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Methodology for the energetic characterisation of rain erosion on wind turbine blades using meteorological data: A case study for The Netherlands

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Abstract

Rain erosion on the leading edge of wind turbine blades is an intricate engineering challenge for the wind industry. Based on an energetic approach, this work proposes a methodology to characterise the erosion capacity of the raindrop impacts onto the leading edge blades. This methodology can be used with meteorological data from public institutions or from direct measurements at the wind turbine locations. The erosion characterisation is analysed using accumulative and per impact erosive variables, that is, total kinetic energy and kinetic energy per impact. To consider the frequency of impacts, two erosive variables are proposed, namely, total kinetic power and kinetic power per impact. These variables are calculated using the data from the Royal Netherlands Meteorological Institute (*Koninklijk Nederlands Meteorologisch Instituut*, KNMI) of the last 25 years jointly with the operation specifications of an actual wind turbine model (Suzlon S111). The main contribution to the erosive variables was found to be the wind speed because it controls the rotational velocity of the wind turbine. Also, the intensity of the rainfall and the frequency of meteorological data logging, that is, the temporal resolution of data, play a significant role.

KEYWORDS

erosion, kinetic energy, leading edge, rain impact, wind energy

1 | INTRODUCTION

Since the 20th century, the use of wind as a sustainable energy source has been increasingly utilised due to the low to null pollution emissions during the conversion in the wind turbines of the kinetic energy from the wind into electrical power. During the last two decades, in order to develop the wind energy industry, the power capacity of the wind turbines has increased notably led by research and innovation. At the beginning of this century, a wind power capacity of 12.9 GW had been installed in the European Union; however, this power capacity had increased to 192 GW in 2019, being installed 13.2 GW power in 2019 alone.[1] This growth has been attained due to the enlargement of the wind turbines, mainly of the blade rotor diameter. Nevertheless, this augmentation in the diameter also entails a rise in the tangential speed of the blade tip and therefore, at the same time, the increase in the erosion on the blade leading edge.[2] For the wind energy industry, this erosive damage boosts the operation and maintenance (O&M) costs, which might easily become approximately 20%–25% of total levelised cost per kilowatt produced over the lifetime of the wind turbine.[3] For example, on average, a blade repair can cost up to $30,000 and the cost of a new blade around $200,000.[4]

Erosion is defined as the progressive material loss from a solid surface due to repeated impacts of solid or fluid particles. Unlike wear, in erosion, there is a fluid contribution to the mechanical phenomenon that is producing the material loss.[5] Semi-empirical models are the logical approach to investigate the erosion due to an erosion theory from basic laws is difficult to derive.[6] Therefore, the access to quality experimental works becomes essential to comprehend and to study the erosion on the wind turbine blade surface. Consequently, the design and development of experimental facilities have played a significant role in erosion research.

Erosion occurs on the leading edge of wind turbine blades mainly on the blade tip area that has been in operation because of various environmental conditions, such as the type of precipitation, being onshore or offshore, wind and gusts, humidity, etc. Raindrops, hailstones,[7] sand[8] and other atmospheric particles impacting wind turbine blades rotating at high speeds are the primary cause of surface erosion on the leading edges. The erosion capacity of the raindrop impacts is thus mainly determined by the impact velocity of the erosive particles, the type of impinging particles, the frequency of impacts, etc. These impacts start modifying the surface roughness, then changing the shape, that is, the aerodynamic profile, of the leading edge and in the end damaging the structural integrity of the blade material. Among all the causes of erosion on the leading edge of the wind turbine blades, rain is one of the most important because it causes erosion since the first moment the wind turbines start working, for example, Wood[9] found that, although the blades are expected to run more than 20 years, rain erosion can occur after only 2 years of operation.

Therefore rain, and more specifically, the amount of rain water, that is, the rain load, in each rainfall event, is interesting to experimental research, and many works can be found in the literature to handle rain data,[10,11] but rain is a natural phenomenon which is complex to simulate due to its stochastic nature. This complexity is derived from several factors, the most important being size, shape and velocity of the raindrops.[12] Apart from this complexity in simulating rain itself, the modelling of the rain as an erosive phenomenon is still lacking the proper solutions, although works as those carried out by Amirzadeh et al[13,14] have contributed to shed light on this issue. The works to develop these models of rain as an erosive phenomenon have been carried out mainly using two distinctly different approaches, that is, the approaches have been considering either the impact force[15] or the kinetic energy transmitted.[16]

This work focuses on the energetic approach which is based on the transmitted kinetic energy by the raindrop impacts onto the leading edge and this approach is the first step to relate erosion to mechanical properties of the impacted body. Nevertheless, the difficulty lies in quantifying the total transferred energy to the bulk of the body through the surface since not all the impact energy is transferred throughout the solid surface, for example, some part of this energy would be transformed in heat. Moreover, all the transferred energy to the inside body is not transformed into fatigue energy which is the main source of the erosion damage, for example, some of the transferred energy creates shockwaves during impact. Although this energetic-based approach has been explored in other cases,[17,18] the studies using actual data and operational conditions of the wind turbines are lacking in the scientific literature.

The aim of this paper is to define a methodology to characterise the erosion capacity, that is, the potential capacity of the raindrop impacts in creating fatigue damage on the blade surface. This methodology is very versatile because it only needs the data of rain volume, rain time, that is, the actual length of the rain events during the temporal resolution, and wind speed; therefore, it can be used with meteorological data from public institutions or directly measured at the wind turbine locations. Apart from the kinetic energy and the kinetic energy per impact, this work proposes novelty the kinetic power as a variable to analyse the rain erosion on a wind turbine blade at a specific location. These variables are then calculated for different stations in The Netherlands using actual meteorological data of the last 25 years for the wind turbine model S111 of Suzlon. Moreover, parameters such as rain type as well as the data log time and the period of data collection have been studied. This analysis and the data on the erosive variables also are useful for the wind industry to which it will provide practical information about erosion capacity of the rainfall. Moreover, they will be useful to decide what meteorological data need to be measured in-field and at which frequency the data needs to be collected for rain erosion prediction of a specific wind farm, that is, the temporal resolution of the data.

