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Chapter 3

Turbine Wake Dynamics

Phillip McKay, Rupp Carriveau, David S-K Ting and Timothy Newson

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/53968

1. Introduction

The extraction of energy from wind across a turbine rotor produces an aerodynamic wake region downstream from the rotor. The wake region is generally associated with a few key characteristics. These include:

- a velocity deficit
- a pressure differential
- an expanding area
- rotation of the wake field
- increased turbulence

Studies of wind turbine wakes range from simplified mathematical approaches to complex empirical models. Wind farm developers also vary in their application of these models for the prediction of losses caused by wakes within a multi-turbine project. While much has been learned in recent years, research continues to reduce uncertainty and increase the accuracy of wake loss calculations. This chapter provides a brief introduction to the accepted principles of wake behaviour, introduces several advanced topics and covers the current state of the art and direction for the future of wake research.

2. Wake fundamentals

Wake influences from one turbine to the next have received the majority of attention in this field of study due to the significant influence this has on performance and reliability. Down-

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stream wake effects are frequently quantified through the use of rotor disc theory and the conservation of linear momentum. The rotor disc refers to the total swept area of the rotor as shown in Figure 1. The expanding wake downstream of the turbine in conjunction with a decrease in wind speed U is also shown.

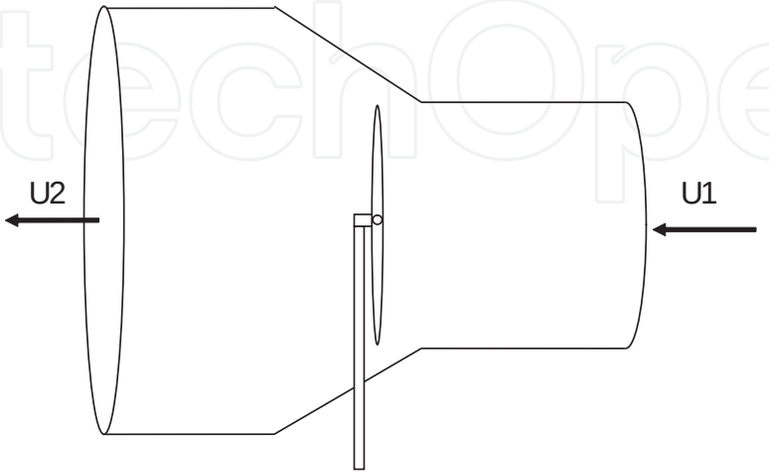


Figure 1. Swept area of wind turbine rotor with expanding wake section [1].

For conservation of mass:

$$\rho A_1 U_1 = \rho A_2 U_2 \tag{1}$$

where ϱ is the air density, A is the cross sectional area, U_1 is the free stream wind speed and U_2 is the wind speed downstream from the turbine. A decrease in wind speed across the rotor area results in a greater downstream area. From elementary energy conservation principles, it can be shown that a high pressure area is formed upstream of the rotor disc and a lower pressure area is formed downstream. This pressure change is due to the work of the rotor blades on the air passing over them. The force of the air on the blades results in an opposing force on the air stream causing a rotation of the air column. This low pressure column of rotating air expands as it moves downstream of the turbine and eventually dissipates as equilibrium is reached with the surrounding airflow [2, 3]. This simplified explanation constitutes what is known as the "wake effect" of a wind turbine [1]. An increase in downstream turbulence is caused by wake rotation, disruption of the air flow across the rotor blades and the vortices formed at the blade tips. This results in less power being available for subsequent turbines.

The Bernoulli equation can also applied to wind turbine wake analysis. The equation follows the concept of conservation of energy:

$$\frac{\rho U_1^2}{2} + p = H \tag{2}$$

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where p is pressure and H is the total energy for the constant streamline. Using the Bernoulli equation and conservation of momentum together the following equation can be developed:

$$U_2 = U_1\sqrt{1 - C_T} \tag{3}$$

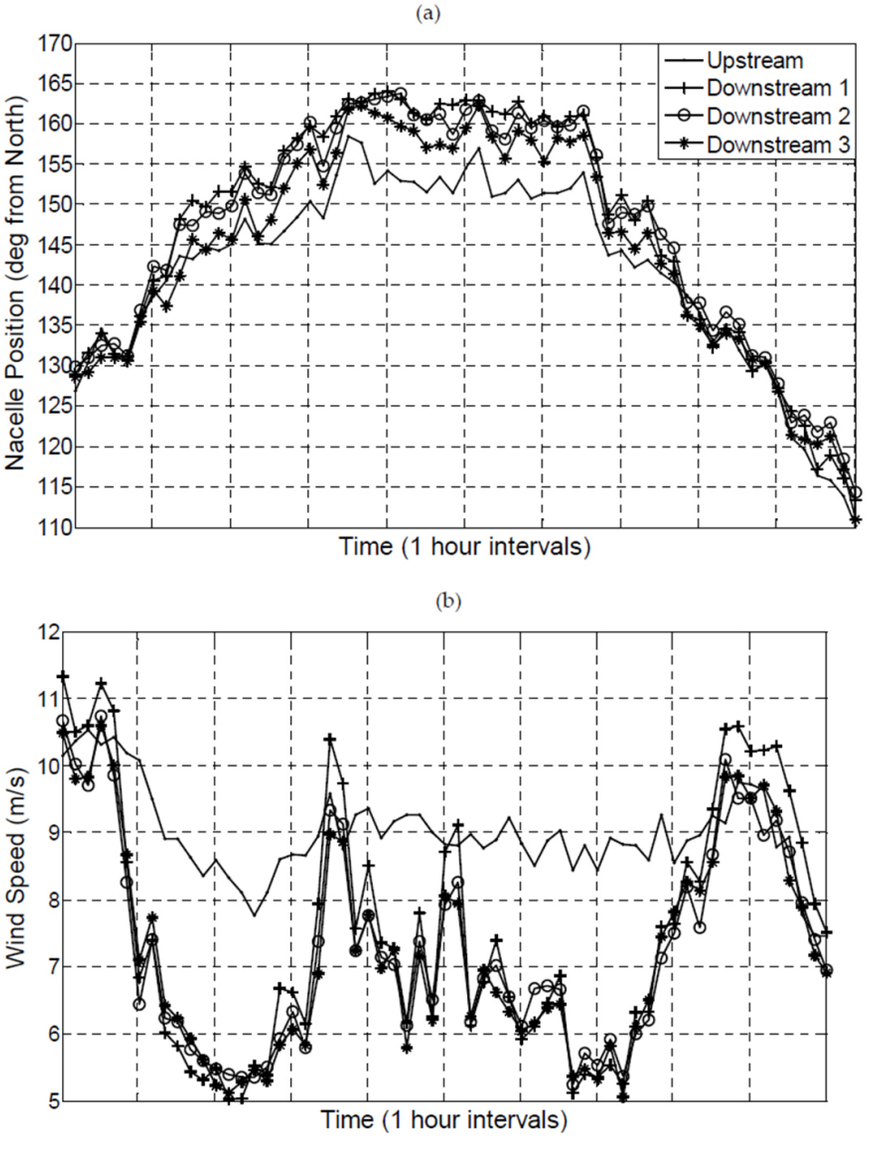
Here C_T refers to the thrust coefficient of the wind turbine. In this way we have a simple wake model for the representation of downstream wind velocity based on the free stream wind speed and the characteristics of the turbine being considered. For more information refer to [4]. While this does include wake expansion it does not consider other factors such as wake rotation. Several other models are currently in use and under development.

