Advanced Operation and Maintenance Strategies Considering Turbine Interaction

António Lourenço
antonio.lourenco@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

July 2023

Abstract

Offshore wind energy is a rapidly growing sector. Reducing costs associated with O&M operations is crucial for enhancing cost competitiveness. This research evaluated the significance of accounting for downtime losses while scheduling preventive maintenance operations for offshore wind turbines. Preventive maintenance involves turbines' shutdown, eliminating wake-induced velocity deficits and their impact on downstream turbines. Wake interactions result in lower wind speeds and, as a result, lower power production in downstream turbines. The primary objective of this study was to determine whether considering wake losses when scheduling preventive maintenance could be an influential factor in selecting turbines for preventive maintenance. The research first analyzed the effect of wake power loss on a row of wind turbines aligned with the wind direction, followed by an assessment in the context of an offshore wind farm. It was found that wind direction is the main variable impacting the wake effect when shutting down turbines for maintenance. The results suggest that accounting for wake losses in preventive maintenance scheduling can lead to a reduction in downtime losses of more than 4%. This finding indicates that maintenance planning should consider turbine interactions to optimize offshore wind energy's overall efficiency and cost competitiveness.

Keywords: Offshore wind, wake modelling, preventive maintenance, optimal operation and maintenance (O&M) scheduling

1. Introduction

Reducing renewable energy costs is crucial to increase the pace of the energy transition from fossil fuels. Since solar and wind are expected to be the main drivers of the energy transition, reducing the costs of these energy sources is essential. Finding ways to reduce the total cost of energy from renewable sources allows for making available more cost-competitive alternatives, which is a much-needed action toward a quicker energy transition.

The leading causes of offshore wind farms' revenue losses are component failure and Operation and Maintenance (O&M) activities. Therefore, in the last few years, an effort has been made to reduce the costs of O&M in offshore wind farms by developing new approaches. However, not much literature currently considers wake effects in planning O&M activities [1, 2]. Preventive maintenance is an O&M strategy often used in offshore wind farms, which, as the name suggests, aims to perform maintenance to prevent and monitor possible failures in each wind turbine. This type of maintenance often requires the shutdown of a wind turbine. In addition, preventive maintenance activities are periodically planned and scheduled yearly, which is crucial for a wind farm operation's reliability. Therefore, several preventive maintenance activities will be performed in every turbine throughout a wind farm's lifetime.

In a wind farm, wind turbines interact with each other through wakes generated from the upstream wind turbines. These interactions result in lower wind speeds at downstream turbines, reducing their energy production capabilities. However, O&M requires wind turbines to be shut down during a wind farm's lifetime. Shutting down a wind turbine will naturally halt its energy generation and remove its wake effect on downstream turbines, increasing their production. It follows that, depending on weather conditions, the sequence of wind turbines to be deactivated for large preventive maintenance campaigns can impact the total power production of a wind farm. Therefore, it may be possible to reduce the revenue losses of a wind farm by shutting down specific wind turbines at a given time to perform maintenance activities.

2. State of the Art

2.1. Power Production of a Standalone Wind Turbine

Offshore wind turbines are almost exclusively upwind Horizontal Axis Wind Turbine (HAWT) [3]. This wind turbine design usually has three blades facing the incoming wind direction. Thus, this configuration reduces the effect of the remaining components on the wind turbine's blade aerodynamic efficiency [4], namely the tower and the nacelle, as shown in Figure 1. The airflow momentum of the wind is converted into aerodynamic forces through the blades, which move the rotor. In turn, the rotor's torque is transferred through a drivetrain that either has a gearbox or is directly connected to the generator.

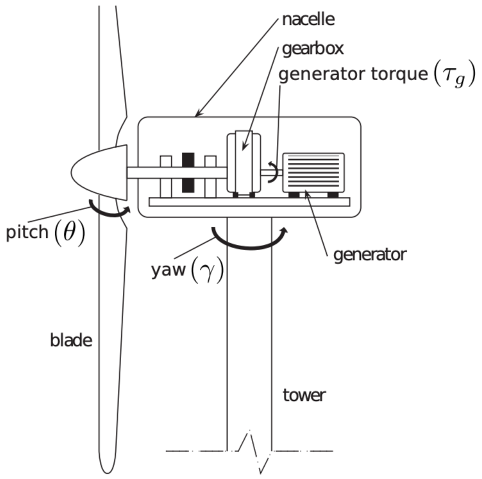


Figure 1: Horizontal-axis wind turbine with its main components and some control variables. Retrieved from [5]

The power production of a wind turbine varies non-linearly with the incoming wind speed. Figure 2 presents an ideal power curve for a variable-speed wind turbine with four different operation regions (I, II, III, and IV). Reference wind speeds separate the operating regions: cut-in, rated, and cut-out wind speed. The cut-in wind speed is the wind speed from which the wind turbine starts generating power, while the cut-out wind speed is the wind speed at which the wind turbine shuts down to prevent damage. Moreover, the rated wind speed is defined as the wind speed at which the wind turbine starts generating the rated power (maximum capacity of power production).

Region I comprises wind speeds up to the cut-in speed. In this region, these wind speeds have insufficient airflow momentum to start the wind turbine operation. As such, there is no power production, and the cut-in speed is defined as the wind speed at which the wind turbine starts generating power [6]. In Region II, the wind turbine operates below its rated power. Variable-speed wind turbines have mechanisms to adjust the revolving speed of the rotor as a function of the wind speed, which allows sustaining the power coefficient C_P at its maximum during the wind speed intervals of this region [7]. In this region, the power production of the wind turbine increases approximately with the cube of the incoming wind speed. The wind turbine generates and maintains the rated power along the wind speeds of Region III. In this region, the wind turbine also uses control mechanisms. However, the control mechanisms actuate differently than region II, as they actuate to sustain the rated power in the wind speed range. The rotation speed and generated power must be sustained not to overload the generator and prevent damage to any components [6]. In Region IV, the wind speed is too high, and the wind turbine is shut off to avoid damage and overload.

