Offshore turbine wake power losses: is turbine separation significant?

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Offshore Turbine Wake Power Losses: Is Turbine Separation Significant?

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Abstract

This paper presents the results of a parametric study of wind turbine wake effects in a hypothetical offshore wind farm with varying turbine separation using a Computational Fluid Dynamics (CFD) model. Results are analyzed from a simulated 40 turbine farm with 60 layout options, 4 wind speeds and 10° directional bins. Results show that increasing turbine separation in one or both directions leads to greater power generation, though this effect diminishes for separations above 8 diameters. Similarly, turbulence intensity is shown to decrease with increases in turbine separation but with little variation beyond 8 diameters. For 3 out of 4 wind speeds when combined with a representative UK offshore wind rose the farm was shown to have an optimal layout orientation along an axis 350°-170°, though the difference in power produced between orientation angles was less than between changes in turbine separation.

Keywords: CFD; Wind Turbine; Offshore Wind; Wakes;

1. Introduction

As the areas allocated for UK offshore wind farms become larger [1], developers are transitioning away from simultaneously locating turbines universally within the area, and towards the evolution of a wind zone by focusing on a series of flexible sub-zones within the allocated area [2]. This process has the financial benefits of staggering the capital expenses and supply chains into manageable size and timeframes whilst also ensuring each sub-zone has a period of operation when they can be more profitable before wake or blockage effects of the adjacent sub-zones

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develop. As a consequence of this, turbine locations in new developments with large zone allocations may be less restricted by the zone's shape than earlier offshore wind farms. This means long-term resource assessments become more significant to the turbine layout design in large farms which are less constrained by government-enforced construction boundaries. Given a constant number of machines, under these conditions developers must balance the costs of longer cables against the potential for higher power generation and lower turbulence induced fatigue.

It is well documented [3] that turbines located downstream of another turbine will be less productive and subject to higher turbulence induced fatigue. However, the UK offshore climatic wind rose exhibits a wide range of prevailing wind sectors [4], suggesting that even if an offshore farm was developed with a regular turbine layout aligned with the local prevailing wind direction, such exact "down-the-line" events would only occur roughly 7% of the time (both directions combined). Although wake effects from such "down-the-line" events can have significant influence over turbine separation design despite their relative infrequency, the events of greater frequency where the wind is not aligned with the farm layout should also be considered for simulation during farm planning.

This work shows the results from computational fluid dynamics (CFD) simulations at a farm level for a theoretical offshore wind farm with 40 turbines and a combined rating of 144MW in 60 different turbine layout options, using 4 wind speeds and 10° directional bins weighted to be representative of the UK offshore climate. Although modern offshore wind farms contain significantly greater numbers of turbines, the layout is considered large enough to draw conclusions about optimal layout spacing within the computing resources available.

2. Method

The CFD simulations were made using Windmodeller to drive the Ansys CFX package of tools [5]. For simplicity and to reduce the computational requirements, all simulations used Reynolds-Averaged Navier-Stokes (RANS) steady state equations neglecting the effects of atmospheric stability and utilised the actuator disk technique for further cost reductions. The turbines simulated were Siemens SWT-3.6 (3.6MW) with a 107m diameter (D) and a hub height 78m above sea level. Turbines were arrayed in either a regular or staggered pattern with 5 rows and 8 columns as shown in Fig. 1 where the row and column separation were constant within each layout option and spacing varied incrementally from 4Dx4D to 8Dx11D respectively between layout options. The 4 wind speeds used in the simulations were 5, 8, 10, and 15ms^{-1} as these are representative of the majority of UK offshore hub height wind speeds as well as being significant locations on the turbine power/thrust curves. Even by utilising the turbine layout rotational symmetry, with 10° direction bins this lead to 3360 individual simulations.
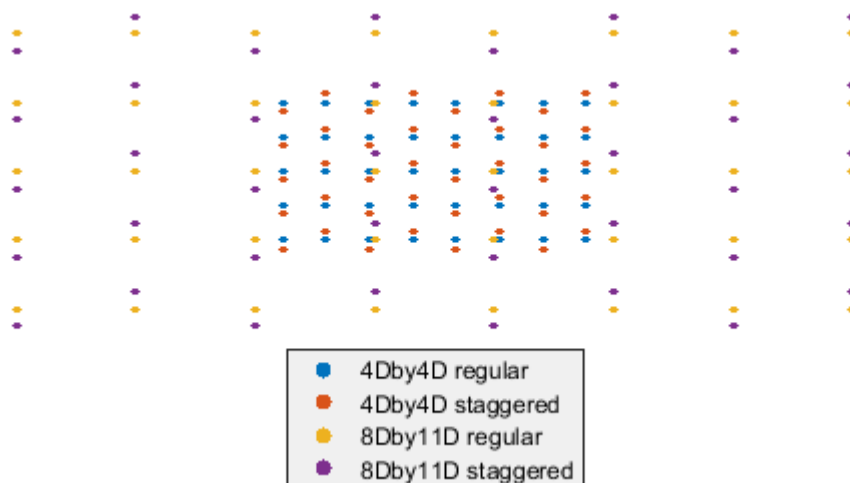

