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Group Dynamics of Commercial Scale Wind Turbines

Phillip McKay
University of Windsor

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GROUP DYNAMICS OF COMMERCIAL SCALE WIND TURBINES

by

Phillip M. McKay

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2011

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Phillip M. McKay

APPROVED BY:

Dr. J. Johrendt
Department of Mechanical, Automotive and Materials Engineering

Dr. T. Bolisetti
Department of Civil and Environmental Engineering

Dr. D. S-K. Ting, Co-Advisor
Department of Mechanical, Automotive and Materials Engineering

Dr. R. Carriveau, Primary Advisor
Department of Civil and Environmental Engineering

Dr. A. Edrisy, Chair of Defense
Department of Mechanical, Automotive and Materials Engineering

26 August 2011

DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I. Declaration of Previous Publication

This thesis includes three original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Thesis Chapter	Publication Title	Publication Status
Chapter 2	Farm Wide Dynamics: The Next Critical Wind Energy Frontier	Accepted for publication in Wind Engineering by Multi-Science
Chapter 3	Wake Impacts on Elements of Wind Performance Alignment and Yaw Alignment	Second round peer review for Wind Energy by Wiley
Chapter 4	Global Sensitivity Analysis of Wind Turbine Power Output	For submission to Journal of Solar Energy Engineering by ASME

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ABSTRACT

The recent rapid development in wind turbine technology and renewable energy policies around the world has led to an influx in large industrial scale wind farms. As both the size and number of turbines in a power plant increase the interactions between these machines is increasingly prioritized for the purpose of optimization. This work includes three publications discussing the group dynamics of wind turbines based on current literature as well as interactions with a Southern Ontario wind farm. A progression is made from the necessity of considering wind farm dynamic effects to the specific area of wind turbine wake as a beneficial topic of study for optimization. The first publication consists of a literature review of the primary topics relating to wind farm dynamics and is followed by a publication describing a specific focus on the yaw behaviour of turbines within a group. The final included publication details a global sensitivity analysis performed to establish areas for optimization.

DEDICATION

This work is dedicated to my creator and sustainer to whom I give credit for all that has been accomplished and to my wife whose love, loyalty and resourcefulness I will forever be indebted to.

ACKNOWLEDGEMENTS

I would like to acknowledge the sage advice and liberating leadership of my primary advisor, Dr. Rupp Carriveau as well as that of my co-advisor, Dr. David S-K. Ting. Your support in every form has been essential. In addition I would like to thank my committee, Dr. Jennifer Johrendt, Dr. Tirupati Bolisetti and Dr. Afsaneh Edrisy for their contributions. Finally, I would like to acknowledge the contributions of Michael Cookson, Joseph Boland, Paul Dawson and Jason Stoner. This work was supported by the Natural Sciences and Engineering Research Council of Canada.

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CHAPTER I

INTRODUCTION

According to the Global Wind Energy Council wind capacity grew by almost 40 GW globally in 2010 with the majority of growth coming from developing countries [1]. This is a reduction in growth rate from previous years due to the state of global economics but indicates the feasibility of wind power as an affordable source of alternative energy and not a luxury for the developed world. In addition the World Wind Energy Association predicts a tripling of the current capacity to 600 GW by the year 2015 [2]. In recent years wind energy has been labelled the fastest growing source for energy in the world [3]. The current boom in the industry has been considered to have sprung out of the slump experienced after the 1970's oil price spike was subdued [4]. Modern wind farm design and operation is then a relatively new field of study. Many of the modern style wind farms are only now reaching the end of their expected lifespan which leaves substantial room for the optimization of wind farm design. Due to the competitive nature of the wind industry many academic institutions have been reliant on simulations using either physical or computational models to better understand the interaction between groups of wind turbines. The lack of access to data from commercial scale wind farms has limited public understanding of the behaviour of these multi-megawatt power plants and so it has been left to turbine manufacturers and professional consultants to detect areas for turbine and farm improvement.

As a result of the installation of large amounts of wind power within close proximity of the University of Windsor and strategic relationships established by the University, access to this data has been made possible. The Kruger Energy Port Alma wind farm is a 101.3 MW power plant composed of 44, 2.3 MW Siemens wind turbines having a rotor diameter of 93 m. Several hundred parameters are continuously recorded from each turbine using a Supervisory Control and Data Acquisition System (SCADA) and stored in summaries of 10 minute averaged data. The following publications make use two years of SCADA data to draw conclusions regarding wind turbine interactions.

A search was undertaken for areas of wind turbine interaction showing potential for optimization. This search led to the composition of Chapter 2, a literature review of a wide range of sources for wind farm dynamics such as turbine to turbine interactions, aesthetics, grid connection, terrain etc. The dynamic effects were separated into three categories; siting, installation and operation and a system for ranking the importance of each specific area based on their level of interaction was developed. By considering the available data and the results of the review wind turbine wake interactions surfaced as a significant area for potential wind farm optimization.

Upon closer examination of the behaviour of turbines subject to wake, unpredicted behaviour was found with the yaw positions of downstream turbines. Due to the independent control systems the turbines rotate out of direct wake to take advantage of more profitable winds from non-alignment directions. These interactions are described in Chapter 3. The chapter focuses on conditions of alignment of turbine nacelle positions and attempts an explanation for the irregular positioning. This is further related to the power developed by the aligned turbine array.

In order to better understand the significance of this yaw behaviour on the overall power output a third journal submission was undertaken to prioritize the most influential inputs to power production. In Chapter 4 a global sensitivity analysis is performed of the power output of a single turbine to eight inputs including temperature, performance and wind characteristic parameters. The Extended Fourier Amplitude Sensitivity Test (eFAST) is used in conjunction with a neural network to establish a sensitivity index ranking the inputs in order of significance for the power signal. The results correlate well with the direction the industry is currently taking adding confidence to the method chosen. Once again wake interactions, especially wind quality, are realized as a significant opportunity for wind farm optimization (outside of turbine design optimization).

Further research is suggested in the area of active wake management and an experiment is suggested in order to establish the validity of the concept. The progress from general group dynamics of commercial scale wind turbines to the specific area of wake management is driven by the unique relationship with local industry and the equally important wind resource present in Southern Ontario. Wind farms must be understood as complex, dynamic systems requiring optimization for the harnessing one of Canada’s greatest and sustainable power sources.

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CHAPTER II

FARM WIDE DYNAMICS: THE NEXT CRITICAL WIND ENERGY FRONTIER

McKay, P., Carriveau, R. and Ting, D. S-K. Farm Wide Dynamics: The Next Critical Wind Energy Frontier, Wind Engineering, Vol. 34, No. 4, 2011.

Phillip McKay[1], Rupp Carriveau[1*], and David S-K. Ting[2]
1. Department of Civil and Environmental Engineering, The University of Windsor, Windsor, Ontario, Canada
2. Department of Mechanical, Automotive, and Materials Engineering, The University of Windsor, Windsor, Ontario, Canada
*Corresponding Author: e. rupp@uwindsor.ca, p. 01 519 253 3000

1. INTRODUCTION

Ambitious targets have been set internationally for renewable energy capacity. Many countries are aiming for penetration levels of 20% and beyond by the year 2030 [1-3]. Responding to these objectives, global wind energy generation grew 31.7 % in 2009 [4]. Following demand, the scale of modern wind turbines has steadily increased. Figure 1 shows this trend beginning in 1990 and ending in 2010. In 2005 it can be observed that wind turbines reached a production capacity of 5 MW with a rotor diameter of 124 m although more common onshore turbines were rated at 3 MW with rotor diameters of 90 m[5].

Offshore wind turbines have not been limited by typical terrestrial constraints such as road restrictions for turbine transport, visual and noise impacts and lower onshore wind speeds[6] and subsequently have reached capacities of 7.5 MW with rotor diameters of 126 m [7] . Innovative ideas such as the Windtec Seatitan have proposed even more substantial power production without increasing rotor diameter following the trend of increased production capacity over time [8]. However, there are often fiscal limits to the maximum nameplate capacity of an individual turbine [9]. Thus wind power has been scaled through the arrangement of multiple turbines into groups or arrays known as wind farms, parks, or plants. The term wind farm dynamics has generally been known in the literature to encompass the areas of inter-turbine wake effects and the effects of a transient generation source on the power grid [10]. We propose here that wind farm dynamics takes into account all dynamic effects of any wind turbine that does not act in isolation from one or more additional turbines. In this paper, a review of the literature addressing multi-turbine dynamic effects has been conducted, and an argument has been made for the study of wind farm dynamics as a critical, multifaceted discipline and not a collection of disconnected subjects. Given the current state of the wind industry and the advancements that have been made in the field of wind farm development it is no longer acceptable to model wind farm effects as the superposition of individual turbines.

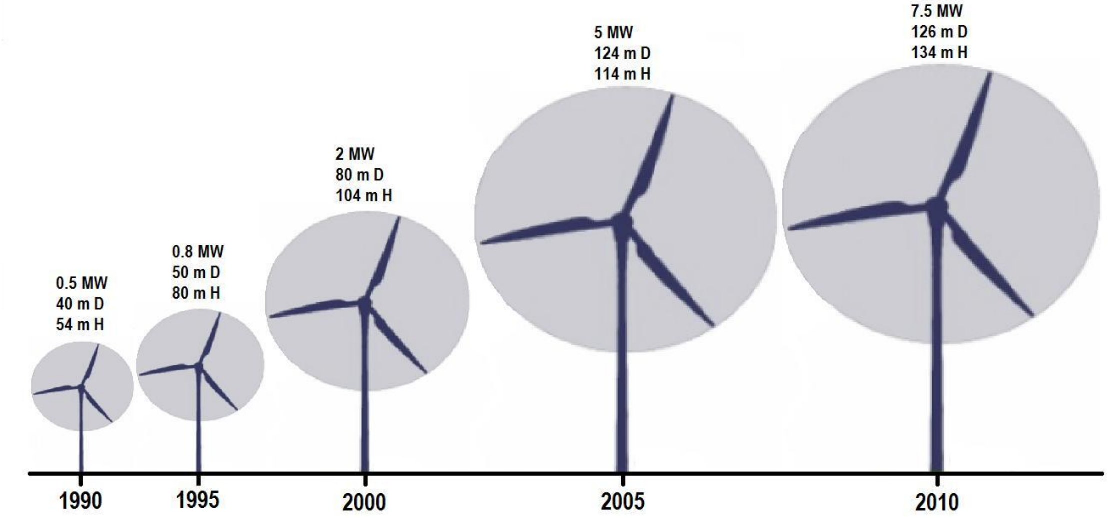

Figure 1 Trend of increasing wind turbine size and capacity over time.

There are distinct characteristics that are established with the operation of groups of two or more wind turbines. In the area of wake effects it has been established that the change in surface roughness caused by many turbines in a localized area requires the farm to be treated as a single entity and not an addition of individual wakes. In other words, the cumulative effect is greater than the sum of individual turbine effects [11]. Similarly, in the case of power production, consideration has been given to treating a wind farm as a single power production unit to be paired with other wind farms in order to smooth the output fluctuations from each farm [12]. This approach can be of great benefit in areas where wind power has begun to play a major role in grid contributions but would be much more complicated to model and control if every single machine was considered. Regarding the control of single generators it has been shown that the shedding of power from upstream turbines can result in improved farm wide production if turbines are operated in conjunction with one another rather than independently [13]. Consequently, it is less important to consider the production of an individual machine than the performance of the entire park.

Many more topics ranging from aesthetics to climate change are greatly dependent on the relationship between two or more wind turbines. A high level perspective of all interactions contributing to farm dynamics is necessary for the development and operation of a competitive multi-turbine wind power plant. Wind farm dynamics as a whole is critical for siting of new wind farms, power output of existing wind farms, as well as the continuing operation and maintenance of a farm. These three areas have been used to classify the various factors contributing to wind farm dynamics. Although many of these areas are well understood, criteria must be developed to strike an optimal balance between competing issues; and without a holistic approach this is not possible.

2. SITING

Locating and assessing the feasibility of a wind farm is one of the most critical elements in the 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. Interactions between wind turbines and nearby wind farms can impact power output, and also have an influence on the surrounding climate and visual landscape.

2.1. INTER-TURBINE WAKE EFFECTS

The downstream wake effect from one turbine to the next has received the majority of attention in this area due to the significant influence that this can have on performance and reliability. Downstream 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 2. The expanding wake downstream of the turbine in conjunction with a decrease in wind speed U is also shown.

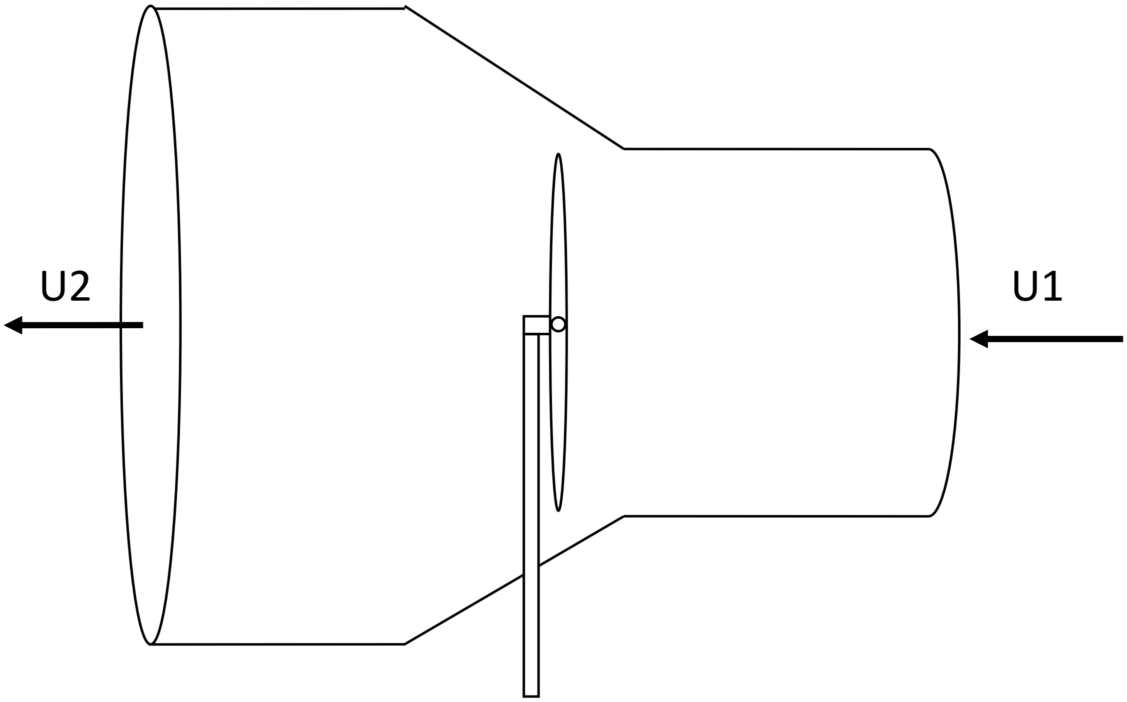

Figure 2 Swept area of wind turbine rotor with expanding wake section.

For conservation of mass:

$$\rho A_1 U_1 = \rho A_2 U_2 \quad \text{.... (1)}$$

Where ρ is the air density, *A* is the cross sectional area and *U* is the wind speed. A decrease in wind speed across the rotor area corresponds to 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 [14, 15]. This simplified explanation constitutes what is termed as the wake effect of a wind turbine. An increase in downstream turbulence results in less power available for subsequent turbines. The study of wind turbine wakes is broken into two parts: near wake and far wake. The near wake region has been concerned with power extraction from the wind by a single turbine whereas the far wake is more concerned with the effect on downstream turbines and the environment [16]. 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 [16-17] with far wake regions dependent on terrain and environmental conditions. The full extent of far wake length is currently still under study but typical turbine to turbine spacing has been taken as 5D [18] to avoid the near wake region with measurable turbulence up to 15D for onshore sites [19] and up to 14 km for offshore [11]. The 5D to 15D wake region has been defined as an intermediate wake region by some [20] with the far wake pertaining to distances farther than 15D. Theoretical models of wakes have generally been concerned with the addition of wake regions for multiple turbines. A simple model for wake region overlap is shown in Johnson and Thomas [21]. 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 Vermeera et al. [16], 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 has been well accepted that the wake created by a wind turbine will have a negative effect on the power output of a subsequent, downstream turbine since there is less available energy in the wind for extraction. It is difficult to quantify the addition of wake effects while siting a wind farm. However, software is widely available for the purpose of maximizing energy capture while minimizing negative effects [14] by applying the principles discussed above. Ideally, the turbines would be 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 as well as the expense of laying wires and the interconnection of machines and substations. 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 [22]. Prevailing winds should be taken into account as well. It may be reasonable to reduce the turbine spacing in specific directions if the probability of wind from directions other than those considered dominant is low.

2.2. Inter-Farm Wake Effects

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 [11] over the water. Christian and Hasager [23] 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 [11]. 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.

The concern of environmental effects has been focused more on coastal regions rather than the vicinity immediately downwind from the farm causing offshore distance to be the main focus. Inter-farm effects for offshore is currently becoming a significant issue in Europe where planned offshore wind capacity has been growing. Corten and Brand [24] discussed the planned installation of 6 GW of capacity over 25 farms of offshore wind in a 10,000 square kilometre area as shown in Figure 3. The figure shows the proportional area under consideration for offshore wind development with regards to the Netherlands along with the average wind speeds as they increase with offshore distance. By the methods described in their work it has been summarized 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. While optimal wind turbine spacing has been studied [18, 22] further work on the limit of minimum wind farm footprint to maximize profitability may be necessary. 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. The next section presents an issue of greater concern to onshore wind farm wake propagation than offshore.

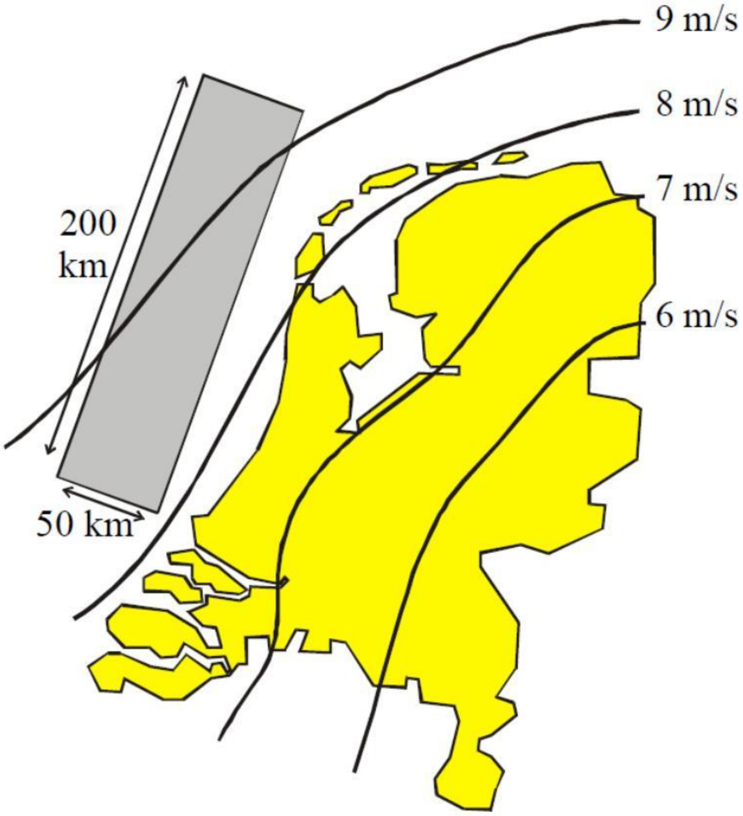

Figure 3 Proposed area for 6 GW of wind power development in the North Sea off the coast of the Netherlands. Image courtesy of Corten and Brand [24].