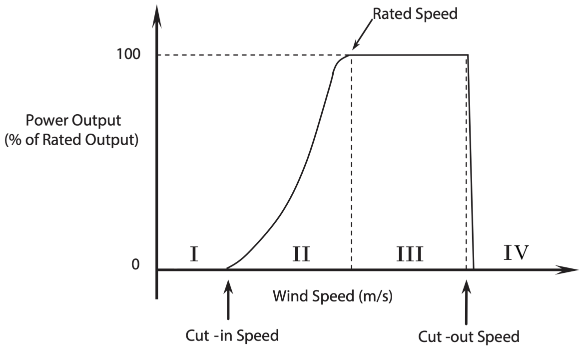


Figure 2: Typical variable-speed wind turbine power curve. Adapted from [5]

2.2. Wind Farm Aerodynamic Interactions

The operation region of wind turbines makes part of the Atmospheric Boundary Layer (ABL) and is characterized by complex phenomena that can difficult the flow modelling around them. Although the complex phenomena that occur at the ABL can be challenging to model, the velocity profile is usually modelled using a simple logarithmic approximation [8]:

$$U(z) \propto \ln\left(\frac{z}{z_0}\right) \tag{1}$$

Power extraction of the wind performed by a wind turbine causes a change in the wind flow downstream. This modified wind flow is named wake. The wake induced by a wind turbine in operation is space and time-dependent. Therefore, as the wake propagates downstream, it has different characteristics that can change over time, influenced mainly by the operation of the wind turbine and by the inflow wind conditions [5]. Furthermore, the wake changes its characteristics based on external site-dependent parameters, such as ambient turbulence and air density.

A wind turbine wake can be characterized by wind velocity deficit, raised turbulence intensity, wake recovery, wake meandering, wake expansion, wake deflection, wake skewing, and vertical wind shear [5]. However, not all characteristics can be assumed as steady-state, namely wake meandering. Therefore, some of them will not be modelled in the present work due to the highly complex phenomena or the assumptions made.

The wind velocity deficit and increased turbulence intensity behind a wind turbine occur due to energy extraction and blade rotation. An operating wind turbine extracts kinetic energy from the airflow that passes through its cross-sectional area. Consequently, the flow region behind the wind turbine is characterized by decreased wind velocity and increased turbulence. As the wind goes through the turbine blades in motion, the wake downstream is induced with a rotational component that creates unsteady loads [9]. This complex region accounts for unsteady events requiring high computational power tools to model them. However, using more straightforward analytical tools to predict wind turbine wake behaviour is possible. For example, as the wake propagates downstream, its expansion is a function of the wind speed, wind direction, atmospheric stability, ambient turbulence, and added turbulence generated by upstream wind turbines [10]. In addition, an isolated wind turbine in a single wake has a wind speed deficit predominantly determined by the thrust coefficient C_T [10], which is given by:

$$C_T = 4a(1-a), \tag{2}$$

where T is the thrust force and a the induction factor.

Accurately assessing the wind turbine wake interactions requires accurate wake models. Numerical wake models can accurately compute the wake effects on downwind turbines; however, these models are computationally expensive. As a result, analytical models are preferred due to their simplicity and low computational cost while still showing sufficiently accurate results for wind farm power prediction [11].

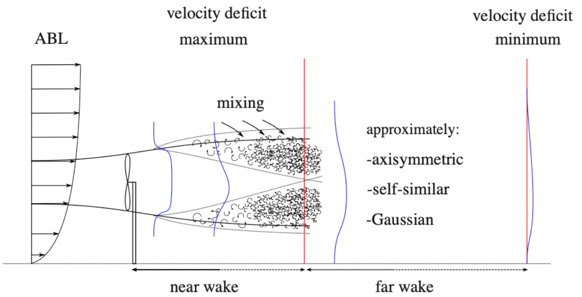


Figure 3: Velocity profile in the wake of a wind turbine for near and far wake regions. The wind flow is represented by the ABL. Retrieved from [8].

As shown in Figure 3, a Gaussian shape can approximately describe the velocity deficit in the far wake region. Several experimental and numerical studies have concluded that the normalized velocity deficit in the far wake region follows a self-similar Gaussian shape [12, 13, 14]. In line with the similarity between the velocity deficit in the far wake region with a Gaussian profile, studies have shown that a Gaussian wake model can provide better results for both partial and full-wake conditions than a top-hat shape wake model, as the Jensen velocity deficit model [11]

2.3. Gauss Velocity Wake Model

This wake model includes variables that allow accurate results compared to the Jensen wake model. Turbulence intensity, one of the parameters included in the model, plays a significant role in wake recovery. As the wake propagates downwind, the rate at which the velocity deficit decreases depends on the turbulence intensity at the wake. Moreover, this phenomenon is attributed to the turbulent mixing with the incoming flow. Higher turbulence intensity leads to faster turbulent mixing with the freestream flow, causing the wake velocity deficit to decrease faster along the downwind distance. Simulations and experimental studies have shown this behaviour [13]. Hence, the power production should be influenced by the atmospheric ambient turbulence and the added turbulence induced by each wind turbine rotor, considering a large wind farm.

