

Response to Reviewer 1

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Reviewer 1

The manuscript quantifies uncertainties in the assessment of end of incubation and erosion-safe operation efficiency for wind turbine blade leading edge erosion, using five precipitation and wind time series at the Riso site, three reference turbines, an impingement damage model, droplet slowdown formulations and Monte Carlo based probabilistic Pareto fronts.

The question addressed is well aligned with the scope of WES, and the dataset assembled at Riso is valuable.

We are grateful to the reviewer for taking the time to provide a construction review. This has greatly helped us improve the paper.

I am recommending major revision. My concerns fall into the following main aspects:

- Some quantitative results that the paper presents as findings are not fully supported by the analysis reported. For example, the inter-sensor differences are confounded with data availability and with the wind input, and this confusion makes their attribution to instrument physics not verifiable

We agree. We have contributed additional analysis using timestamped results and included those in a new section 4.3.4, while sections 4.3.1, 4.3.2, and 4.3.4 are based on all available data in the different time series.

- The methodological core of the study, i.e the probabilistic Pareto front and the Monte Carlo decomposition of weather and material uncertainty, is not reproducible from the paper. For example, the material property distributions on which the paper's most prominent conclusion rests are never specified (see the marked PDF for more specific comments).

We agree. We have expanded the text in section 3.2 much.

- The manuscript requires a thorough language revision before publication. Beyond the individual corrections (see the attached PDF) the issue that are systematic are: a substantial number of sentences are ungrammatical or incomplete (e.g. lines 517-518, 522-524, 640-641), and several sections consist of sequences of single-sentence paragraphs with no connectives, so that the reasoning has to be reconstructed by the reader (e.g. lines 602-605, 616-620). As a result, the text is frequently vague where the authors have the numbers to be more precise. I suggest also to avoid qualitative quantifiers where quantitative measures are available, e.g "good results", "high uncertainty", "much damage" and "little damage", "a modest reduction", "inconsistent results"...

We agree. We have revised the language and improved the text across all mentioned lines, and we have avoided qualitative quantifiers.

- Many figures and captions require improvement in the readability or additional information

Thank you for pointing this out. We have modified figures, legends and captions.

Please note that detailed comments are in the marked PDF attached

Line 8: Abstract is apparently long.

Abstract is reduced from around 2700 characters to around 1900 characters

Line 16: The enumeration starts but not end

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Response to Reviewer 1

Corrected

Line 22: a perception cannot be observed. Please rephrase

Text is rephrased

Line 36: consider more formal wording

Done

Line 41: O&M

Corrected

Lines 49-50: Missing logical connection with the rest of the paragraph

Text is reformulated

Line 51: typo

Corrected

Lines 53-54: Is this finding reported in the same RP? If not, please provide reference supporting the statement

It is reported in the same DNV RP reference. However, the text is modified so it reads 'initiate' instead of 'progression'.

Line 55: rotational speed is not measured in m/s. Please consider rewording (blade tip speed)

Text is changed to impact velocities

Line 57: This is formally incorrect: what the Palmgren-Miner rule accumulates is a dimensionless damage index, not a stress, which has units of Pa

Corrected

Line 123: The sentence is not interpretable as written. Half of the accumulated damage? half of the time to Eol? Please rephrase

The text is rephrased. Now the sentence reads:

The total period of such conditions may vary from a few hours to several days per year, depending on site and weather variability, e.g., in 360 5-min periods (30 hours) up to one-third of blade coating lifetime was found to be exhausted in the Southern Great Plains (Pryor et al., 2025)

Line 136: ?

The sentence is modified

Lines 137-139: The objective of the study is stated in a single sentence and remains too generic as it does not specify anything about selected data and methods, and also it does not report about which specific gap in the reviewed literature it is meant to fill. As it is, the introduction does not sufficiently explain the level of novelty and the expected impact of the work. The problem is compounded by the weak connection between this statement and the SOA review.

We agree. We have revised and added: Now the section reads:

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Response to Reviewer 1

Formatted: Header

The objective of the current study is to investigate the uncertainty in erosion risk assessment of Eol and ESO efficiency across different meteorological data types. Three types of meteorological precipitation data are used in the calculations: conventional rain gauge observations, satellite-based observations, and disdrometer observations. Uncertainties in Eol and ESO efficiency estimates are examined in relation to the meteorological data types, time-series length, aerodynamic effects on impact velocity, and stochastic uncertainties stemming from materials and weather data. A systematic assessment of uncertainties for Eol and ESO efficiency has not been reported previously, based on similar data. Furthermore, the methods used in the current study were developed recently and have not yet been applied systematically across diverse meteorological datasets. Thus, novelty is twofold, including the combination of meteorological data types with recently developed methods. The study provides new insights into the magnitude of these uncertainties—information that will ultimately be relevant to quantifying erosion risk using available meteorological observations. This work lays the foundation for a future goal of mapping erosion risk across Europe based on a standardised, long-term dataset to support decision-making in the wind industry.

