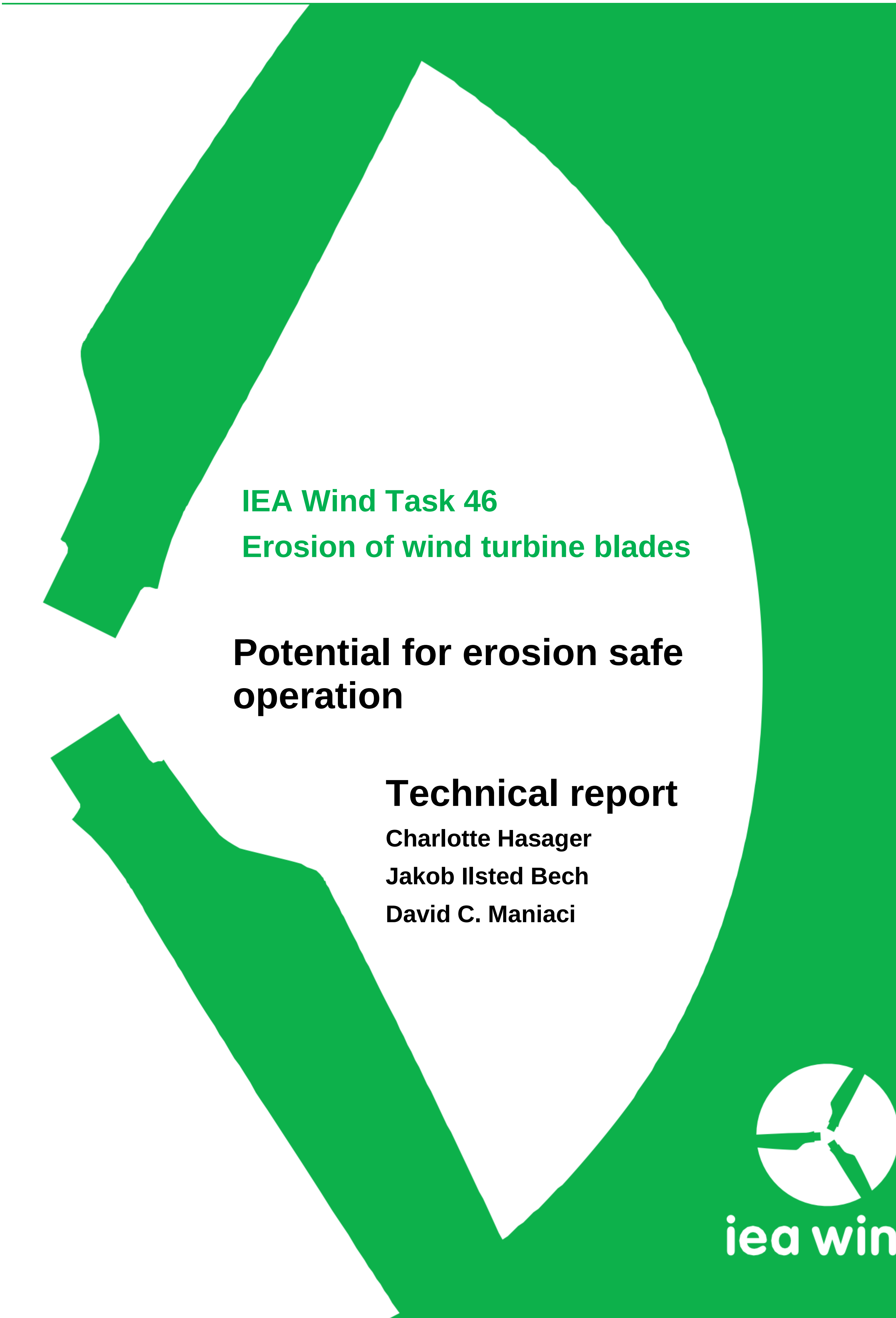

IEA Wind Task 46
Erosion of wind turbine blades

Potential for erosion safe operation

Technical report

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Technical Report

Potential for erosion safe operation

Prepared for the
International Energy Agency Wind Implementing Agreement

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Purpose

This report addresses erosion safe operation (ESO) of wind turbines. ESO is a means of mitigating leading edge erosion (LEE) of wind turbine blades by curtailing the rotor speed during the most erosive weather conditions.