2.3. CLIMATE CHANGE

Apart from wind farm to wind farm interactions, an array of wind turbines has the potential to modify boundary layer conditions and energy content sufficiently to cause a change in the micro-climate of the surrounding environment [25]. The additive effect of individual wind turbine wakes causes a velocity deficit downstream from the wind farm that is capable of altering precipitation deposition as well as vertical mixing of air which can cause desiccation of the land [26]. Research has not been extensive in this area. One of the most comprehensive studies to date was undertaken by Baidya et al. [25]. In this study a wind farm was simulated on the Great Plains region of the United States. It was concluded that wind speed was significantly slowed and the added turbulence from the rotors increases vertical mixing of temperature and humidity as well as surface heat fluxes; enough to have an effect on climate. Barrie and Kirk-Davidoff [27] approached the effect on climate as an abrupt change in surface roughness length rather than a momentum sink. This change in roughness was enough to alter the synoptic meteorology. However, the study was theoretical as the size of the wind farm simulated was extremely large (23% of the North American land area). This work is similar to the results given in Keith et al. [28] where large amounts of wind energy are simulated (2 TW) in a global scenario. The drag added by this amount of wind energy is connected to a 0.5 K seasonal peak temperature gain worldwide. It is also argued, however, that this climate change is overcome by the beneficial effect that such a large amount of renewable energy will have on a global scale.

It is no longer adequate to model the dynamics of a wind farm by superposition of individual turbine wakes [11]. For climate effects and inter-farm relationships the farm must be modelled as a single entity that influences the surface roughness and contributes to the turbulence in the air boundary layer.

2.4. TERRAIN

In addition to multiple turbine wake effects, the terrain in which the wind farm is situated is a critical element in the siting process. As summarized in Lubitza and White [29], wind speed is known to increase as it flows over a hill or ridge but it is difficult to predict what the “speed-up” factor will be for any given land feature or atmospheric condition. It is concluded that an adequate method does not yet exist for the forecasting of wind power generation over varied terrain. Uchida and Ohya [30] describe a method currently under development (RIAM-COMPACT) that is able to predict real wind speeds over a simple ridge on Cape Norma in Japan. The wind farm is shown in Figure 4. The image shows the single ridge with open water on both sides and 10 wind turbines arranged along its length forming a predictable proving ground for this method. The objective of the study is to produce a micro-siting tool for the placement of wind turbines within a farm in the complex terrain of Japan. A relative error between predicted and observed wind speed of less than 1% is recorded over the course of a year in this simple ridge location. Future work is intended to apply this method to more complex terrain.

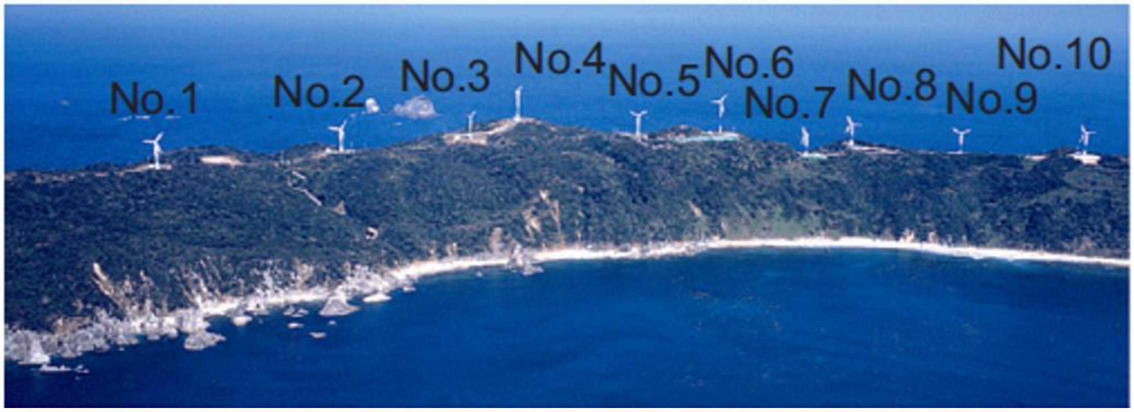

Figure 4 Noma Cape wind power plant Kagoshima, Japan. Courtesy of Uchida and Ohya [30].

Røkenes and Krogstad [31] simulated wind flow over mountainous terrain in a wind tunnel showing that both wind speed and turbulence are increased after the wind passes over a steep slope. In addition, a slope with an unrounded peak can cause turbulence up to six times greater than a rounded slope in the air near the ground. Although an increased wind speed is beneficial for power production, turbulence should be kept to a minimum to prevent frequent failures whether they are minor or catastrophic [32]. This leads to the conclusion that turbine hub height must be greater for these topographical conditions to avoid interaction with the low elevation turbulence. Mountains upstream of a wind turbine can also result in increased turbulence due to separation of the boundary layer. In the case of Røkenes and Krogstad a peak 40% higher than the wind turbine downstream can increase turbulence 2.5 times greater than ambient without significantly increasing mean wind speed. A peak downstream of the turbine shows similar results. From the perspective of wind farm dynamics, complex terrain makes power prediction, analysis of wake effects and turbine placement more difficult. However, it has also been shown that properly placed turbines on a ridge, rounded hill or plateau can be of benefit due to the increased wind speed, see Figure 5, and even decreased turbulence in some cases [31]. Consequently, it is not always beneficial to avoid complex terrain when siting a wind farm.

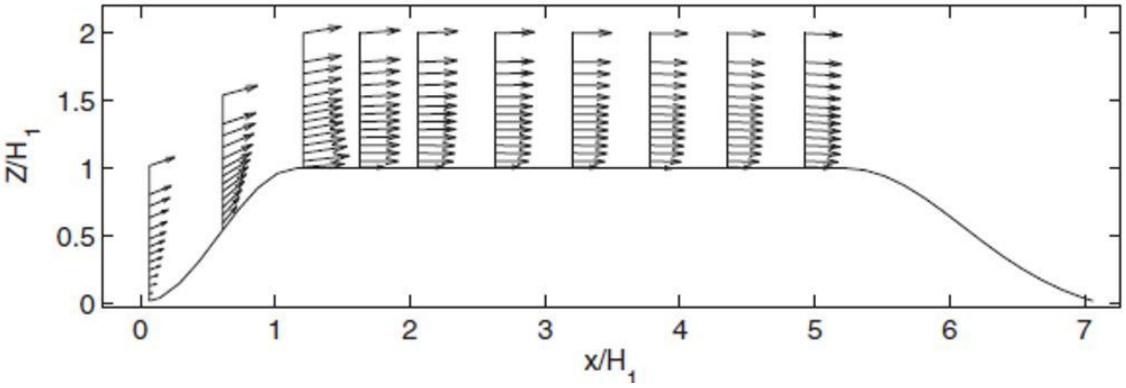

Figure 5 Flow over a rounded hill showing increased wind velocity vectors where Z is vertical height, X is horizontal distance and H_1 is the hill height. Image courtesy of Røkenes and Krogstad [31].

cost of the support structure and may cause the need for a compromise in turbine spacing in order to reduce costs of installation [33].

2.5. AESTHETICS

Another major siting topic of wind farm dynamics is the visual impact of placing multiple turbines in close proximity to one other, the study of wind farm aesthetics. This subject is receiving greater attention as the concentration of wind farms increases, particularly in more densely populated European countries. In many cases a proposed arrangement must be presented to the public or governing authorities for approval. Wind farm design tools are used to determine what viewpoints the farm can be seen from. These tools take into account the topography and probable viewing locations [34]. One method of determining visual impacts is to create photomontages of the potential site. Turbine images are superimposed on photographs of the area and scaled appropriately according to distance, see Figure 6. Some software allows for a video file to be created with moving wind turbines superimposed on the landscape or even 3D virtual worlds.

Figure 6 Photomontage of wind turbines superimposed on a photograph of the countryside in England. Image courtesy of: http://www.envision3d.co.uk/pages/photomontage.htm Copyright © Envision 3D Limited.

Some of the concepts used to provide visually appealing turbine arrangements have been given in Manwell et al. [14] such as harmony, clarity, order, clustering, rhythm, repetition and turbine shape; where turbine shape refers to the shape of the tower and blades as well as the number of blades. There has been a general consensus that 3-bladed turbines are more visually pleasing than 2-bladed due to two main factors. Firstly, 2-bladed machines become a linear element twice per revolution when one blade passes in front of the tower. This gives the negative effect of a change in 'bulk' whereas a 3-bladed machine tends to appear more balanced. Secondly, 2-bladed turbines tend to rotate at a faster speed which appears less peaceful [15]. On a wider scale, clustering of turbines has been found to be more pleasing than arranging them in a simple grid. This allows the eye to pass from one group to another without needing to distribute attention equally over the entire visible farm. Determination of the thresholds of visual impact of a wind turbine has been discussed by Bishop [35]. Computational analysis and public surveys were used to draw conclusions regarding the distance and not just the line of sight from which a viewer observes a wind turbine. It was stated that light scattering due to moisture or particles in the air contributes significantly to the distance at which a wind turbine can be seen. In extremely clear weather situations there can be a visual impact up to 20 km from the site but 5-7 km is more typical. Multiple wind turbines will increase this effect and so the number of turbines simultaneously visible from these distances must be taken into consideration. Torres Sibille et al. [36] have provided a good summary of all of the factors influencing onshore wind farm aesthetic impact and attempts to develop a method for assessing this impact. This has been a difficult parameter to measure due to the subjectivity of a wind farm's visual appearance for an individual observer. It could even be speculated that a population would become accustomed to seeing them in the same way that sky scrapers or power lines have been accepted. Offshore wind farm aesthetic impact is lessened due to the reduced visibility from the general public. However, as indicated in Gee [37] the visibility of a wind farm in the 'seascape' can create a large resistance in the public opinion. In general, wind farm aesthetics is a complicated area of study that is substantially influenced by public opinion. As wind farms grow in size and number, visual impacts and the cumulative effect of multiple turbines cannot be discounted as an important area of wind farm dynamics.

2.6. POWER PURCHASE AGREEMENTS AND LEGISLATION

Financial and legislative agreements cannot be neglected from any discussion regarding wind farm siting. Often, these issues can be the largest obstacles or facilitators to the development of a wind power plant. Regarding Power Purchase Agreements (PPA) Barradale [38] argued that volatility in these contracts has been the root cause of the United States boom-bust history with wind energy and not feasibility of the technology. Without a good PPA the development of an ideal site is not feasible. Zhang [39] discussed that PPAs are highly negotiable and can be very technical. These negotiations may be affected by the size and location of the proposed wind farm which will have an impact on the final development decisions.

In addition, legislation will also have an impact on whether the farm is built including its final configuration. Countries, states or provinces and municipalities are able to promote or deter wind power by deliberately forming the rules and regulations that govern installation and operation of these types of projects. The recent influx of offshore wind projects approved in the United Kingdom are directly related to the encouraging legislation approved making the goal of 20% wind power in the U.K. by 2020 an achievable goal [40]. Once again, project size and location has a major role in the approval process for new applications. On a smaller scale the placement regulations such as setbacks from roads and required distances to existing buildings will add another complication into the micro-siting of a farm. Rules dictating inter-farm distances become a greater issue in areas where multiple developments vie for the same real estate.

There exist many factors that influence the siting aspects of wind farm dynamics. All of these factors are influenced by cost and land owners. Ideal scenarios for micro-siting, terrain selection and aesthetic arrangement are generally not the most cost effective and may even be contradictory. Underground cabling, power stations, commercially available land and foundation costs force a compromise with ideal siting situations. In many cases wind farm developers must compromise turbine placement simply because one or more land owners refuse to allow the erection of a turbine on their property. Several software programs have been developed to aide in the management of these factors such as Garrad Hassan’s “WindFarmer,” Risø’s “Wind Atlas Analysis and Application Program (WAsP),” ReSoft’s “WindFarm” as well as others as summarized in Barthelmie et al [41]. Since these siting decisions cannot be altered once completed, this area of wind farm dynamics is critical in the wind farm design process.

3. POWER PRODUCTION

The connection of a wind turbine to the power grid is costly. The European Wind Energy Association estimates that approximately 9% of a 2MW wind turbine installation cost comes from grid connection [34]. Typically a single grid connection point or point of common coupling will be established for a wind farm to reduce the total expense and complication of connection. Many issues have arisen with the connection of a variable output power plant to the main power distribution system. Regulations have been set in place by grid operators in order to control the power being fed into the system. A comparison of requirements from several European countries was made in Jauch et al. [42] showing that grid codes can be similar but tend to vary depending on the local transmission system operators (TSOs). The increase in wind power penetration in some countries has forced a change in the stringency of grid codes with still more changes to be made [43]. Such connection policies, voltage tolerances, active and reactive power control and other power quality issues all directly influence the wind farm dynamic.

3.1. POWER QUALITY

TSOs require voltage tolerances on power supplied to the system in order to maintain power quality. This requirement varies by operator. For example the International Electro-technical Commission standard for wind power generators is +/- 5% of its nominal value [IEC Standard 61400-21] but a study of a rural site in Canada has shown +/- 10% to be acceptable [44]. Prior to connecting a wind farm to a power distribution or transmission system it is important that the grid can cope with the influx of power. A weak grid can be greatly influenced by a wind farm as the active power produced by the turbines fluctuates with wind speeds. Regarding farm wide dynamics, the number of turbines on the farm will dictate the size of these voltage changes as well as the frequency at which they will occur. The greater the number of turbines the greater the decrease in higher frequency fluctuations (10 minutes to 1 hour or less) [45]. This conclusion highlights the fact that wind turbines have grown in size for economical reasons and not necessarily power production or quality.

The type of wind generators employed on a wind farm will also influence the farm wide power production. For example, the reactive power consumed and delivered must be controlled as it has a direct effect on voltage as explained in Chen and Blaabjerg [46]. Conventional induction generators used in constant speed wind turbines have required the addition of capacitor banks or dynamic reactive power compensation equipment in order to account for changes in reactive power, and thus voltage, that is inherent with changes in active power. Induction generators require reactive power to energize the windings.

Multiple induction generators in a farm can cause a significant voltage change as wind speed drops and causes a corresponding drop in reactive power absorbed. Wound-rotor or doubly-fed induction generators used for variable speed wind turbines are less susceptible to voltage fluctuations due to reactive power changes since the onboard power converters are often capable of controlling reactive power. Depending on the size of the farm and types of generators present, a central reactive power controller has often been used to improve the quality of delivered power [47].

Another form of voltage induced power quality issues is voltage flicker. This is a fast variation in voltage that can cause a visible dimming of lights for consumers. The effect is due to the switching of the capacitor banks mentioned above, wind turbine start up, shut down and any other farm activity associated with a large influx or deficit of power production. This is obviously an undesirable effect but has generally been associated with weak grids that are already at transmission capacity during normal operating conditions.

A certain amount of grid fault ride through capability is also generally required of a wind farm. With wind turbines requiring reactive power for inductance the loss of power for any length of time can cause generators to disconnect. As a result, detailed conditions of fault ride through duration and synchronization are laid out by TSOs. Studies continue on the improvement of turbine response during grid faults as shown in Hansen and Michalke [48]. The details of fault ride through operation requirements along with active and reactive power control codes have been summarized for countries with large wind energy penetration in Tsili and Papathanassiou [49].

Grid connection of wind farms requires consideration of peripheral equipment in order to control active and reactive power to deliver power of a quality that meets local grid codes. Farm size and generator characteristics directly influence what equipment is necessary as well as how and where turbines should be connected. The control of power flow to and from the grid has been a major area of study in wind farm dynamics. It was shown in Muljadi et al. [50] that a wind farm cannot be represented as a single wind turbine but as groups of turbines with unique characteristics specific to each location within the farm. Strategies for managing large numbers of wind turbines and centralizing control of active and reactive power are currently being developed [51-52] as well as models of the dynamic interaction of wind farms and the grid [53-54]. This work is all due to the significant influence that wind farming will have on grid quality and stability in a market of increasing wind power penetration.

3.2. WIND FARM CLUSTERING

In addition to the dynamics of single farm grid connection, the study of multiple farm or wind farm clusters along with establishing a centralized network to create a single point of common coupling is also growing. In the case of Wang et al. [12] a proposed method for linking four, parallel offshore wind farms has shown promise for smoothing out the power delivered to the grid. Conversely, Banakar and Teck [55] discussed the negative effects of multiple wind farms operating close to the same point of connection. They have stated that because of a wind front's ability to influence all farms in a region the fluctuation of production can be amplified enough to cause either a saturation or deficit in the grid. Future work in this area is expected due to the potential benefit it can have as well at the increased density of wind farms globally. It is interesting to note that wind farm clustering depends on the modeling of a farm as a single unit with dynamic behaviour rather than a collection of turbines.

3.3. FORECASTING

A function of transmission system operators is to manage the supply and demand of energy. This is more difficult to manage with a meteorologically dependent power source than conventional sources. To enable the balancing of the system there must be at least an approximation of the power to be delivered by a wind farm. Wind power forecasting has been and continues to be a critical element and focus of research for the operation of a wind farm. It is the responsibility of farm operators to provide estimates to allow the TSO to balance the system. Power prediction techniques vary and are not yet regulated. Forecasting is used for operational control with predictions from seconds to minutes ahead and for power production on the order of hours to days. For short term forecasting, statistical methods have typically been relied on; whereas for the long term, a combination of meteorological and statistical techniques has been used. A summary of software developed for this task was given in Foley et al. [56]. Concerning the dynamics of an entire farm, forecasting of power for a single wind farm is not substantially different between one and many wind turbines aside from the fact that more data can be drawn upon to make a prediction. However, an aggregated approach to multi-farm forecasting methods is being employed increasingly. Focken et al. [57] as well as Han and Changas [58] studied the forecasting error when multiple wind farms are used to predict power rather than just one. It is shown that as the area over which the potential farms increase, the prediction error decreases. This is known as a spatial smoothing effect. Lobo and Sánchez [59] stated that this aggregated approach can also be faster at making predictions. In the case of Pinson et al. [60] the on-shore wind farms in Ireland were clustered by geographical region and data collected from each cluster was used to verify a prediction model for regional wind generation.

