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Assessment of the rain and wind climate with focus on wind turbine blade leading edge erosion rate and expected lifetime in Danish Seas

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A B S T R A C T

Our motivation for investigating the rain and wind climate in the Danish Seas is recent news on leading edge erosion on wind turbine blades at several offshore wind farms. The costs related to turbine blade repair are high. In this study we investigate the rain and wind climate at five coastal and three inland weather stations in Denmark. The coastal stations have much higher frequency of heavy rain than inland stations, in high wind conditions. The hypothesis is that leading edge erosion mainly develops during these few extreme events. The leading edge erosion rates and expected lifetime are calculated assuming similar turbines to be in operation at the eight site. The results of two damage increment models show similar results for the coastal stations but differ for two out of three inland sites. The kinetic energy model shows four times high erosion rates at the coastal sites versus the two inland sites. The accumulated rain model shows site independent erosion. The expected life is on average 3 years of the two damage models. The erosion safe mode control, i.e. reduced wind turbine tip speed during extreme rain events, is presented with relative profit from 2.8 to 4.8%.

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1. Introduction

Meteorology for wind energy focuses on wind observations and wind modelling. The wind speed and wind directions are typically observed during one or more years at a prospected site. The Weibull scale and shape parameters of the fitted mean wind distribution and the fifty-year extreme wind and turbulence statistics are used for the wind farm planning [1,2]. In contrast, no information about the rain climate is collected. In the IEC standard 61400 (IEC 2019) rain is listed as other climate conditions, specifically freezing rain and corrosion.

The motivation for investigating the rain climate for wind energy is the recent focus on wind turbine blade leading edge erosion (LEE) [3]. The LEE both occur on wind turbines offshore and onshore. The technical and economic challenges are greater offshore. There has been news on high repair costs related to LEE at several offshore wind farms [4,5]. The relationship between LEE, rain and tip speed is being established through testing in laboratories using rain erosion tester [6–8]. The rain erosion tester mimics the processes occurring in nature in controlled, accelerated ways. Preliminary results indicate that larger drops are causing faster erosion than smaller drops, and higher tip speeds are causing faster erosion than lower tip speeds. However, the complete interplay between drop sizes, tip speeds and materials is a novel research field with limited quantitative facts to count on.

The LEE may potentially be reduced (or avoided) in case the tip speed is reduced during heavy precipitation events [9]. The study indicates that implementing the so-called erosion safe mode control, i.e. to slow down tip speeds during heavy rain events, may give an economical gain. On one hand, there will be loss of electricity production and income during heavy rain events. On the other hand, there will be reduced repair costs when preventing LEE. In addition, the production loss due to the aerodynamic degradation caused by LEE is reduced [9,10].

Quantitative knowledge on rain events at offshore wind farm sites is lacking in Denmark and elsewhere. Neither has the amount and type of precipitation that may contribute to LEE been quantified, nor has the timing, intensity or duration of precipitation events.

For most application fields the precipitation type (rain, hail, snow, etc.), the rain intensity in mm/h and the accumulated amount during hours to days are measured. A more specialized parameter is the raindrop-size distribution. This is important for
the estimation of soil erosion [11] and for studies on wind-driven rain at buildings [12] and transmission towers [13]. It is customary to rely on empirical relationships between rain intensity during 10 min and drop size distribution [14,15] due to lack of measured raindrop-size distribution data.

The average annual precipitation during 30 years in Denmark shows a pattern with more average rainfall in mainland Jutland and less average rainfall in the eastern part of Denmark [16,17]. The distribution of extreme precipitation does not follow this pattern. In contrast, heavy rain events are more frequent in the eastern part of Denmark including Copenhagen than in western Denmark [18]. The difference arises from the influence of more continental type climate in the east and more maritime type climate in the west.

To assess the rain and wind climate, this study focuses on recent 16 years environmental conditions on rain and wind based on the Danish Meteorological Institute (DMI) weather station data in Denmark. The joint distribution of precipitation and wind speed is of importance for predicting LEE and expected lifetime.

According to Ref. [19]; the blade erosion observed in the field and compared to numerical weather model results using average yearly rainfall shows that the damage rate on a wind turbine section is proportional to that sections’ velocity to the power of 6.7 for surface fatigue using the analytic damage model based upon [20]. Thus, it is critically important to identify the wind speed and thereby potential blade section velocity during precipitation events.

The present study focuses on quantifying the rain and wind climate nearby selected Danish offshore wind farm locations. The specific objectives of the study are to: a) define and outline methodology to estimate precipitation classes relevant for leading edge erosion; b) quantify the precipitation classes in relation to wind speed; c) calculate site-specific rain erosion rates and expected lifetimes; and d) estimate the potential gain of erosion safe mode and its influence on relative profit.