The Gaussian wake model is composed of several papers with contributions from different authors, including M. Bastankhah and F. Porté-Agel [15] [16], Niayifar and Porté-Agel [11] and Dilip and Porté-Agel [17]. This model comprises different modules containing different models: a wake deflection model, a self-similar velocity deficit model and elements of atmospheric stability, including a wake turbulence model. In addition, a wake superposition model is necessary to add up the effects of multiple wakes in alignment. Although the wake deflection model can be crucial in modelling conditions of yaw misalignment, this study assumes that the wind turbines are always aligned with the wind direction. Hence, the wake deflection model can be deemed less important.

The integral form of the streamwise momentum equation is considered to obtain the velocity profile at the far wake region. By applying mass and momentum conservation and neglecting viscous and pressure forces, one can obtain

$$\rho \int U_W \left(U_\infty - U_W\right) dA = T. \tag{3}$$

Equation 3 represents the rate at which the airflow momentum is removed at the wind turbine rotor plane, as A represents the rotor swept area.

The self-similarity in the wake can describe the wake velocity at a certain distance downwind x in the wake centre as

$$U_W = U_\infty \left(1 - C(x)e^{-\frac{r^2}{2\sigma^2}}\right), \tag{4}$$

where $C(x)$ represents the maximum normalized velocity deficit at each downstream location, r is the radial distance from the centre of the wake, and σ is the standard deviation of the Gaussian-like velocity deficit profile at each downstream location.

Integrating Equation 3 from 0 to ∞ after inserting Equations 2 and 4 results in a two-value solution for $C(x)$. However, only the solution that predicts the smaller value for the velocity deficit is physically admissible. Thus, one can obtain the following equation:

$$C(x) = 1 - \sqrt{1 - \frac{C_T}{8(\sigma/D)^2}}. \tag{5}$$

If a linear expansion for the wake region is assumed, the term σ/D can be written as

$$\sigma/D = k^* \frac{x}{D} + \varepsilon, \tag{6}$$

where $k^* = \partial\sigma/\partial x$ is the growth rate and ε is the value of σ/D when x approaches zero. To determine the value of ε, one must equate the total mass flow deficit rate at x = 0 for this Gauss velocity deficit model and the Frandsen wake model [18]. Consequently, the value of ε can be determined by

$$\varepsilon = 0.25\sqrt{\beta}, \tag{7}$$

where

$$\beta = \frac{1}{2}\left(\frac{1 + \sqrt{1 - C_T}}{\sqrt{1 - C_T}}\right). \tag{8}$$

Even though the previous formulation assumed a constant wake expansion k^*, the same authors of the wake velocity deficit described above (Bastankhah and Porté-Agel [15]) showed that the wake growth rate increases as turbulence intensity increases. Therefore, to increase the accuracy in modelling the wake expansion, Niayifar and Porté-Agel [11] proposed an empirical equation as a function of the local turbulence intensity I, given by

$$k^* = 0.3837I + 0.003678. \tag{9}$$

This empirical equation was obtained for a range of conditions ($0.065 < I < 0.15$).

2.4. FLORIS

FLOw Redirection and Induction in Steady State (FLORIS) is a numerical tool developed by the National Renewable Energy Laboratory (NREL) and the University of TU-Delft, which is used to simulate and analyze the behavior of wind turbines in large wind farms. FLORIS considers the wake interactions between turbines and the surrounding atmospheric conditions to predict a wind farm's power output and overall performance.

FLORIS performance has been compared and validated to high-fidelity software results like SOWFA [19] and SCADA data, as demonstrated in multiple studies [20, 21]. The comparisons have shown good agreement between the results of the FLORIS and other simulations.

2.5. Offshore Operation and Maintenance (O&M)

The total lifetime expenditure of a wind turbine can be divided into CapEx, OpEx, and DecEx [22]. The OpEx can be further subdivided into operation and maintenance costs, being the objective of this study to minimize the maintenance costs.

Offshore wind projects can leverage the absence of size constraints to deploy larger wind turbines, which offer greater energy production potential and improved cost efficiency due to economies of scale. Therefore, creating better O&M strategies that enhance power production is crucial to minimize OpEx and improve cost competitiveness.

On the one hand, it is crucial to visit wind turbines regularly to avoid unexpected failures in an offshore wind plant and increase its overall availability. On the other hand, unnecessary visits increase the costs of personnel and vessels available to perform the task without significantly benefiting the offshore wind plant performance. Therefore, a reliable maintenance strategy is crucial in O&M activities. Ultimately, an effective maintenance strategy is a trade-off between human resources, vessel management, and associated risks to the offshore environment conditions [22].

Different approaches can be taken into consideration when it comes to maintenance strategies. Generally, maintenance can be classified into four categories: reactive (corrective), preventive, condition-based, and predictive. Preventive maintenance is considered proactive and aims to avert failure before it occurs. Moreover, this type of maintenance allows for better management of resources since it is planned. Typically, preventive maintenance is performed in specific time windows for conditions that allow on-site interventions. The number of planned interventions per year is calculated based on factors such as meteorological conditions and required time window [23]. A purely preventive maintenance strategy can effectively minimize downtime losses caused by component failure events by proactively conducting maintenance tasks regularly to prevent catastrophic failures and reduce the need for unscheduled interventions. Preventive maintenance strategies are

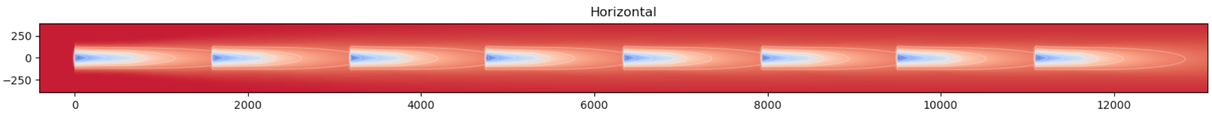


Figure 4: Wake modelling in a scenario with a wind speed magnitude of 8 m/s and a spacing of 8D. Horizontal plane at hub height wake simulation. Colder colors represent higher velocity deficits. IEA 10 MW wind tubines.

described as an optimal maintenance scheduling problem, aiming to reduce costs while granting good power production availability [22].