3.4. ENERGY STORAGE

Wind energy has been identified as benefitting greatly from energy storage systems. The employment of an energy storage system drastically changes the area of wind farm dynamics. By buffering the energy supply of a wind farm to the grid power quality can be improved and the negative effects of wind farm clustering can be minimized. In addition, the profitability of the farm can be greatly increased simply by supplying power at peak demand times rather than as it is produced. An overview of energy storage systems currently in use or under development has been given by Cavallo [61]. These include compressed air energy, pumped water, battery, superconducting magnets, flywheels and regenerative fuel cells. In [61] and later in [62] Cavallo argues that compressed air energy storage (CAES) was the most economically feasible method at the time of writing. There are presently no CAES facilities operating in conjunction with a wind power plant however two facilities exist for the purpose of shifting power from off peak to peak demand hours. Arsie et al. [63] proposed a method for simulation and management of a hybrid CAES/wind power plant combination comparing cost and efficiency for a range of wind farm sizes. Konrad et al. [64] completed a more detailed study of geology and geography, design and configuration and economic and operations analysis for a specific region in Ontario, Canada shedding light on the opportunities that exist for CAES and its feasibility. Some of the literature concurs that CAES systems, more so than other energy storage systems, are currently economically feasible and greatly beneficial to the wind industry [61-63]. However, one analysis by Pickard et al. [65] concludes that underground pumped hydro may be a more feasible method. For a more detailed review of CAES and its application to wind power please refer to Succar and Williams [66].

Although energy storage methods lessen the impact of many aspects of wind farm dynamics, their use would create new areas within this study as the farm is once again treated as a single entity. Management of storage and release strategies would be critical. Siting the farm initially would be drastically affected as accommodation for the storage system would need to be considered. The farm may also be arranged in a different manner to take advantage of more dominant off peak winds since power generated could be transferred to peak demand hours. Power quality could be more stringently controlled, eliminating voltage flicker and reducing conflicts in grids with high wind power penetration. Operation and maintenance strategies may also be changed to ensure maximum power is produced at the highest generating wind speeds possibly forcing more onsite maintenance capacity overnight.

3.5. 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 concerns stopping 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 [67]. The second approach refers to the shut-down or reduction of axial induction of an upstream wind turbine that is producing influential turbulence in order to increase the production of downstream turbines and therefore increase the overall production of the farm [21]. Kjaer et al. [45] briefly discussed the concept of stopping a turbine for the purpose of preventing damage upstream or downstream while Neilsen et al. [67] gave an actual method for quantification of the reduction of turbulence intensity for protection of the downstream turbines. By using turbulence intensity and wake velocity deficit models; a comparison was made with an imaginary wind farm. A reduction in turbulence was observed with wind sector management applied. This approach will generally result in a decrease of wind farm power production as well. The latter concept of increasing wind farm production by reducing axial induction has gained most of its attention from Corten and Schaak [68] of the Energy Research Centre of the Netherlands (ECN). A patent has been granted for the strategies developed at ECN [69] 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 [13] 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 [21] 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. OPERATION AND MAINTENANCE

Operation and maintenance costs can account for 10-20% of the overall non-capital cost of energy for a wind farm [70-71]. Verbruggen [72] stated that costs can be as high as 30-35% of electricity production, with 25-35% of those costs allocated to preventative maintenance and 65-75% corrective maintenance. It is therefore not surprising that much attention is being given to the minimization of this ongoing expense. The main objective of ongoing operation actions is to increase the availability of each wind turbine. It was estimated that commercial onshore wind turbines are available for production over 97% of the time during the lifespan of the machine [45] and between 80 and 95% for offshore [73]. It is the goal of operation and maintenance plans to keep this percentage as high as possible at all times.

4.1. MAINTENANCE SCHEDULING

With multiple wind turbines being maintained within a single farm operation these plans fall under the study of wind farm dynamics. Prioritization of planned and unplanned maintenance as well as farm wide condition monitoring systems must be treated corporately. It is important that scheduling is in place for preventative maintenance to ensure adequate time and personnel are allocated to each wind turbine in the appropriate sequence of machines. A robust logistics plan can reduce the direct and indirect costs of wind farm maintenance [70]. Unplanned maintenance is occasionally required for more than one machine at a time and if there are not sufficient resources to resolve the issues simultaneously one turbine must be prioritized over another. Establishing guidelines for priority setting is important. For example, should the shorter task be completed first? Should the higher producing machine take priority or is there planned maintenance that can be completed at the same time or shifted up out of the schedule? Methods for optimizing wind farm operation and maintenance are currently in use and under study [74-77].

Weather conditions can have a severe effect on maintenance particularly for offshore wind farms [78]. If a site is inaccessible, tasks must be rescheduled, sometimes delayed for days. Offshore sites typically see more frequent weather disturbances since simply getting to the turbine may be just as unsafe as scaling it. Rademakers et al. [75] established recommended weather conditions of wind speed < 1.5 m/s and wave height < 1.5 m in order to maximize accessibility and worker safety. Figure 7 shows a maintenance service boat in favourable weather conditions.

Figure 7 Servicing of offshore wind turbine with corroded base. Image courtesy of Ciang et al. [80].

4.2. CONDITION MONITORING

The collection and communication of data from multiple turbines is important for operational tasks. Anaya-Lara et al. [79] briefly discussed wind turbine SCADA (Supervisory Control and Data Acquisition) systems and the importance of communicating data within the farm and to the TSO. With effective condition monitoring, down time and thus costs for unplanned maintenance can be reduced by addressing issues early and scheduling repairs during appropriate weather [82]. Fault detection in wind energy applications has received a substantial amount of attention. The methods under study and currently in operation are numerous. A review of these techniques goes beyond the scope of this paper, however, interested readers should refer to [80-84]. These publications convey the likelihood of a failure in each wind turbine subsystem and describes the methods that are employed or under development to detect these faults prior to failure. Caselitz and Giebhardt [85] focused on the rotor for online condition monitoring and developed methods to accomplish this. Similarly, Yang et al [86] developed a method for condition monitoring of a wind turbine generator using electrical signal analysis rather than conventional vibration, temperature and oil analysis techniques. The extent to which condition monitoring methods use data from all turbines in a farm has been limited. Some research has considered data for multiple turbines in the development of new monitoring techniques such as Zaher et al. [87]. This approach used historical and newly acquired SCADA data to establish a data base of healthy state data across all wind turbines in order to detect anomalies that may be indicative of fault development.

The majority of attention in this field has been given to the use of isolated fault detection systems installed and operated on a single wind turbine. Using a wind farm dynamics approach to condition monitoring or structural heath monitoring has many advantages because of the amount of data now available across the entire farm. With comparison and cross-correlation of different wind turbine condition monitoring parameters a broader sense of what the healthy state of a wind turbine looks like is established allowing for better decision making and increased confidence in diagnosis.

5. DISCUSSION

It has been established that there are many facets to wind farm dynamics. Each area contains its own challenges and opportunities for wind farm developers and operators but simultaneous consideration of all of these areas is a difficult task. Many organizations in the industry have in-house methods for considering groups of these issues in order to better manage the project. Some software packages are capable of considering multiple dynamic factors like aesthetics, wake, and financial models. With wind farm dynamics taken to its full extent it would be useful to establish an overarching decision support system for all stages of a wind farm project. A flow diagram of a proposed high-level approach to farm-wide dynamics is given in Figure 8. It should be emphasized that the results from this approach could be highly variable depending on how the user assigns significance to each factor. Dynamic factors identified herein as major influences are categorized into three main headings of siting, power production, and operation. The twelve factors are shown interconnected to other factors they have the potential to directly influence. For example, the figure shows terrain under the siting heading. Terrain is shown to have a direct influence on ten other factors that include, for instance, inter-turbine wake effects and aesthetics. The terrain at a site may increase or decrease the wake effects between turbines on the farm. As described above, ridges, mountains and plateaus etc. can increase or decrease wind speed magnitude or turbulence. This will directly affect downstream turbine operation. Similarly, the visibility and capacity to aesthetically arrange turbines on a site are directly related to the terrain in which they are situated. Interactions or influences can also be indirect. Inspection of Figure 8 reveals that in the list of factors influenced by terrain, climate change has been identified to have 5 direct influences of its own, inter-turbine wake effects directly influences 7 factors, etc. If we sum all of these numbers we find terrain indirectly influences 66 other factors. Figure 8 shows the interconnectivity present in wind farm dynamics. There are many dependent relationships between the subjects of wind farm development and operation.

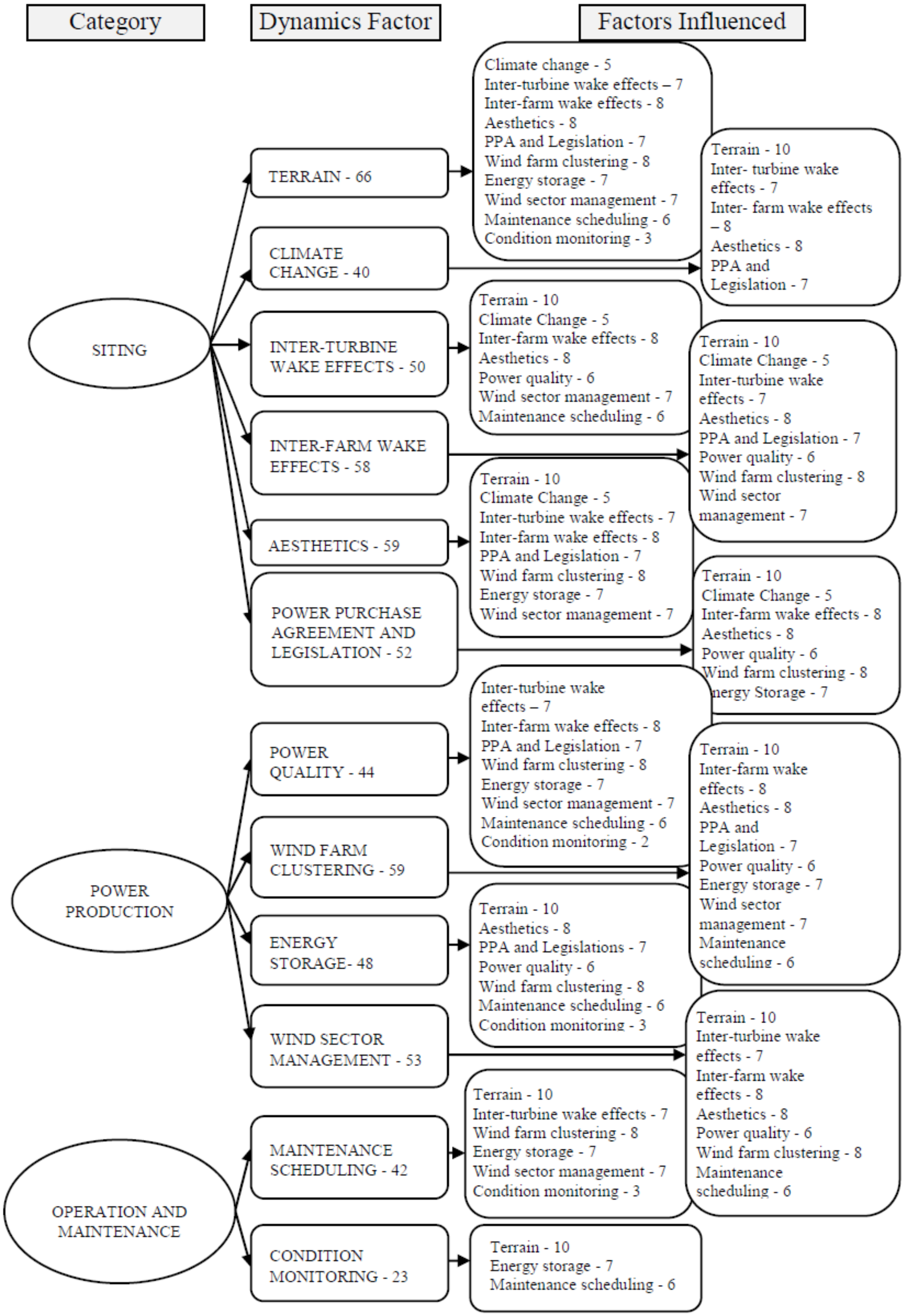

Figure 8 Wind farm dynamics flow diagram. Direct connections between topics and their interactions are shown. The indirect interaction count is given with each of the twelve topics. The indirect interactions are a summation of direct interactions for each identified topic

Table 1 is provided to offer some prioritization of these factors. The table lists the factors from Figure 8 in association with the direct (column A) and indirect (column B) influences. The influences are then multiplied (column C) to produce an influence product. Owing to the magnitude of the direct and indirect values, the ranking is more sensitive to a change in direct influences than indirect. The largest products indicate the greatest degree of connectivity which are subsequently ranked in column D.

	A	B	C	D
Topic	Number of Direct Influences	Number of Indirect Influences	Influence Product (A x B)	Influence Ranking (1 to 12)
Siting				
Terrain	10	66	660	1
Climate Change	5	40	200	11
Inter-Turbine Wake Effects	7	50	350	7
Inter-Farm Wake Effects	8	58	464	4
Aesthetics	8	59	472	2
PPA and Legislation	7	52	364	6
Power Production				
Power Quality	6	44	264	9
Wind Farm Clustering	8	59	472	2
Energy Storage	7	48	336	8
Wind Sector Management	7	53	371	5
Operation and Maintenance				
Maintenance Scheduling	6	42	252	10
Condition Monitoring	3	23	69	12

Table 1 Prioritization table for significance weighting of the various wind farm dynamics topics.

The primary influencing factor in Table 1 is shown to be terrain, followed by aesthetics and wind farm clustering. It is reasonable that terrain is prioritized in many wind projects owing to its affect on many other areas of development and operation. This is confirmed in the direct influences column where terrain exhibits the highest value. For each individual farm other topics may be considered more relevant than the order in which they are prescribed in Table 1. For example the power purchase agreement and legislation will be more important than wind farm clustering for almost all projects; however, the table is representative of degrees of interaction, not the singular significance of each factor. The flow chart in Figure 8 and Table 1 provide a high level tool for visualization of wind farm dynamics; as well as a sample methodology for prioritization of wind farm design and operation factors based on their interactions within the broad range of issues present in the industry.

6. CONCLUSIONS

The concept of wind farm dynamics was defined and its importance to the design, power production, and operation of a wind farm was illustrated. A flow diagram and a simple weighting system to assist in the prioritization of the critical elements of the wind farm dynamics concept were proposed. The interaction between dynamic effects of individual turbines in a farm has a cumulative effect on the behaviour of the farm and its surroundings. Such an accumulation of effects is more complex than the simple sum of its components. In addition to multi-turbine interactions, the influence of one cumulative dynamic effect on another has become a significant issue in wind farm dynamics. In the literature, individual turbine interactions have been treated as a whole in some instances, while others are still considered separately. A holistic approach should be applied to all wind farm dynamic interactions to most effectively develop and manage a profitable wind farm. As the advance of commercial wind turbine technology begins to mature, the greatest opportunities for wind energy profit maximization will be had in the optimization of the group dynamics present in multi-turbine wind farming.

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CHAPTER III

WAKE IMPACTS ON ELEMENTS OF WIND TURBINE PERFORMANCE AND YAW ALIGNEMENT

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Phillip McKay[1], Rupp Carriveau[1*], and David S-K. Ting[2]
1. Department of Civil and Environmental Engineering, The University of Windsor, Windsor, Ontario, Canada
2. Department of Mechanical, Automotive, and Materials Engineering, The University of Windsor, Windsor, Ontario, Canada
*Corresponding Author: e. rupp@uwindsor.ca, p. 01 519 253 3000

1. INTRODUCTION

In 2010 commercial wind farms were being operated in almost 80 countries [1] with over 10,000 farms worldwide [2]. With the continued growth in size and number of wind farms, aerodynamic wake generated by wind turbines is a critical area of study in the wind power industry with potential for large gains in wind farm efficiency. The downstream wake region of a wind turbine can have a detrimental effect on both performance and fatigue loads of another wind turbine operating within this region. Wake models are continuously under revision in order to improve siting techniques for new wind farms as well as existing farms that have potential for wake interactions [3]. Currently a distance of 5 rotor diameters (5D) is generally maintained for minimum turbine spacing in order to prevent excessive wake influences [4]. The wake region extends for a distance greater than 5D in both onshore and offshore applications [5-6], however it is not feasible to place turbines far enough apart to eliminate interaction. Since this interaction will occur, wind turbines are placed as far apart as possible in the local dominant wind directions and grouped closer together in wind sectors that on average receive less wind or are perpendicular to the dominant winds. Cases of direct wind turbine alignment with the wake of an upstream wind turbine have shown losses up to 55-60 % for professionally sited wind farms [7]. Dissipation of the downstream wake occurs as mixing between the low speed turbulent wake region and the free-stream wind velocity takes place. Depending on spacing, terrain, environmental conditions and free stream velocity, recovery can happen before the wind reaches the downstream turbine thereby reducing the wake effect. For an array of machines, the wake losses caused by the first upstream turbine are passed to all turbines in the row with the first downstream turbine impacted the most by a reduction in wake centerline wind velocity while the effects seen by the remaining downstream turbines are significantly less [7-9]. Barthelmie et al. [9] showed that for offshore wind farms the wake region has a distinct center line marked by a maximum velocity deficit with increasing wind velocity at increasing angles from the center line. This paper confirms these general findings as well as the wind velocity deficit recovery across an array of turbines for an onshore wind farm. A decrease in velocity does not necessarily correspond to an increase in turbulence however it is shown that the wake region does characteristically cause an increase in turbulence.

Several methods have been suggested for the mitigation of wake interactions in order to reduce fatigue damage and increase wind farm performance. Active control of the pitch, yaw, and tip speed ratio have been used to manage the axial induction factor allowing for an improvement in wind velocity at the first downstream turbine [10-14]. In the case of Adaramola and Krogstad [10] a wind tunnel simulation was conducted for a limited array of two wind turbines. It was found that by applying an optimized yaw angle to the upstream turbine an overall improvement in the power output of 12 % could be seen. Translation of the data to full-scale is somewhat limited due to low Reynolds number, blockage effect, and other limitations of wind tunnel simulation. Simlar to Adaramola and Krogstad, Corten and Schaak [13] noted a performance improvement of 4.6 % was observed for wind tunnel testing of a 3 by 8 array of turbines by increasing pitch angle of the upstream turbine. This testing was continued for the ECN test wind farm consisting of 5, 2.5 MW turbines. Results showed an improvement in power production of up to 0.5% over all wind directions as noted by Schepers and Van der Pijl [11]. Causes for discrepancy between wind tunnel and full scale experimentation are considered to be due to the usage of data from all wind directions and not simply alignment conditions. When certain conditions occur, such as low wind speeds and directly aligned turbines, the gains can be as high as 40 %. For the experiments considered above the yaw angles were not noted for all wind turbines in the row. This neglects a basic element of full scale wind turbine behaviour. It is shown here that downstream turbines do not remain aligned with the wake centreline but alter their direction to face better wind speeds from a lateral influx of higher velocity wind. This paper seeks to address this gap in the literature and to illustrate the prevalence of this yaw behaviour for an onshore wind farm. This concept may also be considered for the improvement of wake models that have typically overestimated power losses from wake effects [6].

2. DATA COLLECTION

Six months of 10 minute averaged SCADA data from an industrial wind farm situated in Southern Ontario, Canada was assessed to show dynamic yaw behaviour in the presence of upstream wakes. The wind farm consists of Siemens 2.3 MW horizontal axis wind turbines with a rotor diameter of 93 m and hub height of 80 m. Several linear arrays of 3 or more turbines exist within the wind farm. The micro-siting of turbines for an onshore farm generally assume a less grid-like pattern than offshore arrangements due to land availability and terrain characteristics resulting in the majority of turbines within the farm not being positioned in any particular linear arrangement. An array of 4 turbines was used for this study due to the isolation of the row from other turbines and the upstream turbine's proximity to the wind coming off of the large lake situated nearby. It is expected that the wind from this direction will be less turbulent due to flow development over the lake having occurring with a low surface roughness as compared to that over land. Turbine spacing is 5 rotor diameters between each machine in the array. The layout is given in Figure 1. The meteorological data from each wind turbine were available providing wind speed, nacelle position, and standard deviations from these parameters for every turbine in the array. In addition, power output data were obtained.

