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Optimization of the erosion-safe operation of the IEA Wind 15 MW Reference Wind Turbine.

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Abstract. The work describes modelling of erosion of the IEA 15 MW Reference Wind Turbine. Five-year worth of historical time series including wind speed, rain intensity and price of energy was used in the modelling. The work included erosion-safe operation of the turbine where the tip speed was limited during rain events to prevent erosion. The tip-speed limit was defined as a function of rain intensity and price of energy, the distribution of which was subject to an optimization. The objective for the optimization was to maximize the profit. The factors taken into account in the modelling and optimization were: the loss in power curve due to erosion, and the cost of repair and associated downtime. The results indicated that for this particular turbine it would be sufficient to define the tip-speed limit as a function of rain intensity alone. The model showed that 88% of the overall profit loss due to erosion could be saved by running the turbine in the erosion-safe operation. Although some inaccuracy may be associated with the modelling, the results strongly indicate that a significant amount of money could be saved by utilizing the erosion-safe operation on offshore turbines.

1. Introduction

Erosion of wind turbine blades on offshore wind farms has become an important issue for wind farm operators. Current leading-edge protections do not seem to withstand the harsh offshore weather conditions in combination with high tip speeds in the range of 100 m/s. Hence, this increasing issue should be tackled two-fold. On the one hand, advances in leading-edge protection materials are researched together with the mechanisms of their failure and modelling methods, e.g., Slot et al. [1]. Researchers and industry also seek efficient methods of repairing leading edges, e.g., Mishnaevsky [2]. On the other hand, more attention should be paid to innovative operation strategies that will decrease the growth of erosion on the blades. Bech et al. [3] carry out analysis of the influence of rain intensity and tip speed on the growth of rain-induced erosion. Some of the underlying consideration of raindrop parameters used by Bech et al., and consequently in the present work, refer to the work of Best [4].

Further, Bech et al. link the level of erosion with the loss in the aerodynamic performance, and consequently, energy production. They also estimate the cost of erosion-induced blade repairs. Having all the aforementioned factors in place, they propose a method for limiting erosion by decreasing the rotational speed of the turbine during rare and heavy rain events. They propose parameters for such operation and present their potential impact on the long-term energy production and associated profit. Their work is taken further by Hasager et al. [5] who focus on the influence of site-to-site weather



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variations, i.e., the correlation of rain intensity and wind speed, on the potential growth of rain-induced erosion at various sites. They rely on historical weather data. They also propose an alternative engineering model for erosion, which directly links rain intensity and tip speed with the growth of erosion. In the end, they utilize both aforementioned models and historical weather data to estimate the effects of the erosion-safe operation (ESO) on the growth of erosion and long-term profit at various sites.

The present work may be thought of as a continuation of those aforementioned, which investigated more sophisticated approaches to limiting the rotational speed of the turbine under the erosion-safe operation. Aforementioned approaches include either a single or multiple curtailment steps. In such a step, the maximal tip speed is curtailed at certain precipitation value(s). There, price of energy is not considered as a parameter. In contrast, in the present work, the rotational speed of the turbine was optimized as a C0 continuous function of wind speed, rain intensity and price of energy. The objective of the optimization was to maximize the long-term profit from the offshore installation. The estimated cost, duration and frequency of erosion-induced blade repairs were included in the optimization.

2. Data, models, methods and workflow

2.1. Turbine aerodynamic model

In order for the work to be relevant to future installations, the modelling and analysis were carried out on the newly developed virtual IEA Wind 15 MW Reference Wind Turbine, by Gaertner et al. [6]. Having the hub height of 150 m and the rotor diameter of 240 m, this turbine is believed to be representative to offshore installations in foreseeable future. Having the maximum tip speed of 95 m/s, a turbine like this would also likely be affected by erosion.

In the present modelling, the turbine was represented by power curves corresponding to clean and eroded blades, and by a Rotations-Per-Minute (RPM) curve. There is fortunately a number of publications governing the influence of roughness elements on aerodynamic performance, and consequently energy production, e.g., Bak et al [7].