For safety reasons, O&M work offshore requires sufficiently long windows of suitable weather conditions. Consequently, weather restrictions are a significant factor in scheduling O&M activities, as they must be carefully planned and timed to ensure safe and effective execution. In addition, this limitation makes decision-making in O&M activities prone to uncertainty, impacting total costs.

3. Methodology

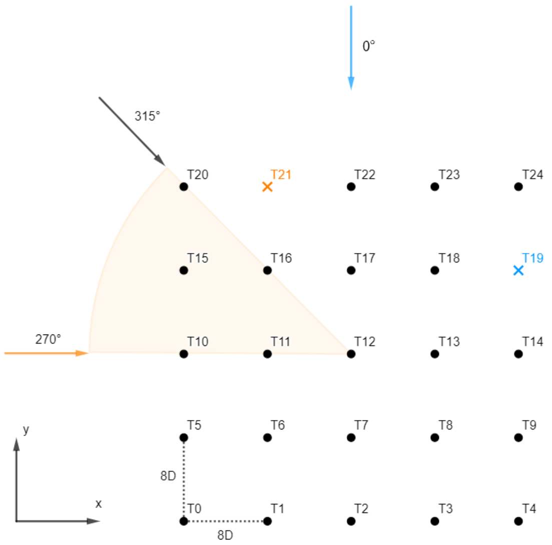


Figure 5: 25 turbine offshore wind farm in a squared layout with 8D spacing. Wind directions are represented with arrows and their respective angle.

Simulations were conducted using the FLORIS tool for different scenarios to quantify how design variables (such as farm layout, turbine model, wind speed magnitude and direction) affect the O&M decisions. The results aim to better understand wind turbine performance behaviour in a wind farm context.

First, the performance of a single wind turbine array was analyzed using the IEA 10 MW turbine model. Eight wind turbines were positioned in a straight line, as illustrated in Figure 4. The analysis consisted of imposing a wind flow aligned with the string of wind turbines so that downstream turbines are immersed in the wake flow of upstream turbines in non-yawed conditions. Then, several scenarios were modelled for different wind speeds (3.3 m/s, 8.0m/s, 11.0m/s, and 12.0m/s)and wind turbine spacing conditions (4D, 6D, 8D, and 10D). This analysis aims to assess the wind turbines' power production in these conditions. Table **??** presents the different simulated cases to assess the power production of each one of the turbines for different conditions.

Second, some preliminary assessments were also obtained, considering a squared layout. Although a line array analysis can provide important clues about the performance behaviour of each turbine in a wind farm, it is still crucial to consider a more realistic layout arrangement. The simulation considered in this section is based on a five-by-five IEA 10 MW wind turbine squared layout equally distanced by eight diameters (8D) in both x and y directions, as shown in Figure 5. As a result, 25 wind turbines are modelled for different wind directions. Given the symmetry of the squared layout, it is enough to only simulate a range of 45 degrees of wind directions, as illustrated in Figure 5 to cover all relevant conditions.

Finally, in order to quantify the potential benefits of implementing an O&M strategy that optimizes preventive maintenance scheduling considering wind conditions and turbine wake effects, a case study was defined considering a squared layout with 25 turbines with a 15 MW power rating. This case study uses 21-year hindcast meteoceanic data from Viana do Castelo, located on the northwest coast of Portugal. This data has hourly information from 1992 to 2012 regarding wind speed, wind direction, and significant wave height. These are the crucial variables that will be used to assess the wind farm's power production and determine if it is possible to perform marine operations in the offshore wind farm.

4. Results & discussion

Concerning the turbine line array analysis, the results have shown that for most of the wind speed magnitudes and spacings, the wind turbine that yields less power is the one immediately downstream of the turbine that faces undisturbed airflow. At this turbine, the velocity deficit is higher. As the combined wakes propagate downstream, the wind speed slightly increases asymptotically in the remaining turbines downwind.

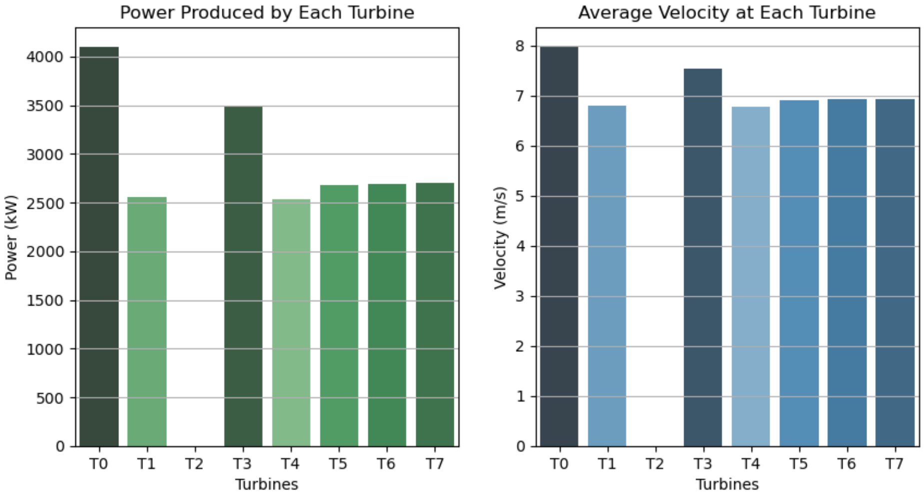


Figure 6: Power (left) and average velocity (right) at each wind turbine for case 7 with turbine $T2$ deactivated.