LEE has been identified as a major factor in increased maintenance costs, decreased wind turbine blade lifetimes and energy output over time. Accordingly, the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) has created the Task 46 to undertake cooperative research in the key topic of blade erosion. Participants in the task are given in Table 1.

The Task 46 under IEA Wind TCP is designed to improve understanding of the drivers of LEE, the geospatial and temporal variability in erosive events; the impact of LEE on the performance of wind plants and the cost/benefit of proposed mitigation strategies. Furthermore Task 46 seeks to increase the knowledge about erosion mechanics and the material properties at different scales, which drive the observable erosion resistance. Finally, the Task aims to identify the laboratory test setups which reproduce faithfully the failure modes observed in the field in the different protective solutions.

This report is a product of Work Package 3 Wind turbine operation with erosion.

The objectives of the work summarized in this report are:

- To describe the potential for leading edge erosion safe operation.
- To seek participation from industry and research funders towards a coordinated project designed to assess viability and cost-benefit of leading edge erosion safe operation.

Table 1 IEA Wind Task 46 Participants.

Country	Contracting Party	Active Organizations
Belgium	The Federal Public Service of Economy, SMEs, Self-Employed and Energy	Engie
Canada	Natural Resources Canada	WEICan
Denmark	Danish Energy Agency	DTU (OA), Hempel, Ørsted A/S, PowerCurve, Siemens Gamesa Renewable Energy
Finland	Business Finland	VTT
Germany	Federal Ministry for Economic Affairs and Energy	Fraunhofer IWES, Covestro, Emil Frei (Freilacke), Nordex Energy SE, RWE, DNV, Mankiewicz, Henkel
Ireland	Sustainable Energy Authority of Ireland	South East Technology University, University of Galway, University of Limerick
Japan	New Energy and Industrial Technology Development Organization	AIST, Asahi Rubber Inc., Osaka University, Tokyo Gas Co.
Netherlands	Netherlands Enterprise Agency	TU Delft, TNO
Norway	Norwegian Water Resources and Energy Directorate	Equinor, University of Bergen, Statkraft
Spain	CIEMAT	CENER, Aerox, CEU Cardenal Herrera University, Nordex Energy Spain
United Kingdom	Offshore Renewable Energy Catapult	ORE Catapult, University of Bristol, Lancaster University, Imperial College London, Ilosta, Vestas
United States	U. S. Department of Energy	Cornell University, Sandia National Laboratories, 3M

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Executive Summary

Erosion safe operation (ESO) of wind turbines is a mitigation method suggested to limit leading edge erosion (LEE) by slowing down (curtailing) the turbines during few short periods of heavy precipitation in windy conditions. The slowing down will cause a loss in energy production, hence there will be a loss in annual energy production (AEP). The AEP loss will cause a loss in revenue. However, the loss in revenue from energy production may be balanced by reduced operation and maintenance (O&M) costs. Furthermore, wind turbines operating with eroded blades are known to have poorer aerodynamic performance than turbines with clean blades. ESO will limit LEE and ensure turbines will for longer time operate with less eroded blades, hence produce relatively more energy. The many factors to decide and optimize the application of ESO need careful consideration. To date, ESO is not used in the wind energy community. The present report aims to clarify the relevant knowledge needed for preparing a full scale testing of ESO.

1. Introduction

Wind turbine operations with erosion occur when the leading edges of wind turbine blades are eroded. Leading edge erosion (LEE) appears on many wind turbine blades. Leading edge protection (LEP) systems are applied to the outer part of the blades to prevent erosion. Eroded blades are typically repaired to limit further erosion and to prevent structural failure (Mishnaevsky et al., 2021).

Wind turbine operations with eroded blades cause some loss in annual energy production (AEP) caused by the changes in the aerodynamic performance compared to clean blades without erosion. The AEP loss due to eroded blades with increased surface roughness has been reported to be 0.5 to 5% from wind tunnel tests (Sareen et al., 2014; Maniaci et al., 2016; Bak et al., 2020; Kruse et al., 2021), and CFD modeling (Özçakmak et al., 2024). Analysis of field data from operating wind farms have been used to asses the AEP loss due to erosion. However, it is complicated to assess due to many factors' interplay (Malik & Bak, 2024; Malik & Bak, 2025).