The study of wind turbine wakes is broken into two parts: near wake and far wake. The near wake region is concerned with power extraction from the wind by a single turbine, whereas the far wake is more concerned with the effect on the downstream turbines and the environment [7]. Opinions on near wake length have varied, but can be considered to fall in the range of 1 to 5 rotor diameters (1D to 5D) downstream from the rotor disc [5-6], with far wake regions dependent on terrain and environmental conditions. The full extent of far wake length is currently still under study, but may range from up to 15D for onshore sites [8] and up to 14 km for offshore [9]. The 5D to 15D wake region has been defined as an intermediate wake region by some [10], with the far wake pertaining to distances farther than 15D.

Data from an array of turbines within a commercial scale wind farm are given in Figure 2. The turbines are in a straight line with a separation of 4 rotor diameters. Time series data for nacelle position, wind speed and power are given for a wake event affecting 4 turbines. This specific event has a wind direction moving from 120 to 170 degrees from north, clockwise as positive, over a time span of approximately 10 hours. This can be seen in the nacelle position plot for all four turbines in Figure 2a. During this time period the wind direction passes through the alignment condition of 145 degrees from north. An alignment condition refers to a wind direction measured by the lead (upwind) turbine that is coincident with the straight line formed by the turbine row. The nacelle position plot shows the turbines tracking the wind direction while the wind speed plot (Figure 2b) reveals a drop in wind speed for the downstream turbines between the nacelle position range of TA +/- 15 degrees, where TA refers to direct turbine alignment. In addition, the power is shown to drop along the with wind speed (Figure 2c). This is evidence of wake interaction between the four machines. Vermeer et al. [5] found that the wake velocity recovers more rapidly after the first turbine leaving the most dominant effect between the upstream and primary downstream turbine.

The profile of the measured velocity deficit caused by the wake in an array of 4 wind turbines is given in Figure 3. The upstream nacelle position was used as the reference wind direction. The wind speeds of the downstream turbines are given with respect to this wind direction and show the wake centerline as well as the profile of the outer edges of the region. Upstream wind speeds less than 5 m/s are not included due to the added complexity of low wind conditions and cut-in behaviour of the turbines. Wind speeds greater than 11

m/s are also neglected due to the lack of data at these higher speeds and the reduction in wake pronunciation. The wake region extends across a range of 30 degrees (TA +/- 15 degrees) on average for a wind speed range of 5-11 m/s. A number of features are evident in this Figure. The first downstream turbine exhibits the greatest drop in wind speed at approximately 35 %. The second downstream turbine appears to recover by approximately 5 % with respect to free stream velocity under direct turbine alignment. The third in the row shows similar behaviour to the second.



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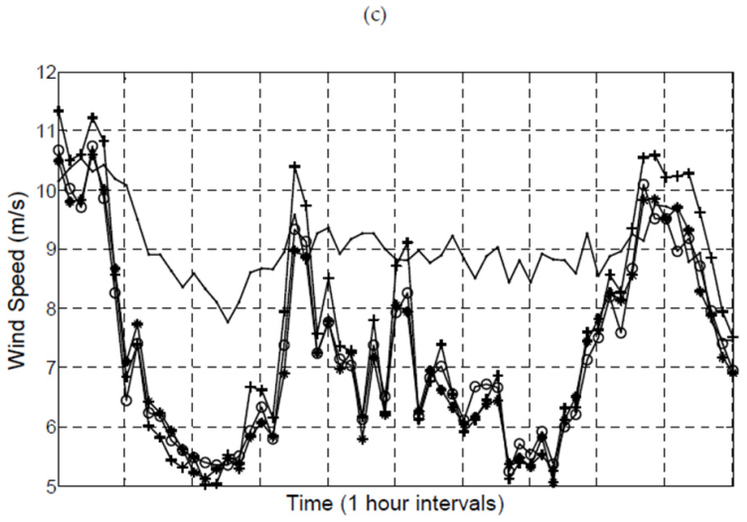


Figure 2. Time series SCADA data for a period containing a case of turbine alignment. a) nacelle position, b) wind speed and c) power [11].

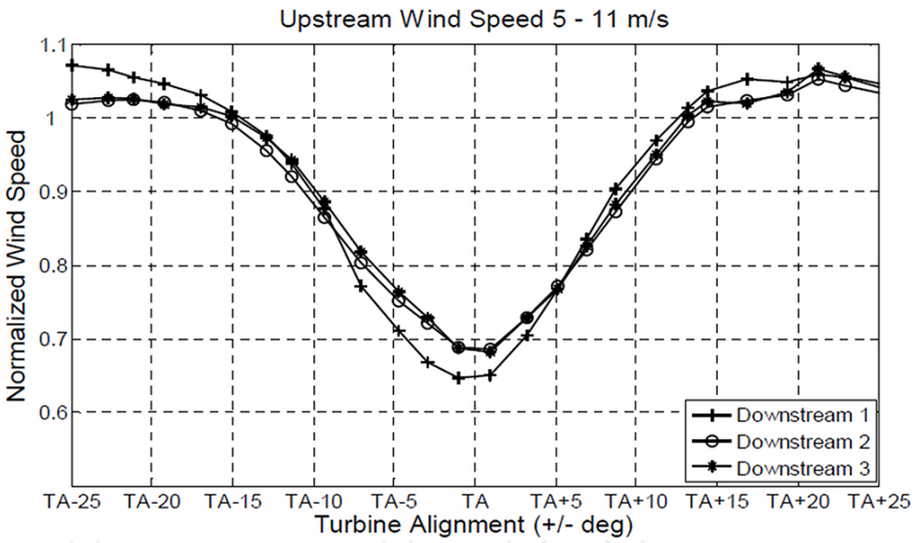


Figure 3. Array wake profile for an upstream turbine wind speed range of 5-11 m/s, considered her e as the free stream wind speed. The data are averaged over 6 months. Wind speed is normalized by the upstream turbine (free stream) wind speed: downstream wind speed/upstream (free stream) wind speed [11].