The financial perspective is especially valuable as site-to-site variability of the maintenance costs associated with erosion are currently disregarded in the planning process. Maintenance cost analyses for icing turbine blades in cold climates shows preventive methods to be more profitable than corrective costs [21]. LEE is one out of several optimization problems related to turbine blades and aerodynamic low performance sensitivity to leading edge roughness is one of these [22]. Some wind farm operators admit that, depending on the location and turbine type, some offshore turbines require blade repairs carried out as frequently as every second year whereas others may operate many years without the necessity to repair [4,5]. More than that, offshore repairs are particularly expensive, as they require the use of specialized vessels and crews within available weather windows, on top of the ever-present cost of turbine downtime. There is interest in predicting which locations are the worst in terms of erosion and finding ways to decrease the rate of erosion.

The paper structure includes description of material and methods in Section 2 with three sub-sections. The first on weather data analysis including quality control. The second on leading edge erosion, damage modelling, erosion rate and expected lifetime. The third on turbine characteristics, climate input and erosion safe mode control. Section 3 presents the results on occurrences of threshold rain intensities as function of wind speed bins, the site-specific erosion rates and expected lifetime results and finally the financial potential of erosion safe mode control. Section 4 presents the discussion and Section 5 the conclusion.

2. Materials and methods

The analysis is structured around the assumption that leading edge erosion is caused by raindrops impinging the blades and that reduced tip speeds during intense rain events may prolong life, reduce aerodynamic loss in annual energy production and reduce repair costs. Fig. 1 shows a flow chart for the analysis. The materials and methods related to the precipitation and the winds are presented in Section 2.1 including quality control of precipitation data. Section 2.2 presents the materials and methods related to the leading edge erosion damage modelling, the erosion rate and the lifetime assessment method. Section 2.3 deals with the materials and methods related to erosion safe mode control involving the turbine characteristics of the selected wind turbine, the control settings for turbine operation and the comparison of revenue without and with erosion safe mode control.

2.1. Weather station data including quality control

Precipitation observed at selected Danish weather stations by DMI is the fundament for the analysis. The probably most potentially harmful precipitation types are hail and heavy rain. The analysis focuses on quantification of occurrences of rain intensity for different wind speed bins. Hail is not considered due to lack of reliable data.

We choose to define precipitation classes using the conventions in meteorology: light rain less than 1 mm/h, moderate rain 1–10 mm/h, heavy rain 10–20 mm/h and violent rain higher than 20 mm/h. The rain intensities are combined with wind speed bins (0–3; 3–6; 6–9; 9–13; ≥13 m/s) to identify the fraction of rain events potentially causing LEE.

Analyses of rain and wind speed data over a period of 16 years are performed for a number of coastal and inland weather stations. The aim is to assess the rain intensity and wind speed occurrences percentage of time exceedance.

A thorough data quality control and identification of the most likely hydrometeor type is performed before the rain is identified. We only allow rain and sleet (liquid precipitation) to enter into the analysis but exclude snow and hail.

The DMI weather stations selected in the study include coastal stations to represent the offshore climate while the inland stations represent the land climate. The criteria for selection of weather stations are the availability of observations of precipitation, precipitation type, temperature and wind speed observed every 10 min for several years. We prefer high temporal resolution to resolve the statistics with much detail. The 10-min data is the highest temporal resolution available from the stations. For the
data periods see Table 1.

The coastal stations Hvide Sande, Thyborøn and Skagen at the North Sea coastline are the Horns Rev offshore wind farms conditions as well as potential future wind farms: Nordsøen A where the 800 MW wind farm Thor is in planning, Nordsøen B and Jammerbugt. The coastal station Anholt represents the Anholt offshore wind farm in the Kattegat Strait and potential future wind farms, Hesselø A and B [24]. The coastal station Vindebæk represents the Nysted/Rødsand and Kriegers Flak offshore wind farm areas in the Baltic Sea. The three inland stations Billund, Karup and Aalborg represent the inland climate in Denmark. The locations of the selected weather stations and offshore areas are indicated in Fig. 2.

Instrumentation at the DMI weather stations are cup anemometers (Vaisala WAA151), wind direction (Vaisala WAW151), temperature sensors (Vaisala HMP155) and weather sensors (Vaisala FD12P). Precipitation sensors include several types, see Table 1 for details. The resolution is 0.1 mm/h for all except RIMCO with 0.2 mm/h. The weather sensor data give information on the hydrometeor types: rain, drizzle, snow, melting snow, freezing rain, ice pellets, snow grains and hail.

The mean annual precipitation is calculated using the gap-filling interpolation method [23]. Data for the period 2011 to 2017 is available and listed in Table 1. Prior to 2011 the gap-filling method was not implemented. The data include hydrometeor types. The driest location is Anholt with 556 mm, and wettest is Billund with 1012 mm.

2.1.1. Quality control of precipitation data

The present study focuses on hydrometeor types of liquid precipitation. Liquid and solid precipitation data has undergone intense quality control, to quantify as accurately as possible the liquid part, i.e. rain and sleet, hereafter mentioned as “rain”.

The precipitation data quality control includes threshold check, gross-value check and consistency check versus weather type following the principles of [25,26]. Single station based methods are applied.

In the threshold check each 10-min precipitation observation (Pobs) is compared to different threshold values. First, Pobs is tested versus a threshold Tp1% corresponding to a probability of 1% for Pobs > Tp1% [27]. Next Pobs is tested versus the thresholds Tp5y, Tp10y and Tp20y, that represent the 10-min precipitation amount at return periods 5, 10 and 20 years respectively, according to the method in Ref. [28]. It is based on national values of the frequency of intensities as a function of precipitation duration.