Fig. 1. Example relative turbine layouts showing the extremes in range of turbine separations.

3. Results and Discussion

This work is primarily focused on simulating the expected conditions within an offshore wind farm, namely the mean wind farm level power output to the grid rather than specific and infrequent worst case scenarios of power loss due to turbine wakes aligning with farm layout. During planning it is the potential for trends in financial return at a farm level that will guide the initial layout decisions. It is also important however to build a general understanding of where the potential losses occur along individual rows of turbine. As such, Fig 2 shows the expected "down the line" power ratio (with respect to the first turbine) for the central row of turbines where the flow is parallel to the turbine alignment, with different colours representing different turbine separation options. It is unsurprising that at all speeds, the staggered array suffers lower power losses than the regular array for similar speeds, due to the relatively longer distances between directly wake affected turbines. It is of note that the small difference in power ratios between $8ms^{-1}$ and $10ms^{-1}$ is likely due to similar levels of turbine thrust coefficient between these speeds, although the overall power output increased with speed (not shown here). The increase in power ratio at the second turbine for some staggered arrays suggests that turbine separation combined with flow blockage effects could be utilised to artificially increase local wind speeds, although the lack of this occurring at $15ms^{-1}$ suggests this would improve output only at lower wind speeds. Whilst the separation between turbine rows and columns within the farm were consistent between the regular and staggered arrays, staggering the turbine layout in the span-wise direction effectively increases the overall turbine separation, especially when considering "down the line" scenarios. The effect of this is best seen with a $5ms^{-1}$ inflow where the initial turbines in the regular array utilise most of the available energy leaving downstream turbines little resource to extract. By contrast, the staggered turbines are sufficiently further apart in the stream-wise direction for significant flow recovery to be utilised by downstream turbines. The spike in power ratio at turbine position 3 for the $5ms^{-1}$ regular array suggest something similar may also be possible in regular arrays, if alternate turbines are switched off in low wind speed conditions.
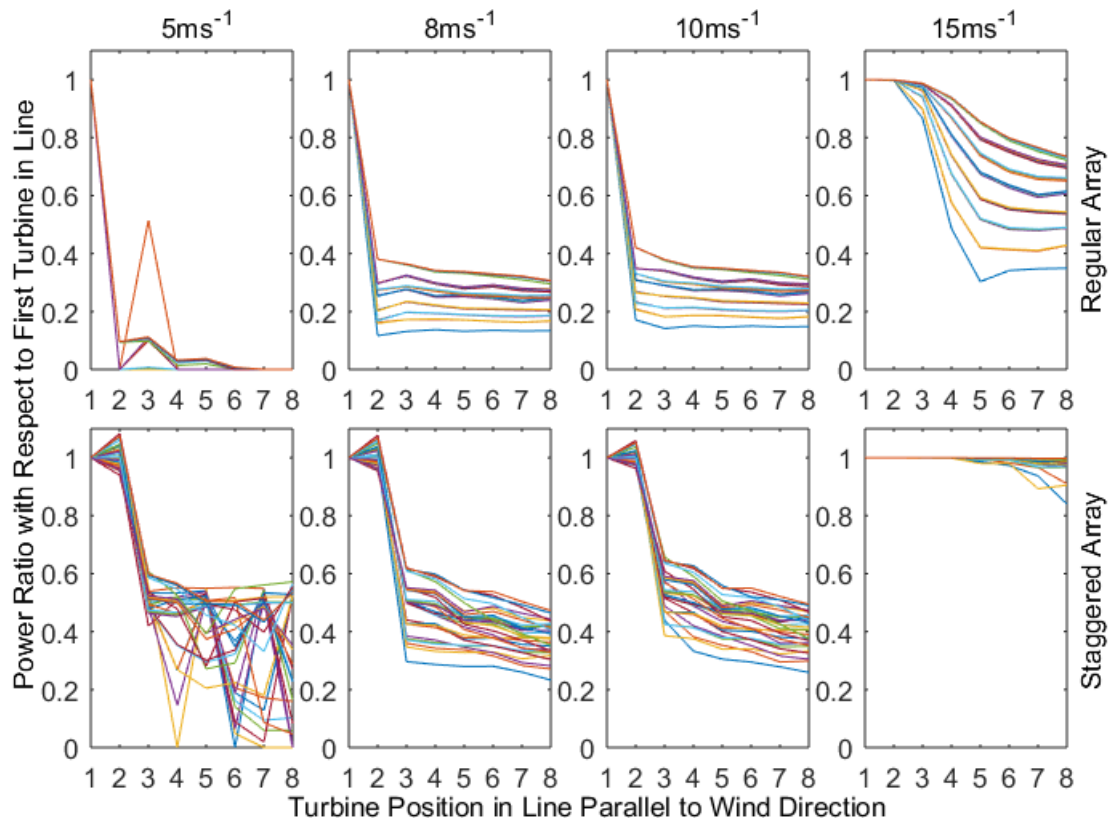