This recovery is also observed by Barthelmie et al. [12] where momentum drawn into the wake by lateral or horizontal mixing of the air external to the wake region is attributed to the recovery of wind velocity. In the case of Barthelmie et al. the offshore wind farms of Nysted and Horns Rev in Denmark were used to profile the wake regions in the farm's grid style arrangement. The findings revealed the largest wind velocity deficit after the first turbine with a smaller relative wind speed loss after the initial wake interaction with the first downstream machine. Here the velocity continues to decrease for downstream turbines due to wake mixing from neighboring turbine rows.

It has proven useful to concentrate analysis on more narrow bands of wind speeds as each wind speed tends to produce a measurably different result in turbine behaviour. The wind response for the wind speed range of 8-9 m/s is given in Figure 4. This exhibits the same trends as shown in Figure 3 for a more narrow wind speed range. The power coefficient profile for the same wind speeds is shown in Figure 5 where the power coefficient is taken as:

$$C_P = \frac{8P}{\pi\rho U_\infty^3 D^2} \tag{4}$$

The values were estimated using the upstream wind speed reading as free stream velocity,, with P representing power produced by the turbine, ϱ is the air density, and D is the rotor diameter. The coefficients are plotted for each turbine including the upstream lead turbine. The wake boundaries produce a power coefficient in the range of 0.40 or greater with a minimum at the wake center of 0.14.

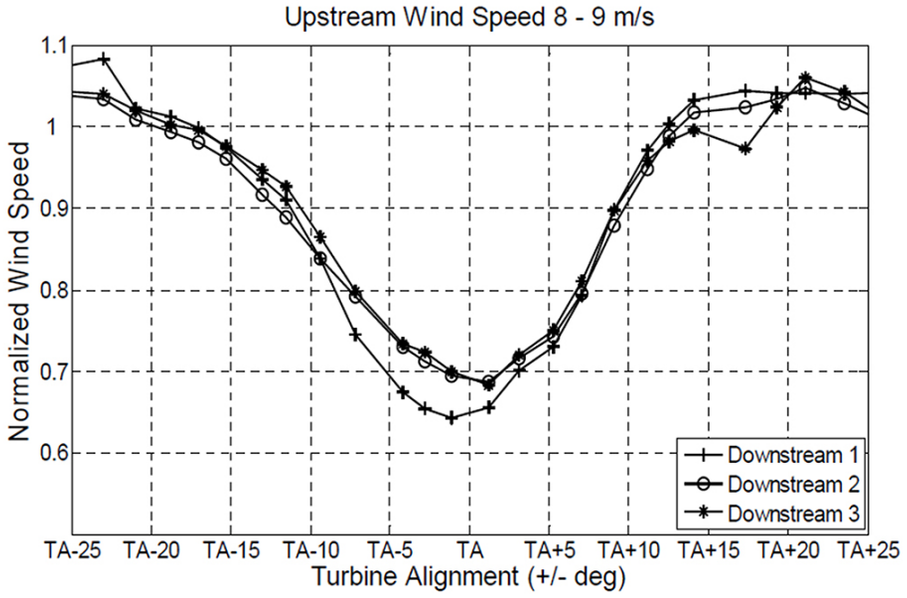


Figure 4. Normalized wind speed for an upstream turbine (free stream) wind speed of 8-9 m/s averaged over 6 months [11].

In Figure 6, turbulence intensity is implied through consideration of the standard deviation of wind speed. Deviations were calculated by the wind farm SCADA system and provided at 10 minute intervals. For the wind turbines discussed above, the downstream wind speed standard deviation is shown. A clear peak in deviation occurs approximately at turbine alignment +/- 10 degrees with a trend in nominal deviation towards the outer edges of the wake region. Turbulence increases are not excessive and are much less than observed for some special weather events; however, the trend shown in Figure 6 is consistent and may have potential to cause issues over the long term life of the turbine. This is due to the in-

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creased fatigue loading caused by the frequent fluctuations. In addition, increased variation in wind speed along the length of the rotor may contribute to damaging loads. It can also be seen that the greatest wind speed standard deviation does not necessarily correspond with the greatest loss in power. For example, downstream 3 experiences the highest standard deviation under wake conditions but shows the lowest power deficit in Figure 5.

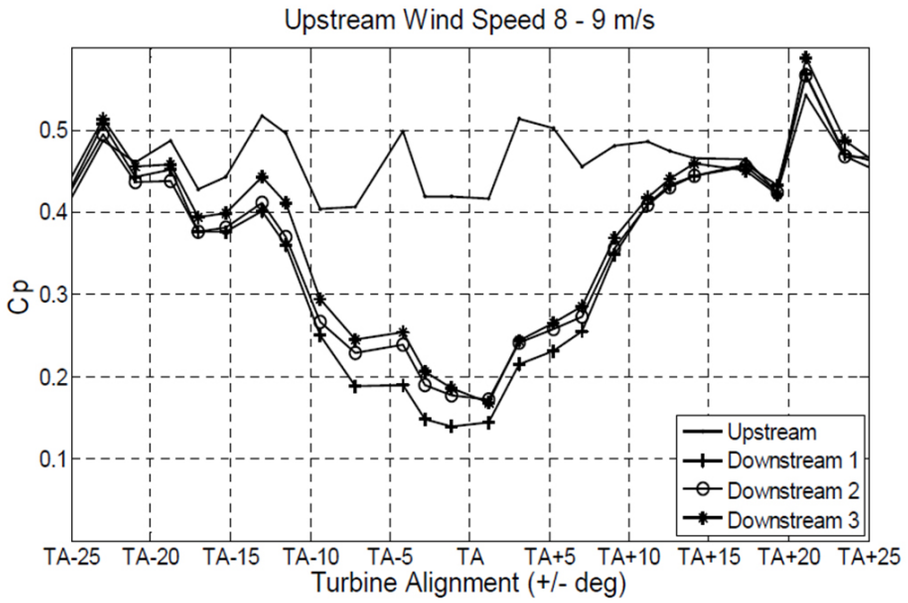


Figure 5. Array power coefficient profile for an upstream turbine wind speed of 8-9 m/s averaged over 6 months [11].