Gross-value check is testing for physically unrealistic values. The threshold Tgross is determined from weather extremes \( P_{\text{max}} + \Delta \), for \( \Delta \) an arbitrary high value; Tgross is perceived as instrument error. It is true that \( T_{\text{p1y}} < T_{\text{p5y}} < T_{\text{p10y}} < T_{\text{p20y}} < T_{\text{gross}} \). The observations marked as error from this method are subsequently manually examined in regard to radar data, the stability of rain during time, the general weather situation, other rain data and the local variation in temperature, wind direction and speed, weather type and relative humidity.

2.1.2. Methodology to identify liquid precipitation

Studies have shown that the FD12P sensor has certain problems in classification of hydrometeor type, especially for precipitation near the freezing point [29,30]. According to a WMO inter-comparison study of optical weather sensors ability to discriminate the precipitation type, the FD12P sensor performed the best of all sensors with a high level of detection for rain and snow [31]. Even though some drawbacks were found, e.g. light rain sometimes detected as snow or mixed precipitation, and light snow as drizzle. But most importantly, hail was not reported, although the manufacturer claims this capability. This mismatch was also reported in an exploratory study within the framework of EUMETNET [32].

The critical point in the present study is to identify and eliminate solid precipitation data, and data that most likely is solid precipitation. This is to include only rain data in the analysis on LEE. Thus, a method is developed for quality assurance of FD12P weather type that is based on the calculated probabilities of snow and rain.

To distinguish between rain and snow a method often used is a simple air temperature \( (T_a) \) threshold, or a two-threshold method with a linear zone between the lower and upper threshold temperatures, \( T_{\text{d(snow)}} \) and \( T_{\text{d(rain)}} \), to distinguish snow, sleet and rain. These simple methods are problematic. More advanced probability functions based on empirical values give far less bias between observed and calculated precipitation type e.g. Ref. [33]. Suggested empirical functions include exponential, hyperbolic tangent and sigmoidal forms to present the probability distributions for snow, \( f_{\text{snow}} \) [33,34].

Considerations on which of the temperatures, dew point temperature \( (T_d) \), wet bulb temperature \( (T_w) \) or air temperature \( (T_a) \), to use for the classification of precipitation type are as follows. The surface temperature of a hydrometeor is similar to \( T_a \) and \( T_d \) when relative humidity \((RH)\) is near 100%, thus the probability function can be based on these temperatures [35]. For RH much less than 100% it is not necessarily true.

A solid hydrometeor falling through dry air will evaporate from the surface and this cooling effect will allow the hydrometeor to

| Station       | Annual precipitation (mm) | Precipitation start of observations | Weather type start of observations | Rain gauge type and periods |
|---------------|----------------------------|------------------------------------|-----------------------------------|-----------------------------|
| Aalborg       | 723                        | 2003-02-28                         | 2009-06-24                        | Geonor 2003 to 2013-02-27   |
| Anholt        | 556                        | 2002-01-01                         | 2002                              | RIMCO 2013-02-27             |
| Billund       | 1012                       | 2003-08-22                         | 2005-11-29                        | From 2013-02-28              |
| Hvide Sande   | 674                        | 2002-01-01                         | 2002                              | Vaisala Geonor 2002         |
| Karup         | 868                        | 2003-02-13                         | 2005-06-13                        | From 2013-02-28              |
| Skagen        | 625                        | 2002-01-01                         | 2002                              | From 2013-12-16              |
| Thyborøn      | 794                        | 2002-01-01                         | 2002                              | From 2014                   |
| Vindebæk     | 591                        | 2006-05-29                         | 2006                              | From 2015-06-25              |

Table 1

DMI weather stations mean annual precipitation from 01.01.2011 to 31.12.2017 based on the gap-filling interpolation method of [23]. In the present study precipitation observations and weather type observations from starting dates in the table until 31.03.2018 are used. The rain gauge types and periods per station are listed.
maintain the solid phase also through air with $T_a > 0$. In principle, the temperature of the hydrometeor ($T_h$) can be calculated from the meteorological variables observed at the weather stations, assuming the measurements represent equilibrium between the falling hydrometeor and the surrounding air [34]. One assumption may be that $T_h$ equals $T_w$ at the weather station even though, in certain atmospheric conditions, it may not be fulfilled. The surface RH is not necessarily fully representative of the conditions of the air mass through which the precipitation is falling. This may affect the uncertainty of the hydrometeor classification.

Based on the calculated $T_w$ and the observed precipitation type, a probability function for snow $f_{snow}(T_w)$ is determined. The sigmoidal fits to the observations and the empirical constants $b = 0.083$ and $c = 126.124$ as in Ref. [34]:

$$f_{snow}(T_w) = \frac{1}{1 + be^{cT_w}} \quad (1)$$

The constants are valid in Denmark. Fig. 3a shows high correlation between the observed snow and $T_w$. According to Ref. [36] that based their analysis on radar data, sleet prevail between $T_a$ 0° and 1 °C with a sharp transition from snow to rain at around 0.5 °C. The indication is that in the coolest part of the $T_a$-distribution it is most likely snow and in the warmer part mainly rain. It is hence assumed that the distribution of form (Eq. (1)) also represents the probability for sleet.