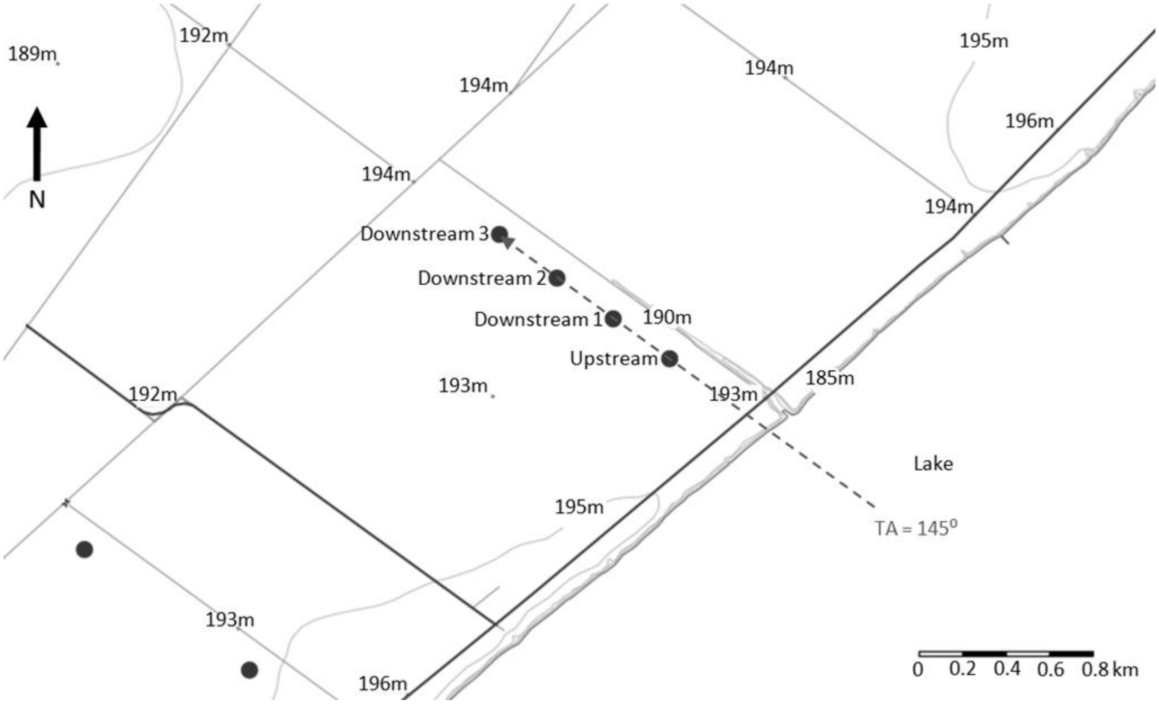


Figure 1 Wind Turbine Array Map. Elevations above sea level indicated for roads and contour lines. Turbine Alignment condition (TA) is marked. Map modified from Natural Resource Canada's Toporama – Topographical Maps (http://atlas.nrcan.gc.ca/site/english/maps/topo/index.html).

The data set spans from August 1st 2010 to January 30th 2011 covering the fall through several winter months in the southern Canadian climate. The wind rose of wind direction probability for the six month data set is given for the case of the upstream turbine in Figure 2. During this time period the wind favours a westerly direction as indicated by a greater probability of occurrence between approximately 210 and 350 degrees from North (clockwise as positive).

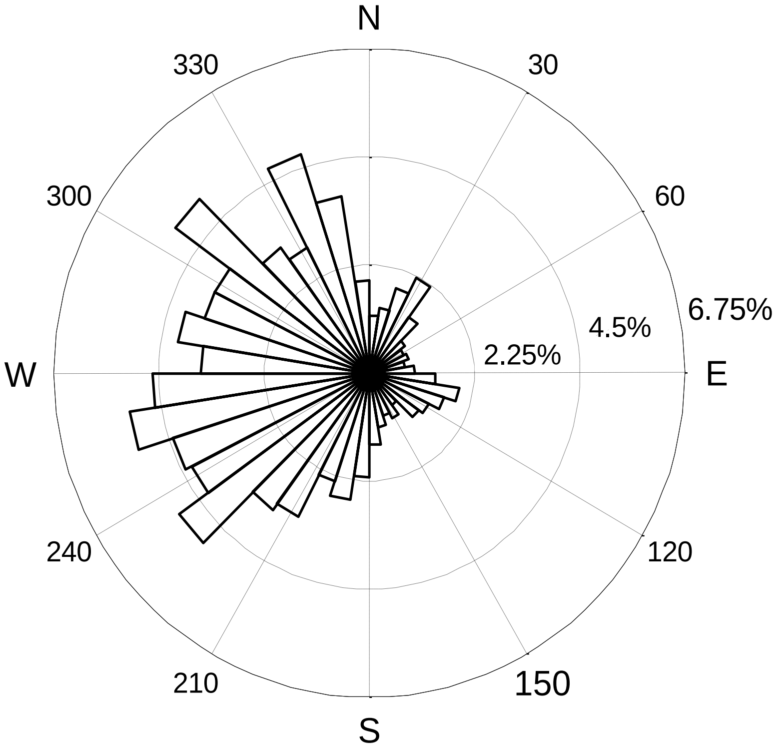
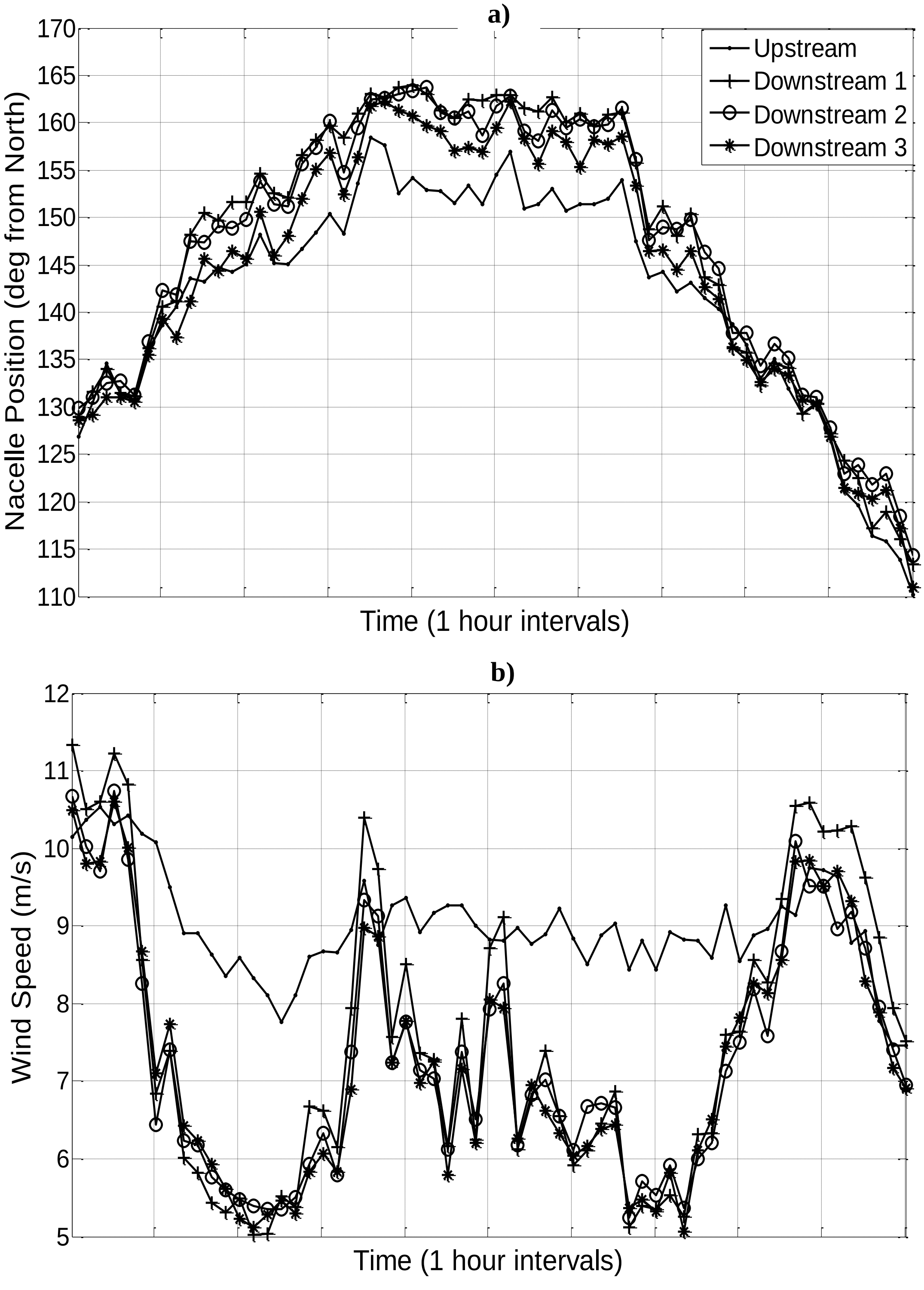


Figure 2 Wind rose indicating percentage of wind direction probability. Data are for the upstream turbine over the six month data set for all power producing winds (3-25 m/s).

3. WAKE CHARACTERISTICS

The wake profile is quantified for each wind turbine in the array. Time series data for nacelle position, wind speed and power are given for a single event and shown in Figure 3. 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 3a. 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 3b) 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 at 145 degrees (the angle the linear array makes with due North). In addition, the power is shown to drop along with wind speed (Figure 3c). This is a clear indicator of wake interaction between the four machines. Vermeer et al. [6] found that the wake velocity recovers more rapidly after the first turbine leaving the most dominant effect between the upstream and primary downstream turbine. In the array of four turbines shown in Figure 3 it can be observed that the deficit between the upstream and the first downstream turbine is never exceeded between the first and second, second and third etc. There are minor differences between each downstream turbine but there is not as significant a difference as that referenced to the upstream turbine, suggesting a recovery of wind speed between the subsequent downstream machines. For example, if no energy was added to the wake region downstream of the first downstream turbine, the power extraction for the subsequent turbines would quickly fall to zero. As is evident, however, the power developed by all downstream turbines is very similar.

This recovery is also observed by Barthelmie et al. [9] where momentum drawn into the wake by lateral or horizontal mixing of the air external to the wake region is credited with 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 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 the wake mixing from neighboring turbine rows.


a)
Nacelle Position (deg from North)
170
165
160
155
150
145
140
135
130
125
120
115
110
Time (1 hour intervals)
Upstream
Downstream 1
Downstream 2
Downstream 3
b)
Wind Speed (m/s)
12
11
10
9
8
7
6
5
Time (1 hour intervals)

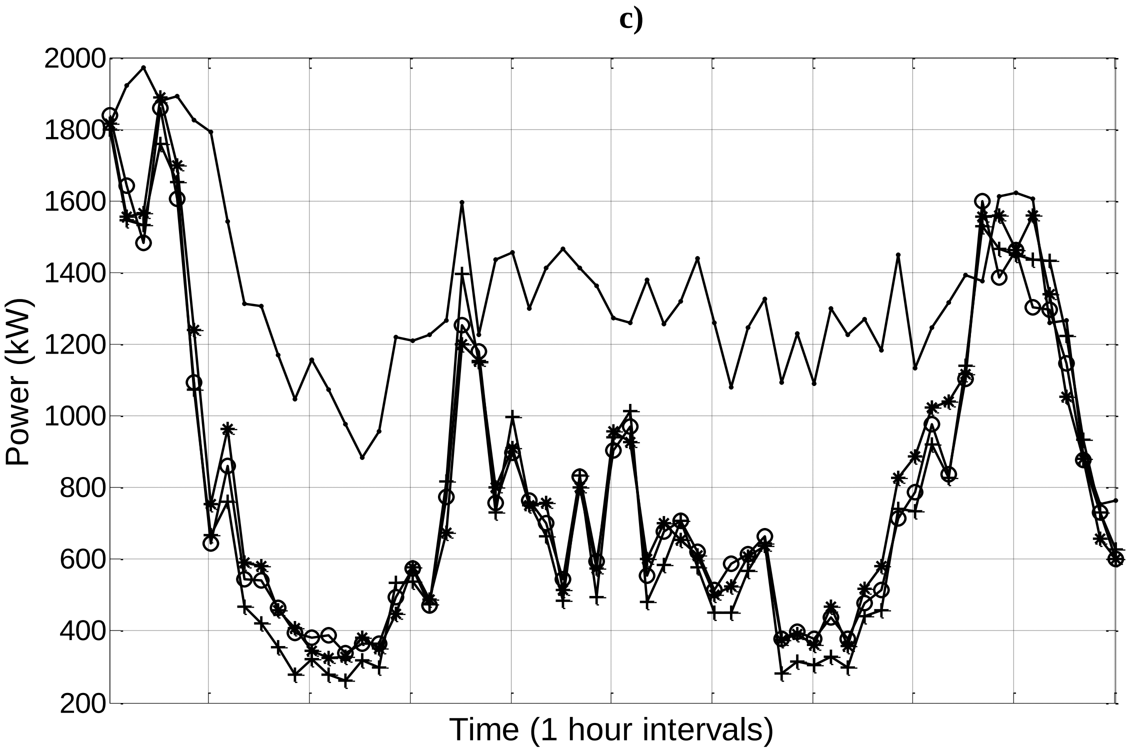


Figure 3 Time series SCADA data for a period containing a case of turbine alignment. a) nacelle position, b) wind speed and c) power.

For the six months of available data in the present study, the wake profile is mapped and given in Figure 4. The upstream nacelle position was used as the reference wind direction as it is expect to be the least disturbed by surrounding turbines. 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 considered in this paper 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 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. As indicated in Figure 2, the probability of wind occurring from the direction of direct alignment taken at 145 degrees is low. The more limited data from this direction are used due to the expected reduction in wind shear as the wind comes from the lake and not over land as shown in Figure 1.

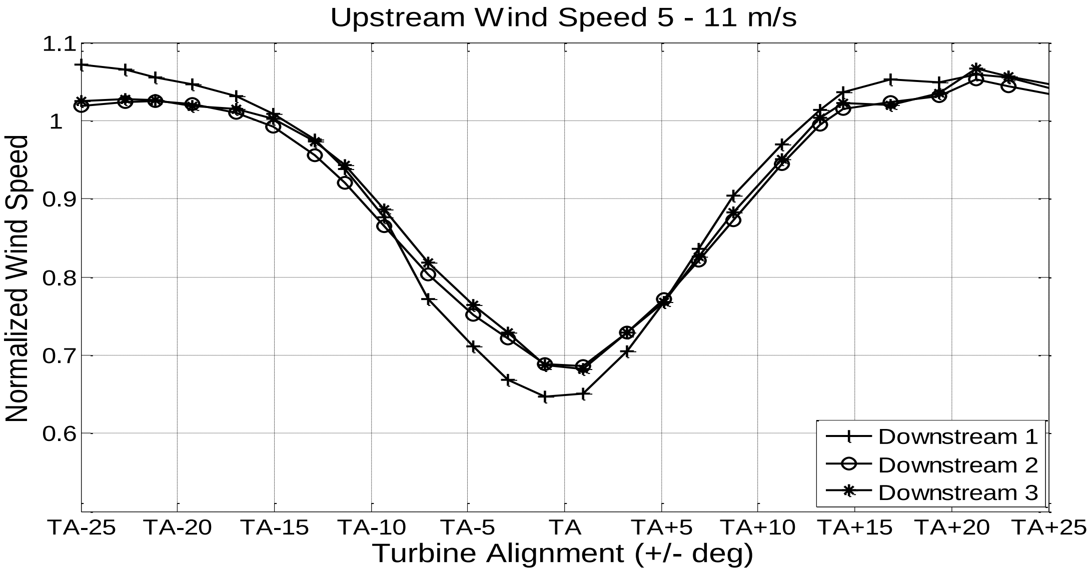


Figure 4 Array wake profile for an upstream turbine wind speed range of 5-11 m/s, considered here as the free stream wind speed. The data are averaged over 6 months. Wind speed is normalized by the upstream turbine (free stream) wind speed: downstream wind speed/upstream (free stream) wind speed.

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 5. This exhibits the same trends as shown in Figure 4 for a wider wind speed range. The power coefficient profile for the same wind speeds is shown in Figure 6 where the power coefficient is taken as:

$$C_P = \frac{8P}{\pi \rho U_\infty^3 D^2} \quad \text{............} \ (1)$$

The values were estimated using the upstream wind speed reading as free stream velocity with P as power produced by the turbine, ρ being 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.

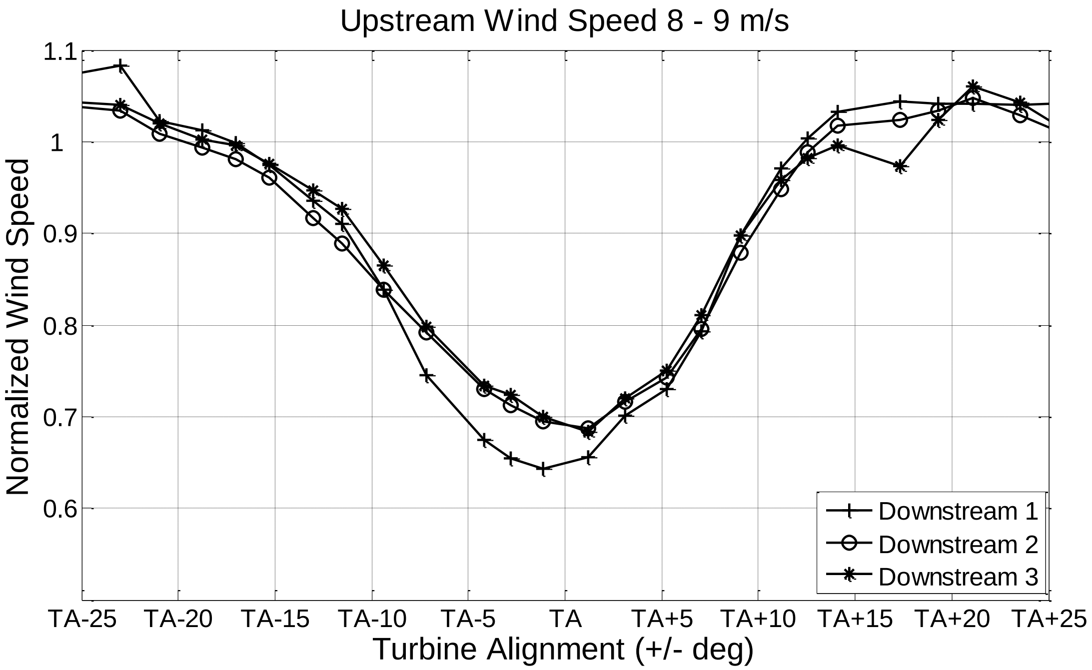


Figure 5 Normalized wind speed for an upstream turbine (free stream) wind speed of 8-9 m/s averaged over 6 months.