The power curves corresponding to clean and eroded blades are presented in Figure 1. Note that the aforementioned power curve corresponding to eroded blades was modelled on a high level based on prior experience and did not include direct considerations of specific airfoils. The pre-rated part of the power curve was scaled by 97.8% (the 11.0 m/s point by 98.2%) to obtain a conservative decrease in the Annual Energy Production (AEP) of 2.0%. That is, assuming exemplary Weibull probabilistic wind-speed distribution scale and form parameters of 5.85 and 2.09, respectively. The reason to choose a conservative 2% decrease in the AEP over a higher value was feedback from some industry representatives who claim that erosion-induced measured drop in the AEP is less significant than some literature or even wind tunnel tests could indicate. None the less, authors believe that it would be unrealistic to eliminate this factor.

2.2. Modelling of the growth of erosion

In order to model the growth of erosion on the blades as a function of tip speed and rain intensity, the so-called kinetic energy model of Bech et al. was used. This model favors the influence of kinetic energy of each droplet impact. A consequence of using this model is that a short yet intensive rainfall associated with larger droplets can make significantly more damage to the blade than a long lite rainfall associated with smaller droplets. Another model of the growth of erosion (see Hasager et al.), i.e. accumulated water column model, was used as a verification of the optimization methodology. In that model, the amount of rain falling on the blade is the key parameter rather than the kinetic energy of droplets. Generally, an engineering model of erosion represents a way of extrapolating results of accelerated erosion tests, i.e. [8], (carried out at tip speeds significantly exceeding 100 m/s) to tip speeds of operating turbines. Note that the exact physical mechanism of erosion is not yet known in detail enough to confidently state which of the available engineering models is the most accurate, and what exact parameters govern the phenomenon. Further, the exact mechanism and growth of erosion

depends on material properties of the leading edge (see Slot et al.) and may be hard to accurately generalize. It is also worth mentioning that erosion is a non-linear process that may be split into two periods. The first period is incubation where no visible damage is present on the surface. Accordingly, no noticeable production loss occurs. The second period is the one when visible damage occurs on the surface. Depending on the severity of damage, it may create a production loss. Most turbine operators seem to claim that it is most beneficial to repair blades before a significant damage and loss in energy production occur. In the present modelling, a time series of turbine operation is generated. In this time series, the growth of erosion is related with a relatively small gradual loss in energy production occurring from the start of operation to the point when a repair is carried out. That point occurs when the modelling indicates that a significant damage has occurred on the blade. The loss in the energy production is modelled by an interpolation between the clean and eroded power curves. At the point of occurrence of significant damage, it is the eroded power curve that is in use. After the repair, the clean power curve is restored and the degradation process repeats.

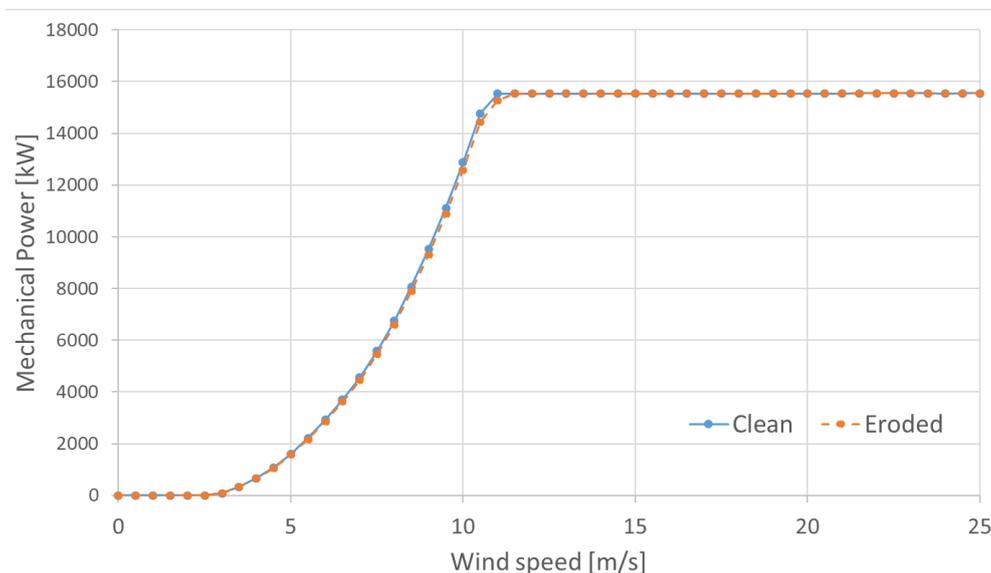


Figure 1: Mechanical power curves of the IEA Wind 15 MW RWT. The *Clean* curve is the reference. The *Eroded* curve was created in the present work and corresponds to a 2% loss in the Annual Energy Production (AEP).