2 | MATERIALS AND METHODS

First, the proposed methodology to characterise the rain erosion on the wind turbine blades will be described. This methodology would be useful to set up investigations both experimentally, for example, to design erosion test facilities or to define the experimental conditions in leading edge protection lifetime tests, and numerically, for example, to determine the parameters of the rain impact simulations. Furthermore, the meteorological data and the wind turbine specifications used in the study to obtain the results are detailed in the last two sections. In general, a rain event is considered when it rains during the discretized time of the meteorological data, but it does not necessary rain all this discretized time. For example, if a meteorological data is 1-day discretised, a rain event is considered when it rains during sometime of that day.

2.1 | Methodology to characterise rain erosion

This methodology works with three meteorological data sets; rain volume, rain time and wind speed. From this data, the rain intensity I can be calculated dividing the total rain volume per surface by the rain time. Using the rain intensity, the raindrop diameter with the highest probability density during rain fall is obtained by means of a size distribution of raindrops. In literature, these size distributions are represented by different forms,[19] for example, exponential,[20] logarithmic[21] or non-parametric[22] forms. To calculate raindrop size distributions for onshore wind turbines, typically Best's exponential[20] form is used. Best's raindrop distribution is also used in this study. Finally, the terminal velocity of a falling raindrop is obtained from the measurements of the free fall velocity of varying water drop sizes through stagnant air carried out by Gunn and Kinzer,[23] as they are shown in Figure 1.

The kinetic energy of a single raindrop impact e_k depends on the raindrop mass m_d and the impact velocity v_i as follows:

$$e_k = \frac{1}{2} m_d v_i^2. \tag{1}$$

In the context of wind turbine erosion, the impact velocity can be determined through velocity vector calculations of three components, namely, the blade velocity v_b, the wind speed v_w and the terminal velocity of the raindrop v_d. The blade velocity component is variable in the direction which depends on the angle of the blade position θ being $\theta = 0$ at the half of the downward direction (see Figure 2). The terminal velocity component of the raindrop is perpendicular to the ground. And finally, assuming that the raindrops are fully entrained in a horizontal wind, that is, the raindrops are shifted horizontally along with the wind, the component of wind speed is parallel to the ground (Figure 2). Therefore, to cover the full rotor sweep, the impact velocity depending on the blade the rotation angle θ can be written[7]:

$$v_i = \sqrt{(v_b + v_d \cos\theta)^2 + (v_d \sin\theta)^2 + {v_w}^2}. \tag{2}$$

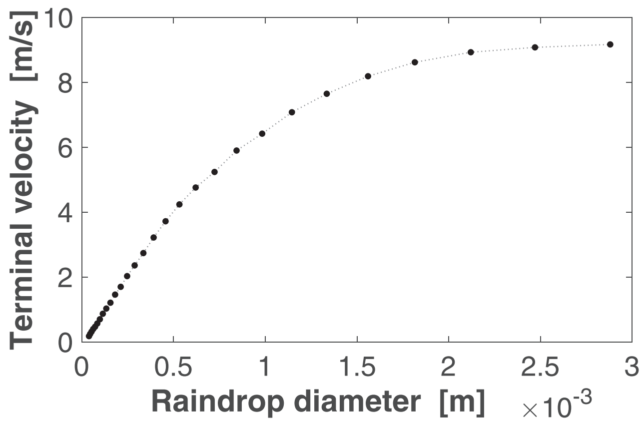

FIGURE 1 Terminal velocity of raindrops depending on the raindrop diameter

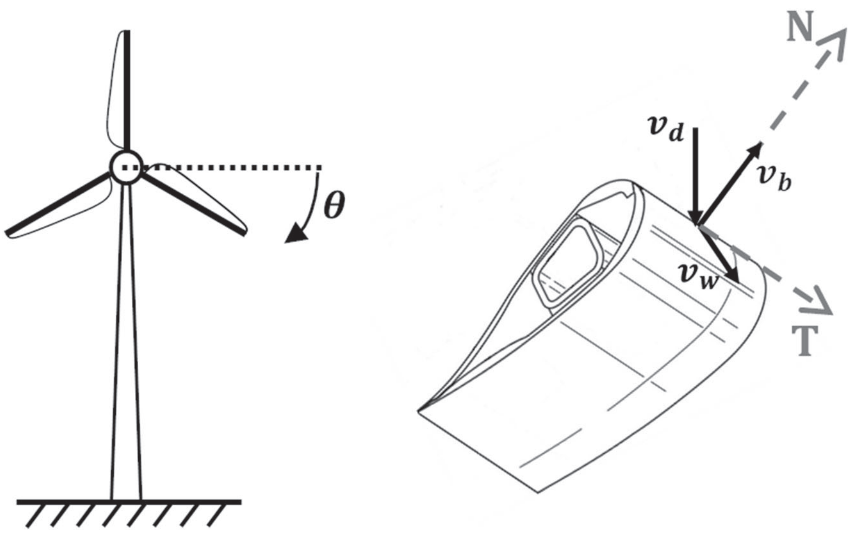

FIGURE 2 Schematic references for the blade rotation angle and the impact velocity components on the leading edge