Line 166: Missing comma

Corrected

Line 182: these are three non-consecutive years. Please avoid calling this a "three-year time series", and state how the concatenation is handled in the damage accumulation.

Corrected and explanation given. The text reads:

Analysis based on rain gauge and cup anemometer data from 19 non-consecutive years (2002 to 2006, 2012 to 2025) is performed. The concatenation is done, omitting years 2027 to 2011 and linking the time series for damage accumulation, ignoring the missing years.

Line 222: LEP material

Corrected

Line 222-123: The description of the impingement damage model does not state where on the blade damage is accumulated. Droplet impingement is distributed both along the span, since impact velocity scales with radial position and only the outer blade operates near maximum tip speed, and along the chord, since the LEP covers a curved surface on which local collection efficiency, local velocity and impact angle vary. Infact, impacts away from the stagnation region are oblique and only the normal velocity component contributes to the water-hammer pressure. Please clarify the assumptions of the model.

We agreed. To clarify our study, we have added:

The results reported in our study are for the tip only, not the radial position along the span, nor along the chord.

Line 223: This is formally wrong. A stress is measured in Pa, or MPa, probably authors are referring to the fatigue damage index

Corrected

223-124: The role of this assumption is unclear, since all reported results are the time to first Eol. If repair cycles are not used in the analysis, remove the sentence; otherwise explain where it enters.

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Response to Reviewer 1

~~True. Sentence is removed.~~

Line 225: Disdrometers give directly measured DSDs, why to use Best's distribution? Please clarify

~~Good point. We added:~~

~~In the current study, the Best model is chosen to ensure consistency across the three types of meteorological observations.~~

Lines 232-233: This sentence is not sufficiently clear. In particular, it is not clear what “sweep” refers to

~~We agree. We added text and an additional reference:~~

~~The rain droplet impact velocity varies over a full rotor sweep, with higher impact velocity at the leading edge during upward motion and lower during downward motion (Keegan et al., 2013). The rate of damage scales non-linearly with impact velocity; thus, variations in impact velocity during the rotor sweep of the blades are also included, accounting for the small increases in velocity that lead to exponential increases in erosion.~~

Line 239: no numerical value of ESO_eff is reported anywhere in the manuscript. The paper here defines a quantitative metric and then never uses it. Please either report ESO_eff values or remove the definition and state the comparison in terms of a clearly defined quantity such as Eol extension per unit AEP loss.

~~Good point. The section is removed and a major revision is done. The text replaces lines 239-256. The text reads:~~

~~The environmental variables used to predict leading edge erosion are wind speed (u) and precipitation rate (I). For normal operation, the turbine operates at nominal rotor speed in all weather conditions. For ESO, curtailing the turbine during heavy precipitation events reduces damage. The optimal ESO depends on the weather, material, and turbine tip-speed curve. The ESO rotor speed (ω_{ESO}) ranges between the minimum rotor speed (ω_{min}) and the standard nominal rotor speed ($\omega_{nominal}$). The ESO rotor speed curve is described by~~

$$\omega_{min} \leq \omega_{ESO}(u, I) \leq \omega_{nominal}(u) \quad (\text{Eq. 1}).$$

~~The optimal ESO strategy balances the trade-off between extended blade life and AEP loss. A trade-off metric (η_{ESO}) is defined from the marginal change in power (P) to the marginal change in damage accumulation rate (D). The partial derivatives of power $P(u, \omega)$ and damage $D(u, I, \omega)$ are used to quantify the cost of coating life at any timestep from~~

$$\eta(u, I, \omega) = \frac{\partial P / \partial \omega}{\partial D / \partial \omega} = \frac{\partial P}{\partial D} \quad (\text{Eq. 2}).$$

~~The set of solutions along the Pareto front offers a basis for selecting the preferred balance between damage and AEP loss. The framework generates a continuous range of optimal strategies along the Pareto front to assess the efficiency of ESO. Thus, the user can define the~~

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specific balance between coating life and energy yield, i.e., select a specific strategy for the ESO. Each chosen strategy provides unique points on the trade-off curve between coating life and energy yield. The framework was developed by Madsen et al. (2026). A Pareto front represents the set of solutions for which no solution outperforms any other solution in the set. Variability in precipitation rate, wind speed, and material impacts the ESO efficiency results.