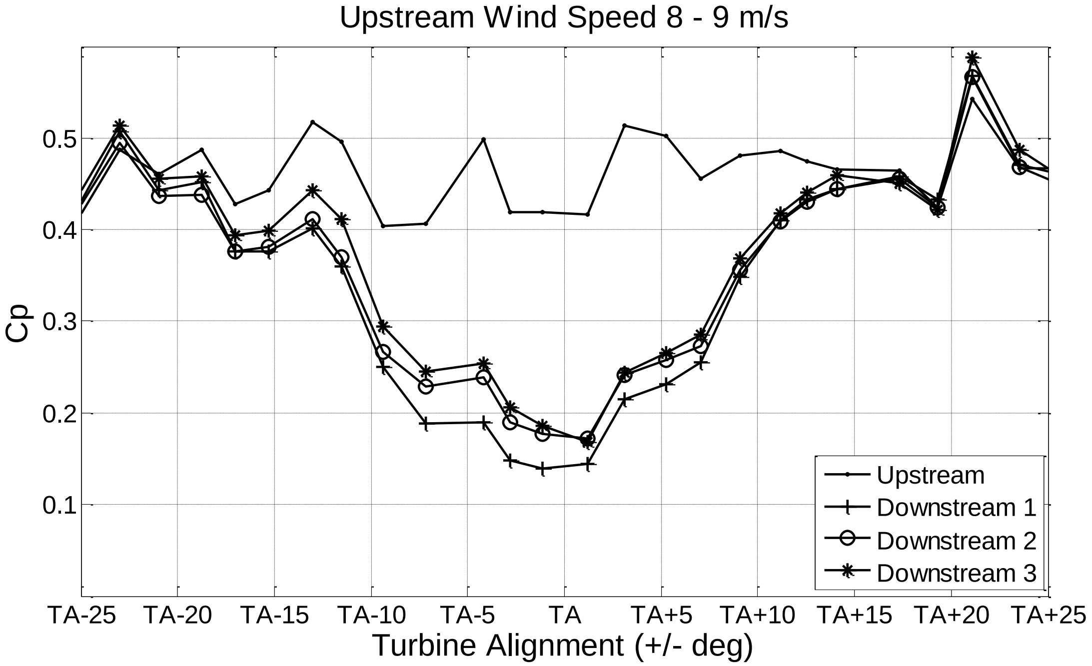


Figure 6 Array power coefficient profile for an upstream turbine wind speed of 8-9 m/s averaged over 6 months.

In Figure 7, turbulence intensity is implied by considering the standard deviation of wind speed. Deviations are calculated by the 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 at approximately TA +/- 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 7 is consistent and may have potential to cause issues over the long term life of the turbine. This is due to the increased fatigue loading caused by the frequent fluctuations. In addition, increased variation in wind speed along the length of the blades 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 6.

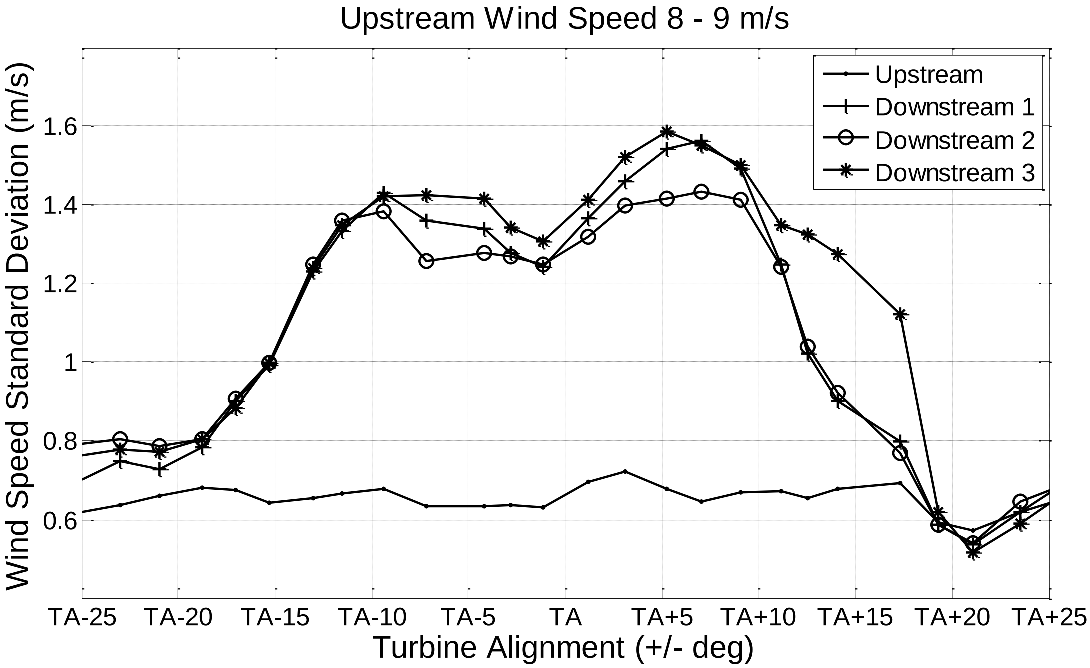
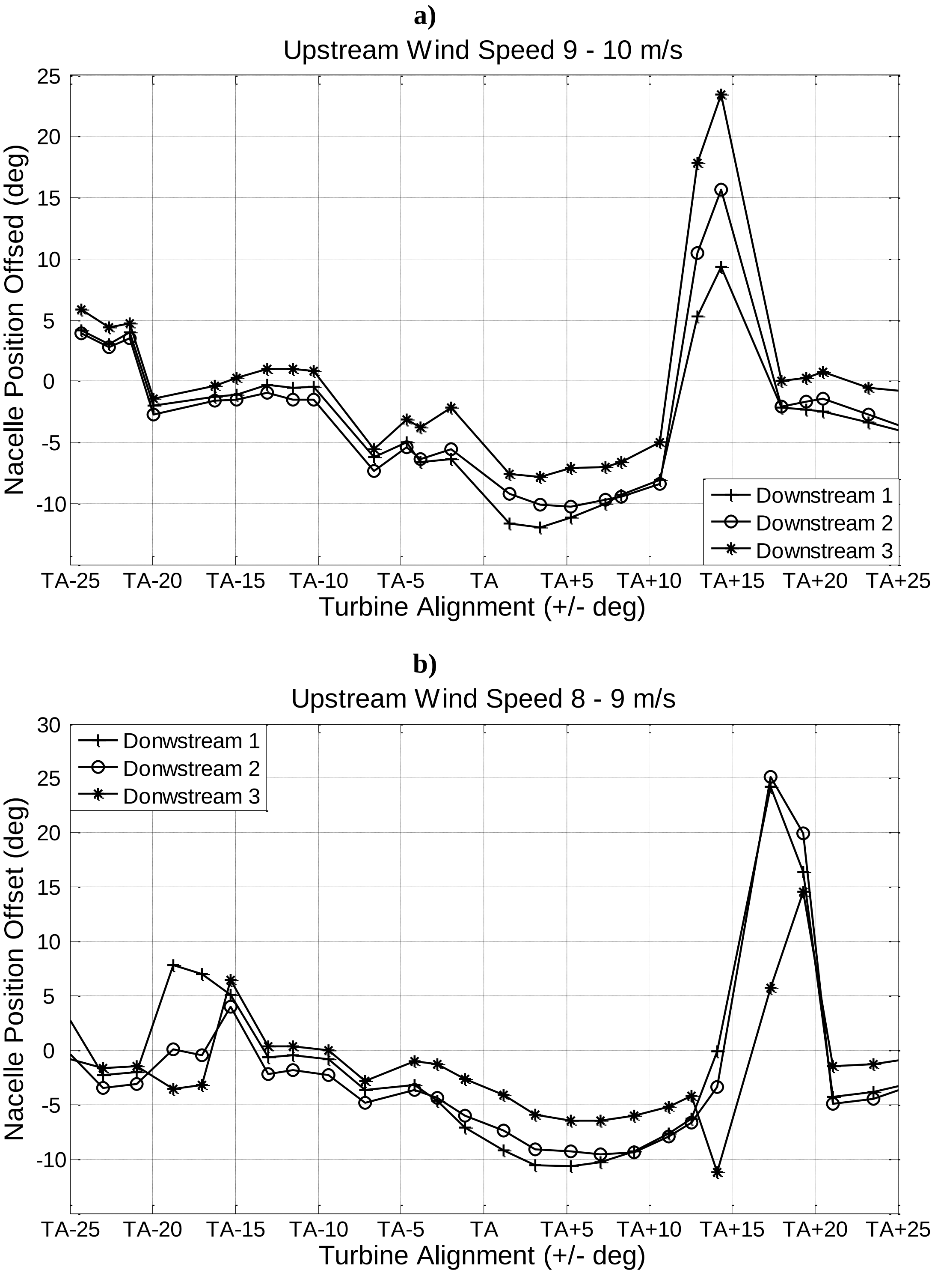


Figure 7 Wind speed standard deviation for upstream wind speeds of 8-9 m/s averaged over 6 months.

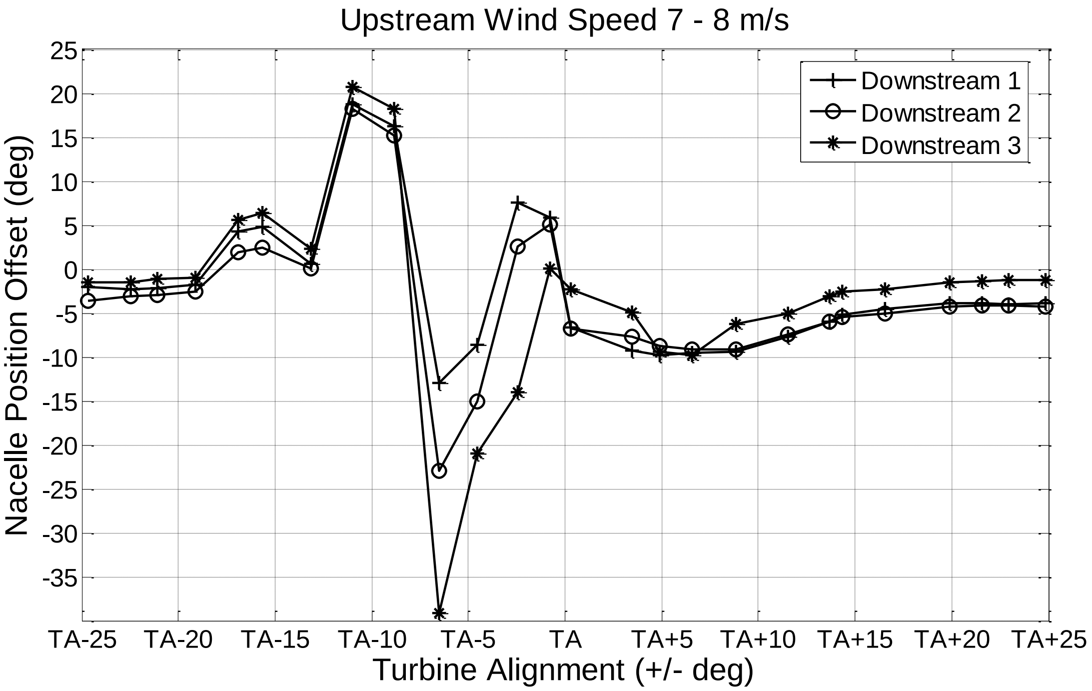
It is evident that there are other external factors that contribute to the definition of these profiles as they show irregularities and not a smooth shape. It is expected that the 6 month averaged data has reduced the effects of short term, isolated fluctuations in wind speed, humidity, temperature, air density and inhomogeneous wake at the downstream turbine and so there is a consistent fluctuation in the wind speed under turbine alignment conditions which will be discussed in the next section. Seasonal and site specific wind conditions likely contribute to the small scale unpredictability of wake velocity deficit and turbulence intensity.

4. WAKE INFLUENCED YAW POSITIONING

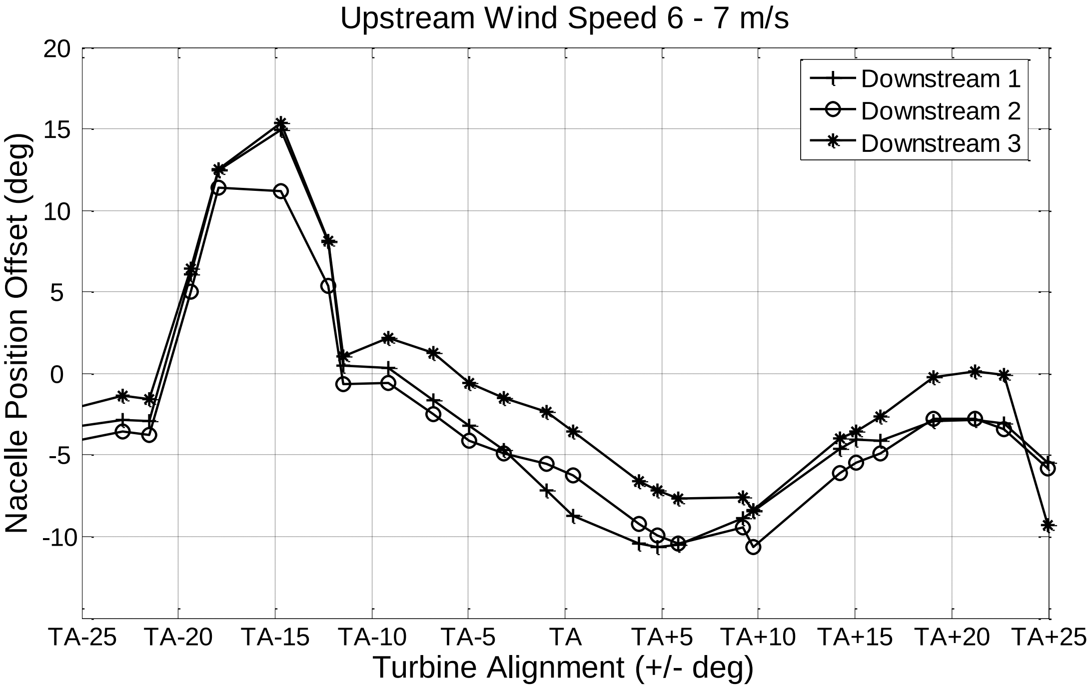
Wind turbines are typically independently controlled, relying on the data collected from the meteorological station situated on the back of the nacelle to dictate response. The turbine continually adjusts the orientation of the nacelle in order to face the best consistent wind direction. They typically only initiate a yaw movement after the new wind direction has been observed for a specified time so as to avoid constant “hunting” under rapid wind direction fluctuations. The higher the wind speed the less time required to justify a change in yaw position for the turbines under study. Figure 8 shows data for a range of wind speeds. The figures represent the downstream nacelle positions subtracted by 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.


a)
Upstream Wind Speed 9 - 10 m/s
Nacelle Position Offsed (deg)
25
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)
Downstream 1
Downstream 2
Downstream 3
b)
Upstream Wind Speed 8 - 9 m/s
Nacelle Position Offset (deg)
30
25
20
15
10
5
0
-5
-10
Donwstream 1
Donwstream 2
Donwstream 3
TA-25
TA-20
TA-15
TA-10
TA-5
TA
TA+5
TA+10
TA+15
TA+20
TA+25
Turbine Alignment (+/- deg)

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)

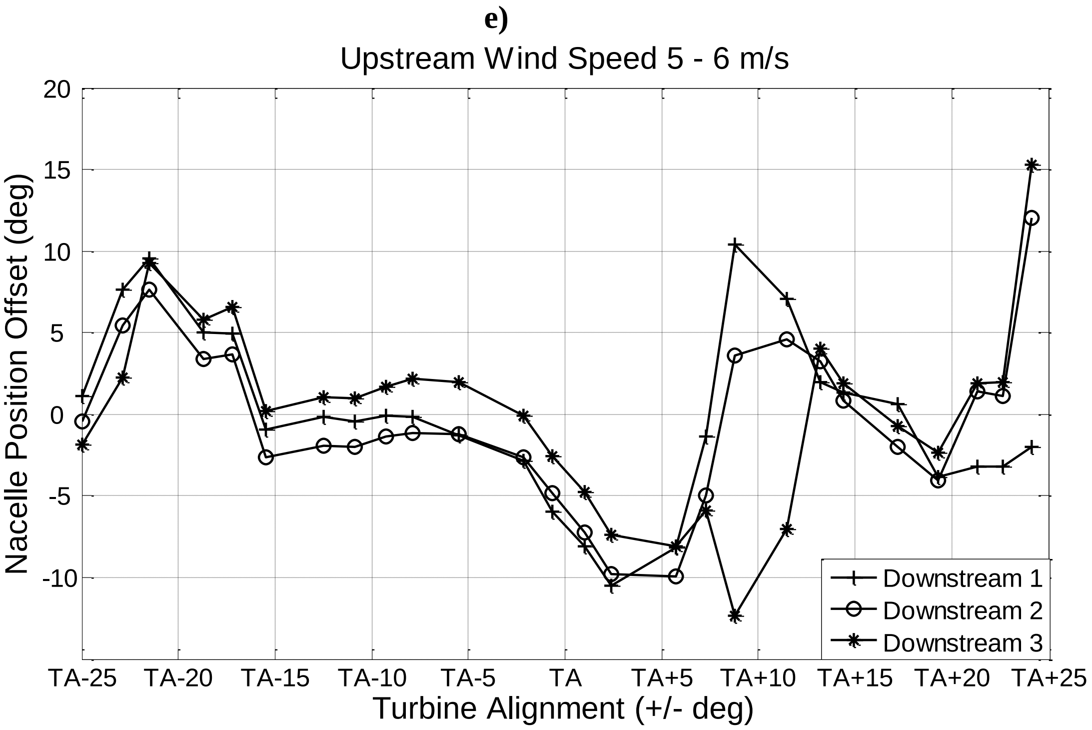


Figure 8 Nacelle misalignment between wind turbines for 6 months averaged data. a) 9-10 m/s, b) 8-9 m/s, c) 7-8 m/s, d) 6-7 m/s, e) 5-6 m/s/ Lead upstream nacelle position is subtracted from each downstream turbine nacelle position.

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 additional two 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 6, the separation of the lines for each downstream turbine are less defined. The third downstream turbine once again exhibits unique behaviour.

