



Rain Erosion Maps for Wind Turbines Based on Geographical Locations: A Case Study in Ireland and Britain

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Abstract

Erosion rates of wind turbine blades are not constant, and they depend on many external factors including meteorological differences relating to global weather patterns. In order to track the degradation of the turbine blades, it is important to analyse the distribution and change in weather conditions across the country. This case study addresses rainfall in Western Europe using the UK and Ireland data to create a relationship between the erosion rate of wind turbine blades and rainfall for both countries. In order to match the appropriate erosion data to the meteorological data, 2 months of the annual rainfall were chosen, and the differences were analysed. The month of highest rain, January and month of least rain, May were selected for the study. The two variables were then combined with other data including hailstorm events and locations of wind turbine farms to create a general overview of erosion with relation to wind turbine blades.

Keywords Wind · Turbine · Maps · UK · Ireland · Erosion · Rainfall · Composites · Testing

1 Introduction

Wind energy has become an increasingly popular choice of renewable energy with many countries across the world attempting to become carbon neutral [1]. This has resulted in a major research focus within the wind energy sector, addressing all aspects of energy conversion. This boom has had a very significant impact on the design, manufacturing and efficiency of the turbines and their blades [2]. One common advance is to install much larger blades, however, this is coupled with substantially greater tip velocities of the blades. These increased velocities create a higher risk of degradation of the leading edge due to impacts from rain erosion [3]. With tip speeds from turbines reaching 300mph, the repeated impact of raindrops is sufficiently energetic to erode the material. The erosion rates of wind turbines have a direct relationship to the environment they are erected. More rainfall will result in more erosion of turbine blades [4].

Typically wind turbine farms are constructed in barren locations due to land availability, wind speeds and away

from local beauty spots; however, this results in turbines being subjected to harsh conditions and in some locations heavy rainfall. Within this case study, data from the Met Office [5, 6], Irish weather data [7] and experimental data will be combined to map the UK and Ireland in terms of erosion on wind turbine blades. This is being carried out to display the relationship between the locations of wind turbine farms and their environment. This will, in turn, also aid in visualizing the wind farms that are at higher risk from erosion degradation and will require more maintenance. This is to mitigate failures and increase power output by keeping the blades smooth and promoting greater aerodynamic efficiency.

2 Methodology and Results

The procedure began by collating data from the Met office and Irish weather data. With this data an average rainfall map over the last 20 years was created. It should be noted that the turbine blades will inevitably experience varying rainfall rates throughout the year, which will, in turn, result in varying erosion rates. To map this phenomenon, the months of highest and lowest rainfall were chosen which were January and May, respectively. Showing the two extremes of rainfall months will provide more insight than a yearly average and

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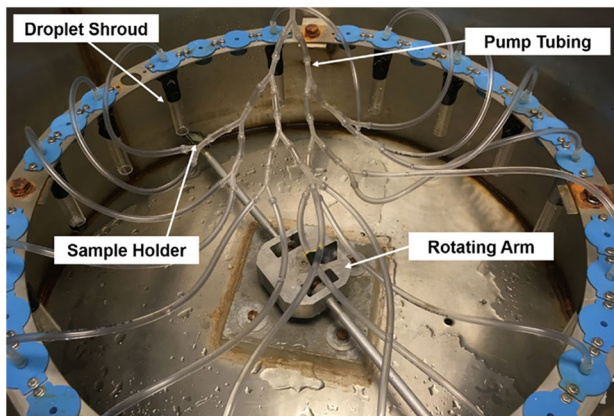