2.3. Historical weather and price-of-energy data

The present model relies on historical wind-speed and rain-intensity 10-minute-bin time series from Hvide Sande, Denmark, covering years 2013-2017, (courtesy of Danish Meteorological Institute), the same as the data used by Hasager et al. It is not entirely clear how long of a time series is necessary to accurately reflect 25 years, being the life time of a typical turbine. However, the authors believe that the 5 years of data provide a representation of 25 years with uncertainty not higher than that of other factors in the modelling. The reason for choosing Hvide Sande is that it is placed at the western coast of Jutland, see Figure 2. With primarily western winds, see Figure 3, out of all locations in Denmark available to the authors, it is the most representative to offshore conditions of the North Sea. The wind speed was extrapolated from the measurement height of 10 m to the hub height of 150 m using the wind profile power law with the alpha exponent of 0.143.

In order to include the market price of energy in the model, the aforementioned historical weather data was synchronized with historical price of energy covering the same location, i.e., so-called Elspot Price for the bidding zone DK1, covering Jutland and Funen, see [9].

Figure 4 presents the price of energy as a function of wind speed. First of all, it is clear by looking at the scatter that price generally decreases with increasing wind speed. What is more interesting in the present context, is the scatter of data points. It is visible that the market is such that for a single value of wind speed, multiple values of price occur over time. This variation is the reason for including the price of energy in the optimization. The underlying logic may be outlined as follows. If at certain wind speed and rain intensity the turbine brings significant earnings, it may be beneficial to allow for higher tip speed and consequently larger growth of erosion than in the case when at the same weather conditions less profit is made per kWh. The question to answer is whether this effect is of importance in practical terms, i.e., can it be utilized to increase profit.

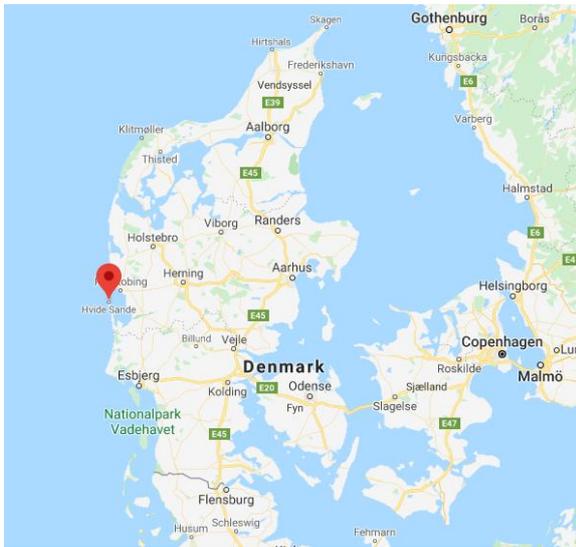


Figure 2: Map of Denmark showing the location of Hvide Sande (Ref. Google Maps, accessed March 1st 2020).

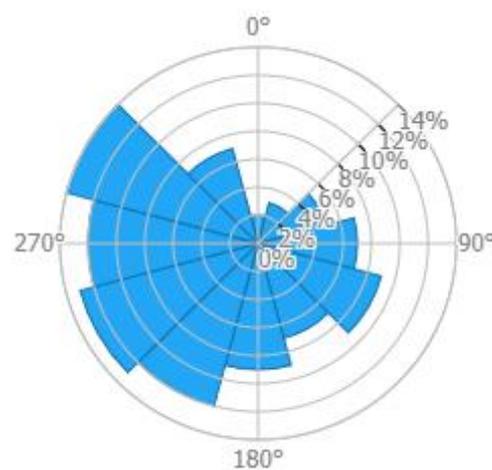


Figure 3: Wind frequency rose of Hvide Sande, Denmark (Ref. Global Wind Atlas, accessed March 1st 2020).