As the wind turbine blades are rotating, the average squared impact velocity during a full rotation cycle, that is, the blade going from $\theta = 0$ to $\theta = 2\pi$, is

$$\bar{v}_i^2 = \frac{1}{2\pi}\int_0^{2\pi}\left[(v_b + v_d\cos\theta)^2 + (v_d\sin\theta)^2 + {v_w}^2\right]d\theta = {v_b}^2 + {v_d}^2 + {v_w}^2. \tag{3}$$

Therefore, and following the calculations for impacts from DNV GL,[24] the kinetic energy per impact on average for a rain event can be expressed as

$$\bar{e}_k = \frac{1}{2}V^d\rho_w\bar{v}_i^2 = \frac{4\pi}{6}R^3\rho_w\left({v_b}^2 + {v_d}^2 + {v_w}^2\right), \tag{4}$$

where V^d is the raindrop volume during the rain event assuming a spherical drop, ρ_w is the water density (approximately 1,000 kg/m^3) and R is the raindrop radius.

To calculate the kinetic energy E_k of a rain event, firstly, the number of impacts N per surface area of the blade leading edge needs to be calculated. Consequently, defining the specific volume V_e of rain water as the rain intensity I divided by the terminal velocity of the raindrops v_d, the number of raindrops D in a volume of rainfall is given by

$$D = \frac{V_e}{V^d} = \frac{I}{V^d v_d}. \tag{5}$$

As the rain is a stochastic phenomenon, the raindrops can be assumed as uniformly distributed in space and additionally as the terminal velocity v_d is low compared to the blade velocity v_b, thus the impact frequency F, that is, the number of raindrops per unit projected area of the leading edge per time, of the travelling blade through the rainfall can be written as

$$F = Dv_b = \frac{Iv_b}{V^d v_d}. \tag{6}$$

Finally, defining V^t as the volume of rain per surface during the rain event, the number of impacts N per leading edge projected area is calculated multiplying by the rain time t:

$$N = Ft = \frac{Iv_b t}{V^d v_d} = \frac{V^t}{V^d}\frac{v_b}{v_d}. \tag{7}$$

Therefore, during a rain event, the kinetic energy E_k on the leading edge surface due to the impingement raindrops can be calculated:

$$E_k = \sum\nolimits_{i=1}^{N}\bar{e}_k = \sum\nolimits_{i=1}^{N}V^d\rho_w\bar{v}_i^2 = \frac{1}{2}V^t\rho_w\frac{v_b}{v_d}\left({v_b}^2 + {v_d}^2 + {v_w}^2\right). \tag{8}$$

The kinetic energy per impact (Equation 4) and the kinetic energy (Equation 8) are the main parameters to predict the damage by erosion in models with an impact-energetic approach[17] or accumulated rain-energetic approach.[14] The impact-energetic approaches are sensitive to rain events of high intensity and the accumulated rain-energetic approaches to low intensity rain events, as it is found recently by Hasager et al.[25] It is not clear yet which approach is more appropriate to simulate the erosion damage. Also, these models are not considering time, that is, frequency of the impingement raindrops, which is an important factor in rain erosion testings[26] (RETs) and in the mechanical behaviour of viscoelastic materials.[27] Therefore, this work proposes two variables, namely, kinetic power and kinetic power per impact, as erosive parameters. The kinetic power P_k for a rain event is defined as

$$P_k = \bar{e}_k F = \frac{1}{2}I\rho_w\frac{v_b}{v_d}\left({v_b}^2 + {v_d}^2 + {v_w}^2\right). \tag{9}$$

And the kinetic power per impact p_k is defined as follows:

$$p_k = \frac{P_k}{N} = \frac{1}{2}\rho_w \frac{V^d}{t}\left(v_b{}^2 + v_d{}^2 + v_w{}^2\right). \tag{10}$$

As it can be seen, these variables P_k and p_k depend on the frequency of the impingement raindrops (see Equation 6). Therefore, they are dependent on how the kinetic energy is distributed in space and time. Figure 3 shows how different the probability density distribution of the rain events can be depending on the erosive variable, for example, a smooth distribution of kinetic energy compared with a more random distribution of the kinetic power. Moreover, we think these variables could provide the needed link to translate the results from accelerated experimental tests to the real operating conditions of wind turbines since time is included.

2.2 | Meteorological data

The erosive variables, that is, kinetic energy E_k (Equation 8), kinetic power P_k (Equation 9), the kinetic energy per impact e_k (Equation 4) and kinetic power per impact p_k (Equation 10), were calculated using meteorological data from the Royal Netherlands Meteorological Institute (*Koninklijk Nederlands Meteorologisch Instituut*, KNMI) of the last 25 years (since 1994 until 2018).[28] Specifically, the meteorological parameters were the total volume of rain per square meter, the rain time and the average of the wind speed observed at different weather stations every hour giving a total of 219,144 values for each of these parameters. It is important to note that, during a rain event, the minimum reported rain volume per hour was 0.05 L/m^2 and the wind speed was measured using an anemometer at 10 m or higher to ensure measurements in open area.

The resolution of these 1-h discretized data was 0.1 L/m^2 for the rain volume, 0.1 h (360 s) for the rain time and 0.1 m/s for the wind speed. These measurement resolutions of meteorological data are used to obtain the mean squared of the energetic calculations errors through the results unless otherwise stated.

2.3 | Wind turbine specifications

The model S111 of SUZLON[29] wind turbine has been considered for all the following calculations. This model with 111.8 m diameter is a variable-speed wind turbine, that is, the rotational velocity depends on the wind speed. The rotational velocity increases linearly as a function of the wind speed from a cut-in wind speed of 3 m/s up to a wind speed of 11.5 m/s where the rated speed is reached resulting in a tip velocity of 76 m/s. The cut-out wind speed is 21 m/s.