Fig. 1 Whirling arm rain erosion rig

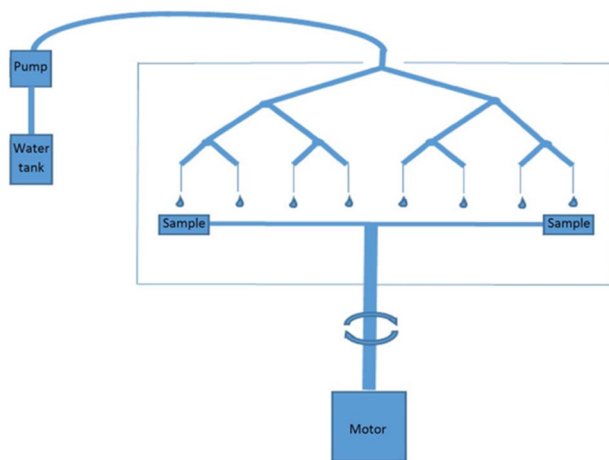


Fig. 2 Whirling arm schematic

allow for contrast to be observed between the 2 months. The result of this can be seen in Fig. 3.

Upon the completion of this map an experimental process in the Tribology laboratory at the University of Strathclyde was carried out to relate rainfall across the country to the degradation of wind turbine blades. There are many different ways to test for rain erosion [8]; however, the test method used for this case study is the whirling arm setup [9]. This consists of a large chamber with induced rainfall from hypodermic needles; in the centre of the chamber is a rotating arm which holds the material sample at the end. Adjusting the rotational speed of the spinning arm will adjust the impact velocity the sample encounters with the water droplet. The experimental setup can be seen in Fig. 1 and a schematic is shown in Fig. 2.

The material used in this experiment was G10 epoxy glass which is a similar glass fibre epoxy composite used within the wind turbine manufacturing industry [10]. The

impact velocity was set to 60 ms^{-1} as this will simulate the leading edge of 2 MW turbines with a diameter of 100 m. One of the assumptions that was made to relate the experimental data to the weather data was that the wind turbines were always turning when it was raining. Although this might result in an overestimation in erosion, it is deemed a worst-case scenario that has a possibility of occurring.

All the variables which were kept constant including impact velocity, temperature and rainfall were all calibrated before the experimental campaign began. The impact velocity was calibrated using light transducer which was held close to the rotating shaft where a thin reflective strip was placed. A light source was focused onto the shaft and the transducer would give an electrical output when the light was reflected from the reflective strip each time it would rotate. The rain fall was calibrated by running the rain system for five hours and the water tank which feeds the rig was weighed periodically every 30 min to calculate the water consumed and hence the rainfall rate. The pump used was a peristaltic pump which proved to be extremely reliable and hence outputted 50 mm/h every 30 min. The temperature inside the rig was also measured and kept at 29°C , a temperature calibration test was carried out during the calibration of the rainfall where the temperature was measured using a probe inside the chamber and a reading was taken every 30 min for the five hours and the temperature only fluctuated $\pm 1^\circ \text{C}$.

The same procedure was carried out for all samples which included a 48-h drying period before measuring the mass and kept in the same container to ensure the conditions when the sample was drying were kept constant. After the 48 drying period the samples were weighed on a balance accurate to 0.00001 g and the mass of the sample was measured five times equally spaced out over one hour. From this a measurement error of $\pm 0.001\%$ and standard deviation of $1.09\text{E}-05$ was calculated for the neutral water and a measurement error of $\pm 0.019\%$ and standard deviation of $1.16\text{E}-04$ for the saltwater experiment.

The construction of the rainfall map (Fig. 3) allows the setup for the experiment to be finalised. The key to the map displays: Below 50 mm, 50 mm, 75 mm, 100 mm, 150 mm, 200 mm, 300 mm, 500 mm and above 500 mm. The rainfall rate of the whirling arm rig is 50 mm/h therefore for the time each sample exposed to rain erosion can be determined, this is.

shown in Table 1.

The chosen measurement for erosion is mass loss as a percentage of the original sample. The mass of the test material was measured before the experiment and after each exposure time. This would result in a direct numerical relation between the average monthly rainfall and the erosion as a mass loss.