Fig. 2. Power ratios along the central turbine row for different turbine layouts with respect to the power output from the first turbine in the row.

As previously mentioned, if aligned with the prevailing wind (and its opposing direction) UK offshore wind farms only experience "down the line" events for roughly 7% of the time [4], so it is important to consider the farm's potential productivity from all directions. Figure 3 displays the simulated expected power for each array configuration and wind speed assuming an equal likelihood of each wind direction. Although such a uniform wind rose is unrealistic for British waters, the figure displays the significance of turbine separation to power output for key wind speeds. Typically, farm layouts with greater turbine separations return larger expected power production. This is most significant for the 10ms^{-1} wind speed although also significant at the 2 lower speeds, however, turbine separation appears to have little impact at incident wind speed of 15ms^{-1}. Figure 3 also shows that there is value in increasing the turbine separation in both directions as well as utilising a staggered array layout, even when averaged across all wind directions. Below rated wind speeds there is still some difference in power output even between the larger separation distances, although whether this is a significant quantity for developers depends on other factors. Here we are assuming a fixed number of turbines are available to be built whereas in reality, installing another row of machines possibly with individual machines closer together may be more beneficial.
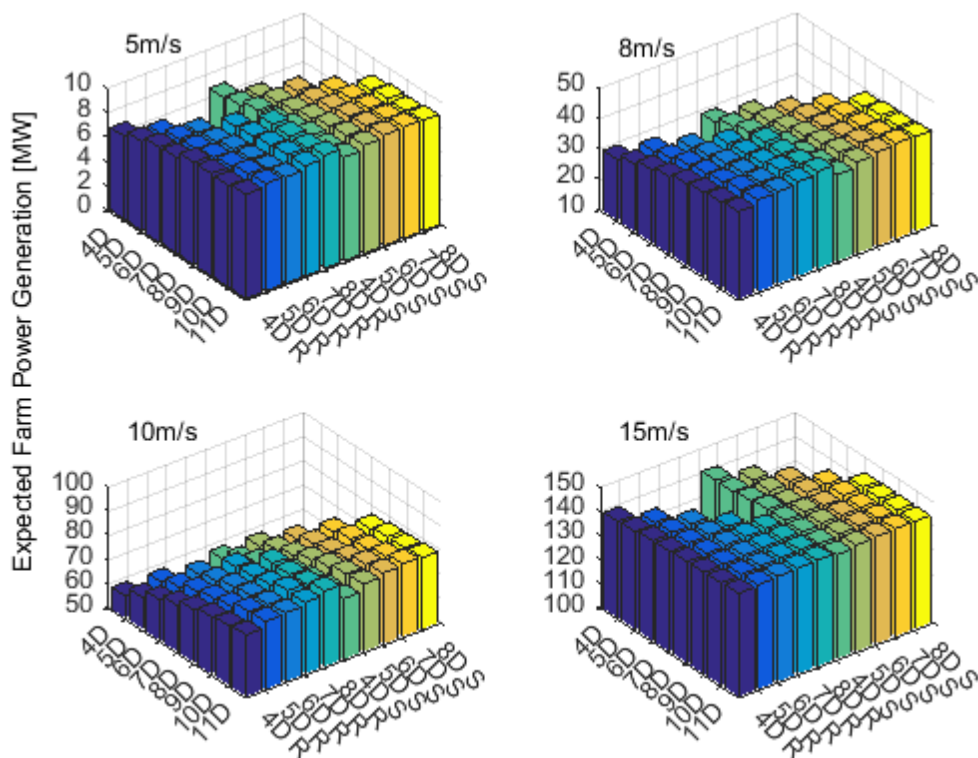