Based on the function $f_{snow}(T_w)$ a threshold (thrs) value $T_w(thrs)$ at $-0.4$ °C represent the 99% probability for snow. In case the observed hydrometeor type is sleet or rain at $T_w \leq T_w(thrs)$, the precipitation is assumed to be snow, and excluded from the rain climate analysis.

At higher temperatures, it is not as straight forward to establish the threshold value for $T_w$. The combination of RH and $T_a$ at which a hydrometeor just can remain solid is used following [37]. In Ref. [38], a probability of snow at 30% is proposed for separation between rain and sleet. This threshold may cause some mixed precipitation events to be included in the data set. To avoid that, we use 1% to be completely sure to exclude all mixed and solid precipitation types. For a probability for snow at 1%, the empirical values of $T_a$ and RH are shown in Fig. 3b as hatches. The observed precipitation is assumed to be rain in case $T_a \geq 2.3$ °C and observed RH > RH(thrs). The curves for RH(thrs) are calculated and shown in Fig. 3b. Thereafter the re-classified observations of sleet and snow are made. For observed weather types not complying to the above criteria, i.e. if $T_w > T_w(thrs)$ and $T_a < 2.3$ or $RH \leq RH(thrs)$, the denominator value is used and only rain and sleet enter the analysis. The method is validated by random sampling and testing the re-classification in the perspective of weather conditions in general, and weather type observation before and after. A reasonable result is found.

In summary, the valid number of liquid precipitation data at the stations range from 90 to 99%. The amount of non-liquid precipitation is between 2 and 5% at the stations.

The precipitation and wind distribution is given as the percentage of time a given rain intensity observed at a rain gauge is exceeded for specific wind speeds as LEE is related to concurrent high rain intensity and high wind speed. The results are presented in Section 3.1.

### 2.2. Site-specific erosion rate and expected lifetime analysis

In order to compare the erosion load at the eight sites, a lifetime analysis is made by assuming that there is installed one similar wind turbine at each of the locations listed in Table 1. The calculation of the expected life and accumulated damage is similar to the method presented in Ref. [9].

#### 2.2.1. Damage models

In the present study the rain erosion test data presented in Ref. [9] are used for the analysis. Two different interpretations of the rain erosion test data are used.

The first interpretation method is the kinetic energy model also used in Ref. [9]. It is expressed as the number of impacts per unit area to cause damage as a function of the kinetic energy of each impact.
N = 18 * E^-4.63 \quad (2)

N is the number of impacts per m² to cause damage and E is the kinetic energy in joule of each drop relative to the leading edge just before impact.

The second interpretation method is the accumulated rain model. It is the accumulated water on the leading edge to cause damage as a function of the velocity. Here the impact fatigue is assumed independent of the drop size distribution. The intensity of impacted water is \( I_t \)

\[ I_t = V * v \]

Here V is the amount of liquid water in a volume and \( v \) is the velocity of the blade travelling through the rain field. \( h \) is the accumulated impacted rain after time \( t \).

\[ h = I_t * t \]

Fitting a power function to the rain erosion test data, we get

\[ h = 1.5 * 10^{19} v^{-9.26} \]

The rain erosion test data and fitted Wöhler curve is shown in Fig. 4.

### 2.2.2. Erosion rate and expected life at the eight sites

The erosion rate is calculated by the two methods, the kinetic energy model and the accumulated rain model.

The Wöhler curve (or SN curve) describes the relation between cyclic stress (repeated applied loads, e.g. from drops) versus the number of cycles to failure for a given material. Combining the load time history and the Wöhler curve and using the Palmgren-Miner’s rule based on a linear damage hypothesis it is possible to determine the accumulated damage and expected fatigue life of the material [3].

For each time step the wind speed is used to calculate a rotor tip speed. The average rain intensity is used to calculate a rain field as described in Ref. [9]; with drop size and falling velocity according to section 2.3. Equations (2) and (5) are then used to calculate the expected life for the kinetic energy model and the accumulated rain model, respectively. The damage increments are then calculated using the Palmgren-Miners sum.

\[ M = \sum \frac{n_i}{N_i} \]

Here, \( i \) is the load level number, \( n_i \) is the number of cycles at level \( i \), \( N_i \) is expected cycles to failure at level \( i \) based on test data, and \( j \) is the number of load levels. A damage increment is illustrated in Fig. 5 \( n_i \) impacts at a kinetic energy with an expected fatigue life of \( N_i \) impacts adds an incremental damage corresponding to \( n_i/N_i \). When using this model, it is assumed, that the impacted surface fails, when the sum of damage increments, \( M \), reaches 1.

When analyzing the erosion fatigue based on the time series, the erosion rate is calculated as the average yearly accumulated damage. The damage per rain amount is calculated as the erosion rate divided by the annual rainfall. The expected life is calculated as 1 divided by the erosion rate, which is equal to the expected time for the accumulated damage (according to equation (6)) to reach the value 1. Damage increments for each time step is limited to maximum 1, which in rare cases may be exceeded according to the model.