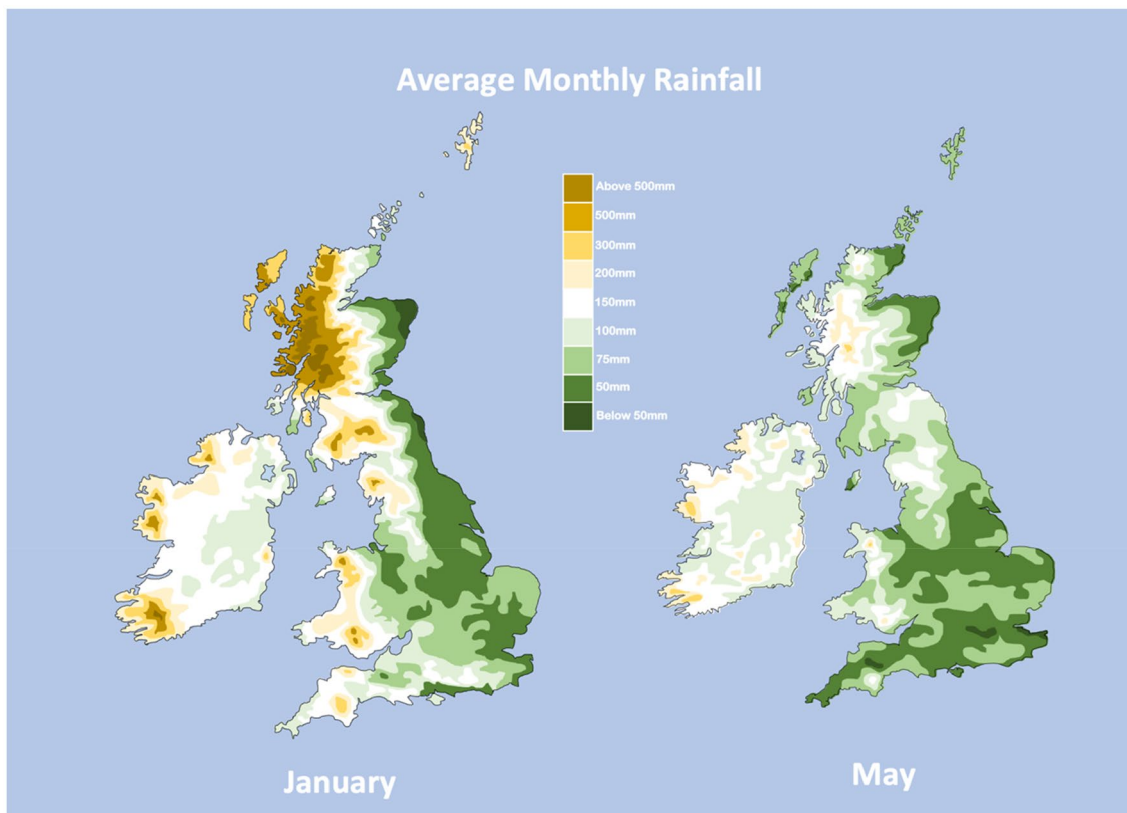


Fig. 3 The average rainfall in the months of January and May

Table 1 Exposure time in erosion rig to achieve required rainfall

Rainfall (mm)	Exposure Time (min)
50	60
75	90
100	120
150	180
200	240
300	360
500	600

This methodology was repeated with saltwater instead of rainwater to simulate offshore conditions. The saltwater used was a 3.5% saline solution which most accurately describes the seawater in the UK and Ireland [11]. The results and errors can be seen in Table 2.