3 | RESULTS AND DISCUSSION

Table 1 summarizes the results of the erosive variables depending on the effect of impact velocity contributions (see Equation 3) for the SUZLON S111 blade tip in the station of Rotterdam (The Netherlands) for 25 years (1994–2018). The first column sums up obtained values for the erosive variables taking into account all the impact velocity contributions, that is, blade velocity, wind speed and terminal velocity. The second columns present the values if only the contributions of the blade velocity and the wind speed are considered for the calculus and third column if only the contribution of the blade velocity is considered.

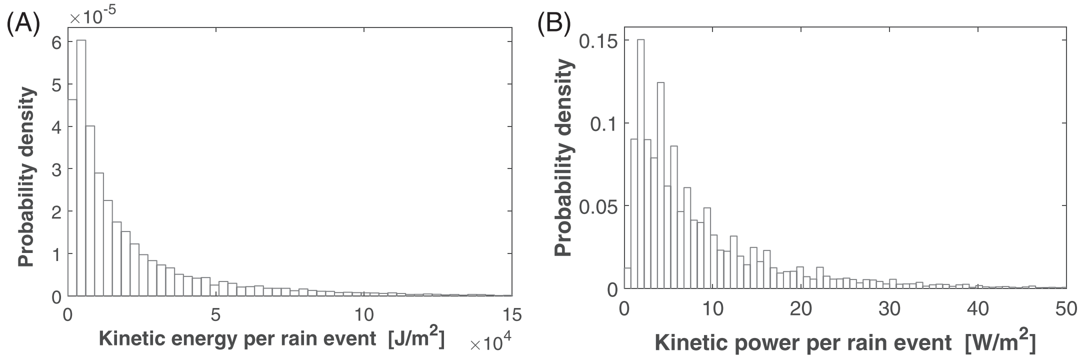

FIGURE 3 (A) Kinetic energy and (B) kinetic power distributions of the rain events in Rotterdam for 25 years

	Total (b + w + d)	No terminal velocity (b + w)	Only blade velocity (b)
E_k [J/m^2]$\cdot10^6$	492.6 ± 0.6	490.0 ± 0.6	483.1 ± 0.5
P_k [W/m^2]$\cdot10^3$	211 ± 1	210 ± 1	207 ± 1
$\bar{e}_k$ [J/impact]$\cdot10^{-3}$	1.06 ± 0.01	1.05 ± 0.01	1.04 ± 0.01
$\bar{p}_k$ [W/impact]$\cdot10^{-7}$	7.35 ± 0.03	7.31 ± 0.02	7.22 ± 0.02

TABLE 1 Calculated values of the erosive variables depending on the different velocity contributions (b for blade, w for wind and d for raindrop) for the operating range of the wind turbine SUZLON S111 in Rotterdam station for the last 25 years (1994–2018)

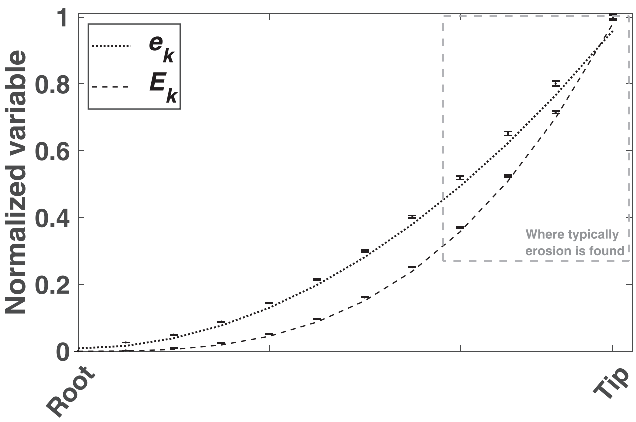

FIGURE 4 The normalized total kinetic energy and kinetic energy per impact depending on the distance from the blade root

3.1 | Contribution of the velocities

From these results, it can be established that the blade velocity plays the major role in the value of the three erosive parameters mainly due to the terminal velocities (limited around 9 m/s, see Figure 1) and the wind speeds (between 3 and 21 m/s) being lower than the blade tip velocities (ranging from 48 to 76 m/s) for the S111 model. These can be extrapolated to other wind turbine models especially with higher diameter. Therefore, the impact velocity can be approximated to only the tip blade velocity without introducing a high error, in this case up to 2%.

Although the fact that the blade velocity is dominant over the other impact velocity contributions may be well known, one should bear in mind that the calculations of the erosive variables require wind speed and terminal velocity data. For example, the wind speed controls the rotational speed of the rotor and hence the blade tip velocity in operation. Thus, although the direct effect of the wind speed is negligible in the impact velocity determination, the wind speed strongly affects their values through the blade velocity. And, although the terminal velocity of the raindrops can be neglected for calculation of the impact velocity, the erosive variables E_k and P_k depend on the terminal velocity of the drops (see Equation 8–9). The results suggest that all higher order terms of v_d can be neglected in Equation 5–10. Moreover, the rain data itself are essential in the calculation of the erosive variables as there is rain erosion only when it rains.

3.2 | Erosive behaviour along the blade length

Figure 4 shows how the erosive variables change along the blade length. The total kinetic energy E_k presents a cubic relationship with the distance from the root blade while the relationship is quadratic for the kinetic energy per impact e_k. It is well known that the rain erosion of the blade is mainly present at the tip with almost no erosion damage along the rest of the blade length,[7] which could partially be explained by this two exponential behaviours. But interestingly, as the erosion damage is not found distributed along the whole blade length in 'real-life', these results could also indicate that there might be a threshold below which the erosion capacity is negligible, that is, the impact does not drive enough energy to cause erosion damage. This fact has been observed in several investigations,[30,31] and this erosion behaviour along the blade length for wind turbines should be considered in the ongoing studies for erosion on the blade leading edge.[32] More specifically, the erosion behaviour shifts along the blade length need to be studied more deeply with measurements of the erosion of wind turbine blades in operation.