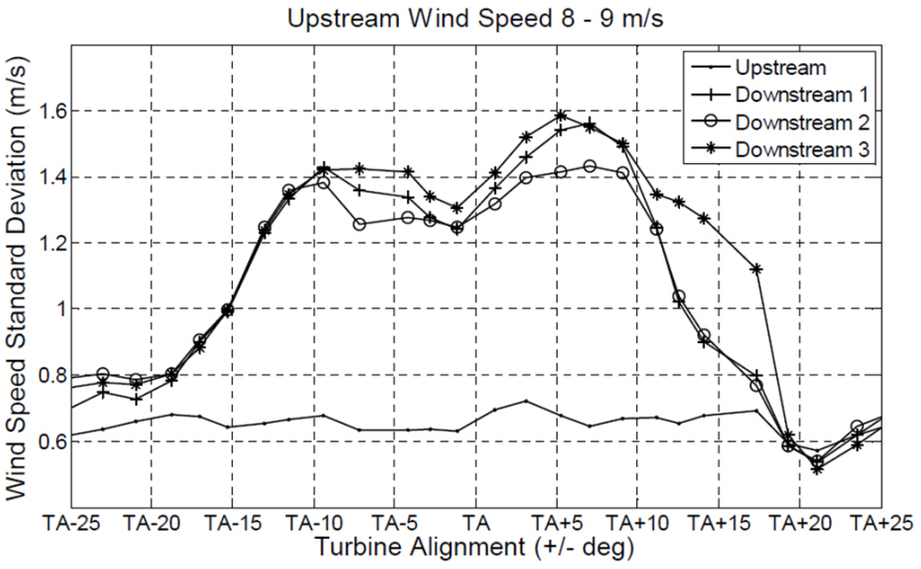


Figure 6. Wind speed standard deviation for upstream wind speeds of 8-9 m/s averaged over 6 months [11].

It is evident that there are other external factors that contribute to the definition of these profiles as they show irregularities and do not exhibit a smooth shape. It is expected that the 6 month averaged data has reduced the effects of short term, isolated fluctuations in wind speed, humidity, temperature, air density and inhomogeneous wake at the downstream turbine and so there is a consistent fluctuation in the wind speed under turbine alignment conditions. Seasonal and site specific wind conditions are likely to contribute to the small scale unpredictability of wake velocity deficit and turbulence intensity. Inter-turbine wake effects are quantifiable and are accounted for in all major wind farms projects. However, there is still a large amount of uncertainty and error in the modeling of wind turbine wakes and associated power losses. The next section discusses wind farm siting and its importance in minimizing uncertainty in the planning stages of a wind project.

3. Siting

Locating and assessing the feasibility of a wind farm is one of the most critical elements in a wind farm business plan. Maximum energy extraction from the investment is dependent on where the site is located and where each individual turbine is positioned within that site. Wake interactions between wind turbines and nearby wind farms can substantially impact power output.

Wind farm developers expend significant resources collecting data for site assessments. Topography, surface roughness, the local wind profile, turbine types, power curves, municipal site restrictions and other data are collected and processed to maximize profitability. Wind Farmer and WindPRO are commonly used software packages delivering a range of services from wake modeling to visual impact studies. While much of the assessment is based on available data and numerical calculations, a portion of the analysis is dependent on user preferences. Depending on the investors and farm developers, varying levels of uncertainty may be accepted in different areas of the study. For example, a developer may choose to install a single meteorological tower for profiling of the wind resource at the center of the site under consideration to reduce costs. Another developer may choose to install two or three towers to drive down uncertainty caused by extrapolation of the recorded data across the area of the site. Some sites can have unique curtailment requirements depending on neighboring properties or bat and bird migration.

A variety of models have been developed to simulate wakes within a wind farm. The most widely used models include the:

- Park
- Modified Park
- Eddy Viscosity
- Deep-Array Wake Model

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Brower [13] summarizes these models and their differences. The WAsP software commonly used for analysis of wake within a wind farm by site assessment tools makes use of the Park model. By accounting for geographical and ground surface conditions, the variation in wind speed profiles can be estimated along with expected wake propagation intensity. This estimation allows for "micro-siting" or individual placement of turbines within a wind farm while minimizing wake losses.

The addition of wakes in an array is difficult to model. A simple model for wake region overlap is shown in Johnson and Thomas [14]. The model indicates a 42% loss in power production for a turbine 3.75D downwind of the first and a 70% loss in power for a 3rd turbine 6.25D from the first and 2.5D from the second. However, experimental data, as summarized by Vermeer et al. [5], would indicate that the third turbine in the row sees little effect from the first, but is significantly affected by the second. It is concluded here that a turbine is only noticeably affected by the closest upstream machine. It is difficult to quantify the addition of wakes while siting a wind farm. Ideally turbines are spaced at distances great enough to negate wake effects; however, this is not always economically feasible due to the cost and availability of real estate in addition to the expense of laying cables and the interconnection of machines and substations. The staggering of turbines can be used to minimize effects but it is difficult to avoid interaction completely because of the conical nature of wind turbine wakes [15]. As a result, wind farms are typically arranged for maximum turbine spacing in the directions of the prevailing winds with closer spacing in the directions receiving less frequent winds. In general, the spacing in the prevailing wind direction ranges from 6-10 rotor diameters and 3-4 diameters in cross-wind directions. Figure 7 illustrates a wind rose with a distinctly dominant wind sector.

The study of wake is not restricted to inter-turbine relations. As the number of wind farms increase globally, the distance between wind farms has been gaining importance. Offshore wake from a small wind farm has been seen to propagate for 14 km [14] over the water. Christian and Hasager [16] used satellite imaging to study wake effects of two large wind farms, Horns Rev and Nysted, off the coast of Denmark. The images show a trail downwind of the farm that propagates for 20 km before near-neutral conditions are reached. Offshore wind farm wake dynamics have been considered to propagate farther than onshore due to less atmospheric turbulence; which is required for wind speed recovery [9]. Without this turbulence, mixing of the wake area with the surrounding atmosphere takes longer and can result in wake effects at a greater distance from the farm. Inter-farm effects for offshore is currently becoming a significant issue in Europe where planned offshore wind capacity has been growing. Corten and Brand [17] discussed the planned installation of 6 GW of capacity over 25 farms of offshore wind in a 10,000 square kilometer area. By the methods described in their work it has been concluded that an inter-farm loss of 5-14% is probable. This is substantial and raises many concerns especially in situations where wind farms are not owned and operated by the same company and the possession of wind resources is debated.

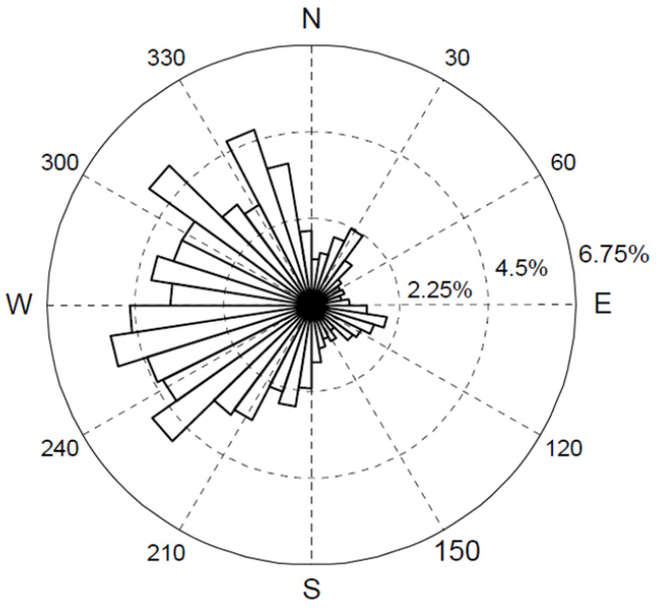


Figure 7. Wind rose indicating percentage of wind direction probability. Data are for the upstream turbine over the six month data set for all power producing winds (3-25 m/s) [11].