Table 2 Mass loss results from erosion testing

Exposure time (min)	Cumulative rainfall (mm)	Neutral water mass loss (%) ($\pm 0.001\%$)	Saltwater (3.5% saline solution) mass loss (%) ($\pm 0.019\%$)
60	50	0.037	0.001
90	75	0.046	0.014
120	100	0.055	0.071
180	150	0.073	0.075
240	200	0.091	0.120
360	300	0.127	0.205
600	500	0.199	0.276

3 Rainfall Map

The rainfall mostly averages between 50 and 500 mm of rain with some few areas showing more extreme rain. It is clear that the month of May experiences considerably less rain as it shows highs of 300 mm whereas this rate is fairly common in January. The areas of intensity are very similar in both months with the west coast of Scotland showing a high rainfall and also the west coast of Ireland, predominantly the south west coast of Ireland displaying very heavy rainfall. These are historically harsher climates due to the prominent westerly wind from the Atlantic [12]. This leads to further erosion as the largest windfarms are located in these areas due to the increased power output from the consistent wind [13]. This is a very common trade-off when building a windfarm as the conditions that yield the most power generation are also the conditions which deteriorate the turbine blades most rapidly, therefore the life of the turbine blade will be reduced [14].

Part of the experimental process was also to understand sea water effects which help describe the erosion behaviour of offshore wind turbines. This was completed by running a saltwater solution (3.5% saline solution) through the experimental rig to simulate offshore conditions. Previous work on this topic by the current research group showed similar results to the saltwater exposure in this investigation. This had concluded that the saltwater proved more erosive when subject to high velocity impacts from the leading edge of the turbine blade and would create larger, more destructive cracks and loss of material from the sample [15]. The added effect of the more consistent wind from offshore conditions with the sea water climate is conducive to an erosive atmosphere and hence a short life span of turbine blades. Offshore wind farms have many other problematic characteristics including the corrosive nature of sea water which will attack any metallic parts and the anchoring of the structure to the seabed. However, the remote locations and the large blade size allows very significant energy capture [16]. Even though offshore wind turbines encounter major drawbacks such as increased levels erosion and corrosion, the advantage of having the open space to build larger, more efficient wind turbines with more consistent wind makes them economically viable [17].

4 Erosion Maps

Once the rainfall maps were created the link between rainfall rate and erosion rate could be made as mentioned previously. This allowed the same maps to be created with the

key displaying erosion as a percentage mass loss of the tip of a theoretical turbine blade at the leading edge.

The results showed a maximum mass loss of 0.199% which relates to 500 mm of rainfall and a minimum mass loss of 0.037% which relates to 50 mm of rainfall. Although mass loss is not the most precise measurement for erosion when compared to imaging samples and identifying gauges, cracks and loss of material [18, 19]; it does allow for a broader comparison between samples.

The measurement of mass loss can be loosely linked to the efficiency of the turbine, which is also why this measurement was used to map erosion across the UK and Ireland. With all material lost from the wind turbine blades it will affect the aerodynamic profile of the blades, with more mass lost the greater the effect it will have. The disturbed airflow over the blade will impede the performance of the turbine. A damaged blade will require a higher airflow or blade angle to produce the same output [20]. This has been proved experimentally within the literature which considered the drag coefficients of compromised blades [21] and also the microscopy of material subject to rain droplets at high velocities [22].

The degradation of the sample should erode in three distinct stages. The first is the initiation period; where the sample is at its smoothest and difficult to penetrate, this is when the turbine blades are brand new and operating at optimal efficiency. Secondly is steady state erosion; where the sample has been impacted by a critical number of droplets to affect the surface roughness of the sample enough to instigate more considerable erosion which continues at a constant rate. It is during this stage that the turbine starts to decline in efficiency. Lastly the third stage is the final erosion region where the erosion rate decreases, however, this is when the turbine blade is at its most vulnerable and the erosion on the blades can begin to become structural weak points [23]. It is important to locate areas of significant erosion across the country as the timing of maintenance to repair or replace blades is crucial in the optimisation of power production from wind turbine blades.

The rainfall data is only available on land, therefore there was no offshore rain data to compare to the offshore erosion data. From the experiments using saltwater (3.5% saline solution) there was a higher mass loss at the higher exposure times compared to the neutral water tests. To compensate for this a border of approximately 10 miles was created offshore around the islands and assumed to be one grade above the adjacent onshore erosion rate. For example, the mainland of Shetland displayed an erosion of 0.046% mass loss therefore a 10-mile boundary off the coast of Shetland was created displaying the next grade up in the key which is an erosion of 0.055% mass loss. This is displayed in Fig. 4.