A Monte Carlo-based probabilistic Pareto fronts method was developed by Madsen et al. (2026). The approach is based on a combination of uncertainty quantification of materials and weather data.

For materials, the approach is based on uncertainty quantification of SN-curve predictions using whirling-arm rain-erosion test data. The power-law relationship between stress amplitude and the number of cycles to failure forms the foundation.

For the material used in the current study, the damage rate is proportional to impact speed (V_{imp}), with the best-fit values of $c=3.35 \cdot 10^{18}$, $m=8.61$, and a residual standard deviation 0.13.

$$D \propto c V_{imp}^m \text{ (Eq. 3).}$$

Uncertainty quantification for predictions of the SN-curve from the relationship between stress amplitude and the number of cycles to failure was obtained from the posterior distribution of the coefficients using Bayesian linear regression. The posterior distribution provides a full probabilistic description of the regression coefficients, enabling uncertainty quantification in predictions of the SN-curve (Appendix C in Visbech et al., 2025). In the current study, uncertainty quantification of the VH-curve is performed using liquid impingement of water rather than a specific number of impacts.

For weather data, the approach is based on the joint distribution of wind speed and precipitation rate, sampled as concurrent pairs randomly selected from the weather time series. The number of selected weather data points sums to one year of observations. The random sampling is done with replacement. The uncertainty in weather data due to annual variability is introduced through the random selection process. It is recommended to have a multi-year time series. The number of Monte Carlo realisations was 100, using probabilistic uncertainty quantification for the material and randomly selected joint wind speed and precipitation rate time series. The Monte Carlo method enables uncertainty analysis for weather and materials around the Pareto front.

If only the uncertainty due to weather is assessed, the wind speed and precipitation rate data are randomly selected from a longer time series, spanning one year's worth of data samples. At the same time, the material properties are used deterministically. Alternatively, the uncertainty due to material is assessed by keeping the weather data deterministic and applying uncertainty quantification to material properties. The total uncertainty from weather and materials is assessed using a Monte Carlo simulation, with weather sampled randomly and material properties quantified with uncertainty. It may be noted that variability in EoI is also seen for normal operation. In other words, not all blades at one turbine or all turbines within a wind farm will experience the same damage level in the given environment.

Line 239: Is this the "cumulative stress" reported before? dD is never defined before

Response to Reviewer 1

Modified, please see above

Line 239: How is this loss computed?

Modified, please see above

Lines 245-246: Madsen et al. (2026), is an AIRE project deliverable report and not a peer-reviewed publication. Since the probabilistic Pareto front and the Monte Carlo uncertainty decomposition are the central methodological contributions used in the paper, please give a clear description reporting the sampling unit, whether sampling is with or without replacement, the number of realisations, and how the set of curtailment strategies spanning the Pareto front is generated.

Modified, please see above

Line 250: The probability distributions assumed for the weather and (especially) material properties are never specified in the paper. Please state the distributions and their justification.

Modified, please see above

Line 260: Please be more specific about the relevance of each of these ~~parameters~~ parameters

We have modified. The text reads:

The turbine tip speed curve, hub height, rotor diameter, blade airfoil, cut-in and rated wind speeds, and minimum and maximum rpm are relevant parameters. The tip speed curve is used in the damage calculation, the hub-height is used in the extrapolation of wind speeds and AEP calculation, the blade airfoil is used in the droplet slowdown while cut-in, rated and cut-out wind speed and minimum and maximum rpm are used in the end of incubation and erosion safe operation calculation. The rpm is used in damage calculation.

Line 267: The information about wind should not be in the section of wind turbines. Consider to add a dedicated section for the wind data and its processing

We agree. We have made new section 3.3 about wind speed analysis.

Line 268: this is a quite high roughness length for a flat terrain. Please argument this choice

True. We have added two references. Sogachev and Dellwik provide details on the specific site and roughness while Hasager and Jensen deal with effective roughness, useful in terrain with inhomogeneous surfaces. The text reads:

The roughness length represents an effective roughness length (Sogachev and Dellwik, 2017; Hasager and Jensen, 1999).

Line 275: Please specify how the Spearman coefficient is computed (over which samples, whether zero-precipitation samples are included, and how the resulting ties are handled). This matters because the results depend strongly on the treatment of zeros

We agree. We have added. The text reads:

All samples in the concurrent time series are included, including zero values (though not missing years). For the resulting ties, the values are assigned mid-ranks.

Lines 289-290 (Figure 4 caption): What is the red dashed line?

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Response to Reviewer 1

It is trendline, now included in caption.

Figure 5 caption: What is the red dashed line?

