect and analyze results from the implementation and testing phases.
    2. Prepare a paper summarizing findings, methodologies, and implications erosion predicition

References

1. Bech, J. I., Johansen, N. F-J., Madsen, M. B., Hannesdóttir, Á., & Hasager, C. B. (2022). Experimental study on the effect of drop size in rain erosion test and on lifetime prediction of wind turbine blades. Renewable Energy, 197, 776-789. https://doi.org/10.1016/j.renene.2022.06.127

WP5 Erosion Mechanics & material properties

WP5 Aim & Scope: Appropriate **modelling techniques and material properties** characterization methods **will be defined and used** to understand erosion mechanics for LEP system technologies and **to quantify the influence on the performance**.

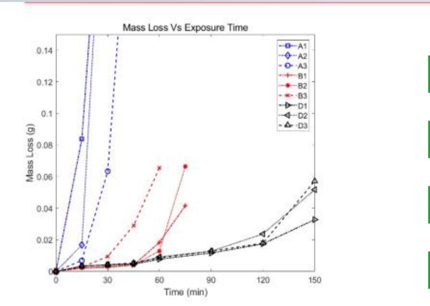


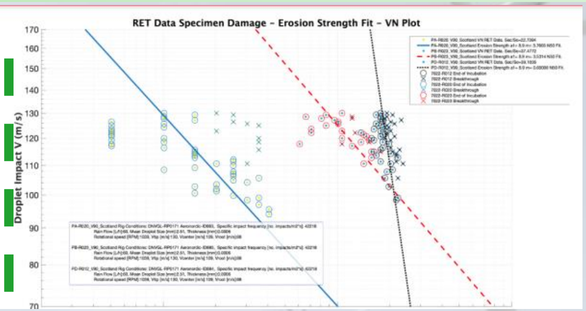
Year/År	2023	2024	2025
WP5 Erosion mechanisms and material properties			
WP5.1 Damage progression models	D5.1		
WP5.2 Multilayer systems and interphase		D5.2	
WP5.3 Compile test data for models validation			D5.3

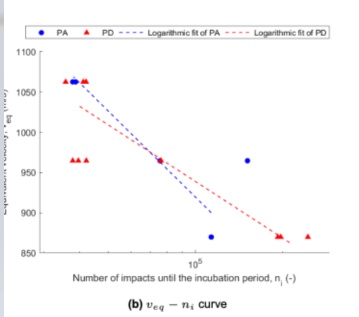
*Fernando Sánchez, CEU, fernando.sanchez@uchceu.es

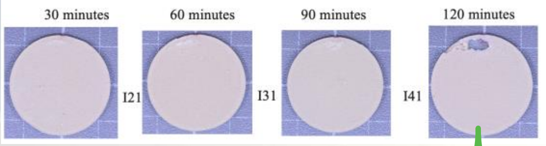
RESULTS: Specific Technical Activitity. WP5.1 Damage models based on fundamental material properties & WP5.3 Compile Test Data for models' validation

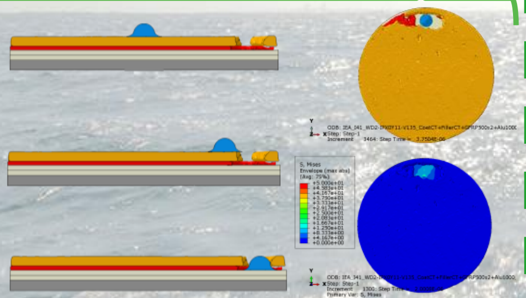
- ✓ Test Data for UV Degradation combined weathering and RET; Different chemistry comparison
- ✓ Damage progression analysis based on 1) images V-N curves, 2) intermediate mass loss measurements and 3) micro CT and 3D scanner for damage progression based on intermediate geometry evolution (with WP3)