Fig. 3.Expected farm power output by layout assuming a uniform wind rose. R and S denote a regular or staggered array respectively

A uniform wind rose is unrealistic, however, so the rest of this work will assume the UK average offshore wind rose as calculated by [4] when weighting simulated outcomes from multiple directions. It is logical to assume that if the wind rose is non-uniform, there will be an optimum alignment angle between a farm with a regular array layout and the wind rose. Here we define this as the clockwise angle between the prevailing wind direction of 240° and the horizontal row of turbines in Figure 1. Figure 4 shows how the simulated productivity of the wind farm changes by roughly 2% with variation in the alignment, as averaged across all turbine separation options. The maximum power output from a staggered array is achieved consistently at 80° from the East/West parallel, implying an optimal farm orientation with respect to the prevailing wind of 110°. The optimal angle for a regular turbine layout below rated wind speeds is any angle between 60° and 80° from the East/West parallel, implying a 90°-110° optimal angle from the prevailing wind, although for above rated wind speeds, other offset angles are only marginally more productive.

Interestingly, for a location on the other side of the Atlantic but slightly lower latitudes, [1] found an optimal alignment between their modelled farm and the East/West Parallel of 75°.
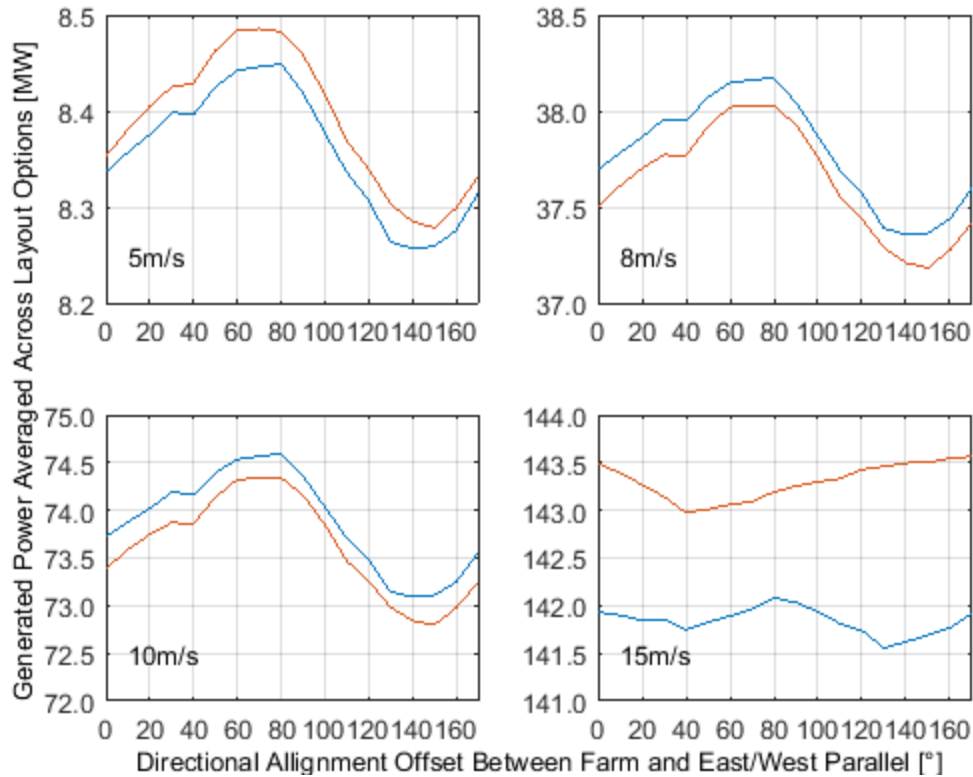

Fig. 4. Average regular (Blue) and staggered (Red) farm power output by layout orientation, assuming an average UK offshore wind rose.