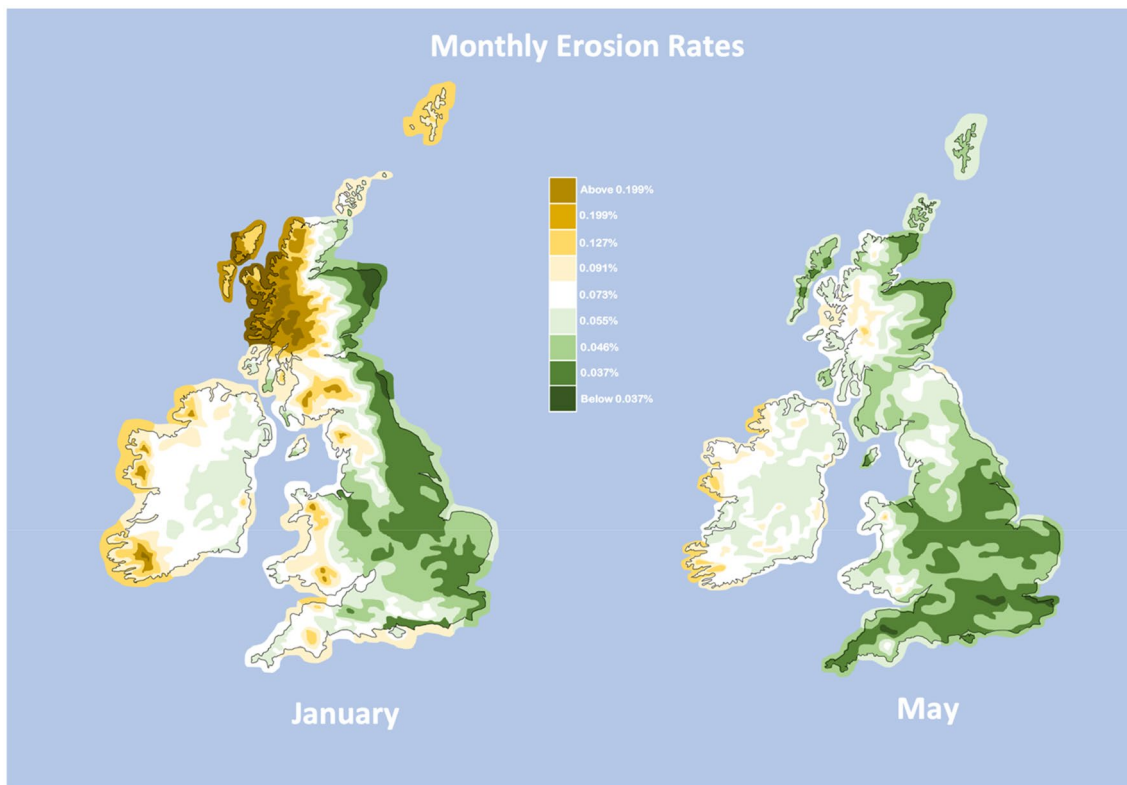


Fig. 4 The monthly erosion rates of the tip of a turbine blade along the leading edge in January and May

5 Points of Interest on Erosion maps

Construction of these maps now allows for further comparison to be made including locations of major wind farms and also areas of high hail rates which is displayed in Fig. 5. Even though the rainfall rate maps cover all precipitation, it is important to locate areas of high hail impact as these tribological actions can be detrimental to its structural integrity. Although the probability of hail striking wind turbine blades is very low and the damage would be difficult to ascertain, and it could possibly be masked as the outcome of heavy rainfall erosion, the implications of hail impacts have been proven experimentally to cause substantial damage. In a study looking into ballistic ice impacts, it was shown that the impact would delaminate and crack the composite material [24]. This would not only create a weak point in the blade structure itself but also create an initiation site for rain erosion to occur and for crack propagation into the structure of the blade. The areas of frequent hail are shown in Fig. 5 as the red overlay, and from the maps it is clear that the west coast is more adversely affected by hail. Unfortunately, there was limited data on hail in The Republic of Ireland; therefore, assumptions on this issue for this area of the map need to be treated with caution.