However, for higher wind speeds, C_T significantly decreases in a short range. Therefore, the impact of the wake will be different, as C_T greatly influences the wake. Higher thrust levels in wind turbines result in faster wake recovery due to increased turbulence but also lead to a greater velocity deficit downstream [1]. In contrast, lower thrust levels result in slower wake recovery rates [24].

After checking the performance behaviour of the wind turbine line array aligned with the wind direction, a further analysis was conducted by deactivating one wind turbine at a time. This analysis aims to assess the performance behaviour of each turbine in the context of executing preventive maintenance. Likewise, the total power generated by the turbine line array is determined for each deactivated turbine.

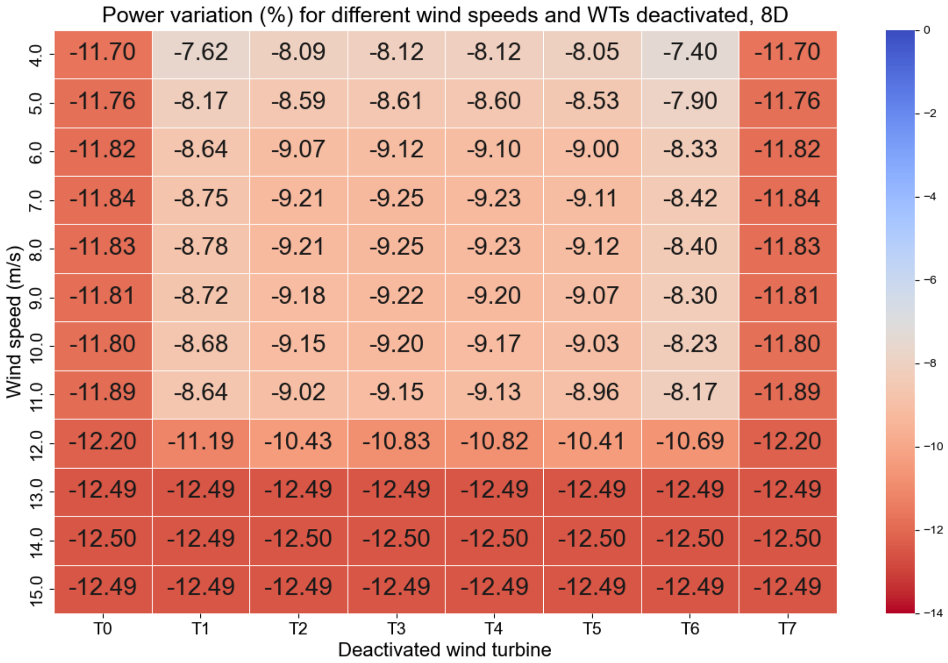
For example, in Figure 6, one can see the results for power production and average wind velocity at each turbine when the third turbine ($T2$) is shut down. On the one hand, if all wind turbines were active, wind turbine $T3$ would be generating 2695 kW, with an average inflow wind speed of 6.93 m/s. On the other hand, for the same conditions, if turbine $T2$ is deactivated, turbine $T3$ would be generating 3479 kW, with an inflow wind speed of 7.54 m/s. Nevertheless, the increased power production of turbine $T3$ does not compensate for the power loss from the deactivation of turbine $T2$. In fact, the total power generated is reduced by around 9.2 % when the turbine $T2$ is deactivated.

The power variation was computed for multiple wind speeds to understand better the performance of the entire wind turbine line array upon the deactivation of one at a time of its wind turbines. As a result, Figure 7 presents a table with the power production variation for each respective deactivated wind turbine. The inflow wind direction remains constant and parallel to the alignment of the wind turbine line array.

On the one hand, it can be seen that for velocities higher than 13 m/s at hub height, the power variation is equal to -12.5 % for every deactivated wind turbine. This constant power loss in the turbine line array for every deactivated wind turbine is explained by the fact that wind speeds equal to or above 13 m/s induce every turbine to operate at the rated wind speed or above. Therefore, every wind turbine generates 10 MW. On the other hand, for undisturbed airflows and farm operating conditions that lead to an incident wind speed at turbine level that falls between cut-in and rated-wind speeds, it can be seen that different selected wind turbines impact the total output power differently.

It can be observed that the first $T0$ and last $T7$ wind turbines induce more power losses when deactivated compared to the remaining ones. In the studied line array layout, these turbines have the particularity of being under undisturbed airflow ($T0$) or not causing a wake to any turbine downstream ($T7$). All the other wind turbines ($T1 - T6$) are under the two conditions mentioned: they both operate in waked flow and aggravate the wake flow on downstream turbines. Therefore, when all wind turbines are available for maintenance, these results suggest which turbines have a lower impact on power losses when shut down.