2.4. Workflow and optimization

The aforementioned components work together in a framework where the operation of the turbine is modelled in a time-marching manner, i.e. the modelling method produces a time series. The modelled turbine produces energy according to its power curve and wind resource. Produced energy creates income depending on the corresponding price of energy. Turbine efficiency, taxes and costs other than those associated with erosion-induced repairs are excluded from the present analysis.

At the same time, the tip speed (which depends on wind speed and the RPM schedule) and the rain intensity dictate the growth of erosion. The gradual growth of erosion translates into a gradual decrease in the below-rated region of the power curve, and a corresponding decrease in energy production. Once erosion reaches a certain level, a repair of the blades is modelled. According to feedback from the industry, repairs are typically carried out in 2-4 year intervals, although many factors come into play. If the model indicated a significantly different interval, tuning could be necessary.

A modelled repair translates into downtime of the turbine and is associated with a certain cost of repair. Although it is difficult to accurately estimate what a repair of a 15 MW offshore turbine will cost and how long it will take, a downtime of 6 days and a cost of 20k Euro per turbine did not seem unrealistic. In the end, the balance of income and expenses on repairs decides on the profit.

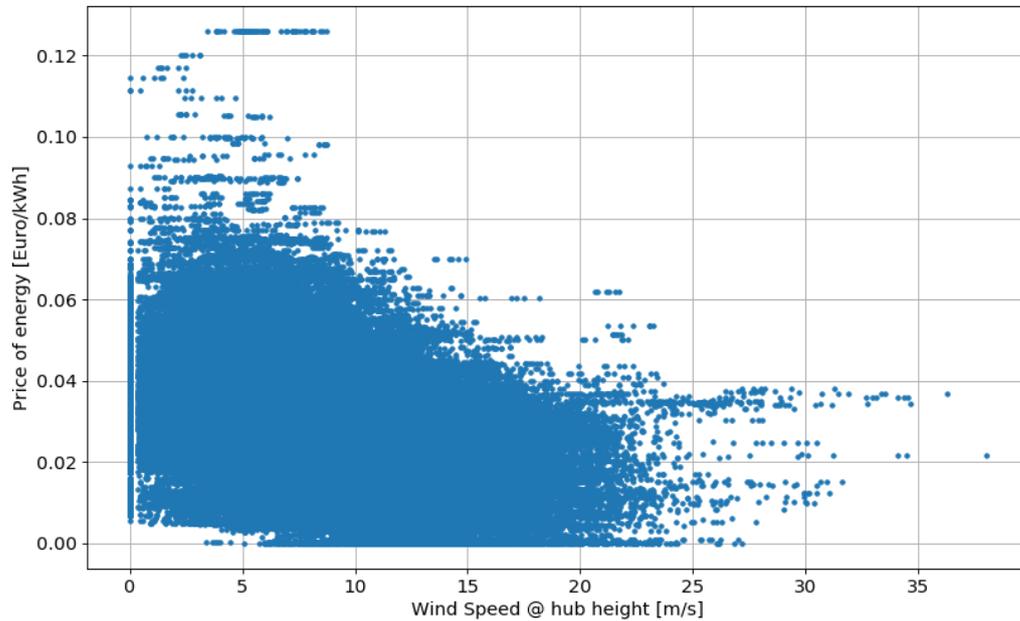


Figure 4: Historical (2013-2017) Elspot price of energy for bidding zone DK1, covering Hvide Sande, plotted as a function of wind speed at the 15 MW RWT hub height.

The difference between the reference and erosion-safe operations of the turbine is as follows. In the reference, the RPM schedule is only a function of wind speed whereas in the erosion-safe operation, RPM is a function of wind speed, rain intensity and price of energy. In the modelling, this dependency is governed by a multivariate interpolation. Sixteen control points were used to define the tip speed limit as a function of rain intensity and price of energy. The number of control points and their position were adjusted manually. The control points undergo an optimization using the Sequential Least Squares Programming method (SLSQP) with the objective of maximizing the profit. Then, the optimal limit is imposed on the default RPM schedule of the turbine.