Onshore wind farm wake propagation is reduced by complex terrain and vegetation. As stated above, onshore wake propagation has been measured up to 15 rotor diameters downstream of a turbine. While optimal wind turbine spacing has been studied [7, 15Bryony L.D.P and Cagan, J., An Extended Pattern Search Approach to Wind Farm Layout Optimization, Proceedings of ASME IDETC: Design Automation Conference, 2010, 1-10.] further work on the limit of minimum wind farm footprint to maximize profitability may be necessary.

4. Special topics in WAKE

4.1. Wind sector management

Wind sector management refers to a process of attempting to maximize the cumulative wind farm output through an active optimization of wind turbine energy capture. There are currently two common approaches to this technique. One form of wind sector management is concerned with the shutting down of wind turbines downstream of a machine, which is creating a turbulent wake large enough to increase fatigue loads on the turbine. This can be more broadly stated as the curtailment of a wind turbine or turbines during special wind conditions that could cause fatigue damage [18]. The second approach refers to the curtailment of an upstream wind turbine that is producing influential turbulence to increase the

production of downstream turbines and therefore increase the overall production of the farm [14]. Kjaer et al. [19] briefly discussed the concept of stopping a turbine for the purpose of preventing damage upstream or downstream while Neilsen et al. [18] gave an actual method for quantification of the reduction of turbulence intensity for protection of the downstream machines. These approaches will generally result in a decrease of wind farm power production as well. The concept of increasing wind farm production by reducing axial induction has gained most of its attention from Corten and Schaak [20] of the Energy Research Centre of the Netherlands (ECN). A patent has been granted for the strategies developed at ECN [21] after wind tunnel testing showed an overall increase in production of 4.5% in a 6 row arrangement of turbines. The concept was explained in Schepers and Pijl [22] where results from ECN's full scale experimental wind farm were also given. The results from the full scale farm show power gains of less than 0.5% when averaged over all wind conditions. However, performance increase is most noticeable when wind direction causes alignment of turbine wakes and also when wind speeds are below optimum rated speeds. This concept was also discussed in Johnson and Thomas [14] where a theoretical study was completed and control strategy developed which showed gains in wind farm power output. Although the overall increase in power production is not large it is important to note that very little alteration is required to achieve this improvement. A strategic change in control methods with no modification to hardware has the potential to make economic sense. Future research in this area is anticipated.

4.2. Wake influenced yaw positioning

Wind turbines are typically independently controlled, relying on the data collected from the meteorological station situated on the back of the nacelle to dictate response. The turbine continually adjusts the orientation of the nacelle in order to face the best consistent wind direction. They typically only initiate a yaw movement after the new wind direction has been observed for a specified time to avoid constant "hunting" under rapid wind direction fluctuations. The turbines under consideration decrease the necessary consistent wind speed duration required to command a change in yaw position as the wind speed increases. Figure 8 shows data for a range of wind speeds. The Figures represent the downstream nacelle positions subtracted from the upstream nacelle position where a difference of zero represents perfect alignment with the lead upstream turbine. As the wind direction measured by the upstream turbine approaches direct alignment with the turbine array, the downstream turbine increases its yaw misalignment with respect to the upstream turbine. However, there are angles showing consistently large differences in yaw position that are not direct alignment. The Figures show that the nacelle direction offsets change as wind speeds decrease. A nacelle position offset with a greater positive magnitude indicates the downstream turbine remains at an angle counter clockwise from the upstream turbine while a negative offset corresponds with the downstream turbine positioning itself clockwise from the lead upstream machine.

Some patterns can be observed in the different plots although there is significant variation from one wind speed to the next. A steady increase in nacelle position misalignment for the

array occurs in the wake zone, with greater offsets more likely to occur at TA +/- 5 to TA +/- 20 degrees (off wake centre). The first downstream turbine shows the least offset and the third downstream turbine shows the greatest offset. There is a large amount of variation in magnitude and profile of turbine misalignment for each upstream (free stream) wind speed range shown, however a distinct increase is evident for the nacelle position range encompassing the wake zone as defined above. One possible cause of misalignment peaks are the vortex streets on the outer edges of the upstream wake profile. When free stream wind speed is not at turbine alignment (i.e. not coincident with the turbine array line) the downstream turbine instrumentation may experience increased turbulence and rotational velocity in the wind. This could be due to the wake's outer edge of tip vortices passing over the wind speed and direction sensors of the downstream turbine. Similar results are evident for other arrays within the wind farm. An array of six wind turbines with identical linear alignment and spacing shows an increase in yaw misalignment within the wake region (Figure 9). The first downstream turbine has the smallest offset with progressively larger offsets down the array. There are distinct peaks in the alignment offset with an approximate return to 0 (+/- 2 deg). However, the two additional turbines for this arrangement complicate the interactions. As shown in Figure 9, the third downstream turbine agrees with the pattern in magnitude but its direction of rotation is opposite to the rest of the turbines in the array. Furthermore, the separation of nacelle position offset between the downstream turbines is less defined. This adds to the unpredictability of the yaw behaviour within the array, since it is not obvious which turbine will show the greatest offset or at what wind direction it will occur. A potential source of some of these complications may be due to the mixing of each subsequent turbine vortex street when not in direct turbine alignment as discussed earlier. This lack of distinction is further evidenced in the power coefficient profile shown in Figure 10. Although similar to the power coefficient profile given for the array of four turbines in Figure 5, the separation of the lines for each downstream turbine is less defined. The third downstream turbine once again exhibits unique behaviour.