It is trendline, now included in caption

Line 306: Please clarify briefly what “more comprehensive” implies.

Good point. We have modified. The text reads:

Examining the impact on Eol for three reference turbines is based on the droplet slowdown impact efficiency, evaluated using two methods (DNV, 2021; Barfknecht and von Terzi, 2024). The method recommended by DNV (2021) is a simpler method compared to the advanced method by Barfknecht and von Terzi (2024), which includes the airfoil shape as well as droplet size and shape.

Lines 306-307: Please revise the grammar

Done

Line 308: This sentence is left here with no premise and no consequence. Please order the text in a way that the sentences are meaningful and supported by data, results and clear methodological descriptions

Done

Line 329-330 (Figure 7 caption): The three subfigures seem not correlated or should be better explained in the caption. Legend would help reading the subfig a and b

True. We split into two figures. New Fig. 7 (previous Fig. 7a and 7a) and Fig. 8 (previous Fig. 7c). The captions are expanded for clarification.

(all subsequent figure numbers are updated)

Lines 344-345 (Figure 8 caption): Legend is missing

Included

Lines 396-397 (Figure 10 caption): A legend and more information in the caption would help reading the figure. The shaded areas may be confused with PDF or frequency distribution functions, but their area size is different.

We agree. Note Fig. 10 is new Fig. 11. We added in the text:

The frequency distribution of Eol plotted in Fig. 11 using Monte Carlo simulations is based on a non-consecutive 19-year time series.

We add in the figure caption:

Figure 11. Frequency distribution of erosion safe operation efficiency Pareto fronts showing relative AEP loss and absolute end of incubation for 100 Monte Carlo simulations and indicating the median value (black vertical lines) for a) weather, b) material, and c) total combined uncertainties, based on rain gauge and cup anemometer observations for non-consecutive 19 years and assuming an IEA 15 MW turbine was installed at Risø, DTU

Line 405: This implies that missing periods are effectively treated as zero precipitation in the damage accumulation. Please: i) normalise the accumulated damage by data availability, or

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restrict all sensors to concurrent timestamps, so that instrument properties are separated from availability; ii) report the availability normalised values alongside the raw ones. Without this fix, every inter-sensor Eol difference in the paper can be confounded with data availability

Good point. Thank you for the suggestions. Our primary aim was not to make one-to-one comparisons between sensors. We are primarily interested in Eol and ESO efficiency using all available data. Thus, when we randomly sample wind and precipitation pairs for the Monte Carlo simulation, we keep all samples rather than restrict them, as we believe it is important to have a good base to select from. We are already low on data samples, having less than one year for the three disdrometers.

For 2021, when most data are available from the three disdrometers, we describe variations in precipitation amount and average wind speed based on the available data. We could scale precipitation based on the available samples, but this does not explain the differences in precipitation among the three sensors. The wind speed difference concurrent with the disdrometer is minor (less than 0.2 m/s). We modified the text:

Rain gauge data show variations in total yearly precipitation from ~400 to ~1000 mm yr⁻¹ (Fig. 4b). IMERG shows from ~400 to ~800 mm yr⁻¹ (Fig. 5b). Disdrometers show from ~350 to 600 mm yr⁻¹ (Fig. 6b). The result indicates under catch in disdrometers. The amount of missing data from Parsivel² (~12%), Parsivel² top (~16%), and Thies (~24%) cannot account for the differences. In contrast, Thies, with the most missing data, shows more total yearly precipitation than Parsivel² and Parsivel² top. Average annual wind speeds vary between years and with height. Higher winds are seen from NEWA (at 150 m) compared to the cup anemometer (at 125 m) and the sonic (at 60 m) in Figs. 5a, 4a and 6a, respectively. 2021 exhibits a lower annual average wind speed than 2020 and 2023 from all data sources. The average yearly wind speed in 2021 from sonic concurrent with Parsivel², Parsivel² top and Thies differ from 7.2 to 7.4 m s⁻¹ (Fig. 6a) while the observed total precipitation in 2021 differs from below 400 mm to more than 600 mm (Fig. 6b). In 2021, rain gauge and IMERG both showed ~750 mm. Examining the accuracy of each sensor type is beyond our scope. High-quality sensor data is collected. Our focus is on uncertainties in the assessment of Eol and ESO efficiency based on available time series.

We do not consider it valid to scale Eol or ESO efficiency results due to non-linearities in the functions.

We chose to do an analysis restricting to concurrent timestamps. This analysis is based on three data types (rain gauge, IMERG and Parsivel²) timestamped for years 2020, 2021 and 2022 and we calculated Eol and ESO efficiency. The results on concurrent timestamps are presented in new section 4.3.5, to make it clear that results in this section can be compared between sensors. In contrast, results in section 4.3.1 to 4.3.4 are based on all data.