In order to assess the value of including the price of energy as a variable in the optimization, an additional optimization was carried out in which the dependency on the price of energy was excluded. This optimization is referred to as ESO 1 whereas the one that included the dependency on the price of energy, ESO 2.

3. Results and discussion.

Tip speed defined as a function of wind speed, rain intensity and price of energy is (being a function of three variables) difficult to visualize. A plausible way of presenting the resulting tip speed distributions is by visualizing the resulting limits to the maximum tip speed. Those limits are imposed on the reference RPM schedule, and are visualized as a function of rain intensity and price of energy at and . Note that the optimized distribution of the tip-speed limit is bound by the minimum and maximum tip speed of the 15 MW turbine, i.e., 63 and 95 m/s, respectively. represents an optimization where dependency on the price of energy was disabled (referred to as ESO 1). Orange markers in both figures show control points of the optimizations. Blue markers show the underlying tip-speed time series bound by the resulting limits, i.e., the surface plots. Note that most of the underlying data lies at rain intensities below 20 mm/h, and the price of energy below 0.08 Euro/kWh. Further, in five-year worth-of data there is no point above 15 mm/h and 0.45 Euro/kWh at the same time.

The results presented in show that the SLSQP optimizer ‘noticed’ the dependency on the price of energy once that was enabled, generally increasing the limit towards higher prices (referred to as ESO

2). Although the dependency of the tip speed limit on the price of energy was reflected in the optimization, the corresponding increase in profit relative to the ESO-1 case was marginal and not visible within four significant digits. The ESO-1 case, given the modelling approach and parameters, already increased the profit (earning from production minus cost of repair minus repair-induced downtime) to 99.8% of the ideal case (no erosion-induced loss in production and no repairs). Hence, there was simply very little space for further improvement. Those results indicate that it may be sufficient to define the tip-speed limit as a function rain intensity alone, and accordingly, the tip speed or RPM as a function of wind speed and rain intensity. However, results may vary depending on the conditions.

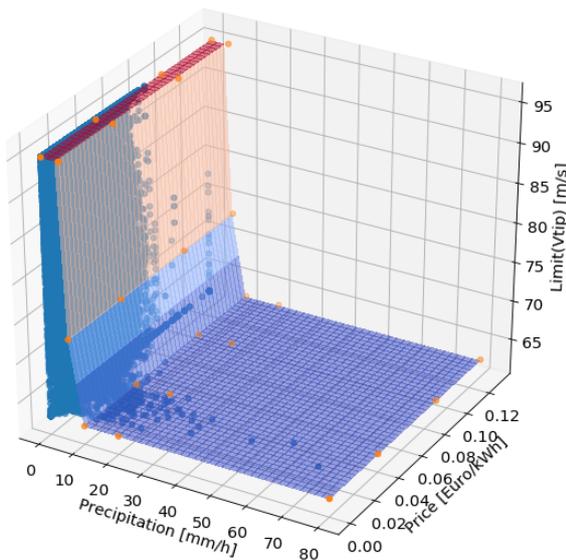


Figure 5: Optimal tip-speed limit plotted as a function of rain intensity [mm/h] and price of energy [Euro/kWh] where dependency on the price was disabled. Orange markers show optimization control points. Blue markers show the underlying data, i.e., tip-speed time series.

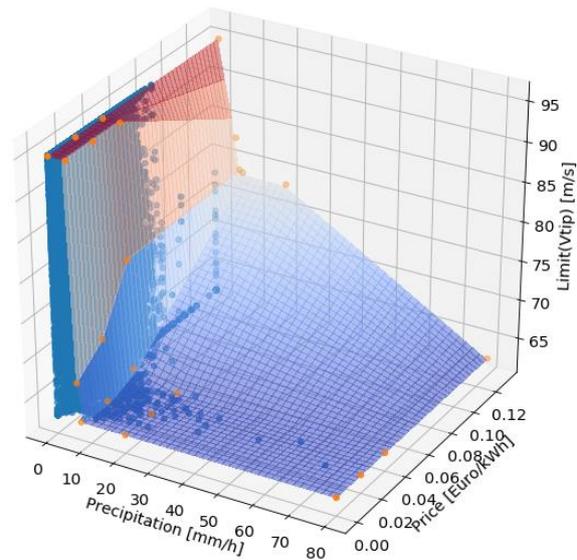


Figure 6: Optimal tip-speed limit plotted as a function of rain intensity [mm/h] and price of energy [Euro/kWh]. Orange markers show optimization control points. Blue markers show the underlying data, i.e., tip-speed time series.