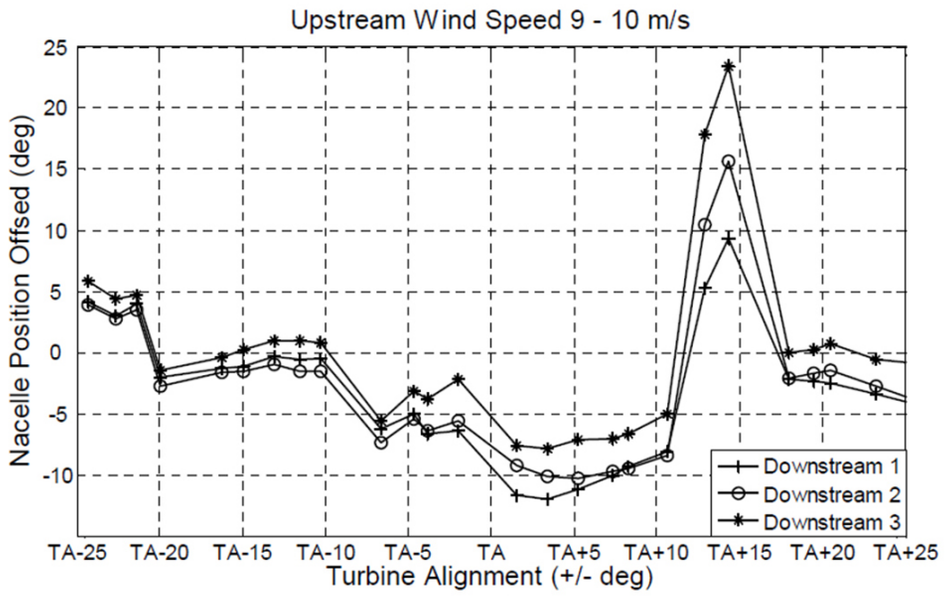
4.3. Turbine operational sensitivity to wake

With wake interactions accepted as an unavoidable fact it becomes useful to quantify the sensitivity of the operation of two turbines to this interaction. The purpose of quantification relates to the mitigation of negative effects and optimization of performance within the wake region. McKay et al. [23] presents the application of the Extended Fourier Amplitude Sensitivity Test method for determination of downstream turbine power output to upstream turbine operational parameters.

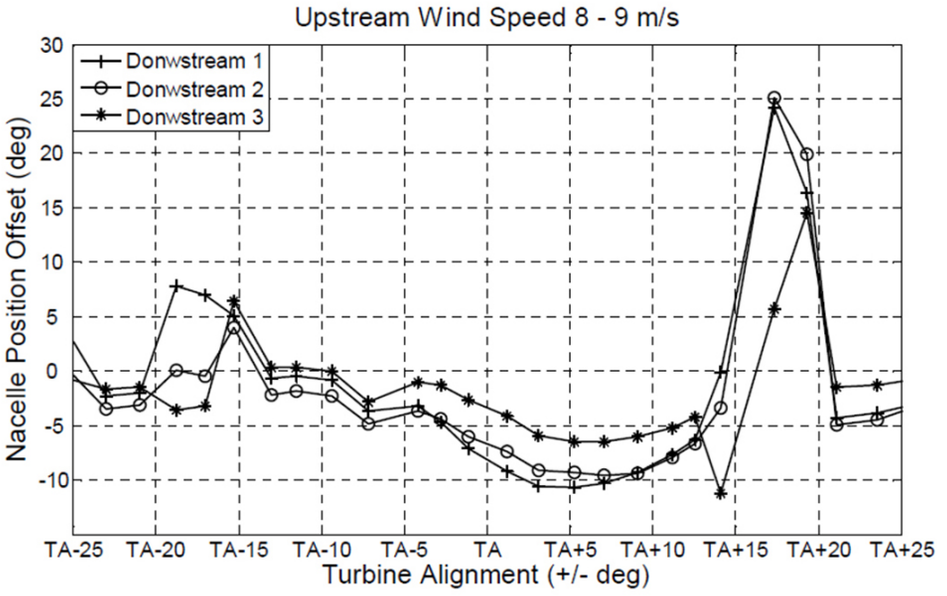
A global sensitivity analysis of eight fundamental operating parameters on wind turbine power output is performed. By comparing the sensitivities of normal operation to wake conditions, a better understanding of group turbine behavior is obtained. The most significant characteristic that is evident in the presented analysis is the effect that the introduction of wake has on turbine performance. For a turbine operating in the wake of an upstream machine, power production is most sensitive to wind speed standard deviation above all parameters included in this study, excluding wind speed itself as shown in Figure 11.

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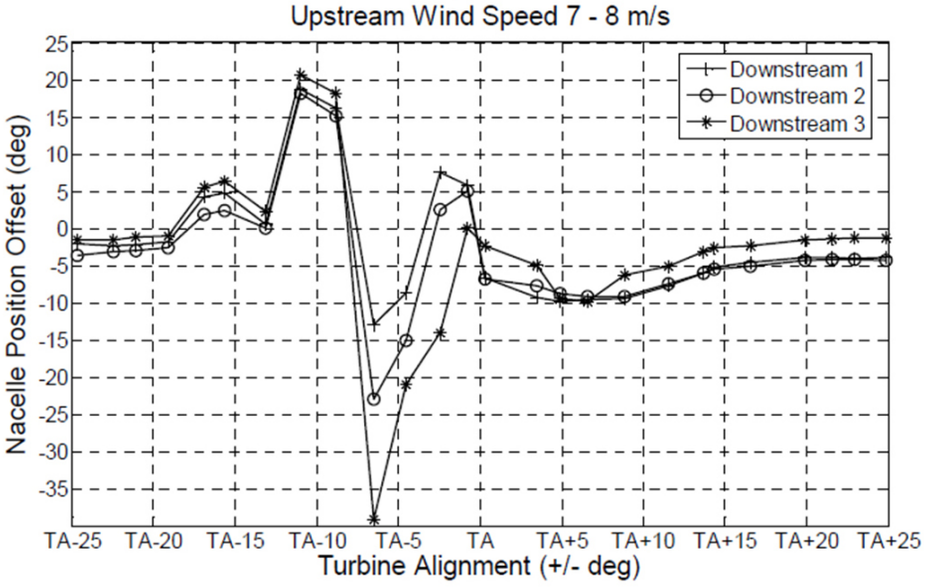
(a)



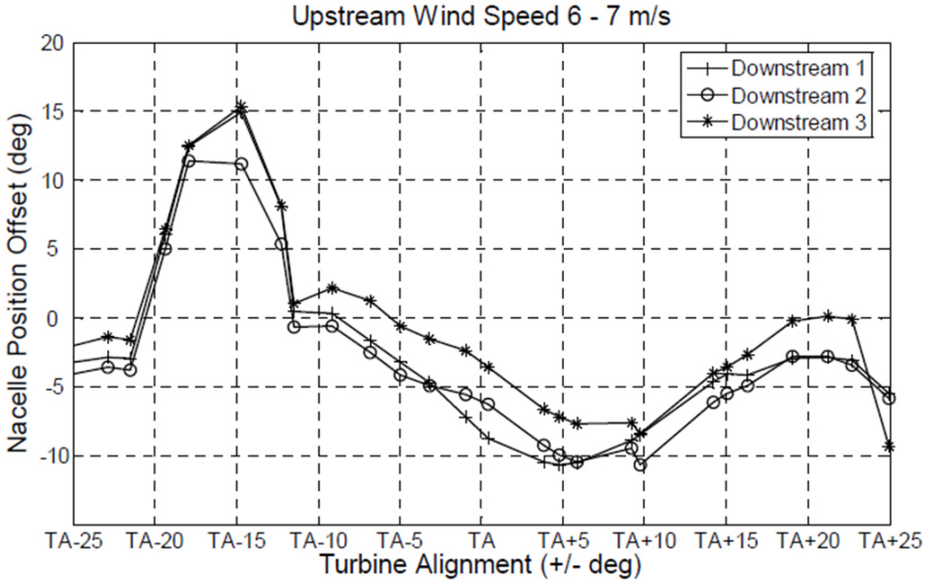
(b)