Regarding the wind farm squared layout, the results suggested that the wind farm's power production behaviour after shutting down every turbine for multiple wind speeds does not significantly impact the best sequence of turbines to shut down for maintenance. The selection of a wind turbine



Wind speed (m/s)	T0	T1	T2	T3	T4	T5	T6	T7
4.0	-11.70	-7.62	-8.09	-8.12	-8.12	-8.05	-7.40	-11.70
5.0	-11.76	-8.17	-8.59	-8.61	-8.60	-8.53	-7.90	-11.76
6.0	-11.82	-8.64	-9.07	-9.12	-9.10	-9.00	-8.33	-11.82
7.0	-11.84	-8.75	-9.21	-9.25	-9.23	-9.11	-8.42	-11.84
8.0	-11.83	-8.78	-9.21	-9.25	-9.23	-9.12	-8.40	-11.83
9.0	-11.81	-8.72	-9.18	-9.22	-9.20	-9.07	-8.30	-11.81
10.0	-11.80	-8.68	-9.15	-9.20	-9.17	-9.03	-8.23	-11.80
11.0	-11.89	-8.64	-9.02	-9.15	-9.13	-8.96	-8.17	-11.89
12.0	-12.20	-11.19	-10.43	-10.83	-10.82	-10.41	-10.69	-12.20
13.0	-12.49	-12.49	-12.49	-12.49	-12.49	-12.49	-12.49	-12.49
14.0	-12.50	-12.49	-12.50	-12.50	-12.50	-12.50	-12.50	-12.50
15.0	-12.49	-12.49	-12.49	-12.49	-12.49	-12.49	-12.49	-12.49

Figure 7: Power variation for each deactivated wind turbine at different wind speeds. Distance between turbines of 8 rotor diameters.

to be shut down for maintenance is more heavily influenced by wind direction than wind speed magnitude, as the farm yield losses are more affected by the former. Therefore, given the negligible impact of the wind speed in the sequence of wind turbines that minimizes the power losses upon deactivation, it was assumed that considering a single wind speed was adequate to assess the sequence of turbines for all the operational wind farm's wind speeds. The choice of a wind speed of 5 m/s at a 10-meter reference height was based on the mean wind speed value of the meteorological data used in the case study.

Concerning the case study, it aimed to investigate the differences in downtime loss caused by selecting different turbines to perform maintenance. The obtained results were computed based on the following assumptions:

- Preventive maintenance must be performed on all wind turbines.
- Preventive maintenance was performed whenever possible. As discussed earlier, forecasts have high fidelity up to 72 hours of lead time. Forecasting the ocean and weather conditions for a long lead time is not feasible. Therefore, to ensure the execution of preventive maintenance to all wind turbines of a wind farm, preventive maintenance is performed when the necessary conditions are met. In this way, the probability of executing maintenance to all wind turbines in a year is high.
- Turbines are shut down at the beginning of each maintenance 10-hour shift, being reactivated at the end of each maintenance shift.
- It was considered that each visit to a turbine for preventive maintenance is fully independent of the previous one. In other words, no precedence rules were considered.
- Each year was independent, meaning a wind turbine with maintenance performed in December 1992 could initiate preventive maintenance in January 1993, for example.

Three scenarios were considered to assess the obtained results:

- **Preferable scenario**: this scenario refers to the maintenance scheduling of the estimate of the set of turbines that minimizes downtime losses in the wind farm during the preventive maintenance period.
- **Sequential scenario**: this scenario refers to a case in which preventive maintenance is performed sequentially and consecutively to the same turbines by order. Downtime losses are not taken into account to schedule maintenance.
- **Least preferable scenario**: this scenario refers to the maintenance scheduling of the estimate of the set of turbines that maximizes downtime losses in the wind farm during the preventive maintenance period.

The scenarios considered were intended to provide a scope for the actual operation of an offshore wind farm by being compared to each other. On the one hand, the preferable scenario was intended to demonstrate a close-to-optimum result in

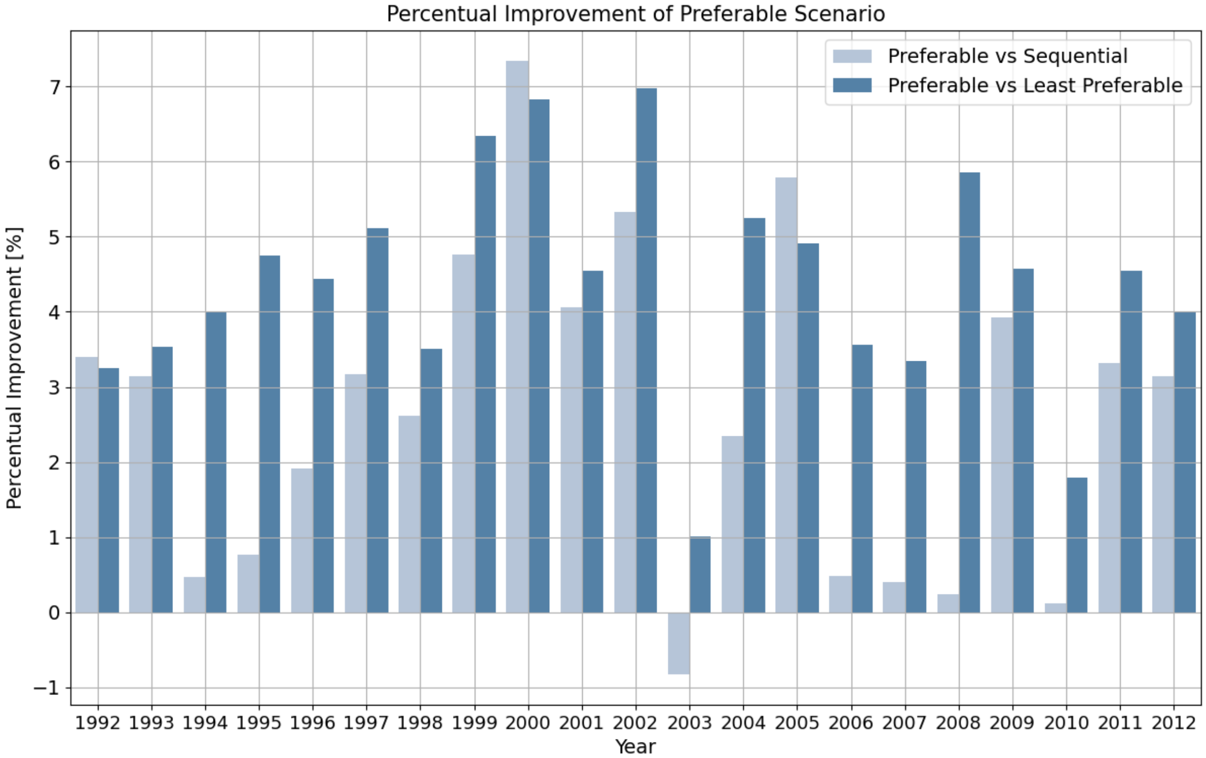


Figure 8: Percentual improvement of downtime losses in each year due to preventive maintenance. Results obtained using the algorithm.