Curtailment of renewable power generators is well known, and may be applied for reasons like grid load management (Klinge et al., 2012) and noise mitigation (Nyborg et al., 2023).

The root cause for LEE is the environmental impact of precipitation, aerosol dust, weathering from UV radiation, and changes in temperatures and humidity in the rotor-swept area. The key driver for LEE is liquid precipitation in the form of rain. Solid precipitation in the form of hail causes harsher erosion than rain, but as rain prevails much more frequently than hail, rain is considered the key driver of LEE.

2. Erosion safe operation of wind turbines

2.1. Erosion safe operation of wind turbines

Erosion safe operation (ESO) of wind turbines is a mitigation method to limit erosion by curtailing the rotor speed of the wind turbines at particularly erosive conditions.. It is anticipated that ESO may limit erosion progression, such that blade erosion repair will be needed at longer intervals or not at all (Bech et al., 2018). Curtailment will result in less energy production during ESO, and the overall challenge is to define a balance between reduced blade erosion and reduced energy production (Barfknecht et al., 2022; Ripoll et al., 2023). It is complex due to the many perspectives involved.

According to rain erosion tests, LEE develops more rapidly at high impact speed than lower (Springer, 1976). The whirling arm rain erosion test experiments using modern LEP coatings showed that larger droplets cause faster erosion progression than smaller droplets (Bech et al., 2022; Barfknecht & von Terzi, 2025). Different rain droplet sizes in a rain erosion tester are controlled by the set-up of the flow of water and the needle sizes.

Weather conditions control different rain droplet sizes in the field environment. In general, rain events with heavy rainfall are characterized by many large droplets, while slight and moderate rainfall events have fewer large droplets and consist of many smaller droplets. Rainfall droplet sizes are observed in only a few locations globally with disdrometer. Micro rain radar (MRR) and weather radars provide other data sources on droplet sizes. Common rain gauges widespread around the globe observe the rain rate (mm/hour). Rain rate is also called rain intensity.

For many applications, only rain amount is an important parameter, but retrieving the rain droplet size distribution is relevant for LEE. Established methods to estimate the droplet size distribution from rain rate are the models by Best (1950) and Marshall-Palmer (1948). Different droplet sizes' efficiency in hitting wind turbine blades in the field is a function of the blade geometry, turbine operation, wind speed, and droplet sizes (Prieto & Karlsson, 2021; Barfknecht & von Terzi, 2025).

2.2. Implementation of erosion safe operation

To the authors' knowledge, the implementation of ESO on a turbine has not yet been tested. There are many issues to consider to move into using ESO. Information on each topic listed below is needed to prepare an ESO optimization scheme.

1. Leading edge protection (LEP) durability
2. Wind turbine characteristics
3. Aerodynamic performance and AEP loss of eroded blades
4. Cost of repair and monitoring erosion
5. Weather conditions
6. Near-real-time rain observation
7. Revenue on electricity
8. Turbine load and safety
9. Grid compliance
10. Wind farm asset planning

2.2.1. Leading edge protection (LEP) durability

LEP durability is known from either rain erosion tests (Bech et al., 2022) or from field inspections combined with weather information at the locations (Eisenberg et al., 2018; Prieto & Karlsson, 2021; Visbech et al., 2023). Quantifying how fast an LEP will erode when exposed to rain droplets with specific impact speed is necessary. Erosion progression may be nonlinear in time, i.e., the erosion progression may depend upon the erosion stage. The eroded rough surface with cracks and pits will absorb the impact differently to a clean surface, and the rougher surface most likely has an accelerated erosion process (Tempelis et al., 2025).

2.2.2. Wind turbine characteristics

The most important characteristic of a wind turbine for LEE is the maximum tip speed of the blade. The tip speed will define the impact speed of the droplet on the blade. The maximum tip speed is reached when the wind speed at hub height is at or above rated speed. The higher the maximum tip speed, the faster the erosion. Furthermore, wind turbines are located in wind farms, and the wind farm layout and wake between wind turbines will impact the production differently with and without ESO (Visbech et al., 2024b).