3.3 | Log time of meteorological data

The meteorological data from the KNMI are registered each hour but this logging capability of data is not always possible especially for wind turbines at remote locations, for example, offshore wind farms. Therefore, to investigate the effect of the log rate on the erosive variables, log times of 6 h, 1 day and 1 year were studied. In order to calculate the erosive variables at different log times, the accumulative rain volume, the accumulative rain time and the average wind speed are considered for the different log times.

Figure 5 shows how the log rate of meteorological data affects both the accumulative total kinetic energy E_k and the kinetic energy per impact e_k. The results show a slight decrease in these erosive variables for the log times of 6 h and 1 day, around 1% and 6%–8% respectively, comparing to the results of 1-h log time. However, the reduction is significant for 1-year log time, 40% for the total kinetic energy and 29% for the kinetic energy per impact. Therefore, the accumulative erosive variables as total kinetic energy seem more sensitive to the log times. This significant decrease in the values of the erosive variables for the 1-year log time is mainly due to the use of the average wind speed for this log time since average values for long times do not allow to capture the large variability in wind speed.

To monitor and prevent the rain erosion on the leading edge blade by the wind industry, the log rate of meteorological data should be as high as possible to obtain more accurate values of the erosive variables. But, in view of the results, the log times of 1 day or shorter do not present significant differences between them and also expecting that, especially in areas with low weather variation in very short times, shorter log times than 1 h would not show a high gap in the erosive-variable results. Therefore, for remote locations or/and with complicated communication where logging of data can be very demanding, in view of these results, a recommendation of daily data log could be enough to characterise the erosion capacity of the rain in a wind turbine location.

3.4 | Types of rain by intensity

The rain is typically classified depending on its intensity. Therefore, an analysis on how the erosive variables are affected depending on the rain intensity was carried out following the classification of the United Kingdom's national weather agency (Met Office).[33] This classification establishes that light rain is up to 2 mm/h, moderate rain between 2 and 10 mm/h, heavy rain between 10 and 25 mm/h, very heavy rain between 25 and 50 mm/h and violent rain is at intensities higher than 50 mm/h.

Figure 6A shows how the different types of rain by intensity contribute to the total kinetic energy. The main contributions are due to the light rain (57%) and moderate rain (39%). The other three types of rain, heavy, very heavy and violent, add around 3.5%, 0.4% and 0.02%, respectively, being less than the 4% of the total. Bearing in mind that, during the last 25 years in Rotterdam, there were 18,965 light rain events, 3,475

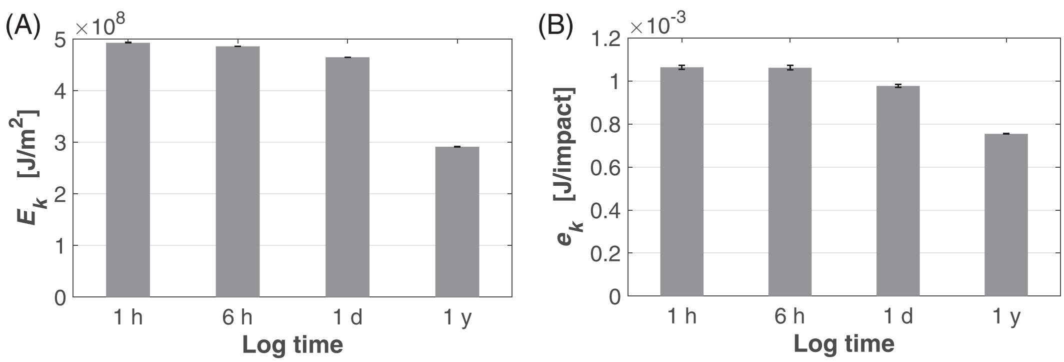

FIGURE 5 (A) Total kinetic energy and (B) kinetic energy per impact using different log times in Rotterdam for 25 years (1994–2018)

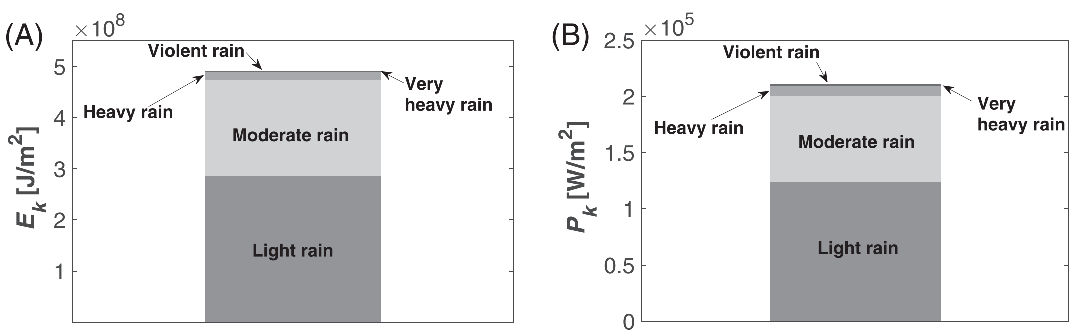

FIGURE 6 (A) Contributions of the rain types to the kinetic energy and (B) kinetic power depending on the rain type in Rotterdam for 25 years

moderate rain events, 149 heavy rain vents, 17 very heavy rain events and only 1 violent rain event. It can be noted that the moderate rain events contribute almost equally to the total kinetic energy as the light rain events, although the number of moderate rain events is less than a quarter of the light rain events. Figure 6B shows similar results but, in this case, at high intensities, that is, heavy, very heavy and violent rains, the contributions to the total kinetic power add up to almost 6%.