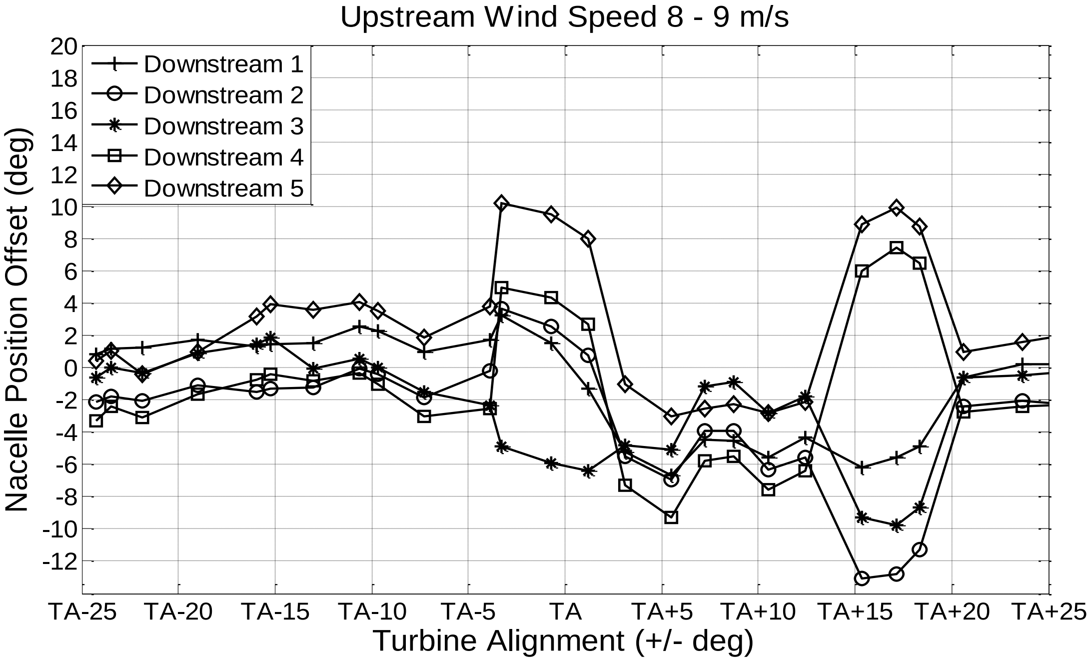


Figure 9 Nacelle misalignment between wind turbines in array of 6 machines for 6 months averaged data. Lead upstream nacelle position is subtracted from each downstream turbine nacelle position.

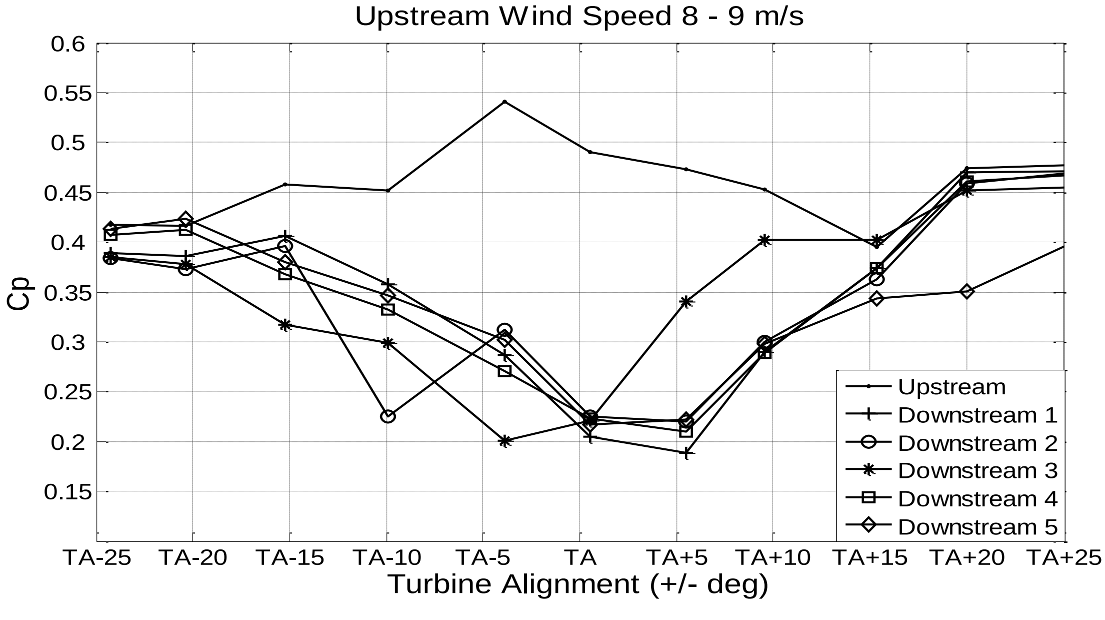


Figure 10 Six turbine array power coefficient profile for an upstream turbine wind speed of 8-9 m/s averaged over 6 months.

5. DISCUSSION

Wake behaviour under yawed flow conditions has been extensively studied using wind tunnel models by Dahlberg and Medici [14], Haans et al. [15], Parkin et al. [16] and Adaramola and Krogstad [10]. Various methods are employed to determine wake properties in these conditions such as hot-wire and hot-film anemometry, particle image velocimetry (PIV) and flow visualization techniques. Parkin et al. [16] provided insight into wake skew angles or the angling of the wake away from its axial flow centerline. The PIV velocity profile results for a model wind turbine in a wind tunnel show wake deflection favouring the direction with the downstream blade. The experiment also included a downstream wind turbine operating in the wake of the upstream machine. The models consisted of double bladed turbines with a generator and load circuit for control of tip speed ratio and measurement of power output. Wake deflection caused by upstream yaw resulted in a clear increase in available wind velocity for the downstream turbine. This characteristic has been seen earlier in a study performed by the Royal Institute of Technology (KTH) using smoke for flow visualization of a wind tunnel model. There is a clear deflection of the wake towards the side of the downstream blade. Dahlberg and Medici [14] further this study using a similar setup to Parkin et al. having a two, double bladed turbines with a generator but with adjustable blade pitch.
The effect results in better wind availability for downstream turbines directly aligned with the upstream machine since the wake is deflected from the path of the downstream turbines. These results are confirmed by Haans et al. [15] where skew angle increase is shown to correlate directly with an increase in yaw angle for wind tunnel models. In this testing a two bladed wind turbine is situated in an open jet wind tunnel. Pitch is adjustable with no other control of tip-speed ratio.

Another characteristic of wind turbine wake is lateral and vertical mixing of free stream wind with the wake area. Calaf et al. [17] used Large Eddy Simulation techniques to describe the instantaneous contours of streamwise velocity for an array of wind turbines. Turbine rotors are simulated using actuator disk theory by using average disk velocity. Barthelmie et al. [9] showed similar results for lateral mixing in the case of full scale offshore wind turbines as earlier discussed. Lateral and vertical mixing as well as wake skew angle theories can be applied to Figure 8. However, there are two major differences between the wind farm data collected and the computer and wind tunnel simulations conducted in these experiments. The first is that the upstream wind turbine is always assumed to be facing directly into the wind and therefore never under yawed conditions. This reduces the correlation between the experimental and full scale data to the direct alignment condition. The second difference is that the downstream turbines are free to yaw as dictated by their independent controls. In all of the experimental results referenced above, the downstream turbine yaw positions are either fixed or not given. This either constrains the machine to direct alignment regardless of higher wind velocities coming from offset angles; or introduces some uncertainty in the response of the downstream turbines. Based on the full scale results presented in this paper it is expected that yaw misalignment would occur at the simulation level producing altered results and could further our understanding of wind farm dynamic behaviour. It has been observed that many wake models overestimate velocity deficit, especially at low turbulence levels, when compared to full scale data [6]. The natural tendency for wind turbines to adjust out of alignment in order to capture better wind may contribute to this model error. Regarding active wake management or wind sector management, it can be seen that a reduction in axial induction of the upstream turbine has the potential to reduce the magnitude of the velocity deficit as observed by the downstream turbines [10, 14]. It is also possible that this performance improvement may occur in a different fashion than expected. A reduction in upstream induction by control of pitch, yaw or tip speed ratio will change the effect to the incoming atmospheric boundary layer and therefore the vertical and horizontal mixing. This in turn may change recovery times and distances for the wake region causing a change in yaw behaviour. It has yet to be studied whether this will result in an improvement in array performance in the way that active wake management simulations have shown or whether the changes will be negligible regarding power output.

The importance of wake control is put into perspective by consideration of the probability of occurrence of turbine alignment +/- 25 degrees. For the site discussed and the array of turbines under study, the probability of nacelle position is plotted in Figure 11. Two years of nacelle position data was available to provide a wind rose independent of seasonal effects. Although not the dominant wind direction, turbine alignment at 145 degrees from North still occurs approximately 1.5% of the time. A wind direction 180 degrees from turbine alignment must also be accounted for since it will cause alignment in the array from the opposite direction. These directions coupled with the range of angles covered by the wake profiles discussed above contribute to a probability of occurrence of 26.7% over the two year period recorded. It was shown in the previous section that multiple, linear arrays of turbines are present within the farm and display similar behaviour to that under study. Therefore the scope of the issue is extensive.

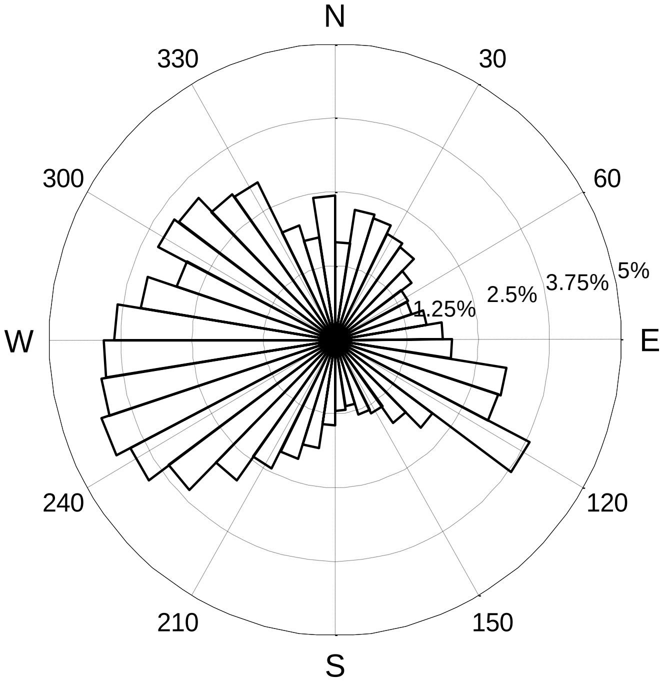


Figure 11 Wind rose indicating percentage of wind direction probability. Data is for the upstream turbine over 2 years for all power producing winds (3-25 m/s).

Comparing Figure 13 with Figure 2 provides some insight into the seasonal effects present in the six month data set as the distribution is more evenly spread around the wind rose. The probability of wind direction falling within turbine alignment +/- 25 degrees including both alignment conditions 180 degrees apart showed that probability is over 2.5% greater overall for the six months of Fall/Winter conditions.

Although the benefits of active wake control are evident, the lack of adoption of these methods in industry may be due to some uncertainty in the affects on turbine health.

While reducing the axial induction upstream decreases the downstream turbulence, it is not fully understood what the negative effects of forced yaw operation are on the upstream turbine. Assessment of offshore foundation loads in the Utgrunden wind farm showed concerns of increased loading under forced yaw operation and resulted in not pursuing active wake control [18].

Improved detection methods for wind speed and direction for full scale turbines has the potential to further our understanding of the wake region as well as improve performance of existing turbines. The current industry standard for meteorological condition detection depends on anemometers and wind vanes mounted on the nacelle of the turbine downstream from the rotor blades. This provides information on wind speed and direction from turbulent wind that has already passed through the rotor. Light Ranging and Detection (LIDAR) is currently becoming a more affordable method for the detection of wind parameters and has many benefits for wind turbine operation. These devices utilize lasers to detect wind speed and direction upstream of the rotor while mounted downstream on the nacelle of the turbine. One unit produced by Catch the Wind Inc. claims detection up to 300 m upstream of the rotor with field tests resulting in a 10 % improvement in wind turbine power output [19]. Applicability of this technology under turbine alignment conditions may be high. As the downstream turbines naturally trend towards misalignment under wake conditions, LIDAR has the potential to detect changes in wind direction and adjust yaw position to capture the continually changing wind. In addition, this technology can predict gusts and extreme winds before they come in contact with the rotor allowing for some mitigation of damages caused by the more turbulent wind experienced under these conditions. Drawing data from an area or volume instead of a point also aids in the detection of better wind resources due to the large swept area of the rotor. Issues may arise in upstream detection methods if the system does not allow the turbine to initially yaw from direct turbine alignment by nature of the lateral influx of higher wind speeds only developing downstream of the detection area. The LIDAR detection distance would need to be set closer to the rotor in order to capture these late arriving lateral influxes. An example of this potential is given in Figure 14.

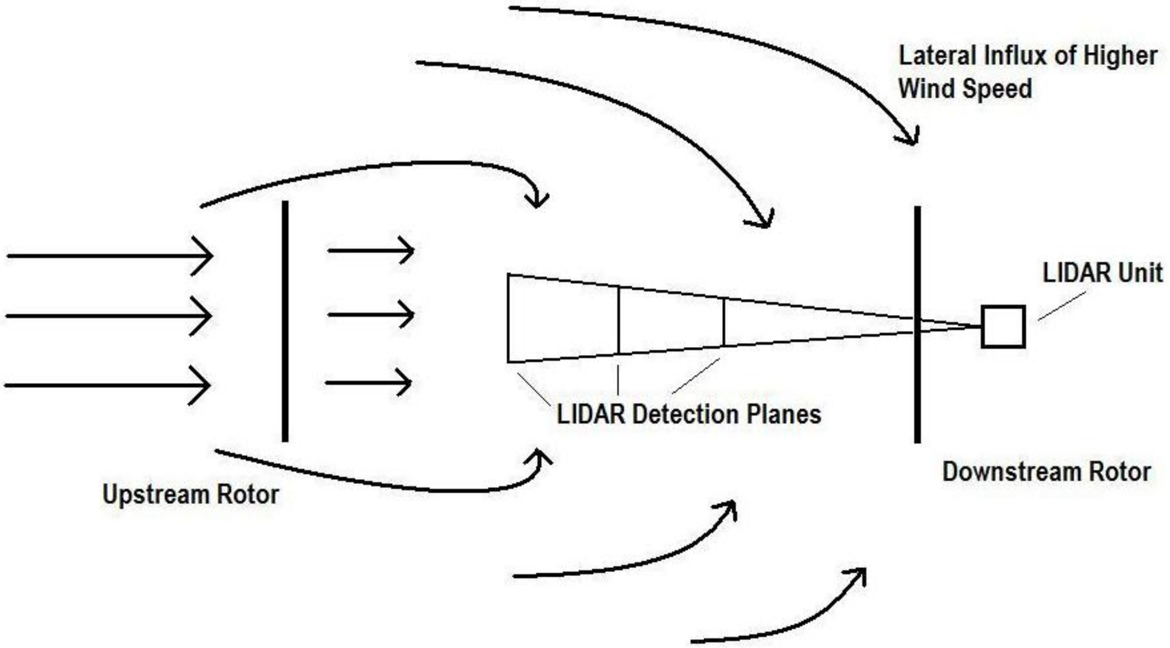


Figure 12 Possibility for LIDAR overshoot due to lateral influx of higher wind speeds developed downstream from LIDAR detection planes.

Figure 12 shows a LIDAR unit set to detect wind speed and direction farther upstream than the development of free stream velocity mixing from the right hand side. Current technology allows for the measurement of several upstream positions allowing for this to be overcome if the issue is properly identified. Universal adoption of the LIDAR equipment for wind turbine daily operations would greatly expand our understanding of wind velocity profiles and contribute to more advanced strategies for turbine control.

6. CONCLUSIONS AND FUTURE WORK

A study of wind turbine wake zones has been conducted for a commercial scale wind farm in south-central Canada using six months of SCADA data. Wind velocity deficit, power coefficient, wind speed standard deviation, and yaw alignment were characterized for a linear array of four wind turbines over a range of wind speeds. It was observed that the wake profile corresponds with wake studies from other wind farms. However, the positioning of wind turbine nacelles for specific wind directions revealed behaviour that had not been clearly accounted for in the literature. Under direct influence of upstream wake, downstream turbines adjusted their yaw position away from the free stream wind direction in order to capture the higher wind speeds present in the lateral mixing of free stream and wake flows. This has not previously been considered in wind tunnel and computational research as it would require an additional degree of freedom to allow independent yaw of individual downstream turbines adding complexity to these studies. It is also evident from the literature that this has not been widely studied with full scale experimentation.

Active wake management techniques have been pursued by others in an effort to exploit the growing knowledge of wind turbine wakes to improve overall wind farm production. It has been reasoned that a reduction in axial induction by active control of yaw, pitch, and tip speed ratio under direct turbine alignment conditions may achieve this based on wind tunnel and computational modeling. However, a reduction in axial induction can alter lateral and vertical mixing of free stream wind and therefore alter the yaw alignment of the downstream turbines. The effects induced by active wake management are still largely unknown and will require further testing in full scale situations as well as in wind tunnel and computer simulations where the downstream turbine is free to pursue higher wind speed not necessarily aligned with the wind tunnel flow direction.

Future work includes full scale experiments that will examine upstream wind turbine curtailment in order to measure the effects on yaw and power output of the downstream turbines. This work will enable the quantification of yaw alignment issues as well as assess the potential for improved power output for linear arrays. These objectives will be pursued in an effort to contribute to the validation of active wake management techniques for improving wind farm performance.

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CHAPTER IV

GLOBAL SENSITIVITY ANALYSIS OF WIND TURBINE POWER OUTPUT

For submission to ASME for publication in the “Journal of Solar Energy Engineering.”

Phillip McKay[a], Rupp Carriveau[a*], David S-K. Ting[b], and Jennifer Johrendt[b]

a. Department of Civil and Environmental Engineering, University of Windsor, 401 Sunset Ave., Windsor, Ontario, Canada, N9B 3P4

b. Department of Mechanical, Automotive, and Materials Engineering, University of Windsor, 401 Sunset Ave., Windsor, Ontario, Canada, N9B 3P4

*Corresponding Author: e. rupp@uwindsor.ca, p. 01 519 253 3000

1. INTRODUCTION

Much effort has been made to explain the operation of modern commercial scale wind turbines. The instrumentation installed on these machines has developed into a substantial battery of temperature, speed, vibration, strain, flow, electrical and crack detection sensors capable of relaying significant information to wind turbine designers and operators [1-2]. Different techniques are employed in the analysis of this information. Some of these methods include wavelet analysis [3], statistical analysis [4], neural networks and artificial intelligence [5] as well as regression analysis [6]. The majority of these methods are used for structural health monitoring systems in order to detect damage before catastrophic failure. This paper, however, focuses on the use of neural network modelling and statistical, sensitivity analysis in order to detect opportunities for wind farm optimization. Two years of data from a wind farm having forty-four, 2.3 MW Siemens wind turbines are used to train, validate and test a neural network in order to model power production. The input and output parameters of the neural network are given in Table 1. The model is used to perform a global sensitivity analysis using the extended Fourier Amplitude Sensitivity Test (eFAST). This method for sensitivity analysis is also introduced in Kusiak and Zhang [4] where it is compared against linear correlation and predictor importance techniques for the detection of vibration sensitivity in a wind turbine. The result of the eFAST method is a set of sensitivity indices ranking sensitivity of the output to the input parameters as well as interactions between the inputs. For the present study the results show a direct alignment of prioritization of wind turbine operational parameters with the natural direction the industry has taken as the technology has developed. The capacity to rank all inputs according to their level of influence is displayed and the results discussed. Overall the eFast method is further developed as a good tool for sensitivity analysis and its application to wind turbine power optimization.