2.2.3. Aerodynamic performance and AEP loss of eroded blades

The aerodynamic performance of eroded blades is different from clean blades (Sareen et al., 2014; Maniaci et al., 2016; Bak et al., 2020; Kruse et al., 2021; Özçakmak et al., 2024). Repair of blades ideally re-establish clean blades but may not always achieve fully the original blade shape and aerodynamic performance (Fang et al., 2023; Forsting et al., 2023). AEP loss of eroded blades is known to occur, but the exact values are difficult to verify. Results from the field have been used to estimate AEP loss (Maniaci et al., 2020). A tool has been developed to relate the erosion level to the AEP loss (Bak, 2022). It is anticipated that the ESO will prolong the time with little AEP loss due to erosion as the erosion progression will be postponed and limited. AEP and AEP loss depend upon the wind climate for a specific turbine, wind farm layout, and wake effects (Visbech et al., 2024a).

2.2.4. Cost of repair and monitoring erosion

Cost of repair average values for LEE indicate that the costs are significant (Mishnaevsky & Thomsen, 2020). The cost of repair dependent upon access to the turbine, whether on land or sea, the weather windows, the size of the turbine, the time it takes to repair and cure, the loss of revenue during downtime, the cost for technicians, repair robots, monitoring erosion with inspections with drones, analysis of photos and other data on erosion categories and severity levels, and repair material cost. In general, severely eroded blades take longer time and are more costly to repair than less eroded blades.

2.2.5. Weather conditions

Long-term weather conditions on wind speed and rain must be assessed using local observations (Hasager et al., 2021; Verma et al., 2021; Caboni et al., 2024; Pryor et al., 2025), numerical model results (Hannesdóttir et al., 2024), or satellite derived products (Badger et al., 2022; Dimitriadou et al., 2024). One question is, what is the expected AEP and AEP loss for the wind climate of the specific wind turbine and wind farm? The key knowledge needed to answer this is knowledge on the co-existing of rain (and hail) events during periods when the wind turbines are operating near or at rated speed. Time-series data are needed (Castorrini et al., 2024). Castorrini et al. (2024) make clear that using average wind and average rain instead of timeseries to estimate the expected lifetime is likely to predict longer lifetimes than using the timeseries for the estimation.

Another question is how many hours per year are critical for the specific turbine and LEP. It may be a short time when most erosion is expected at some sites (Caboni et al., 2024). Some locations have weather conditions for which ESO appears relevant (Hasager et al., 2021; Verma et al., 2021; Hannesdóttir et al., 2024). The number of hours with highly erosive weather events is distributed differently, making some locations more prosperous for ESO than others (Pryor et al., 2025).

2.2.6. Near-real-time rain observation

It is paramount to have a reliable rain (and hail) signal at high temporal resolution in near-real-time at or near the wind turbine(s) to initiate and end a period with ESO. The input can be from a micro rain radar (MRR) observing the falling rain and enabling ESO before the more damaging hydrometeors impact the blades at the 1 to 2-minute lead time (Tilg et al., 2020) or weather radar at 5 to 15-minute lead time (Barfknecht et al., 2024).

2.2.7. Revenue on electricity

The electricity market and prices vary through time and location. The expected energy production in the forthcoming hours is traded on the market. The wind farm operator aims to produce the planned electricity to earn revenue and avoid financial loss if the planned electricity is not produced. Windy conditions often correlate with lower electricity prices in areas with abundant wind energy. ESO in such regions may come with limited financial loss.

2.2.8. Turbine load and safety

During the operation of wind turbines, it is necessary to consider the load and safety at all times. A question may be how often and how much an optimal ESO strategy will be seen from, e.g., revenue or extended blade lifetime (Visbech et al., 2024b).

2.2.9. Grid compliance

Curtailment of wind farms using ESO may result in short-term fluctuation in electricity production for the grid. It needs to be considered how this, e.g., a large offshore wind farm using ESO, will impact the grid.

2.2.10. Wind farm asset planning

A new wind farm will operate with clean blades until the end of the incubation of LEP. The roughness will increase, and the AEP loss will start due to erosion. During this period, planning blade inspection and preparing repair campaigns is relevant. It will cover most of a wind farm's operational lifetime, and ESO might be a viable mitigation strategy. When a wind farm is near the end of life, it may be irrelevant to limit erosion as the blades will be decommissioned soon.