Figure 7A shows how the kinetic energy per impact rises sharply as rain intensity increases, especially at high intensities, for example, the kinetic energy per impact is double the average value for moderate rains but around 5, 9 and 15 times for heavy, very heavy and violent rains, respectively. Otherwise, the kinetic power per impact, see Figure 7B, presents sharper rises with 7 (heavy), 19 (very heavy) and 60 (violent) times the average value.

Comparing the results for the kinetic energy (Figure 6A) and the kinetic energy per impact (Figure 7A), it can be found why the accumulative variable E_k is more sensitive to low intensity rain events and the variable per impact e_k is greatly affected by high rain intensities. Therefore, we believe that both variables will be needed to develop erosion models where more experimental research is necessary and would likely depend on the leading edge material properties.

The knowledge gained from the results of the erosive variables, especially the per impact variables, shown in Figures 6 and 7 can help in designing and developing control strategies for wind turbine operations to limit erosion during rainfalls. For example, to reduce the kinetic energy per impact, the speed of the rotor can be reduced. To achieve a kinetic energy per impact similar to the average of the total rain, around 1.06 J/impact (see Table 1), the speed of the rotor needs to be reduced by 33% in the moderate rain events, 58% during the heavy rain events, 71% for the very heavy events and 83% for the violent rain events. If the kinetic power per impact is taken into account, the reduction should be 28%, 64%, 83% and 96% (almost a complete stop), respectively. Therefore, in the case of Rotterdam, using kinetic power per impact as reference parameter, the rotor velocity needs to be reduced less at moderate rains than when using kinetic energy per impact. At high rain intensities (≥heavy), the reductions in rotor velocity need to be quite large for kinetic power per impact. To understand which parameter should be used in control strategies, specific experimental studies of erosion are required.

3.5 | Locations throughout The Netherlands

All previous results of the erosive variables, as it was pointed out before, were calculated for the meteorological station of Rotterdam (station number 344). In this section, the change in erosive variables depending on the location has been studied. As The Netherlands is not a complex country orographically, three stations were selected to cover the north (Eelde), the east (Twenthe) and the south (Maastricht) with Rotterdam in the west. As no offshore data are available, three additional stations were selected close to the coast to analyse the possible effect for offshore wind turbines, these stations are Lauwersoog in the Wadden Sea, Vlissingen in the Rhine Delta and De Kooy in the North Sea. Figure 8 gives the exact location of the different KNMI stations.

Figure 9 shows the results of the total kinetic energy and total kinetic power for the different locations in The Netherlands. This results show that these variables are higher on average for the coast locations. A similar result, for Denmark, has been found by Hasager et al.[25]

As the differences in rain are not significant in a flat country like The Netherlands, the main factor for this increase in the kinetic energy of the coast locations should be due to the higher wind speeds on the coast, bearing in mind that only seven stations are analysed. From the Table 2, the difference, that is, comparing the maximum and minimum values, in rain time and in average rain intensity among the different locations is around 15% and 9%, respectively, but amount to 55% in the average wind speed.

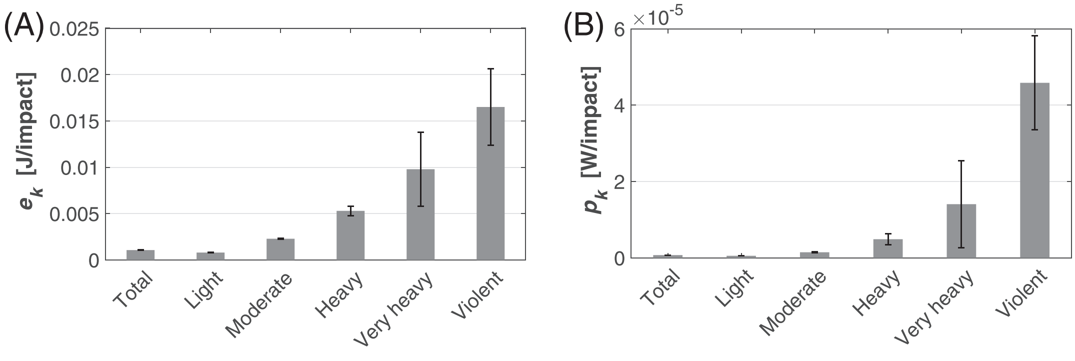

FIGURE 7 (A) Contributions of the rain types to the kinetic energy per impact and (B) kinetic power per impact depending on the rain type in Rotterdam for 25 years (mean squared error in error bar)

FIGURE 8 Meteorological stations with their numbers of the KNMI throughout The Netherlands used in this work

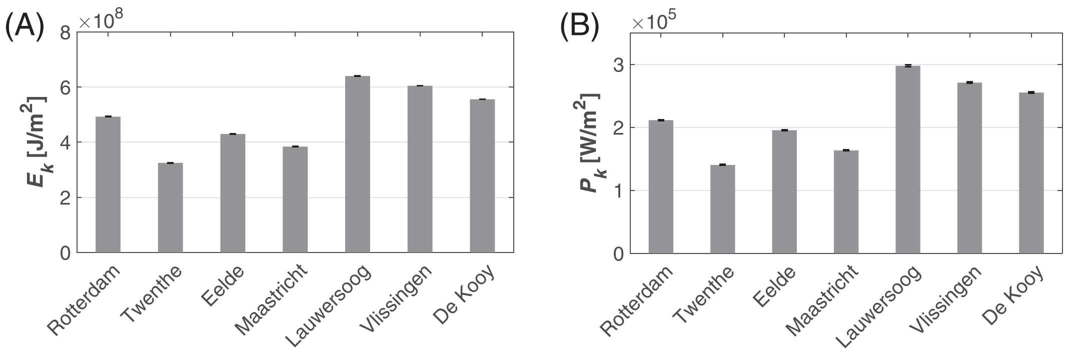

FIGURE 9 (A) Total kinetic energy and (B) total kinetic power in different locations of The Netherlands for the last 25 years (1994–2018)