The results on the erosion rate, the damage per rain amount and the expected lifetime for a similar turbine at each of the eight weather stations using the kinetic energy model and the accumulated rain model are shown in section 3.
2.3. Erosion safe mode control

[9] suggest a method of decreasing the rate of erosion by decreasing the tip speed during rare heavy rain events. In the present work, this method is taken further by utilizing the concept of decreasing the tip speed during heavy rain in combination with:

- The historical rain and wind data analyzed in Section 2.1.
- The two damage models for estimating erosion rates presented in Section 2.2.
- The parameter sweep meant to visualize the influence of two driving parameters.
- An optimization algorithm meant to present the full potential of the considered method.

The two parameters governed by the parameter sweep and the optimization are:

- Rain threshold (mm/h) — the amount of rain at which the modelled turbine is switched from its default operation to the Erosion Safe Mode (ESM), i.e. the mode with reduced maximum tip speed.
- Tip speed limitation (m/s) — the value of maximum allowable tip speed when the turbine operates in the ESM during heavy rain.

The objective function in the optimization algorithm is the increase in the profit from the modelled turbine due to ESM relative to the version where no ESM is available. For each site, the turbine model is assumed to operate throughout the available time series of rain and wind data. The cost modelling follows the assumptions from Ref. [9]. The assumed values are as follows:

- 50 Euro/kWh — the price of electricity
- 20 000 Euro — the cost of repair of 3 blades
- 2 days — turbine downtime due to repair of 3 blades

2.3.1. Rain field

The drop sizes are not observed in the current data sets. For each rain intensity a homogenous drop size, $D_{50}$, is assumed. $D_{50}$ is a value of the drop diameter, $d$, such that 50% of the water in the atmosphere is comprised by drops with diameter less than $D_{50}$[14]. The falling velocities as a functions of drop sizes are calculated from a power function fitted to the data of [14].

2.3.2. Extrapolation of wind speeds to hub-height

The wind speeds and wind directions are observed at 10 m height above ground at the DMI weather stations. Local obstacles, surface roughness and terrain influence wind observations. Lee effect and speed-up vary as function of the wind direction at each local station. In this study, the wind speeds at turbine hub height at the sites are calculated as actual wind speed at 100 m using the WASP program [39]. Examples of the wind speed conversion factors from 10 m to 100 m for four sites are shown in Fig. 6.

2.3.3. Turbine characteristics

In the present study the calculations are based on the Vestas V52 850 kW pitch-regulated variable-speed wind turbine. The tip speed at rated rotational speed (RPM) is assumed to be 90 m/s and is thereby greater than the tip speed of an original Vestas V52 wind turbine but in line with many new turbines regarding the rated tip speed [9].

The wind turbine has a cut-in wind speed of 3 m/s, where the tip speed is 23 m/s. The tip speed increases linearly as a function of the wind speed up to wind speed of 11.5 m/s, where the rated rotational speed is reached, and the tip speed is 90 m/s.

The erosion safe mode results for the eight weather stations assuming a similar turbine in operation at each site are presented in Section 3.

3. Results

3.1. Rain and wind climate

Based on rain and wind speed observations from the eight weather stations the concurrent rain and wind climate statistics are quantified at each station. It is based on the quality control data as explained in Section 2.1.

The percentage of time a given rain intensity observed at a rain gauge is exceeded is calculated. This gives an overview of the percent of time all rain intensities occur at a specific site independent of wind speeds. The result for the five coastal stations is presented in Fig. 7a—e and for one inland station in Fig. 7f. The black dashed curves shows the rain intensity average yearly values independent of wind speed.

LEE occur mainly for high wind speeds concurrent with high rain intensity. Thus, the rain and wind climate is calculated for
several wind speed bins. The wind speed bins include very weak winds $0-3$ m/s, low winds $3-6$ m/s, moderate winds $6-9$ m/s, high winds $9-13$ m/s and very high winds larger than $13$ m/s. The wind speeds are observed at 10 m height above ground. In Fig. 7 the colored curves shows the percent of time the rain intensity is exceeded as function of the wind speed bin.

Interestingly, at all coastal stations heavy rain occur during conditions of very high wind speeds ($\geq 13$ m/s). In contrast, the inland station has no occurrences of heavy rain events during very high wind conditions (notice the red curves in Fig. 7).

Table 2 lists for the eight weather stations, the statistics on the rain and wind occurrences of exceedance intensities independent of wind speeds (the average yearly values). The occurrences of exceedance intensities for heavy and violent rain for high wind speeds ($\geq 9-13$ m/s) and very high wind speeds ($\geq 13$ m/s) are also listed in Table 2. It can be noted that violent rain at winds $\geq 13$ m/s does not occur at inland stations while coastal stations have these rain and wind conditions between 5 min and 16 min per year. Violent rain at winds $\geq 9-13$ m/s occur rarely or not at inland stations while coastal stations have 30–45 min average per year. Heavy rain at winds $\geq 9-13$ m/s occur at inland stations around 20 min per year while coastal stations have these rain and wind conditions around 2–4 h per year. In summary, clear differences in the rain and wind conditions are noted at the different weather stations.