In terms of average power produced relating to the farm orientation shown in Figure 4, it is interesting that for speeds where the turbine thrust coefficient is at its highest (8-10ms⁻¹) a regular array out-performs the staggered array whilst for wind speeds associated with lower turbine thrust coefficients a staggered turbine array produces more power on average. This may be a feature of averaging results from the numerous turbine layouts or it may be a feature of the turbine specifications chosen for this work. Either way the difference in average power output between array options is small. To investigate this further, Figure 5 shows the expected power output from each turbine layout, subject to each wind speed, assuming the optimal farm orientation with the UK average offshore wind rose. It is clear that the differences in average power output between regular and staggered arrays shown in Figure 4 are significantly smaller than the differences in power output between various turbine separation distances when below rated power. The increases in power output available by increasing turbine separation are most significant when increasing turbine separation in both rows and columns simultaneously rather than in either one direction. Above rated power however there is a greater difference in power output between regular and staggered arrays than between similar layouts with small increases in turbine separation, though this is less significant at larger turbine separations as more turbines within the farm operate at rated power and cannot increase output any further.

The results so far show that spacing turbines further apart leads to higher power productivity. However, even with the large development zones available in UK Round 3, space is not limitless and a compromise will need to be found. To assist with deciding how many turbines to locate in a given area, Figure 6 shows the respective power densities for each turbine layout considered in this work. The figure assumes the farm is aligned optimally with the UK offshore wind rose and each of the four wind speeds are weighted according to their proportional frequencies [4]. The figure shows that despite producing lower levels of overall power, the regular array layout with turbines separated by 4D in both directions results in the most power generated per square kilometre.
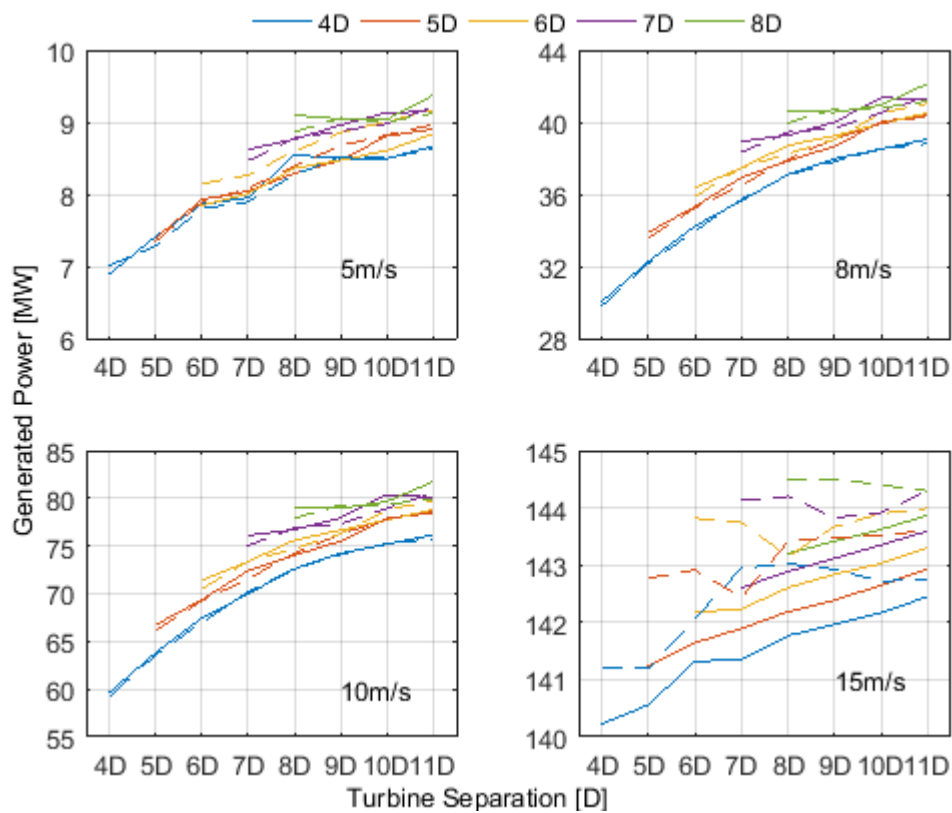
Fig. 5. Expected power output from regular (solid) and staggered (dashed) layouts, assuming optimised farm orientation.
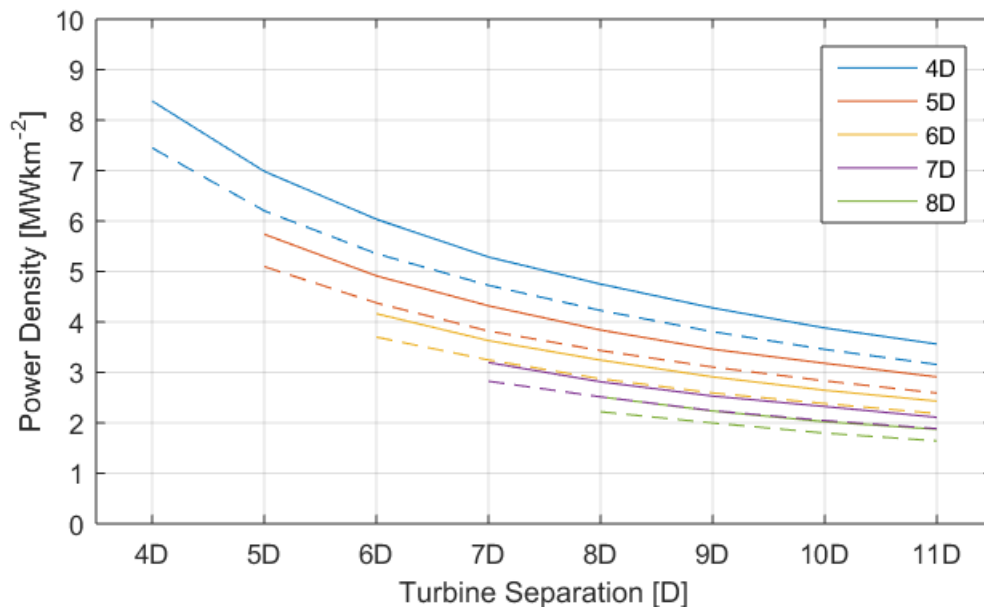

Fig. 6. Expected power density for regular (solid) and staggered (dashed) layouts, assuming optimised orientation and UK wind speed frequency.