The kinetic energy per impact (Figure 10A) and the kinetic power per impact (Figure 10B) also show higher values in the coast locations, but less marked than the accumulative variables. Another difference between accumulative and per impact variables is that the station of Vlissingen has the highest values for the variables per impact while the highest values of accumulative variables are found in Lauwersoog. This fact shows why both types of erosive variables need to be considered to characterise the erosion capacity because it is not clear which type implies a higher erosion capacity, for instance higher total kinetic energy or higher kinetic energy per impact. This fact needs to be studied by field measurements, especially in situ measurements in wind farm locations.

Finally, even in a country with a plain orography like The Netherlands, which is practically flat, relatively high differences in the values of the erosive variables were found. Therefore, as stated before, the rain impact measurements in the wind turbine locations would be beneficial for the

	Avg. wind speed [m/s]	Total rain time [h]	Avg. rain intensity [mm/h]
Rotterdam	6.30 ± 0.02	14,315 ± 15	1.35 ± 0.01
Twenthe	5.30 ± 0.02	13,620 ± 10	1.24 ± 0.01
Eelde	6.02 ± 0.02	14,935 ± 15	1.25 ± 0.01
Maastricht	5.87 ± 0.02	13,980 ± 10	1.23 ± 0.01
Lauwersoog	8.08 ± 0.02	15,920 ± 20	1.21 ± 0.01
Vlissingen	8.22 ± 0.02	14,165 ± 15	1.32 ± 0.01
De Kooy	7.44 ± 0.02	14,275 ± 15	1.28 ± 0.01

TABLE 2 Meteorological data with mean squared error in different locations throughout The Netherlands during the operating range (cut-in v_w = 3 m/s and cut-out v_w = 21 m/s) for the last 25 years (1994–2018)

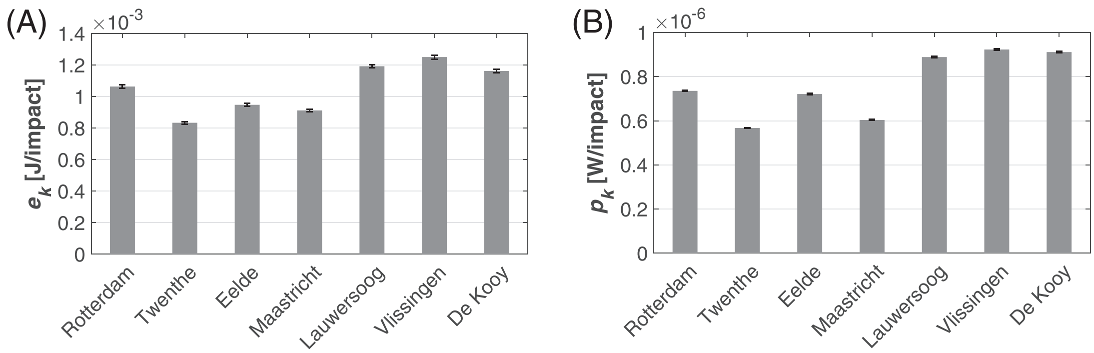

FIGURE 10 (A) Kinetic energy per impact and (B) kinetic per impact in different locations of The Netherlands for the last 25 years (1994–2018)

wind industry in order to accurately calculate the erosive variables which could be used in lifetime prediction models of the leading edge protection systems. Moreover, the in situ data log of rain volume and rain time during operation time together with the data log of wind speed, which is already logged by SCADA system, will also be useful to schedule the maintenance on the wind turbines.

3.6 | Period of meteorological data

Access to a long series of meteorological data could be limited. The KNMI provides free access to a long series of meteorological data but, not at all locations, data for 25 years are available. Moreover, for meteorological services in other countries, the attainability to data for long periods could be restricted. Therefore, in this section, how shorter periods of meteorological data affect the erosive variables is studied. This fact is not a weather variable but, as the erosive variables could be useful to predict and prevent rain erosion for the wind industry, the effect of the period of available meteorological data needs to be analysed to establish for how long they should be recorded to obtain accurate values. Accordingly, the erosive variables were calculated using the data of only the last 15 years (2004–2018), the last 5 years (2014–2018) and also the last 2 years (2017–2018) in comparison with the last 25 years (1994–2018) used for the previous results. In this case, the total kinetic energy was calculated annually, and the error bars represent the annual standard deviation (see Figure 11).

Figure 11 shows no significant effect on the annual results of the erosive variables in the station of Rotterdam which reflects a negligible relevance of the data interval in this location. This unaffected behaviour of the erosive variables is also found in other analysed locations, as Vlissingen and Twenthe. However, in stations as Maastricht (Figure 12) and De Kooy, the results show a decrease for shorter periods of data series. This fact is found more noticeable for the total kinetic energy; therefore, the accumulative variables are more sensitive to the time of data series. Moreover, a high annual standard deviation was found making the variability in the meteorological conditions from 1 year to the next evident.

These annual results provide a yearly indication of the erosive capacity which could be used as a predictive parameter in lifetime prediction models[14,17] for the erosion protection systems of the wind turbine blades. These lifetime prediction models become useful to reduce the O&M costs in the wind industry, for example, to more efficiently schedule the repair of erosion protection systems on the blades.