We added a pre-ample on the ESO results to clarify:

ESO is investigated using all available datasets, without filtering concurrent timestamps across different joint time series types, which would reduce the number of samples. Four main topics are considered: 1) Impact of droplet slowdown method for assessment of ESO efficiency for three turbines using the longest time series (section 4.3.1); 2) ESO efficiency probabilistic Pareto fronts for weather and material uncertainties using the longest time series for one turbine (section 4.3.2); 3) ESO efficiency probabilistic Pareto fronts for total uncertainties using three types of time series from non-concurrent, non-consecutive 3-year time series for one turbine (section 4.3.3); 4) ESO efficiency probabilistic Pareto fronts for total uncertainties using

Response to Reviewer 1

three time series from non-concurrent 1-year disdrometer time series for one turbine (section 4.3.4); Finally, a restricted time series is used to assess Eol and ESO efficiency (Pareto front) using three types of time series from concurrent (timestamped), non-consecutive 3-year time series for one turbine (section 4.3.5).

Similarly, we added a pre-ample on Eol results to clarify:

Eol is investigated using all available data sets, without filtering concurrent timestamps across the different time series, as that would reduce the number of samples. Four main topics are considered: 1) Impact of droplet slowdown method for assessment of Eol for three turbines using the longest time series (section 4.2.1); 2) Eol per year using all available samples in five time series for one turbine (section 4.2.2); 3) Eol sensitivity analysis on 'representative years' vs. the longest time series for one turbine (section 4.2.3); 4) Impact of temporal resolution on Eol using all available samples in five time series for one selected year for one turbine (section 4.2.4).

The results with concurrent timestamped data are shown in new Fig. 14 (replacing old Fig. 11 and new Table 8 (replacing old Table 5).

A further analysis based on concurrent, timestamped data is pairing the resampled 30-min rain gauge with NEWA and the resampled 30-min Parsivel² with NEWA. The results are included in new Fig. 14 and new Table 8. This enables comparison of rain gauge, IMERG and Parsivel² for the non-consecutive 3-year period, using same wind speed. The results are reported in section 4.3.5.

Line 425-427 (Figure 11 caption): Please state in the caption which wind source is paired with each precipitation source

Done in new Fig. 14 replacing old Fig. 11. Plus we included results with rain gauge and disdrometer paired with NEWA.

Lines 446-447 (Figure 12 caption): see comment on Fig10

Done.

Lines 464-465 (Figure 13 caption): See comment on Fig10

Done

Lines 517-518 ungrammatical or incomplete

Modified (deleted)

Lines 522-525: Please improve the grammar

Modified (deleted)

Line 566: This is an important conclusion of the paper (it is in the abstract and in the conclusions), and it is entirely determined by the material property distributions assumed in the Monte Carlo, which are never specified

True. We have included description of material properties in section 3.2. The material properties uncertainty is based on peer-reviewed journal article (Visbech et al., 2025). Now cited, and further description is provided. The text reads:

Response to Reviewer 1

For materials, the approach is based on uncertainty quantification of SN-curve predictions using whirling-arm rain-erosion test data. The power-law relationship between stress amplitude and the number of cycles to failure forms the foundation.

For the material used in the current study, the damage rate is proportional to impact speed (V_{imp}), with the best-fit values of $c=3.35 \cdot 10^{18}$, $m=8.61$, and a residual standard deviation 0.13.

$$D \propto cV_{imp}^m \text{ (Eq. 3).}$$

Uncertainty quantification for predictions of the SN-curve from the relationship between stress amplitude and the number of cycles to failure was obtained from the posterior distribution of the coefficients using Bayesian linear regression. The posterior distribution provides a full probabilistic description of the regression coefficients, enabling uncertainty quantification in predictions of the SN-curve (Appendix C in Visbech et al., 2025). In the current study, uncertainty quantification of the VH-curve is performed using liquid impingement of water rather than a specific number of impacts.

Lines 602-605 single-sentence paragraphs with no connectives

Text is deleted

Lines 616-620 single-sentence paragraphs with no connectives

Text is deleted

Lines 640-641 ungrammatical or incomplete

Text is deleted

Lines 675-685: The conclusion section itself should report the main take aways. It is strange to see this paragraph detached from the rest of the section. Furthermore, here authors write with a register unsuited to a journal conclusion, including rhetorical questions. Please rewrite as declarative statements. Note also that the recommendations rest on inter-sensor differences whose causes are, at present, hypotheses.

We agree. The conclusion is modified.

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