3. Experiment planning

3.1. Planning at wind turbine and wind farm scale

Planning an ESO experiment would require one wind turbine in case the effect of ESO on LEE progression is not assessed but hypothesized to happen. Such an experiment would demonstrate the technical implementation of a near-real-time rain signal, a wind farm control strategy based on preferred settings, and the impact on energy production.

If two identical neighboring turbines are used, it would be possible to monitor erosion progress on both, with one turbine in regular operation and the other in ESO. A weak contrasting colored coating could be applied on both turbines and monitored for changes in erosion progression.

LEE is a stochastic process, and it is difficult to conclude based on a few samples. Thus, implementing ESO on several turbines compared to several turbines in regular operation within a wind farm would be a robust experiment. It would be preferable to apply it for a wind farm in a harsh climate indicated to have good potential using ESO. A weak contrasting colored coating could be applied on all turbines and monitored for changes in erosion progression.

3.2 Erosion safe operation

Erosion of winds turbine blades may be considered as a cumulative process. When the sum of incremental damages reaches a critical value the surface starts to disintegrate. The damage increment added to the leading edge structure or LEP material during a rain event increases linearly as function of the impinged rain and exponentially as function of the rotor speed.

Erosion safe operation involves reducing the rotor speed under particular conditions where the added erosion damage is too high relative to the consequtive generated power or other measures. Such curtailment strategies are well known e.g. in noise mitigation (Nyborg et al., 2023), and rotor speed reduction is a common feature in modern wind turbine controllers.

Erosion safe operation consists of curtailment indication parameters and criteria, mitigation actions and evaluation parameters.

Here we define three catagories of potential parameters and criteria for curtailment: Precipitation; Impingement; Rate of damage. The indication parameters and criteria are presented.

3.2.1 Precipitation parameters (meteorology parameters)

Precipitation parameters reflect the actual presence of hydrometeors in the local athmosphere.

- Liquid water content [-]
- Rain rate [m s^{-1}]

- Fall velocity [m s^{-1}]
- Drop sizes [m]
- Kinetic energy of falling droplets [J]
- Temperature [K]
- Radar reflectivity [dBZ]

3.2.2 Impingement parameters (combined meteorology and turbine parameters)

Impingement parameters describe the interaction of the precipitation parameters and the properties and operational parameters of the turbine, such as the blades' tangential velocity and the airfoil geometry.

- Blade velocity [m s^{-1}]
- Impingement efficiency (aerofoil, droplet size and velocity dependent) [-]
- Impact velocity [m s^{-1}] (blade velocity + droplet fall velocity)
- Impingement rate [m s^{-1}] (based on tip speed and rain field)
- specific impact frequency (ASTM G73) [s^{-1}]
- specific impact frequency (DNV GL RP 0171) [m^{-2} s^{-1}]
- rate of kinetic energy of impact [J m^{-2} s^{-1})]

3.2.3 Damage rate (these are material dependent)

The damage rate is a function of the impingement parameters and the performance of the leading edge structure, e.g. measured by RET in the sense of drop-size dependent VH or VN curves*.*

- Maximum damage rate [s^{-1}] (based on LEP VN or VH curve, tip speed and rain field)
- Maximum damage per unit energy produced [kWh^{-1}]

3.2.4 Erosion control strategies, evaluation criteria and threshold values

The erosion control strategy consists of indicating parameters, threshold values and curtailment velocities. Curtailing the rotor rotational speed to reduce the immediate rate of damage will normally cause a reduction of generated power, except for intermediate wind conditions, where the turbine operates below rated power and rated torque. In such situations the torque may be increased while the RPM is decreased, and thus the power output can be maintained.

When and how much to curtail depend on multiple factors including the grid load, emmidiate spot market electricity prices, blade condition and service schedules.

- Threshold value depends on actual cost of electricity as a parameter for evaluation (hourly time scale)
- Time to next repair campaign (weeks-months-years)
- Rest life of blade (adaptive residual life VH curve) (weeks-months-years)

- Current condition of blade (weeks-months-years)
- Conditioned on inspection and erosion level progression (weeks-months-years)

4 Key Conclusions/Recommendations

Erosion safe operation (ESO) have not yet been implemented even though the economical benefits appear promising for wind turbines located in highly erosive environments. Knowledge relevant for testing ESO is available. It is recommended to do a full scale experiment, to demonstrate the technical implementation.