The seasonal variation in the rain intensity and wind speed at Hvide Sande is shown in Fig. 8. In the spring there are no occurrences of high rainfall intensity during high wind speeds while in the autumn heavy rain frequently and violent rain occasionally occurs during high wind speeds. The seasonal data indicate during which time of the year LLE mainly takes place.

In summary, heavy rain occurs at all coastal stations during high wind conditions. In contrast, heavy rain rarely occurs during high wind conditions at inland stations. Please note that the winds are observed at 10 m height.

### 3.2. Erosion rate and lifetime

The model results on the erosion rate, the damage per rain amount and the expected life for the eight sites are listed in Table 3. The calculations are based on the methods described in Section 2.2.

The turbines at the coastal stations have an expected leading edge blade life in the range of 3 years. The turbines at the inland stations have an expected life of 3–13 years. A major difference between the two models results is for two of the inland stations, Aalborg and Karup, where the kinetic energy model estimates roughly three times longer life than the accumulated rain model.

#### 3.3. Erosion safe mode control

The ESM results based on the materials and methodology presented in Section 2.3 are presented below. Fig. 9 presents the profit due to ESM from the modelled modified Vestas V52 utilizing the cost model presented in Section 2.3 and the historical rain and wind time series from Hvide Sande. Model results of (a) the kinetic energy model and (b) the accumulated rain model are shown.

The kinetic energy model shows the maximum increase in profit of 3.1% at the precipitation threshold of 4.8 mm/h and the tip speed limitation of 42 m/s. The optimum is relatively flat in terms of the tip speed limitation but narrow in terms of the precipitation threshold.

The accumulated rain model shows the maximum increase in profit of 4.6% at the extremely low precipitation threshold of 0.1–0.5 mm/h and the tip speed limitation of 57 m/s. Note that the precipitation threshold of 0.1 mm/h is the lower bound of the study. The optimum is again relatively flat in terms of the tip speed limitation but narrow in terms of the precipitation threshold. In principle, the accumulated-rain results would dictate to trigger the ESM at any measurable rain event.

Sensitivity of the modelling with respect to the location is analyzed by optimizing the rain threshold and the maximum tip speed at all eight locations using both damage models. The Sequential Least Squares Programming (SLSQP) method is used to solve the optimization problem. The results are presented in Table 4.

Depending on the damage model and location, the modelled increase in profit due to ESM varies between 1.5 and 6.5%. The models do not generally show significant variation of optimal parameters depending on location.

In order to carry out a successful full-scale experimental validation of ESM on a turbine similar to the one modelled, and based exclusively on present results, one could decide to trigger ESM at 1 mm/h precipitation. This is for the following reasons. First, despite the differences between the models, Fig. 9 indicates that both models show relatively good results, i.e., increase in profit, at 1 mm/h precipitation and at tip speeds between 30 and 60 m/s. In such a case, a conservative approach could dictate to set the experimental limitation on the tip speed at 60 m/s, i.e., not to restrict it more than necessary. This idea is explored further by analyzing the eight weather station sites with both models and

![Fig. 6. Wind speed conversion factors from 10 m to 100 m height as function of wind direction at four weather station sites.](image-url)
Fig. 7. The graph shows the average yearly variation of percentage of time of exceedance of rain intensities (in mm/h) for five different wind speed intervals (0–3; 3–6; 6–9; 9–13; >13) (in m/s) and the yearly sum independent of wind speed for coastal weather stations. a) Anholt, b) Hvide Sande, c) Skagen, d) Thyborøn and e) Vindebæk and inland weather station f) Aalborg.

Table 2
Rain and wind climate values at the eight DMI weather stations from 2002 to 2018 for rain intensity violent (> 20 mm/h) and heavy (> 10 mm/h) for three wind speed bins showing the exceeded number of hours per year.

| Rain intensity | Wind speed (m/s) | Coastal stations | Inland stations |
|----------------|-----------------|------------------|----------------|
|                |                 | Anholt (hrs)     | Hvide Sande (hrs) | Skagen (hrs) | Thyborøn (hrs) | Vindebæk (hrs) | Aalborg (hrs) | Billund (hrs) | Karup (hrs) |
| Violent        | 0–9             | 1.99             | 1.93             | 1.64         | 2.15         | 2.47         | 1.38         | 0.44         | 1.05        |
|                | 9–13            | 0.46             | 0.39             | 0.57         | 0.45         | 0.35         | 0.02         | 0            | 0           |
|                | 13              | 0.07             | 0.16             | 0.12         | 0.05         | 0.07         | 0            | 0            | 0           |
| Heavy          | 0–9             | 7.32             | 8.08             | 7.45         | 11.32        | 8.24         | 8.08         | 2.58         | 5.05        |
|                | 9–13            | 1.93             | 2.33             | 2.56         | 2.9          | 1.53         | 0.35         | 0.16         | 0.12        |
|                | 13              | 0.51             | 0.92             | 0.54         | 1.54         | 0.34         | 0.03         | 0            | 0.03        |
respective parameter values of 1 mm/h and 60 m/s. The results are presented in Table 5.