Finally, from these results, the period of meteorological data that would be necessary to characterise the erosive capacity of the rain in a specific location would not be quite long, at least in The Netherlands. As it was found, the meteorological data for the last 5 years are enough to obtain results of the variables without significant difference with the data for the last 15 or 25 years. However, the annual deviation shows high

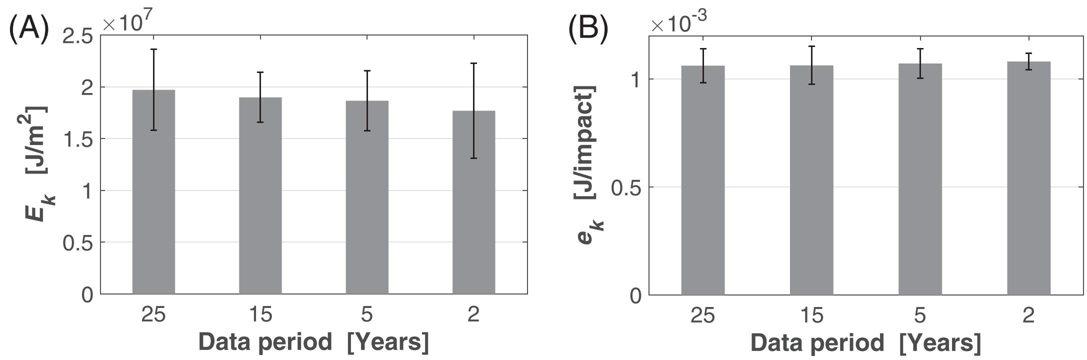

FIGURE 11 Annual erosive variables: (A) kinetic energy and (B) kinetic energy per impact, depending on the period of the data series in the station of Rotterdam

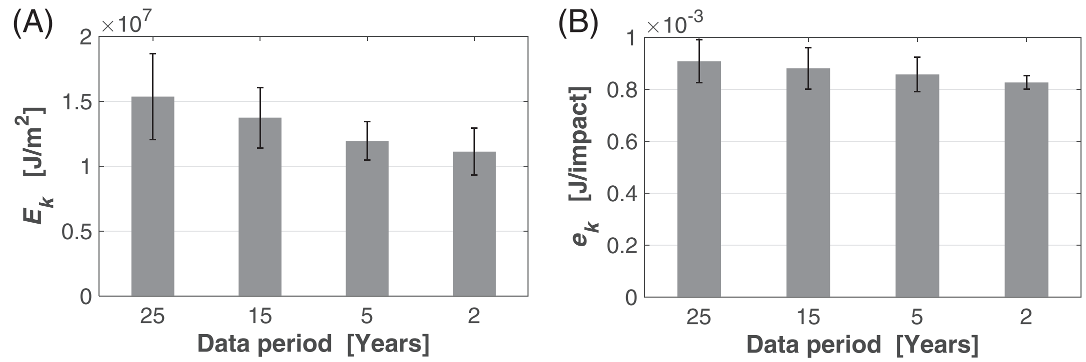

FIGURE 12 Annual erosive variables: (A) kinetic energy and (B) kinetic energy per impact, depending on the period of the data series in the station of Maastricht

variability in the meteorological conditions between the years. Thus, to characterise the erosion capacity of the rain in a specific location, the period of data to be considered has to be long enough to minimize this variation. Similarly, to select an adequate leading edge protection system of a wind turbine blade, a balance between the period of data and the associated variation needs to be found.

4 | CONCLUSIONS

A methodology to characterise the erosion capacity of raindrop impacts on wind turbine blades has been proposed using actual meteorological data, and the following conclusions are established:

a. The main contribution to the four erosive variables kinetic energy E_k (Equation 8), kinetic power P_k (Equation 9), kinetic energy per impact e_k (Equation 4) and kinetic power per impact p_k (Equation 10) is due to the blade velocity which is controlled by the wind speed. Although the wind speed is the major contribution to determine the erosion capacity, the rain data, such as rain time and rain volume, are also relevant mainly because they keep the global meteorological data limited to only the rain events.
b. The total kinetic energy and the kinetic energy per impact follow different behaviours along the blade length, a cubic and square function, respectively.
c. The values of the erosive variables are significantly affected for long log times, for instance a year, in which the average wind speed is not representative of the variable wind conditions. One-day log times seem to be adequate, especially for remote locations, to calculate the erosive variables without introducing significant error.
d. The moderate and light rains mainly contribute to the accumulative erosive variables, as total kinetic energy. The heavy, very heavy and violent rains almost have negligible contributions due to the limited rain events of these rain types. However, the per impact erosive variables, as kinetic energy per impact, greatly increase with the intensity of rain although they represent a reduced number of rain events.

e. The erosive variables are strongly affected by the place where the meteorological data are recorded, even in relatively small countries with simple orography as The Netherlands. The coast locations exhibit higher values of the erosive variables in the case of data from The Netherlands.
f. The effect of the period of data series in the annual values of the erosive variables depends on the locations, for example, unaffected in Rotterdam station and slight differences in Maastricht station. Although in our case, no general behaviour can be determined in function of the data series period, due to the high annual standard deviation, long-term historical data are advised to predict erosion behaviour and to develop effective models with solid capacity of prediction avoiding short temporal effects in the weather of wind turbine location.
g. The annual values of the erosive variables present high standard deviations from 1 year to the next ones. This variability makes the real-time meteorological measurements and in situ data logging during the operational time of the wind turbine imperative to monitor, that is, control the erosion progress through calculation of erosive capacity of the raindrops, and prevent the negative aerodynamic effects due to rain erosion, that is, through prediction of when protection systems need to be repaired or through for instance velocity reduction of the rotor during heavy rainfall.

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