(c)


Upstream Wind Speed 7 - 8 m/s
Downstream 1
Downstream 2
Downstream 3
Nacelle Position Offset (deg)
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
TA-25 TA-20 TA-15 TA-10 TA-5 TA TA+5 TA+10 TA+15 TA+20 TA+25
Turbine Alignment (+/- deg)

(d)


Upstream Wind Speed 6 - 7 m/s
Downstream 1
Downstream 2
Downstream 3
Nacelle Position Offset (deg)
20
15
10
5
0
-5
-10
TA-25 TA-20 TA-15 TA-10 TA-5 TA TA+5 TA+10 TA+15 TA+20 TA+25
Turbine Alignment (+/- deg)

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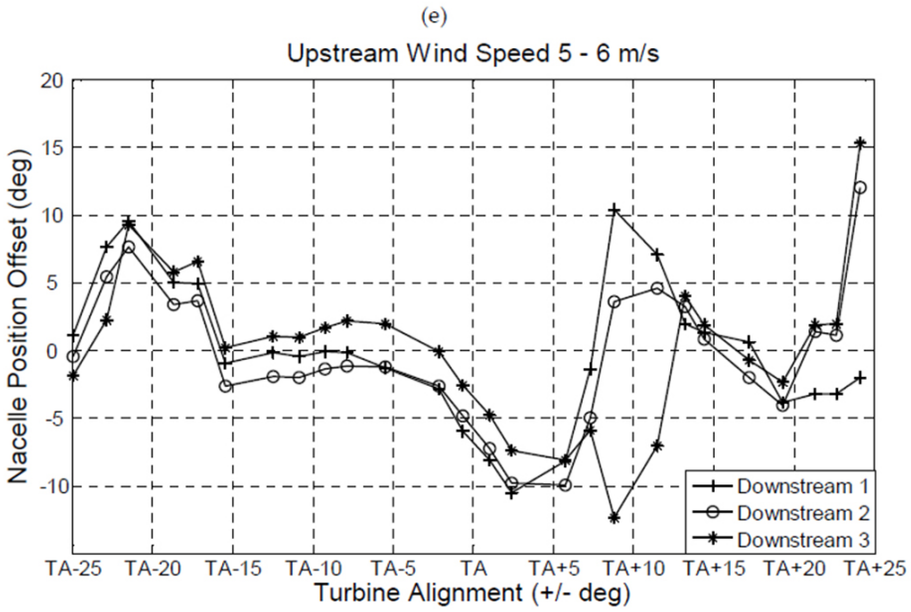


Figure 8. Nacelle misalignment between wind turbines for 6 months averaged data. a) 9-10 m/s, b) 8-9 m/s, c) 7-8 m/s, d) 6-7 m/s, e) 5-6 m/s/ Lead upstream nacelle position is subtracted from each downstream turbine nacelle position [11].

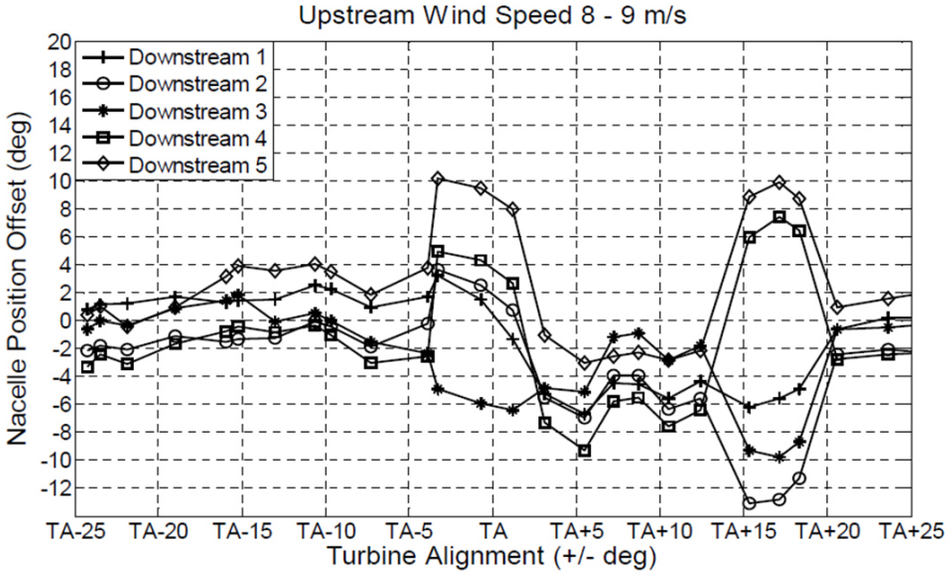


Figure 9. Nacelle misalignment between wind turbines in array of 6 machines for 6 months averaged data. Lead upstream nacelle position is subtracted from each downstream turbine nacelle position [11].

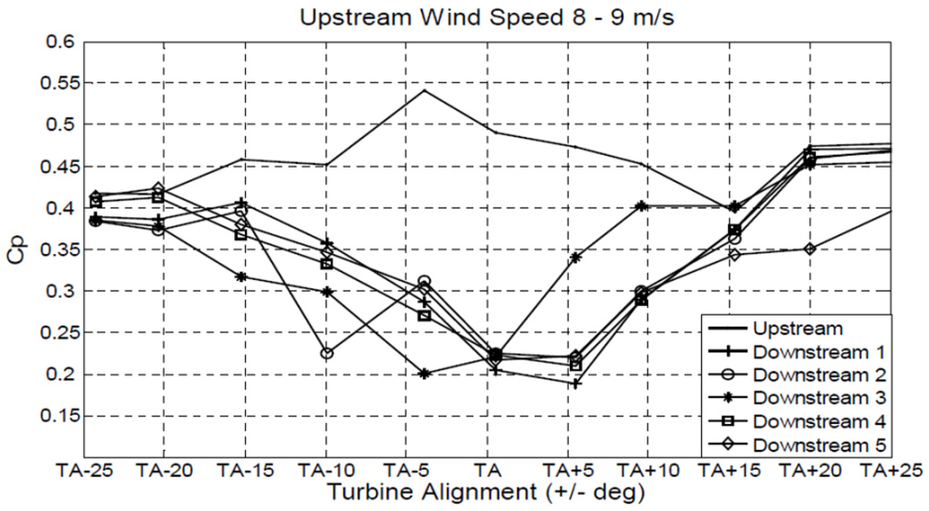


Figure 10. Six turbine array power coefficient profile for an upstream turbine wind speed of 8-9 m/s averaged over 6 months [11].