downtime losses during the lifetime of an offshore wind farm. This scenario used both approaches to schedule maintenance to the turbines that reduce the downtime losses for each meteorological condition of each maintenance shift. On the other hand, the sequential scenario intended to provide results for the case where an offshore wind turbine operator did not consider wake effects when scheduling preventive maintenance. Therefore, the selected turbines for maintenance followed a sequential order to only perform the required yearly maintenance hours for each turbine. Lastly, the least preferable scenario used both approaches to schedule maintenance to the turbines, increasing the downtime losses for each meteorological condition of each maintenance shift. This scenario intends to obtain results demonstrating the highest possible downtime losses caused due to preventive maintenance.

The results obtained can be considered far from the optimum results, especially using the first approach, which used the average wind direction to select the best set of turbines to deactivate in each maintenance shift. Therefore, the selection for maintenance of the set of unique turbines based on the average wind direction does not guarantee that it yields a near-optimum result regarding downtime losses. Furthermore, during each 10-hour shift, the range of wind directions can be broad. As a result, more than using a single wind direction to assess the near-optimum set of turbines for minimizing the downtime losses is required. However, the computation time needed to determine all the possible combinations of downtime losses for each shift is unfeasible using mainstream machines. As a result, a second approach was conducted using a random set of possible turbine combinations.

Figure 8 shows the percentual comparison between the downtime losses of the preferable scenario and the other scenarios when executing the second approach. In this approach, the obtained results are significantly better. With an exception for 2003, every other year presented improvements when applying the second approach. Nonetheless, *Preferable vs Least Preferable* comparison was not always higher than the *Preferable vs Sequential* comparison.

Table 1 presents the total downtime losses during the considered 21 years for each scenario and approach, while Table 2 summarizes the improvements for the 21 years of meteoceanic data for each scenario using the two approaches.

The percentual interval between the set of turbines that induces the lower downtime losses with the set of turbines that generates the higher downtime losses is significant but not prominent. Moreover, a wide range of turbine combinations induces similar downtime losses upon deactivation. Therefore, considering an optimization algorithm that can compute a close-to-optimum solution with low com-

Table 1: Downtime losses of preventive maintenance during 21 years for each scenario and approach.

	Preferable	Sequential	Least Preferable
Downtime losses [MWh] (first approach)	94386.1	95946.0	97141.0
Downtime losses [MWh] (second approach)	93364.4	95946.0	97607.0

Table 2: Percentual improvement of the preferable scenario over the sequential and least preferable scenarios. Preventive maintenance for 21 years for the two considered approaches.

	Preferable over Sequential	Preferable over Least Preferable
Improvement [%] (first approach)	1.63	2.84
Improvement [%] (second approach)	2.69	4.35

putational resources is challenging.

5. Conclusions

The present study aimed to assess the potential impacts of considering wake interactions when scheduling preventive maintenance operations in an offshore wind farm. However, the scheduling decision problem involves a significantly large number of variables, demanding high computational effort. As a result, preliminary analyses were conducted to simplify the problem, identify rules of thumb, and understand which factors significantly influence wind turbine maintenance scheduling when considering farm wakes. The preliminary studies, using FLORIS to simulate simplified farm layouts, provided the means to better understand the problem at a low computational cost.

This research work has suggested some interesting conclusions:

- When a string of wind turbines is aligned with the wind direction, the results suggest that the velocity deficit does not progressively increase for downstream turbines in the string. Instead, the velocity deficit in downstream turbines decreases asymptotically, except for the turbine(s) immediately downstream of the turbine that faces the freestream wind flow, depending on the spacing and wind speed magnitude.
- The performed analysis and obtained results suggest that, for a squared and equally spaced wind farm layout, wind speed and turbine power rating have a reduced or null impact on the decision of which turbines to shut down to minimize downtime losses considering wake effects, in contrast to wind direction, which has a significant impact.
- The number of wind turbines in offshore wind farms is increasing, and in the future, risk-based maintenance approaches that involve only scheduling preventive maintenance for a representative sample of wind turbines every year will likely be implemented. As a result, considering wake interactions for preventive maintenance in only a sample of turbines may present a lower and marginal impact on the downtime losses of bigger offshore wind farms.
- Lower wind speeds yield lower power production. Hence, regarding energy production, low velocities induce lower downtime losses in case of shutting down a wind turbine. However, percentually speaking, the results of this study have shown higher potential when considering wake interactions for scheduling preventive maintenance during periods of low wind speed. Even though the gains are higher in relative terms, they are still small in absolute terms.
- Concerning the overall result of an offshore wind farm during 21 years of hindcast meteoceanic data, it can be concluded that there are improvements in the total downtime losses caused by the deactivation of turbines for preventive maintenance. However, the results suggest that implementing such a strategy yielded a partial improvement potential. In addition, preventive maintenance only covers some of the necessary maintenance operations for an offshore wind farm.

