

Resposns to Reviewer 2

WES Reviewer 2

This paper investigates uncertainty in wind-turbine leading-edge erosion predictions and erosion-safe operation (ESO) using different meteorological data sources at the Risø site. Long-term rain-gauge measurements, high-frequency disdrometer measurements, and IMERG/NEWA data are compared using an impingement-based erosion model and probabilistic ESO Pareto fronts. The authors find that Eol estimates are highly sensitive to record length, while ESO efficiency is strongly affected by temporal and measurement resolution. The authors therefore recommend combining long-term datasets for Eol assessment with high-frequency observations for ESO design and operation. The manuscript reads clearly and presents a the sensitivity to several relevant uncertainty in a joint manner, which I have not seen before. Th use of three reference turbines adds robustness to the study. Some suggestions and remarks below:

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

- 1) The main concern with the manuscript is clear separation of precipitation and wind effects, which I did not see discussed in enough depth. Rain gauge, disdrometer and IMERG precipitation are respectively paired with cup, sonic and NEWA wind speeds. Therefore, differences in Eol and ESO cannot be attributed to the precipitation dataset alone. Wind speed influences the turbine operation, and therefore the blade's peripheral speed for a give precipitation rate, which makes this effect particularly significant. The authors themselves note that some differences may be due to the differences between the NEWA wind speeds and the local measurements. Since long-term measurements are availabel from the cup anemometer and the NEWA dataset, estimations could be repeated "mixing" the data sources. So for instance considerig the raing gauge paired with NEWA wind speed estimations or IMERG observations with cup anemometer measurements, allowin for the effects of wind speed and rain-rate to be separated.

We agree. We have chosen to add analysis pairing rain gauge with NEWA and pairing Parsivel² with NEWA. The results are based on concurrent timestamped data for years 2020, 2021 and 2022. The results are presented in Fig. 14 (replacing old Fig. 11) and Table 8 (replacing old Table 5).

We added text:

The variation in Eol and ESO efficiency might be affected not only by differences in precipitation but also by differences in wind speeds. To eliminate variation in wind speed in the Eol and ESO efficiency results across the three precipitation time series, NEWA wind speeds are paired with the resampled 30-minute rain-gauge and 30-minute Parsivel² data. The results are shown in Fig. 14. It is noted that, for both the rain gauge and the Parsivel², the Pareto fronts are steeper with NEWA than with the cup anemometer and sonic wind speed data, respectively. It corresponds

Resposns to Reviewer 2

to higher wind speeds in NEWA than from the cup anemometer wind speeds observed at 125 m and extrapolated to 150 m, and the sonic wind speeds observed at 60 m and extrapolated to 150 m. The further the extrapolation in height, the greater the deviation in wind speed. Parsivel² resampled to 30-minute, paired with NEWA, shows a Pareto front as steep as IMERG and NEWA, while rain gauge resampled to 30-minute, paired with NEWA, shows a flatter Pareto front. At 0.9% AEP, the rain gauge Pareto front crosses the Parsivel² Pareto front.

The results for Eol using concurrent timestamps and three types of precipitation time series, paired with NEWA, show rain gauge (5.3 years), IMERG (4.8 years), and Parsivel² (7.7 years), based on three non-consecutive years (2020, 2021, and 2023). The percentage difference in Eol between the rain gauge paired with a cup anemometer versus the rain gauge paired with NEWA is 4%, and for Parsivel² paired with sonic versus Parsivel² paired with NEWA 9%. Under catch in Parsivel² is a reason for the longer Eol compared to the two other results.

Some additional details on the methodology would be useful, in particular:

- 2) Section 3.2: it is not clear which material parameters are sampled, their assumed distributions/ranges, or the number of realizations in the Monte Carlo analyses. Please provide the main assumptions here, even if the complete methodology is available in Madsen et al. (2026).

We agree. We have modified the description. 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:

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.

Resposns to Reviewer 2

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.

- 3) Section 3.2: Please specify explicitly whether wind speed and precipitation are sampled jointly as concurrent pairs in the Monte Carlo analysis, thereby preserving their observed dependence

We have clarified. The text reads:

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.

- 4) Section 3.2: The construction of the ESO Pareto fronts could be described in more detail. How are the most damaging periods identified? What curtailment action is applied to the turbine, and how is the corresponding AEP loss calculated? These details would make the methodology much easier to follow.

We have modified and added clarifying text. 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

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

Respos to Reviewer 2

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 $D(u, l, \omega)$ are used to quantify the cost of coating life at any timestep from

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

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 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.

- 5) Temporal-resolution analysis: Please specify how wind speed and precipitation are resampled to the coarser temporal resolutions. Are period averages being taken? Or are the timeseries being sampled on a coarser interval?

We had added text to clarify. The text reads:

The available data sources are resampled to a lower temporal resolution to compare Eol across lower-resolution data. Wind speeds are period-averaged, while precipitation is the total sum in each period.

Minor comments:

- 6) Abstract: "Key results on the uncertainty in assessing Eol are: 1) [..]" there is no poin 2) though...

This is corrected.

- 7) Table 3: There are significant differences in Eol prediction for the three rotors. Is it only due to the differences in maximum tip speed as stated in the text? The difference in maximum tip speed between the IEA 15 and DTU 10MW is not very large (90 m/s vs 95 m/s). So this may be due to the relatively high minimum rpm in the IEA 15 MW? Would be an interesting discussion that could be useful to a broader audience.

Citation: <https://doi.org/10.5194/wes-2026-136-RC2> Good question. We have added the minimum rpm in Table 3. We have added text:

Resposns to Reviewer 2

The IEA 15 MW turbine shows shorter Eol than the other two turbines. This may be explained by the higher hub height (150 m vs 119 and 90 m), which can be associated with higher average wind speeds, higher tip speed (95 m s⁻¹ vs. 90 and 80 m s⁻¹), minimum rpm starting at low cut in wind speed and reaching rated speed (10.6 m s⁻¹) compared to DTU 10 MW and NREL 5 MW rated speed (11.4 m s⁻¹).

We have added text and two equations, in which minimum and maximum rpm enters

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

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

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

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

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