Both damage models predicted an increase in profit at all sites due to ESM with the respective parameter values of 1 mm/h and 60 m/s. Depending on the model and the location, the modelled increase in profit spans between 0.9 and 6.5%. The average profit from the kinetic energy model is 2.0% and for the accumulated rain model 3.9%. To summarize the findings, it should be stressed that the two underlying engineering damage models have not yet been validated in a full-scale manner. The validation is intended as future work, and will hopefully shed light on some of the discrepancies between the two damage models.

4. Discussion

The rain intensity varies much between the coastal and inland stations in Denmark. Heavy and violent rain is found to be much more dominant at coastal stations than inland, in particular for high wind speeds. Comparing the results from the eight Danish weather stations with [40] best correspondence is found to the maritime temperate climate.

Denmark has prevailing westerly winds and the rain climate at the weather stations at the western coasts are expected to represent reasonably well offshore weather conditions, at least some kilometers offshore to where offshore wind farms are located in the Danish Seas. Verification of this assumption cannot be verified due to lack of offshore rain intensity observations.

[19] investigated rain erosion at the Horns Rev 2 wind farm located roughly 60 km southwest of Hvide Sande. They assume a median rain intensity of 0.7 mm/h at Horns Rev 2 based on a weather forecast model with no further explanation other than that the model matches the yearly average rainfall, under reports higher

Table 3

| Damage model          | Coastal stations                  | Inland stations                |
|-----------------------|-----------------------------------|--------------------------------|
| Erosion rate (year⁻¹) | Anholt, 0.35; Hvide Sande, 0.33 | Aalborg, 0.07; Billund, 0.08   |
|                       | Skagen, 0.28; Thyborøn, 0.28      | Karup, 0.12                    |
|                       | Vindebæk, 0.32                   |                                |
| Damage per rain amount (m⁻¹) | Kinetic energy, 0.75; | Aalborg, 0.23; Billund, 0.36 |
|                       | Accumulated, 0.57                 | Karup, 0.29                    |
|                       | Skagen, 0.46; Thyborøn, 0.42      |                                |
|                       | Vindebæk, 0.63                   |                                |
| Expected life (years) | Kinetic energy, 2.9;             | Aalborg, 13.6; Billund, 4.4   |
|                       | Accumulated, 3.0                  | Karup, 11.8                    |
|                       | Skagen, 3.6; Thyborøn, 3.5        |                                |
|                       | Vindebæk, 3.1                    |                                |

Fig. 8. The graph shows the seasonal variation of percentage of time of exceedance of rain intensities (in mm/h) for five different wind speed intervals (0–3; 3–6; 6–9; 9–13; >13) and the sum of all wind speeds (in m/s) for the coastal weather station Hvide Sande during: a) spring, b) summer, c) autumn and d) winter.
The analysis of extreme precipitation events over land in Denmark shows a positive trend, but it is not statistically significant. The accumulated rain model showed a maximum increase of 6.5%. Although both models indicate different optimal operational parameters, a common ground in terms of parameter values was found where both models indicate an increase in profit at all sites. Note that although [5] suggest to improve coatings instead of applying erosion safe mode, they also state that maintenance-free coatings are not available. On top of that, it is rather safe to assume that especially offshore turbines will increase in size and tip-speed in the coming years, making LEE an even bigger issue than it is already. This, together with the present results, indicates that advances should be made in smart turbine operation and in durable coatings.

The LEE of wind turbine blades at Danish offshore sites may be more severe in the future climate with more heavy precipitation. The analysis of extreme precipitation events over land in Denmark shows a positive trend, but it is not statistically significant compared with the uncertainties of the regional estimation model.

Both of the two engineering damage models used in the present work indicates that slowing down the turbine during rain events may increase the profit by providing a beneficiary trade-off between temporary decreases in energy production during the aforementioned events, and the improved blade condition leading to improved overall energy production and reduced cost of repair. Depending on the site, the kinetic energy model showed a maximum increase in profit relative to not using the ESM of 4.3%. The accumulated rain model showed a maximum increase of 6.5%. Although both models indicate different optimal operational parameters, a common ground in terms of parameter values was found where both models indicate an increase in profit at all sites. Note that although [5] suggest to improve coatings instead of applying erosion safe mode, they also state that maintenance-free coatings are not available. On top of that, it is rather safe to assume that especially offshore turbines will increase in size and tip-speed in the coming years, making LEE an even bigger issue than it is already. This, together with the present results, indicates that advances should be made in smart turbine operation and in durable coatings.