Also superimposed onto the map in Fig. 5 is the locations of some large wind farms and the largest in Scotland, England, Ireland, Wales, Northern Ireland and The Republic of Ireland have been labelled [25]. This not only allows for a comparison between the size of the various windfarms in each region but also how adversely affected each one is by the climate and the subsequent erosion. Most of the windfarms are in compromising locations but, as discussed previously, this is a trade-off between greater access to consistent wind to the lifetime of the blades.

6 Areas Which May be Addressed in Future Work

There are some additional modifications which will help optimise these maps when they are recreated with future results. The main extension would be the use of additional data to help aid the validity of the results and as mentioned previously if enough data points are available then a dynamic map could be potentially created.

There are many additions which could be made to the erosion data and the weather data which could provide further insight into geographical differences including the droplet size, pH value and intensity which would aid the erosion

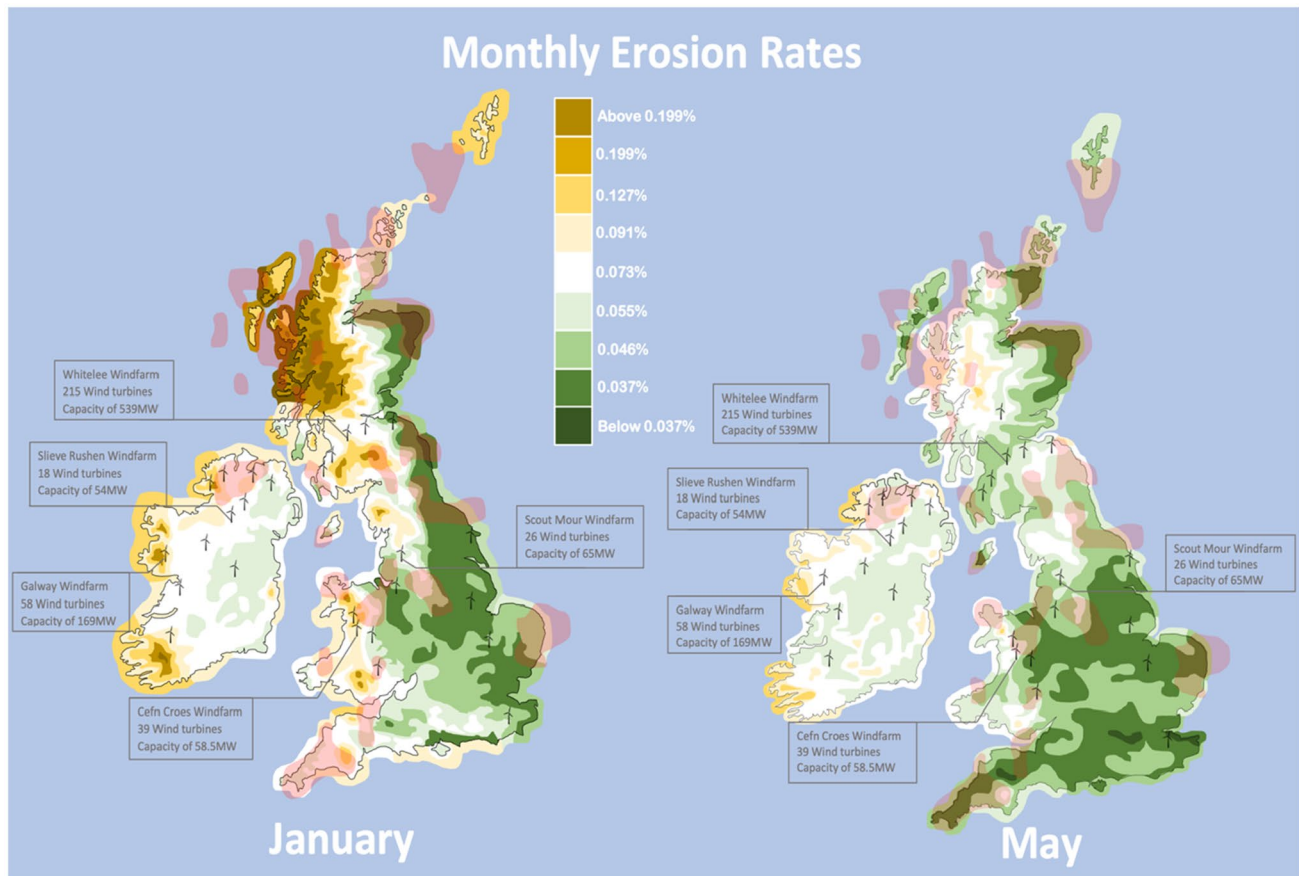


Fig. 5 The monthly erosion rates of the tip of a turbine blade along the leading edge in January and May with overlays of major wind turbine farms and areas of frequent hail

data. These data sets however are difficult to pinpoint as they are mostly stochastic.

The most important evolution for these maps would be the inclusion of offshore rain data to include the large offshore wind farms that could not be included within this study. With almost half of the UK wind energy coming from offshore wind farms [26] the inclusion of this data would provide a more thorough overview of the erosion of the UK and Ireland's wind turbine blades and hence the loss in power due to aerodynamic inefficiencies.

7 Conclusions