2. THE DATA SET

The supervisory control and data acquisition system (SCADA) installed in the Siemens 2.3 MW wind turbine provides many sensory outputs which are collected at different frequencies for multiple purposes. Much of this data is summarized in approximately ten minute averages for archiving. The data used below comes from these summaries. Nine parameters were chosen based on experience in order to maintain the relevance of the model and simplify the analysis. Table 1 provides the allocation of parameters into input/output categories for use in the neural network model.

Input	Output
Yaw Angle (deg from North) Rotor Speed (rpm) Blade Pitch Angle (deg) Wind Speed (m/s) Ambient Temperature (deg C) Main Bearing Temperature (deg C) Wind Speed Standard Deviation (m/s) Yaw Angle Standard Deviation (deg from North)	Power (kW)

Table 1 SCADA parameters allocated as inputs and outputs for neural network development.

The data set extends from January 31, 2009, to January 30, 2011, providing two years of information (81,593 data points per parameter). The time stamps are matched providing synchronized, time series data throughout the data set. The various parameters were chosen based on experience in order to represent the most significant SCADA parameters as well as a representative spread of data from that available. Yaw angle sensitivity represents the dominance of any particular wind direction since a small change in yaw position could affect large changes in power output if there is only one direction capable of producing high power outputs. Rotor speed, blade pitch and wind speed variation are indicators of turbine performance and are expected to have significant influence on power output. The ambient temperature parameter will reveal seasonal effects should they exist. Main bearing temperature variance is expected to deliver information on how much the power output fluctuates in response to greater stresses on the main bearing or if the bearing temperature sees much variation at all. Wind speed standard deviation is an indicator of turbulence. This will reveal any severe power losses due to change in the turbulence content in the wind. Finally, yaw angle standard deviation is included in order to detect any power fluctuations present as a result of large amounts of yaw position “hunting” where the turbine is unable to find a suitable wind direction and begins to yaw excessively.

3. GLOBAL SENSITIVITY ANALYSIS

Saltelli et al. [7] pg 11 noted that the difference between global and local sensitivity analysis comes from the area of the input space explored. In local analysis a single point is taken from the input space allowing for an instantaneous view of sensitivities allowing for the description of output sensitivity for input variation over time. The global approach considers a much wider range of input possibilities in order to substantiate the sensitivity of the inputs across the greater input space available. For our purposes a global technique has been chosen so that the entire set of data available can be utilized to produce a single set of sensitivity indices. It is possible and quite probable, that sensitivity of the output to variance of the input parameters will change under different conditions, however an instantaneous view of sensitivity across the full extent of the data would be less quantifiable in terms of the overall effects therefore driving us to the use of a global method. As discussed in section 3.4 a model is developed using a neural network to relate the inputs to the output allowing for the application of the sensitivity analysis method selected.

3.1 eFAST

The extended Fourier Amplitude Sensitivity Test (eFAST) is rooted in the earlier derived FAST method developed in the 1970's by Cukier et al. [8] which was later extended in 1999 by Saltelli et al. [9]. This extended procedure has previously been applied to wind turbine vibration analysis in Kusiak and Zhang [4]. These methods along with many others attempt to calculate the sensitivity (S) of the variance in the output of a model in relation to a variance in the input as expressed in equation (1).

$$S = \mathrm{var}_x[E(Y|X)]/\mathrm{var}(Y) \text{....(1)}$$

Here X is the input variable and Y is the output. The numerator denotes the expectation of Y conditional to a fixed value for X with the variance taken over this conditional value of input X. The denominator is simply the variance of Y. The FAST method makes use of curves that explore the input space of each input factor X so as to sample from that space along an oscillating curve. Each input receives a unique frequency for the curve so that there is no harmonic interference between factors. These curves are then passed through the model to determine the output Y. A Fourier transform is performed on the output revealing the frequencies present in the signal. The respective frequencies of the inputs are then evident in the Fourier transform of the output signal at varying magnitudes denoting the sensitivity of the output to each input. The sensitivity index is calculated by dividing the individual frequency's magnitude by the sum of all input frequencies present per Equation (1). The following is a step by step procedure used in this article including the extension applied by Saltelli et al.[9] and has been tailored for this application. For additional details on curve and frequency selection as well as the finer points of this method refer to the aforementioned article.

3.2 eFAST Procedure

I. Define the range of data to be selected from for each parameter

The range of each input variable is determined and is used for defining the input space X where $X = [X_1, X_2, \ldots X_n]$ with each X_i representative of an input variable space.

II. Apply the search curve to the input space and define frequencies

The objective of the search curve is to select values from within the variable space of a specific input so that a periodic curve is established that operates within the input's range and has the ability to set the oscillation frequency. Equation (2) shows this transformation for a uniform distribution as suggested by Saltelli et al. [97]:

$$x_i = \tfrac{1}{2} + 1/\pi(\arcsin(\sin \omega_i s)) \ldots. (2)$$

where ω_i is the selected frequency for variable i and s is a set of evenly spaced values for activation of the function and range from $-\pi$ to π for all x_i. Where x_i is now the transformed input data for use in the model. Other curves have been suggested in order to fit the probability distribution of the inputs and are discussed in section 6. The selection of ω_i is critical in order to produce clearly defined sensitivities in the output. Frequencies must be selected for input such that they and their harmonics do not conflict when combined in the model. The term used to describe the characteristics of non-interacting frequencies is incommensurate. Completely incommensurate frequencies are defined by Cukier et al [98] in Equation (3):

$$\Sigma^{n}_{i=1} r_i\omega_i \neq 0, \ -\infty < r_i < \infty \ldots. (3)$$

With ω_i available for selection it is impossible to create a set of values for Equation (3) across the full range of r_i . We then reduce the expectation to selecting frequencies that result in the highest r_i possible. This is done by increasing the frequencies chosen while ensuring no frequencies are harmonics of the others. The ceiling on how high frequencies can be pushed is dependent on the sample size of the evenly spaced parameter *s*. In order to avoid aliasing and Nyquist frequency issues the sample size should be N_s such that:

$$N_s = 4M\omega_{max} + 1 \quad \text{.... (4)}$$

as defined once again by Cukier et al [10]. Here M is the order of harmonics desired to be obtained and ω_{max} is the maximum frequency chosen. It can be seen that for optimal separation in frequencies M should be as large as possible. Computational costs now become a factor and so a balance must be found to optimize the method based on available resources.

III. Run the input data sets through the model

The model is now fed the transformed input variable sets and the output is calculated.

IV. Perform a Fourier transform on the output

The Fourier transform of the model output signal will produce the frequencies present at their associated magnitudes. The individual frequencies present correspond to either the primary effect of an input variable at its fundamental or harmonic frequency. In this way all of the significant contributors to variance in the output will be represented by varying magnitudes on the Fourier transform spectrum the sum of which represents the total variance of the output and therefore the denominator of Equation 1. Dividing each individual frequency present by this sum delivers the primary sensitivity index, S_i, for each parameter.

V. Extending FAST to include total effect indices

While the procedure established so far is useful for the determination of the primary sensitivity indices of each input variable the output signal may contain secondary effects caused by the interaction of two or more input variables. These can have a significant effect on variance and would be useful to know. In order to determine secondary effects the total effect indices (S_{Ti}) are calculated for each input variable. This is accomplished by sequentially setting each input to a unique frequency while the remaining inputs are set to the same frequency. Steps 2 – 4 are repeated once for each variable resulting in *i* number of Fourier transforms. Since all variables except for one are set to the same frequency the total effect of the independently varied input becomes evident in the spectrum with a magnitude proportional to its significance. We now have the total effect indices in addition to the primary effect indices found in step 4.

3.3 ANALYSIS PREDICTION BASED ON SCATTER PLOTS

As a qualitative indication of sensitivity, scatter plots are often used to relate model inputs and outputs. Regarding the data available for this investigation, plotting the various inputs against the outputs also frees the analysis from the errors present in the neural network model described below. This is because the inputs and outputs are numerically known while the model approximates the input/output relationship analytically. By plotting each input against the output one can get a sense of the directness of the correspondence between each input separately. A tighter and more closely packed scatter plot that shows some pattern or recognizable form indicates a strong relationship while a more scattered and shapeless plot indicates a less significant correlation.

The scatter plots of the eight input variables evaluated in this study are given in Figure 1. These plots give an initial sense of what to expect from the eFAST method used below and act as a visual test of the application of this method.

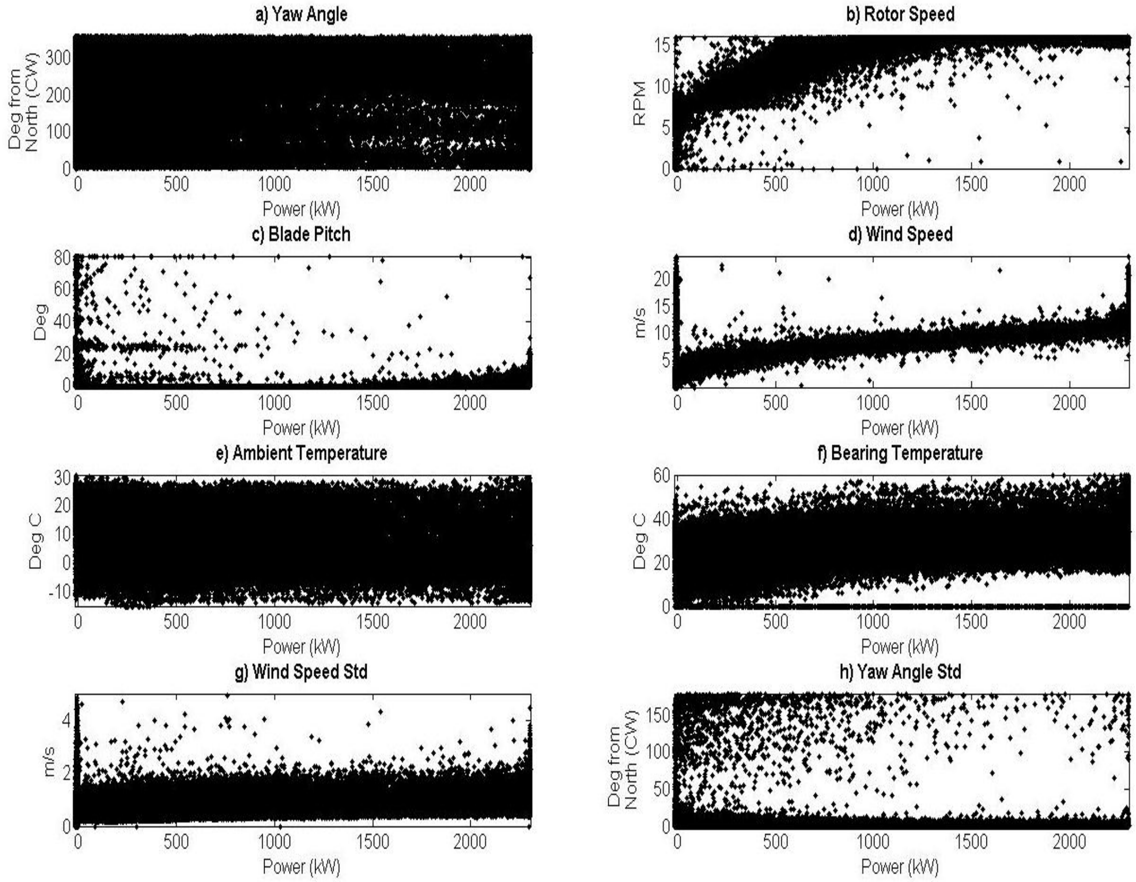

Figure 1 Scatter plots of input parameters against output (power). Where concentrations of data points exist, a qualitative measure of sensitivity is present. Random scattering of points shows a lack of correlation between input and output variance

It is evident from the scatter plots that yaw position, ambient temperature and wind speed standard deviation show little correlation in variance between the inputs (y-axis) and the output (x-axis) with Yaw position being the least significant. There appears to be moderate sensitivity with bearing temperature and yaw angle standard deviation although significant variation does occur. The most highly correlated parameters are rotor speed, wind speed and pitch.

Using the neural network described in the next section, the global sensitivity analysis attempts to quantify these qualitative results and provided a more substantial description of power output's dependency on the above factors.

3.4 NEURAL NETWORK

Matlab's neural network fitting tool was used to iteratively approach a network capable of reasonably describing the input/output relationship of the data. A two layer, feed-forward network with sigmoid hidden neurons and linear output neuron was used. The eleven node network was trained using the Levenberg-Marquardt back propagation algorithm built into Matlab. The network was trained, validated and tested using a 75%/ 15%/ 10% data allocation, respectively. The output error distribution for the network is given in Figure 2. The error is centered around zero (-0.21 kW) with the 95% confidence interval marked. .

While there is room for optimization of the neural network, the error in model predicted power is less significant for our study than the frequency content. There is little concern over the computational expense of the network because the frequency of use is low.

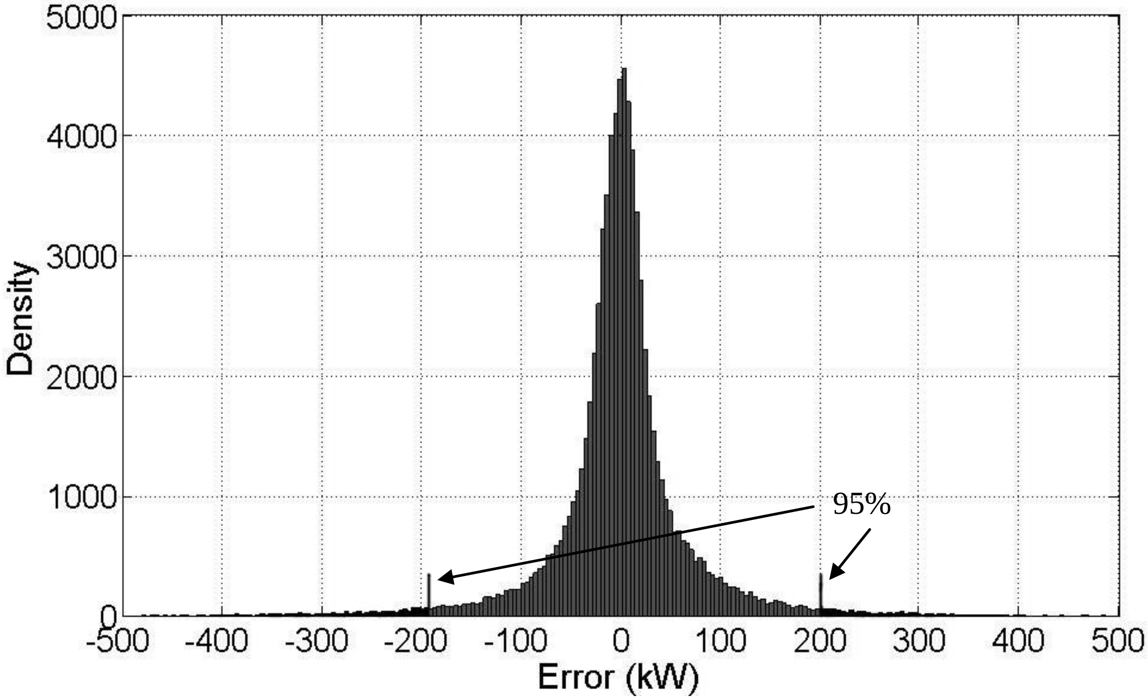

Figure 2 Neural Network error density. The 95% confidence interval is marked.

4. RESULTS AND DISCUSSION

In this section the results of the steps given for the eFast method have been presented for the application to the data sets described above.

I. Define the range of data to be selected from for each parameter

The minimum and maximum values from the data set used to train the neural network are taken for each input parameter. These values are summarized in Table 2. Methods for improvement of data range selection and probability distribution are discussed in the conclusions. For this study the detection of frequencies rather than the accuracy of the output magnitude is the main focus.

II. Apply the search curve to the input space and define frequencies

The search curve used to cross the range of the inputs is given in Equation (5). The equation is a modification of Equation (2) allowing for the inclusion of the data ranges for each input. Table 2 summarizes the input ranges and the frequencies chosen for each input. Equation (5) is computed over the set of equally spaced values, *s*, containing N_s data points as described in Equation (3). The frequencies were chosen based on the reasoning presented in section 3.2. The values are the highest set of frequencies used in the simulation study presented by Saltelli et. al [9] and are therefore understood to be a reasonable selection while pushing the frequencies as high as possible to give a balance between computational expense and being completely incommensurate.

$$x_i = (\text{range}/2 + \text{min}) + \text{range}/\pi(\arcsin(\sin \omega_i s) \qquad \text{for } (-\pi \le s \le \pi) \text{ .... } (5)$$

The search curve is then used to create input values from the input space. The inputs can then be used to propagate the selected frequencies through the model and into the output for analysis by a Fourier transform.

Input factor	Range (min – max)	Frequency Hz (ω_i)
Yaw Angle	0 – 360 deg	145
Rotor RPM	0 – 16.20 rpm	177
Pitch	-1.01 – 81.0 deg	199
Wind Speed	0 – 24.33 m/s	219
Ambient Temperature	-15.0 – 30.90 deg C	229
Main Bearing Temperature	0 – 60 deg C	235
Wind Speed Std	0 – 12.01 m/s	243
Yaw Angle Std	0 – 179.26 deg	247

Table 2 Range settings and frequency selection for input into search curve (5). Frequencies selected based on recommendations in Saltelli et al. [9].

III. Run the input data sets through the model

Using Matlab, the transformed inputs generated using the curve in Step II are input to the neural network. The result is a simulated power signal containing the accumulated frequency data present in the inputs. Figure 3 shows the output signal of the model. It is evident that error exists in the magnitude of the modelled power, however, for the purposes of this investigation the frequency content will remain the focus. It is likely that the negative power values are produced by an uncorrelated input data set. The input values used to train the network were time series arrays while the frequency transformed inputs no longer correlate sequentially.

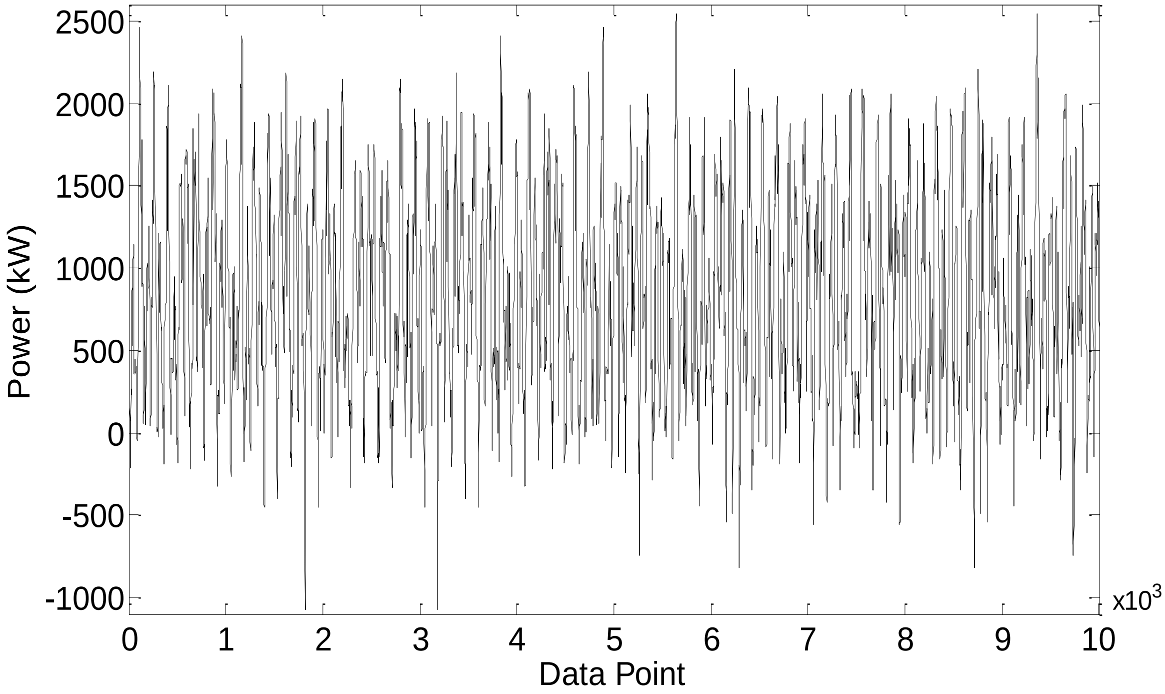

Figure 3 Neural network output for transformed input parameters.