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Table 4
Increase in profit from the modelled modified Vestas V52 at the eight sites resulting from an optimization of the rain threshold and maximum tip speed in the Erosion Safe Mode (ESM) for the kinetic energy model and accumulated rain model.

| Damage model | Coastal stations | Inland stations |
|--------------|------------------|-----------------|
|              | Anholt | Hvide | Skagen | Thyborøn | Vindebak | Aalborg | Billund | Karup |
| Rain threshold [mm/h] | Kinetic energy | 4.8 | 4.8 | 4.2 | 4.2 | 5.0 | 5.4 | 4.8 | 5.8 |
| Maximum tip speed [m/s] | Kinetic energy | 43 | 42 | 44 | 47 | 30 | 48 | 44 | 44 |
| Increase in profit [%] | Kinetic energy | 3.1 | 3.1 | 2.7 | 2.3 | 4.2 | 1.5 | 4.3 | 2.0 |
| Accumulated | 3.6 | 4.6 | 4.0 | 5.0 | 4.2 | 4.2 | 6.5 | 6.0 |
The increase in rain maximum intensity was of the order of 10% from the 1990’s to 2005 [44]. There appears to be a cyclic pattern on long-term variation in extreme rainfall with cyclic periods around 25–35 years observed during more than 100 years [45]. According to the IPCC 5th report [46] indicates increasing precipitation in Denmark. The expected annual average precipitation in year 2050 is of the order 7% ±3% uncertainty) higher compared to present time, and one more day per year with rain above 20 mm/day and three more days with rain above 10 mm/day.

The perspectives for verifying the erosion rate and lifetime in the field will be performed in case relevant data become available. According to Ref. [47] the predicted initiation of erosion along the blade using a model and the initiation of erosion observed in the field at the blades are in agreement.

Testing of the ESM will depend on real-time input of rain and wind information, further insight to the damage models, the turbine types and the leading edge characteristics. For demonstration, a non-conservative approach is suggested to quickly achieve statistically valid results while for future operation a conservative approach optimized for the overall lifetime is envisioned. There is need to study rain erosion more realistically through the design of the rain erosion test device, understand the relationship between the rain characteristics in the atmosphere and in the test environment, e.g. study the acidity of rain [48].

New Wöhler curves both for the onset of erosion (e.g. first pinhole noticed) as well as the time when aerodynamic performance is significantly affected (e.g. an area is eroded) are expected from on-going work using rain erosion testing. Analysis of rain and wind data at sites across the world is on-going which will provide more detailed understanding of the risk of rain erosion in other geographies than Denmark. The rainfall exceedance curves presented by Ref. [40] indicate major differences in rain intensity across the globe. Ref. [5] point to the monsoon climate in South East Asia that may cause high erosion.

Some types of rain gauges systematically record less precipitation, in particular for solid precipitation but also low intensity liquid precipitation in windy conditions. Wind-induced bias correction may be relevant for the accumulated rain model that include low intensity rain in the erosion process.

Finally, a methodology to extrapolate rain and wind climate from specific measurement sites, as demonstrated in the current study, to areas of interest such as nearby offshore wind farms is in progress. The methodology is based on the measure-correlate-predict method combined with rain climate assumptions.

5. Conclusion

The study on the rain and wind climate relevant for predicting the risk of leading edge erosion and the relative profit of using erosion safe mode control is presented at eight sites in Denmark including five coastal and three inland sites.

The rain and wind climate differ between coastal and inland stations with much more heavy and violent rain at the coastal stations than at the inland stations, in particular during high wind speed events. Violent rain (i.e. above 20 mm/h) during wind conditions above 9 m/s occur around half an hour each year at all coastal stations but nearly never at inland stations. Heavy rain (i.e. above 10 mm and below 20 mm/h) occur less than 45 min at inland stations but between 2 and 5 h each year on average at coastal stations for wind speeds above 9 m/s. The coastal climate is expected to represent the offshore climate but this cannot be verified as rain data are not available offshore.

Two damage models, the kinetic energy model and the accumulated rain model are presented. Both are applied in the modelling of hypothetical similar wind turbines located at the eight weather stations.

The kinetic energy model is more sensitive to high intensity rain events and shows a clear difference in the erosion rate and expected lifetime between modelling of five coastal turbines versus two inland turbines. The two inland turbines have four times longer expected life than the coastal turbines. The third inland turbine (in Billund) with high annual rain has similar expected lifetime as the coastal turbines.

The accumulated rain model is more sensitive to low intensity rain events and shows similar erosion rate and expected turbine lifetime at all eight sites. The model does not show site-dependent results.

The modelled increase in profit due to the erosion safe mode, averaged over both of the two engineering damage models at the eight sites, is equal to 3.9%. The kinetic energy model indicates an average increase in profit of 2.8% whereas the accumulated rain model gives 4.8%.

No conclusion to which of the two damage models is more accurate can be given. It is however, expected to depend on the leading edge material properties. On-going rain erosion testing in the laboratory to establish new Wöhler curves may give answers. Meanwhile, testing the erosion safe mode in the field is in planning in order to verify that the erosion safe mode can extend lifetime and be profitable for the turbine owners.

Author contributions

C. Hasager: Develop idea for data analysis, secure funding, manage project and write. F. Vejen: Analyse the meteorological data and write. J. I. Bech: Foster the erosion safe mode concept and analyse damage models and write. W. R. Skrzypinski: Calculate optimization of erosion safe mode and write. A.-M. Tilg: Write, discuss and edit on meteorology. M. Nielsen: Analyse wind data, discuss and write.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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