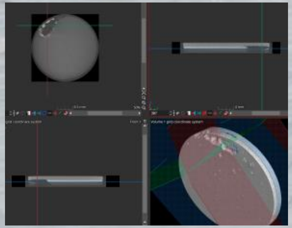


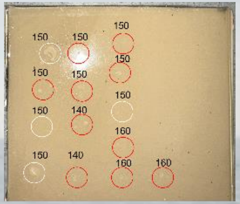


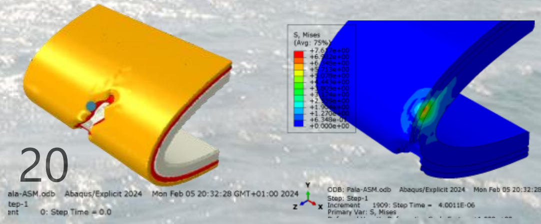


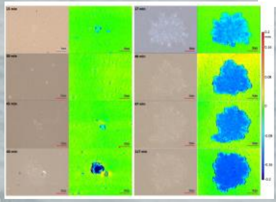






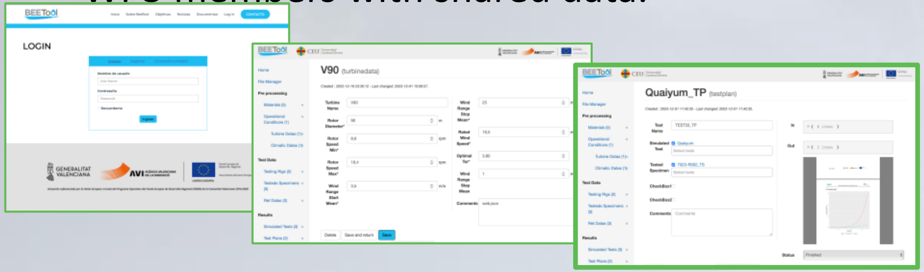


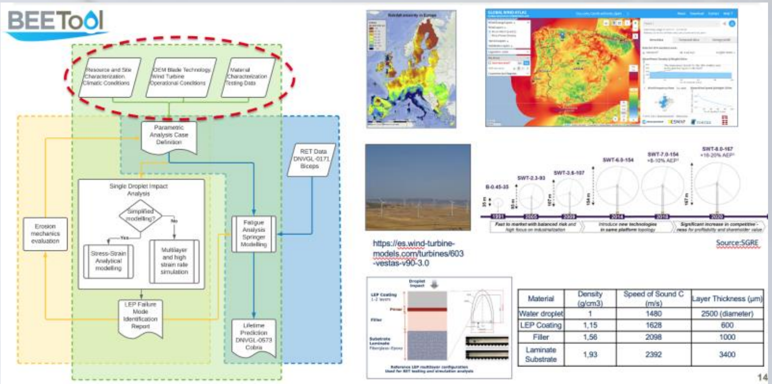




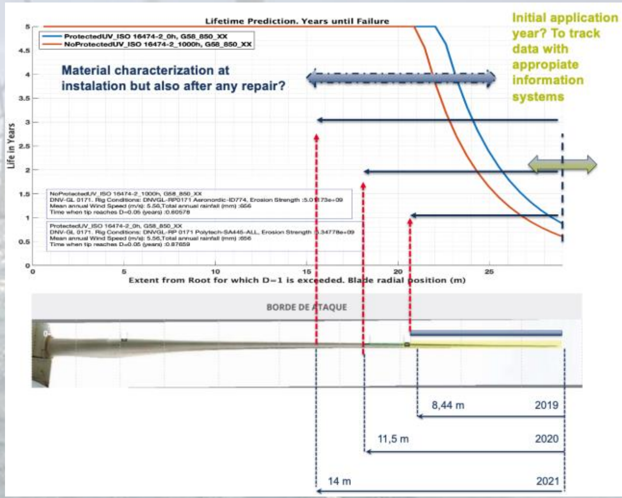
RESULTS: Specific Technical Activities WP5.1 Damage models based on fundamental material properties & WP5.3 Compile Test Data for models' validation

- ✓ Development of a **modelling web-based platform for remote lifetime performance analysis based on DNV-GL RP 0573. ON GOING:** Under validation within WP5 members with shared data.





Material	Density (g/cm3)	Speed of Sound C (m/s)	Layer Thickness (μm)
Water droplet	1	1480	2500 (diameter)
LEP Coating	1,15	1628	600
Filler	1,56	2098	1000
Laminate Substrate	1,93	2392	3400



- ✓ On the development of a **physics- based & experimental data-driven** modelling for wind turbine blade damage progression estimation

iea wind

Operating Agent

Charlotte Bay Hasager (cbha@dtu.dk)

IEA TEM on LEE