References

Badger, M., Zuo, H., Hannesdóttir, Á., Owda, A., & Hasager, C. (2022). Lifetime prediction of turbine blades using global precipitation products from satellites. *Wind Energy Science*, *7*(6), 2497-2512. https://doi.org/10.5194/wes-7-2497-2022

Bak, C. (2022). A simple model to predict the energy loss due to leading edge roughness. In *Turbine Technology; Artificial Intelligence, Control and Monitoring* Article 032038 IOP Publishing. https://doi.org/10.1088/1742-6596/2265/3/032038

Bak, C., Forsting, A. M., and Sorensen, N. N.: 2020 The influence of leading edge roughness, rotor control and wind climate on the loss in energy production, J. Phys. Conf. Ser., 1618, 052050, https://doi.org/10.1088/1742-6596/1618/5/052050, 2020.

Barfknecht, N., Imhoff, R., Von Terzi, D. (2024) Mitigating blade erosion damage through nowcast driven erosion safe mode control. Journal of Physics: Conference Series 2767.3 (June 2024), p. 032001. ISSN: 17426588, 17426596. DOI: 10.1088/1742-6596/2767/3/032001. URL: https://iopscience.iop.org/article/10.1088/1742-6596/2767/3/032001.

Barfknecht, N., Kreuseler, M., de Tavernier, D., von Terzi, D. 2022 erformance analysis of wind turbines with leading-edge erosion and erosion safe mode operation. *J. Phys.: Conf. Ser.* 2265 032009. https://iopscience.iop.org/article/10.1088/1742-6596/2265/3/032009

Barfknecht, N. and von Terzi, D. 2025 Drop-size-dependent effects in leading-edge rain erosion and their impact on erosion safe mode operation, Wind Energ. Sci., 10, 315–346, https://doi.org/10.5194/wes-10-315-2025, 2025.

Bartolomé, L.; Teuwen, J. Methodology for the energetic characterisation of rain erosion on wind turbine blades using meteorological data: A case study for The Netherlands. *Wind Energy* 2021, *24*, 686–698

Bech, J. I., Hasager, C. B., & Bak, C. (2018). Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science*, *3*(2), 729-748. https://doi.org/10.5194/wes-3-729-2018

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

Best, A. The size distribution of raindrops. *Q. J. R. Meteorol. Soc.* 1950, *76*, 16–36.

Caboni, M., Slot, H.M., Bergman, G., Wouters, D.A.J., Meijer, H.J.V.D.M., 2024. Evaluation of wind turbine blades' rain-induced leading edge erosion using rainfall measurements at offshore, coastal and onshore locations in the netherlands. Journal of Physics 2767. https://iopscience.iop.org/article/10.1088/1742-6596/2767/6/062003/pdf

Castorrini, A., Barnabei, V.F., Domenech, L., A.Šakalyté, Sánchez, F., Campobasso, M.S., 2024. Impact of meteorological data factors and material characterization method on the predictions of leading edge erosion of wind turbine blades. Renewable Energy 227. doi:https://doi.org/10.1016/j.renene.2024.120549.

Dimitriadou, K., Hasager, C. B., Nouqueret, E. C., & Hannesdóttir, Á. (2024). Quality assessment of the GPM IMERG product for lifetime prediction of turbine blades in complex terrain. In *The Science of Making Torque from Wind (TORQUE 2024): Measurement and testing* Article 042010 IOP Publishing. https://doi.org/10.1088/1742-6596/2767/4/042010

Eisenberg, D.; Laustsen, S.; Stege, J. Wind turbine blade coating leading edge rain erosion model: Development and validation. *Wind Energy* 2018, *21*, 942–951.

Fang, H., Feng, Y., Wei, X., Xiong, J. 2023 Wind turbine blade damage aerodynamic profile analysis and its repair techniques, Energy Reports, Volume 9, Supplement 6, 2023,1-10, https://doi.org/10.1016/j.egyr.2023.04.041.