Having observed that turbines with greater distances separating them produce more power but at a lower power density, we now consider how turbine separation affects levels of turbulence intensity within the farm. Figure 7 shows how the expected turbulence intensity (having been weighted according to speed and directional frequency distributions) varies with turbine separation distances. For completeness, the maximum and minimum expected values anywhere in the wind farm are shown alongside the mean values. As might be expected there is little difference in the minimum values as these correspond to turbines which experience freestream conditions for significant proportions of the wind directions although some influence is observed from the directional events where such turbines are not in the freestream. It is reasonable to assume most turbines in the simulated farm would register turbulence values similar to the mean expected value whilst the Maximum value shows the maximum expected value throughout the farm during a period of unknown meteorological conditions rather than during a worst case "down the line" scenario. Such worst cases scenarios should be modelled separately to ensure accurate fatigue risk assessments and as such are beyond the scope of this work. Unsurprisingly, Figure 7 shows that increases in turbine separation decrease both the mean and maximum expected turbulence values throughout the farm, as does using a staggered array to a lesser extent, due to increase separation leading to increased opportunity for turbine wake recovery. The significance of varying turbine separation decreases as the separations increase, with only small changes seen for turbine separations greater than 8D in at least one direction.
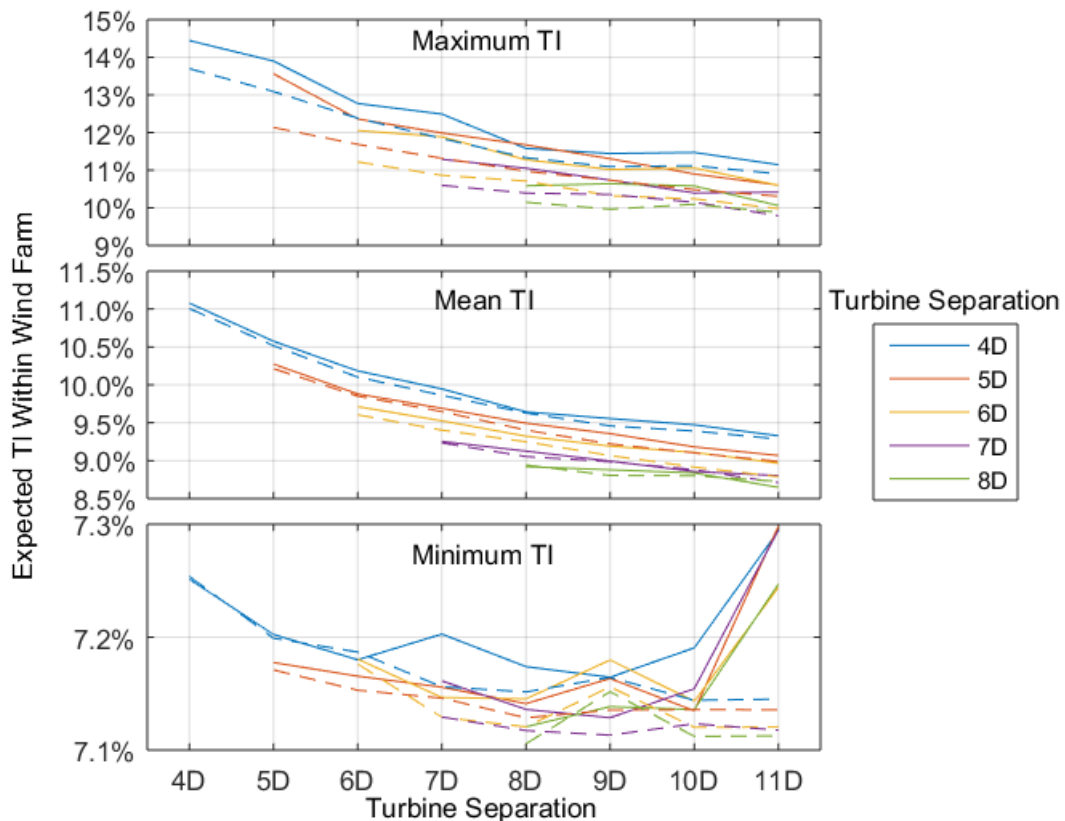

Fig. 7. Expected turbulence intensity at any turbine location within the wind farm

4. Conclusions

This work presented results from CFD simulations of 60 different configurations for turbine layout within an UK offshore wind farm with simulations of 4 different wind speeds at 10° directional bin sizes. The farm was found to have an optimal orientation parallel to the 350°-170° axis in terms of total power production when weighted by

directional frequency according to an average UK climatic offshore wind rose. The difference in productivity due to farm alignment, however, was smaller than the power generation increases with turbine separation distances, although results from both regular and staggered arrays showed that the additional power produced was less significant beyond 8D turbine separation. Links between turbine separation and variation in power output were clearest for wind speeds associated with the highest turbine thrust coefficient, $8ms^{-1}$ and $10ms^{-1}$. Turbulence intensity has also been shown to decrease as turbines are located further apart, most significantly for separation distances less than 8D in either direction but improvements in both mean and maximum turbulence values still observable for the layout with furthest separation (11D by 8D). As a result of these findings and depending on turbine separation constraints, it may be more optimal to consider locating turbines 8D apart from each other as this appears to be where the returns from increased turbine separation become less significant. This could result in available space within allocated development zones for more machines, or reduce the required cabling and wind farm footprint if required. Caution is advised in interpreting the absolute values of these results as these simulation results were obtained using RANS CFD with actuator disks which do not fully resolve the turbulence, however the general trends are likely to be a reasonable representation of reality. Validation against real offshore wind farm data would be beneficial.

Acknowledgements

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