In essence, the method assigns a frequency to the upstream turbine operational parameters under consideration. The frequency data is input into a model which provides a power output signal related to the downstream turbine containing all of the frequency data in varying proportions. A Fourier transform is performed on the output and the resulting frequency content is ranked according to the operational parameters significance. This is shown in Figure 11. The parameters chosen for the study along with their significance rankings are given in Table 1.

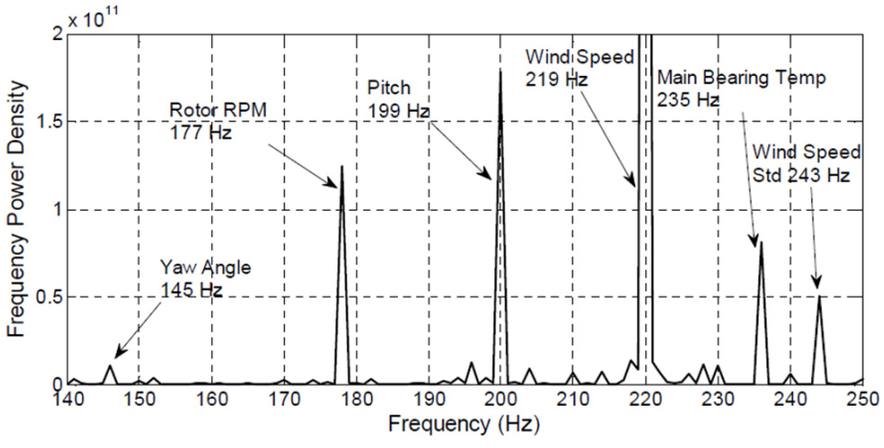


Figure 11. Frequency content of power signal extracted from wake condition data [23].

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Input factor	Total Sensitivity Index ($S_{Ti\ wake}$)
Wind Speed	0.0438
Pitch	0.0234
Rotor RPM	0.0268
Main Bearing Temperature	0.0263
Wind Speed Std	0.0309
Ambient Temperature	0.0206
Yaw Angle	0.0203
Yaw Angle Std	0.0172

Table 1. Sensitivity indices for eFAST method applied to wake conditions [23].

The comparison of results from the single turbine and wake conditions is given in Figure 12. Rotor RPM and wind speed are clearly the dominant features in the Figure followed by relatively similar magnitudes for each of the remaining parameters. Two main features become apparent. Firstly power output is more sensitive to rotor speed than wind speed under normal operating conditions while the reverse is true under wake conditions. The turbines under study are designed to operate at an optimum tip speed ratio therefore the control systems will work to keep the rotor speed at specific RPMs depending on the wind conditions. This links rotor rpm directly to power output. In other words any changes in rotor speed will directly affect the power output of the turbine resulting in high sensitivity. The same is true of wake conditions as well. However, it has been shown above that for a turbine experiencing wake, changes in wind speed cause changes in power loss. Very high wind speeds reduce the power losses due to wake while wind speeds falling between 5 and 11 m/s can have a substantial effect on production. As a result, the power output becomes dependent on wind speed for power losses in wake in addition to the dependence of normal, non-wake operation.

Secondly, the wind speed standard deviation's increases in sensitivity under wake. This is expected since the extraction of power by the upstream turbine leaves a turbulent rotating wake region. Therefore, variance in wind speed and direction increases. The increase is directly linked to a loss in power for the downstream turbine, increasing sensitivity. By quantifying the sensitivity it is shown that changes in wind speed standard deviation are more critical to power production than all other parameters other than wind speed.

Utilization of this method to identify other power output sensitivities is possible. By further applying this method to more complex data sets, qualitative comparisons can be quantified, and subsequently, priorities can be placed on turbine operational parameters. This can be used for the purpose of optimizing performance or increasing turbine reliability. The results also suggest that through monitoring sensitivity indices, downstream machines may be able

to determine whether or not they are in a wake. Depending on the severity of the turbulence in the wake the turbine could be controlled to mitigate negative effects or improve performance. Additionally, the method could provide another tool to assess the efficacy of the original siting of existing wind farms.

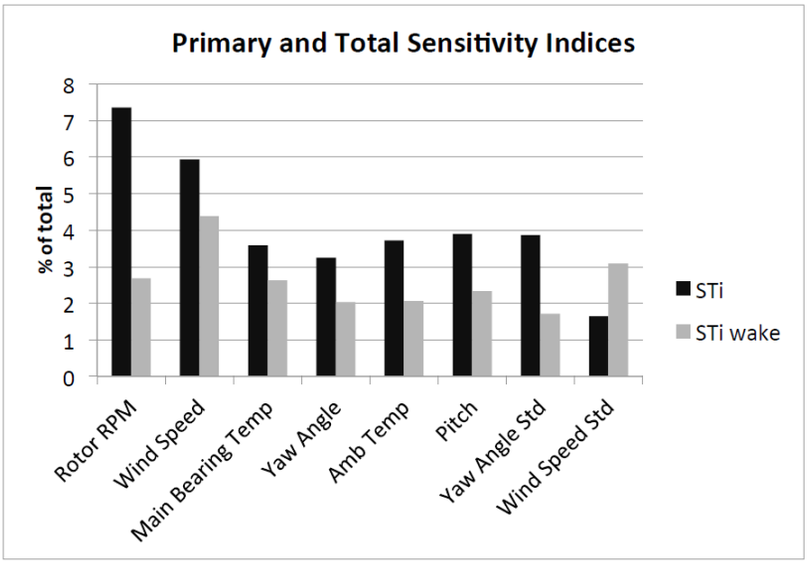


Figure 12. Sensitivity index comparison for wake and non-wake conditions [23].

5. Moving forward

As the wind industry matures major wind farm developers continue to add to their experience in wake loss estimation. These individual organizations continue to refine their predictions and add to databases based on this experience promoting an improved understanding of wake effects and reduced uncertainty in the planning stages. Academic research continues in this area. However, strong demand continues for larger and larger wind farms, particularly offshore. With increased wind farm densities both on and offshore, inter-farm wake dynamics have become a growing concern. Subsequently, there is a notable need for highly reliable wake mixing and long distance wake propagation models. As evidenced in this Chapter, opportunities remain for continued commercial wind farm optimization.

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