Forsting, A. M., Olsen, A. S., Sørensen, N. N., & Bak, C. (2023). *The impact of leading edge damage and repair on sectional aerodynamic performance*. Paper presented at 2023 AIAA SciTech Forum, National Harbor, Maryland, United States.

Gaudern, N., 2014, A practical study of the aerodynamic impact of wind turbine blade leading edge erosion. J. Phys.: Conf. Ser. 524 012031 (http://iopscience.iop.org/1742-6596/524/1/012031)

Hannesdóttir, Á.; Kral, S.T.; Reuder, J.; Hasager, C.B. Rain erosion atlas for wind turbine blades based on ERA5 and NORA3 for Scandinavia. *Results Eng.* 2024, *22*, 102010.

Hasager, C., Vejen, F., Bech, J. I., Skrzypiński, W. R., Tilg, A.-M., & Nielsen, M. (2020). Assessment of the rain and wind climate with focus on wind turbine blade leading edge erosion rate and expected lifetime in Danish Seas. *Renewable Energy*, *149*, 91-102. https://doi.org/10.1016/j.renene.2019.12.043

Hasager, C. B., Vejen, F., Skrzypinski, W. R., & Tilg, A.-M. (2021). Rain Erosion Load and Its Effect on Leading-Edge Lifetime and Potential of Erosion safe Mode at Wind Turbines in the North Sea and Baltic Sea. *Energies*, *14*(7), Article 1959. https://doi.org/10.3390/en14071959

Klinge Jacobsen, H., & Schröder, S. T. (2012). Curtailment of renewable generation: Economic optimality and incentives. Energy Policy, 49C, 663-675. https://doi.org/10.1016/j.enpol.2012.07.004

Kruse, E. K:, Bak, C., and Olsen, A. S.: Wind tunnel experiments on a NACA 633-418 airfoil with different types of leading edge roughness, Wind Energy, 24, 1263–1274, 2021.

Malik, T. (Accepted/In press). *Wind Turbine Performance Assessment: Detecting the Effects due to Changes in Blade Aerodynamics*. Technical University of Denmark. https://doi.org/10.11581/DTU.00000348

Malik, T. H. and Bak, C.: Full-scale wind turbine performance assessment using the turbine performance integral (TPI) method: a study of aerodynamic degradation and operational influences, Wind Energ. Sci., 9, 2017–2037, https://doi.org/10.5194/wes-9-2017-2024, 2024.

Malik, T. H., & Bak, C. (2025). Challenges in detecting wind turbine power loss: the effects of blade erosion, turbulence, and time averaging. *Wind Energy Science*, *10*, 227-243. https://doi.org/10.5194/wes-10-227-2025

Maniaci, D.C., White, E.B., Wilcox, B., Langel, C.M., van Dam, C.P., Paquette, J.A. 2016 Experimental Measurement and CFD Model Development of Thick Wind Turbine Airfoils with Leading Edge Erosion. Journal of Physics: Conference Series, 2016. 753(2): p. 022013. https://iopscience.iop.org/article/10.1088/1742-6596/753/2/022013/pdf

Maniaci, D.C., Westergaard, C., Hsieh, A., and Paquette, J. A. 2020 Uncertainty Quantification of Leading Edge Erosion Impacts on Wind Turbine Performance, J. Phys.: Conf. Ser. 1618 052082, https://iopscience.iop.org/article/10.1088/1742-6596/1618/5/052082/pdf

Marshall, J.S.; Palmer, W.M.K. The distribution of raindrops with size. *J. Meteorol.* 1948, *5*, 165–166

Mishnaevsky Jr., L., Hasager, C. B., Bak, C., Tilg, A.-M., Bech, J. I., Rad, S. D., and Fæster, S.: Leading edge erosion of wind turbine blades: Understanding, prevention and protection, Renew. Energ., 169, 953–969, 2021.