References

[1] Francisco Haces-Fernandez, Hua Li, and David Ramirez. Improving wind farm power output through deactivating selected wind turbines. *Energy Conversion and Management*, 187:407–422, May 2019.

[2] Junqiang Zhang, Souma Chowdhury, Jie Zhang, and Achille Messac. Optimal Scheduling of Preventive Maintenance for Offshore Wind Farms. In *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Indianapolis, Indiana, September 2012.

American Institute of Aeronautics and Astronautics.

[3] Subhadeep Bhattacharjee. Wind power technology. In *Sustainable Fuel Technologies Handbook*, pages 123–170. Elsevier, 2021.

[4] S. Mathew and G.S. Philip. Wind Turbines: Evolution, Basic Principles, and Classifications. In *Comprehensive Renewable Energy*, pages 104–123. Elsevier, 2012.

[5] S. Boersma, B.M. Doekemeijer, P.M.O. Gebraad, P.A. Fleming, J. Annoni, A.K. Scholbrock, J.A. Frederik, and J-W. van Wingerden. A tutorial on control-oriented modeling and control of wind farms. In *2017 American Control Conference (ACC)*, pages 1–18, Seattle, WA, USA, May 2017. IEEE.

[6] Chakib Chatri and Mohammed Ouassaid. Advanced control of PMSG-based wind energy conversion system applying linear matrix inequality approach. In *Renewable Energy Systems*, pages 235–253. Elsevier, 2021.

[7] Md. Faruque Hossain. Energy. In *Sustainable Design and Build*, pages 67–135. Elsevier, 2019.

[8] Benjamin Sanderse. Aerodynamics of wind turbine wakes Literature review. January 2009.

[9] Balram Panjwani, Mihaela Popescu, Jon Samseth, Ernst Meese, and Jafar Mahmoudi. OffWindSolver: Wind farm design tool based on actuator line/actuator disk concept in OpenFoam architecture. *ITM Web of Conferences*, 2:04001, 2014.

[10] R. J. Barthelmie, S. C. Pryor, S. T. Frandsen, K. S. Hansen, J. G. Schepers, K. Rados, W. Schlez, A. Neubert, L. E. Jensen, and S. Neckelmann. Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms. *Journal of Atmospheric and Oceanic Technology*, 27(8):1302–1317, August 2010.

[11] Amin Niayifar and Fernando Porté-Agel. A new analytical model for wind farm power prediction. *Journal of Physics: Conference Series*, 625:012039, June 2015. Publisher: IOP Publishing.

[12] Amin Niayifar and Fernando Porté-Agel. Analytical Modeling of Wind Farms: A New Approach for Power Prediction. *Energies*, 9(9):741, September 2016.

[13] Yu-Ting Wu and Fernando Porté-Agel. Atmospheric Turbulence Effects on Wind-Turbine Wakes: An LES Study. *Energies*, 5(12):5340–5362, December 2012.

[14] Leonardo P. Chamorro and Fernando Porté-Agel. A Wind-Tunnel Investigation of Wind-Turbine Wakes: Boundary-Layer Turbulence Effects. *Boundary-Layer Meteorology*, 132(1):129–149, July 2009.

[15] Majid Bastankhah and Fernando Porté-Agel. A new analytical model for wind-turbine wakes. *Renewable Energy*, 70:116–123, October 2014.

[16] Majid Bastankhah and Fernando Porté-Agel. Experimental and theoretical study of wind turbine wakes in yawed conditions, January 2020.

[17] Deepu Dilip and Fernando Porté-Agel. Wind Turbine Wake Mitigation through Blade Pitch Offset. *Energies*, 10(6):757, May 2017.

[18] Sten Frandsen, Rebecca Barthelmie, Sara Pryor, Ole Rathmann, Søren Larsen, Jørgen Højstrup, and Morten Thøgersen. Analytical modelling of wind speed deficit in large offshore wind farms. *Wind Energy*, 9(1-2):39–53, January 2006.

[19] P Fleming, P Gebraad, J W van Wingerden, S Lee, M Churchfield, A Scholbrock, J Michalakes, K Johnson, and P Moriarty. Sowfa super-controller: A high-fidelity tool for evaluating wind plant control approaches. 1 2013.

[20] Alayna Farrell, Jennifer King, Caroline Draxl, Rafael Mudafort, Nicholas Hamilton, Christopher J. Bay, Paul Fleming, and Eric Simley. Design and analysis of a wake model for spatially heterogeneous flow. *Wind Energy Science*, 6(3):737–758, May 2021.

[21] P. M. O. Gebraad, F. W. Teeuwisse, J. W. van Wingerden, P. A. Fleming, S. D. Ruben, J. R. Marden, and L. Y. Pao. Wind plant power optimization through yaw control using a parametric model for wake effects-a CFD simulation study: Wind plant optimization by yaw control using a parametric wake model. *Wind Energy*, 19(1):95–114, January 2016.

[22] Zhengru Ren, Amrit Shankar Verma, Ye Li, Julie J.E. Teuwen, and Zhiyu Jiang. Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, 144:110886, July 2021.

[23] A. Karyotakis and R. Bucknall. Planned intervention as a maintenance and repair strategy for offshore wind turbines. *Journal of Marine Engineering & Technology*, 9(1):27–35, 2010. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/20464177.2010.11020229.

[24] Jennifer Annoni, Paul Fleming, Andrew Scholbrock, Jason Roadman, Scott Dana, Christiane Adcock, Fernando Porte-Agel, Steffen Raach, Florian Haizmann, and David Schlipf. Analysis of control-oriented wake modeling tools using lidar field results. *Wind Energy Science*, 3(2):819–831, November 2018.