In conclusion, the data from the rainfall within the UK and Republic of Ireland were formatted together to produce an Ireland/Britain map showing the average rainfall across the two countries in both January and May averaged over the last 20 years. These maps were then used as the basis for an erosion experiment converting the rainfall to exposure time within the erosion rig. These results were then arranged on

the map to display the degradation of the turbine blades from rain droplet impacts. This was coupled by a saltwater erosion experiment that used 3.5% saline solution as the droplets to simulate offshore wind turbines which are subject to being eroded by sea water (salt spray corrosion enhanced erosion) in the atmosphere. These two maps were then superimposed to display areas of frequent hail and the locations of each country's largest wind turbine farm. This was carried out in an attempt to visualise the erosion patterns across both Ireland and the UK.

It is clear that the general trend consists of greater erosion in the west coast of both the UK and The Republic of Ireland with the highest erosion areas being the north west of Scotland where the land tends to be at a higher elevation and also the south west of Ireland where there is no protection from the prevailing wind over the Atlantic.

The locations of frequent hailstorms across the UK and the republic of Ireland could be considered stochastic, however, the locations of some major wind farms overlap with frequent hail; this can be seen predominantly in Northern Ireland. This overlap could potentially reduce the lifetime of

the turbine blades at an increased rate due to more powerful impacts from hailstones.

These mapping methods have potential to be used in life-time modelling of wind turbine blades and have the possibility to be developed into a dynamic map that can display changes in new wind farms and changing climates. This is particularly important due to weather changes over long periods of time on the annual cycle.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