Table 1 summarizes the results of optimizations ESO 1 and ESO 2. The AEP values were calculated as the overall energy production divided by five years, i.e., length of the time series, excluding the repair-induced downtime, i.e. as if the repairs did not affect the energy production. Turbine efficiency was not included in the analysis. The ideal-blade case with no erosion and no repairs was taken as the reference.

The default case with no erosion-safe operation had a lower AEP than the ideal by 0.4%. This number seems correct for the following reason. The maximum assumed energy loss due to erosion was 2%. Given that the loss increases gradually, average loss from the start of simulation to the repair was approx. equal to 1%. Then, given that the resulting average repair interval was equal to 2.2 years, the 1% loss over 2.2 year translates to approx. 0.4% loss per year.

The analysis of profit includes the cost of repair equal to 20k Euro and the loss due to repair downtime, equal to 6 days. With a repair every 2.2 year, the default case lost 1.6% in profit relative to the ideal. Given that both modelled erosion-safe cases practically removed the need to repair, the loss relative to the ideal case decreased to 0.2%.

An identical analysis was carried out using another model for the growth of erosion, so called water column model from Hasager et al. The model initially predicted an average repair interval in the default case equal to 1.1 years. To enable a better comparison of both erosion models, the water column model was tuned to return a 2.2 year interval in the default case. Then, the average repair interval of the erosion-safe cases was equal to 18 years.

Further evaluation of the optimization results, especially in the context of their translation to other turbines or sites, could require an insight into the underlying weather data, i.e. occurrence of different rain intensities. Such information is available in Hasager et al.

It is worth mentioning that many factors may affect the growth of erosion and that the authors do not claim that the results presented in Table 1 are accurate. It should also be noted that the rain-induced erosion is not the only factor affecting the lifetime of leading edges. However, the present work reinforced a growing scientific evidence that erosion-safe operation may significantly increase the repair intervals of blades as well as increase the overall profits of turbine operators.

Table 1: Summary of the erosion-safe-operation parameter optimizations ESO 1 and ESO 2.

	<i>Ideal blade</i>	<i>Default</i>	<i>ESO 1</i>	<i>ESO 2</i>
*AEP [GWh]	68.8	68.6	68.7	68.7
*AEP [%]	100	99.6	99.9	99.9
** Annual Profit [k Euro]	9274	9121	9259	9259
** Annual Profit [%]	100	98.4	99.8	99.8
Average Repair Interval [years]	No repairs	2.2	49.5	50.2

(*) Excluding repair downtime

(**) Including cost of repair including downtime, excluding taxes and any other costs

4. Conclusions and future work

Leading-edge erosion has become a source of significant cost for offshore turbine operators. It has also become a popular subject of research both by the scientific community and the industry. New leading edge protection materials are being developed. New engineering models for erosion are being presented. New repair techniques are being utilized. All this work gradually makes the offshore wind energy more competitive and cost effective. However, the problem of erosion has not yet been solved, and a growing scientific evidence shows that part of the solution may be in smart operation of the turbines. The present work proposed such operation for the IEA Wind 15 MW Reference Wind Turbine. In this operation, an additional tip-speed limit was imposed on the default RPM schedule. This limit was defined as a function of rain intensity and price of energy. Historical time series was used to tune the model. The optimization of the model parameters indicated that for this particular turbine it would be sufficient to define the limit as a function of rain intensity alone. The modelling indicated that 88% of the loss in profit due to erosion could be saved by running the turbine in the erosion-safe operation where the tip speed would be decreased during rain events, according to the optimized schedule. Although the underlying modelling may be associated with some inaccuracy, the study strongly indicates that considerable savings could be made by utilizing erosion-safe operation on offshore turbines.

The authors believe that future work should focus on increasing the accuracy of modelling of the growth of erosion, probably by better understanding the underlying mechanisms. Further, a full-scale proof of concept carried out on an offshore turbine would reassure the community that we are heading in the right direction.

5. Acknowledgements.

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