Mishnaevsky, L., & Thomsen, K. (2020). Costs of repair of wind turbine blades: Influence of technology aspects. *Wind Energy*, *23*(12), 2247-2255. https://doi.org/10.1002/we.2552

Nyborg, C. M., Fischer, A., Réthoré, P.-E., & Feng, J. (2023). Optimization of wind farm operation with a noise constraint. Wind Energy Science, 8(2), 255-276. https://doi.org/10.5194/wes-8-255-2023

Özçakmak, Ö. S., Bretos, D., Méndez, B., & Bak, C. (2024). Determination of annual energy production loss due to erosion on wind turbine blades. In *The Science of Making Torque from Wind (TORQUE 2024): Aerodynamics, aeroleasticity, and aeroacustics* Article 022066 IOP Publishing. https://doi.org/10.1088/1742-6596/2767/2/022066

Prieto, R., Karlsson, T. (2021) A model to estimate the effect of variables causing erosion in wind turbine blades Wind Energy, 24 (9) (2021), pp. 1031-1044, 10.1002/we.2615

Pryor, S. C., Barthelmie, R. J., Cadence, J., Dellwik, E., Hasager, C. B., Kral, S. T., Reuder, J., Rodgers, M., & Veraart, M. (2022). Atmospheric Drivers of Wind Turbine Blade Leading Edge Erosion: Review and Recommendations for Future Research. *Energies*, *15*(22), Article 8553. https://doi.org/10.3390/en15228553

Pryor, S. C., Coburn, J. J., and Barthelmie, R.J. (2025) Spatiotemporal Variability in Wind Turbine Blade Leading Edge Erosion. *Energies*, *vol. 18*, *no. 2*, Jan. 2025. https://doi.org/10.3390/en18020425

Ripoll, Á. Ú., Jiang, Z, Verma, A, Zhou, J. 2023 Active damage mitigation of the blade leading edge erosion for a wind turbine during rainfall events. IOP Publishing, 10.1088/1757-899X/1294/1/012001

Sareen, A.; Sapre, C.A.; Selig, M.S. Effects of leading edge erosion on wind turbine blade performance. *Wind Energy* 2014, *17*, 1531–1542.

Skrzypiński, W. R., Bech, J. I., Hasager, C. B., Tilg, A.-M., Bak, C., & Vejen, F. (2020). Optimization of the erosion safe operation of the IEA Wind 15 MW Reference Wind Turbine. *Journal of Physics: Conference Series*, *1618*(5), Article 052034 . https://doi.org/10.1088/1742-6596/1618/5/052034

Springer, G.S. *Erosion by Liquid Impact*; John Wiley and Sons: New York, NY, USA, 1976; p. 278.

Tempelis, A.; Jespersen, K.M.; Mishnaevsky, L., Jr. Fatigue damage mechanics approach to predict the end of incubation and breakthrough of leading edge protection coatings for wind turbine blades. *Int. J. Fatigue* 2025, *190*, 108617.

Tilg, A.-M., Hasager, C. B., Kirtzel, H.-J., & Hummelshøj, P. (2020). Brief communication: Nowcasting of precipitation for leading-edge-erosion safe mode. *Wind Energy Science*, *5*(3), 977-981. https://doi.org/10.5194/wes-5-977-2020

Verma, A.S., Jiang, Z., Ren, Z., Caboni, M., Verhoef, H., Mijle-Meijer, H.V., Castro, S.G.P., Teuwen, J.J.E., 2021. A probabilistic long-term framework for site-specific erosion analysis of wind turbine blades: A case study of 31 Dutch sites. Wind Energy 24, 1314–1336. doi:https://doi.org/10.1002/we.2634.

Visbech, J., Göçmen, T., Hasager, C. B., Shkalov, H., Handberg, M., & Nielsen, K. P. (2023). Introducing a data-driven approach to predict site-specific leading-edge erosion from mesoscale weather simulations. *Wind Energy Science*, *8*(2), 173-191. https://doi.org/10.5194/wes-8-173-2023

Visbech, J., Göçmen, T., Özçakmak, Ö. S., Meyer Forsting, A., Hannesdóttir, Á., & Réthoré, P. E. (2024a). Aerodynamic effects of leading-edge erosion in wind farm flow modeling. *Wind Energy Science*, *9*, 1811-1826. https://doi.org/10.5194/wes-9-1811-2024

Visbech, J., Göçmen, T., Réthoré, P.-E., & Hasager, C. B. (2024b). Erosion safe operation using double deep Q-learning. In *The Science of Making Torque from Wind (TORQUE 2024): Dynamics, control, and monitoring* Article 032047 IOP Publishing. https://doi.org/10.1088/1742-6596/2767/3/032047