- Jonas AE, Gibbs D, While A (2011) The new urban politics as a politics of carbon control. *Urban Stud* 48(12):2537–2554
- Quarton DC (1998) The evolution of wind turbine design analysis: a twenty-year progress review. *Wind Energy* 1(S1):5–24
- Keegan MH, Nash DH, Stack MM (2013) On erosion issues associated with the leading edge of wind turbine blades. *J Phys D* 46(38):383001
- Siddons C, Macleod C, Yang L, Stack M (2015) An experimental approach to analysing rain droplet impingement on wind turbine blade materials. EWEA 2015 Annual Event
- UK actual and anomaly maps [Internet] (2020) Met Office. [cited 1 June 2020]. Available from: <https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-actual-and-anomaly-maps>
- UK: Monthly rainfall 2020 | Statista [Internet] (2020) Statista. [cited 1 June 2020]. Available from: <https://www.statista.com/statistics/584914/monthly-rainfall-in-uk/>
- Walsh S. 01-NEW LONG-TERM RAINFALL AVERAGES FOR IRELAND, National Hydrology Seminar 2012, Off. of Public Works, Tullamore
- Tobin EF, Young TM, Raps D, Rohr O (2011) Comparison of liquid impingement results from whirling arm and water-jet rain erosion test facilities. *Wear* 271(9–10):2625–2631
- Mackie C, Nash D, Boyce D, Wright M, Dyer K (2018) Characterisation of a whirling arm erosion test rig. In 2018 Asian Conference on Energy, Power and Transportation Electrification (ACEPT), (pp. 1–6). IEEE
- Ravi-Chandar K, Satapathy S (2007) Mechanical properties of G-10 glass-epoxy composite. Texas Univ at Austin Inst for Advanced Technology
- A Measure of Salt [Internet] (2020) Earthobservatory.nasa.gov. [cited 2 November 2020]. Available from: <https://earthobservatory.nasa.gov/images/78250/a-measure-of-salt>
- Jones P, Harpham C, Kilsby C, Glenis V, Burton A. UK Climate Projections science report: projections of future daily climate for the UK from the Weather Generator
- Bâra A, Velicanu A, Lungu I, Botha (2020) Natural factors that can affect wind parks and possible implementation solutions in a Geographic Information System. In International Conference on Development, Energy, Environment, Economics, Puerto de la Cruz, Tenerife (pp. 50–54)
- Shokrieh MM, Rafiee R (2006) Simulation of fatigue failure in a full composite wind turbine blade. *Compos Struct* 74(3):332–342
- Pugh K, Rasool G, Stack MM (2018) Some thoughts on mapping tribological issues of wind turbine blades due to effects of onshore and offshore raindrop erosion. *J Bio- Tribo-Corros* 4(3):50
- Li Z, Zhao M, Chen Z (2006) Efficiency evaluation for offshore wind farms. In 2006 international conference on power system technology, (pp. 1–6). IEEE
- Tavner P (2012) Offshore wind turbines: reliability, availability and maintenance. IET
- Pugh K, Nash JW, Raeburn G, Stack MM (2019) Review of analytical techniques for assessing rain drop erosion resistance of materials. In 14th Conference on Sustainable Development of Energy, Water and Environment Systems
- Pugh K, Nash JW, Raeburn G, Stack MM (2020) On analytical tools for assessing the raindrop erosion of wind turbine blades. *Renew Sustain Energy Rev* 137:110611
- R. S. Ehrmann (2014) Effect of Surface Roughness on Wind Turbine Performance. PhD thesis
- Sareen A, Sapre CA, Selig MS (2014) Effects of leading edge erosion on wind turbine blade performance. *Wind Energy* 17(10):1531–1542
- Pugh K, Rasool G, Stack MM (2019) Raindrop erosion of composite materials: some views on the effect of bending stress on erosion mechanisms. *J Bio Tribo-Corros* 5(2):45
- Springer GS (1976) Erosion by liquid impact. Scripta Publishing Co., Washington, DC
- Keegan MH, Nash D, Stack M. Wind Turbine Blade Leading Edge Erosion: An investigation of rain droplet and hailstone impact induced damage mechanisms (Doctoral dissertation, University of Strathclyde)
- Macdonald H, Infield D, Nash DH, Stack MM (2016) Mapping hail meteorological observations for prediction of erosion in wind turbines. *Wind Energy* 19(4):777–784
- UK Wind Energy Database (UKWED) [Internet] (2020). Renewable UK. [cited 3 November 2020]. Available from: <https://www.renewableuk.com/page/UKWEDhome/Wind-Energy-Statistics.htm>

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