IV. Perform a Fourier transform on the output

The Fourier transform of the signal is given in Figure 4. The frequency signatures of the parameters are indicated. Additional frequencies are present and correspond to harmonics of the inputs as well as interaction effects. These interactions will be discussed later. Several features exist in Figure 4 that are not associated with a fundamental frequency. These belong to either a harmonic of a fundamental frequency or an interaction between two parameters. This will be discussed further in the next section.

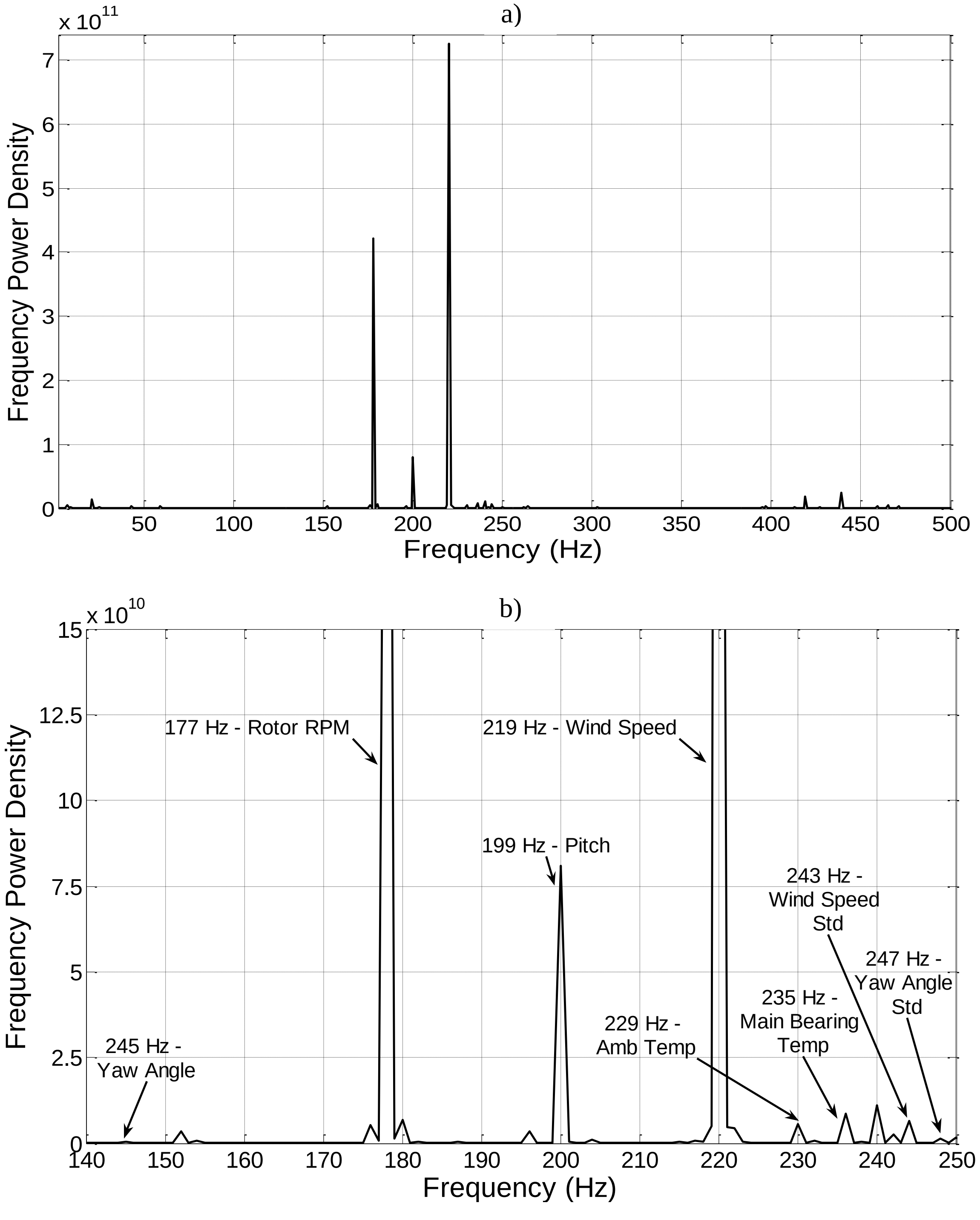

Figure 4 Fourier transform of model output containing frequency information of input parameters for a) frequencies up to two times maximum, b) primary frequencies of inputs. Major frequencies are labelled.

The primary sensitivity indices are given in Table 3. The ranking of the inputs corresponds well with the qualitative results from the scatter plots in Figure 1. However, the Fourier transform permits a less ambiguous ranking and greater distinction between the parameters showing similar sensitivities.

Input factor	Primary Sensitivity Index (S_i)
Wind Speed	0.5774
Rotor RPM	0.3381
Pitch	0.0641
Wind Speed Std	0.0071
Main Bearing Temperature	0.0071
Ambient Temperature	0.0046
Yaw Angle Std	0.0013
Yaw Angle	0.0003

Table 3 Primary sensitivity indices ranked from greatest to least significant

Wind speed and rotor rpm hold the greatest significance for output variance as expected. Pitch is proven to be more significant than yaw angle reinforcing the scatter plot showing the dispersion of yaw positions in the data. It is interesting to note that wind speed standard deviation (associated with turbulence in the wind) while having minor significance is slightly more influential than main bearing temperature as well as seasonal changes represented by ambient temperature as turbulence is a popular area of study in the wind industry. Yaw angle and Yaw angle standard deviation is established as a non-significant contributor to power output indicating that changes in yaw angle do not translate into a change in power output. This is expected since the yaw action is only performed in order to improve power output. Any poor performance numbers such as zero wind speed conditions will result in no change in yaw direction. In addition excessive yaw activity is either not a concern for power production or does not exist for this turbine during the course of the two years studied. In the case of turbine alignment, if input ranges were exclusively considered from those yaw angles in which power output is reduced due to the presence of wake caused by an upstream turbine, the output will likely be more sensitive to yaw.

V. Extending FAST to include total effect indices

The selection of frequencies for the computation of the total sensitivity indices (S_{Ti}) is less complicated than for the primary indices. This is because only two frequencies need to be chosen in order to prevent interference and overlapping harmonics. Values were chosen based on the reasoning developed earlier. The frequency chosen for the i^{th} parameter was 105 Hz with the remaining parameters set to 7 Hz. Total sensitivity is calculated by subtracting the effect of all of the 7 Hz data from the total energy of the Fourier transform. This will leave all effects including primary and higher order interactions of the i^{th} parameter. Table 4 compares the primary and total sensitivity indices.

Input factor	Primary Sensitivity Index (S_i)	Total Sensitivity Index (S_{Ti})
Wind Speed	0.5774	0.9430
Rotor RPM	0.3381	0.3867
Pitch	0.0641	0.0940
Wind Speed Std	0.0071	0.0908
Main Bearing Temperature	0.0071	0.0677
Yaw Angle Std	0.0046	0.0387
Ambient Temperature	0.0013	0.0373
Yaw Angle	0.0003	0.0235

Table 4 Comparison of Primary and Total sensitivity indices

Noise present in the network output resulted in the necessity of elimination of frequencies greater than twice the maximum frequency. This prevents the inclusion of insignificant frequencies the addition of which increases the total sensitivity unjustly as these are not real, observed interactions. The total sensitivity indices give a broader understanding of the importance of the higher order influences on output variance. By computing this value for input 1 we are including all indices shown in Equation (6):

$$S_{T1} = S_1 + S_{12} + S_{123} + \dots S_{1 \dots n} \quad \text{where } n = \text{no. of inputs} \dots (6)$$

producing a ranking scheme more representative of the importance of each input. The first term S_1 is the primary frequency. The remaining terms are the interactions between input frequencies from one to eight where the parameter under study is involved which in the case of Equation (6) is x_1. The interactions create unique frequencies with varying energy. In the present study these combinations have minimal significance. There are no changes in the rankings between the total and first order sensitivities however the separation of the indices do change. Wind speed further dominates the ranking by creating a lager gap with rotor rpm. Most significantly, wind speed standard deviation increases to rival pitch for importance ranking. There is a general increase in magnitude among the remaining parameters but the separation remains similar. The final result of the total sensitivity calculations is a realization of the dominance of wind speed and the importance of wind speed standard deviation and therefore turbulence, with regards to the power output of the turbine.

5. CONCLUSIONS

The eFAST method for importance ranking of the selected wind turbine operational parameters confirms expectations of significance for power output variance. Wind speed, rotor speed and blade pitch angle hold the most significance both in primary and higher order effects. These are major performance indicators for wind turbines and the results serve to confirm the accuracy of the method being used. Wind speed standard deviation gains a mid-level ranking in both the total and primary sensitivity rankings. This places turbulence in the wind as a significant contributor to the turbine performance. It can also be observed that seasonal effects and fluctuations in bearing temperature have little effect on the power output of this turbine at this site. This does not, however, negate their importance for turbine health monitoring. Yaw position and standard deviation come out as insignificant in the ranking scheme. This is understandable since yaw activity does not usually occur under poor power producing conditions. For example, if there is a wind speed of zero, the will be no change in yaw position. It is not until sustained mid-range or high wind speeds when changes in yaw position will be seen.

Due to the uncontrollable nature of wind speed, opportunities for power output optimization must fall on the remaining parameters. Selection of rotor speed strategies is dependent on many factors and therefore cannot be treated as an independent source for improvement. Consideration must be taken regarding required generator speeds, available wind speed and pitch angle. Precision in blade pitch angle and blade design should remain a high priority in the wind turbine design industry due to the large dependence of power output on the pitch position taken. Very little opportunity exists for power optimization by ensuring favourable ambient temperatures and wind speed must be considered above other environmental effects. Wind speed standard deviation remains as a relatively significant influence on power output and a source for performance improvement. Focus can be placed on wake interaction reduction and siting new farms in locations with low wind turbulence. Within the scope of the parameters considered above this remains the primary focus of wind turbine power optimization. This aligns well with the direction the industry has taken in these areas especially the heavy focus on offshore wind power further confirming the benefit of the approach taken in this study.

Potential for furthering this approach for optimization of wind turbine power output can be found in both the method and the application. Improvement can be made with the exploration of the search curve in the input space. The search curves used in this study result in a uniform distribution over the specified ranges however, each input has an individual probability distribution few of which can be treated as uniform. The wind speed and wind speed standard deviation assume a typical Weibul distribution. Rotor speed, blade pitch and yaw angle standard deviation are heavily weighted to one extreme or the other. Ambient and bearing temperatures follow a normal distribution and yaw angle is irregularly shaped. These distributions are given in Figure 5. Additional curves are suggested by Saltelli et al. [9] with a generalized approach to optimum search curve definition given in Cukier et al. [10].

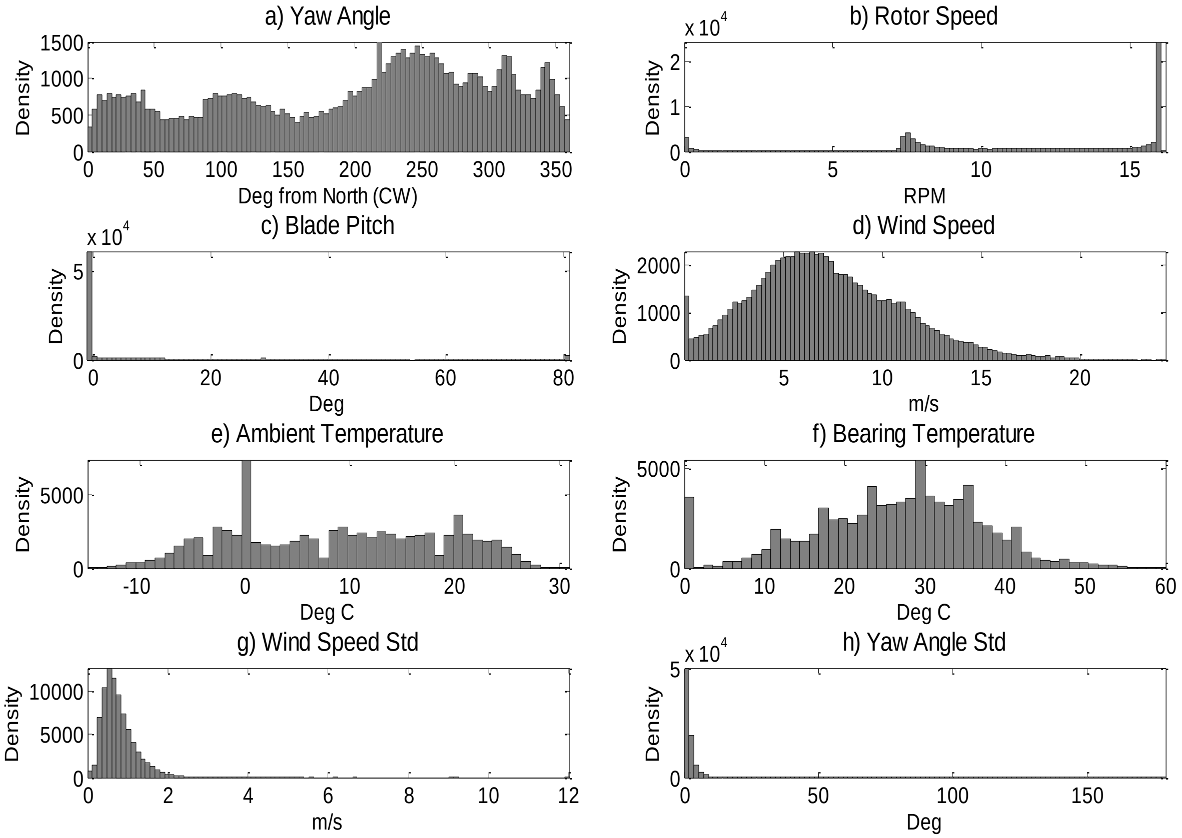

Figure 5 Probability distributions of input parameters.

By using curves that more accurately represent the distributions of the data used to train the neural network, a better understanding of sensitivities is possible for the conditions under which the wind turbine is more regularly subjected. By uniformly distributing the input parameters over their entire range of data an accurate sensitivity to variance is given however this sensitivity is more heavily weighted for conditions which are not as likely to occur.

Application of this method to wind turbines specifically under wake conditions is also predicted to be a valuable analysis. By selecting the input parameters from an upstream wind turbine experiencing free stream, non-wake winds and the output power as that of a downstream wind turbine under wake it is possible to determine the importance ranking of the upstream turbine behaviour on the power output of the downstream turbine. This will allow for the prioritization of power optimization efforts for wind farms subject to wake interactions.

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CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

SUMMARY AND CONCLUSIONS

A progression has been made from the consideration of a diverse collection of dynamic characteristics of commercial scale wind turbine groupings to the specialized topic of wake management. In Chapter 2 it was initially established that grouping large turbines together produces a wide array of complexities that are co-dependent and require prioritization in order to arrive at a wind farm design that achieves the main purposes of the owner. It was seen that at each stage of the life of a wind farm, the interconnectivity of all dynamic effects must be considered at the beginning of the project. A high level method for prioritization of these effects was developed and presented in order to reinforce the importance of the literature reviewed. Terrain is shown to be of fundamental significant in the dynamics of a farm seconded by the manner in which farms are positioned in relation to each other and their visual appeal. These are followed by aerodynamic interactions as well as power purchase agreements/legislation. Other topics such as energy storage, power quality and operation/maintenance are perceived as less significant. However, once constructed a wind farm’s potential for optimization is reduced since there are fewer variables to be controlled. This has led to the research in Chapter 3 which examined the yaw behaviour of wind turbines operating in wake conditions. The results showed that the turbines yaw out of direct alignment with the upstream turbine in order to capture the higher producing winds present from lateral mixing of free stream and wake regions. Arrays containing more than two turbines exhibit an increasing and varied offset as the wind moves down the row. The behaviour is, at present, unpredictable but reveals a lack of understanding in the literature as to its significance. In order to assist with the answering of this question, Chapter 4 makes use of a global sensitivity analysis method for power output on a set of significant turbine parameter inputs. The analysis produced a ranked sent of parameters with respect to their significance on the variation in power output of the turbine. As expected wind speed was found to be most significant followed by rotor rpm and pitch. As previously discussed, these parameters are set upon construction of the farm. However, wind speed standard deviation is revealed as a significant contributor to power variation. This serves to further support considerations of wake management as a viable target for optimization of wind farms. Interestingly, yaw angle does not hold much significance in the ranking scheme developed.

Group dynamics of commercial scale wind turbines must be considered for the optimization of modern wind farm development projects. For established farms the opportunities for optimization are limited. The reduction of turbulence due to wake caused by an upstream turbine shows promise as a potential area for realizing these improvements. Further research is recommended on the application of active wake management techniques on full scale wind turbines.

RECOMMENDED EXPERIMENTS

For existing wind farms there is little that can be done about the main contributors to wind power production. There are no further opportunities to adjust the siting of the farm and micro-siting of the turbines in order to improve the accessible wind resource. The turbine make and model have been chosen and installed eliminating generator characteristics and blade pitch angles as a source for optimization. Wind quality remains as a conceivable area for existing farm optimization. The most evident source for turbulence in the wind comes from a turbine operating within proximity of an upstream turbine. In Chapter 3 section 3.5 the potential for meaningful gains in farm wide power output by active management of the wake region inspire questions of the validity of these claims on a commercial scale wind farm. In order to test the wind tunnel simulations on a full scale turbine array an experiment can be conducted using the standard controls available to the wind farm operator. The following are recommendations for conducting this experiment at the Kruger Energy Port Alma facility. The experiment would be completed with favourable winds having a direction causing alignment of the turbine array and a wind speed of at least 6 m/s. The data collected that is temporarily available to the farm at five samples/sec before it is summarized is to be collected for standard conditions and all turbines in the array. With the wind speed and direction maintained, the upstream turbine is curtailed to 50% of its power output. Curtailment is a readily controllable feature of the turbines and is accomplished by pitching the blades in order to reduce axial induction and reach the required output. The turbine is returned to normal operation. The process is repeated for complete idle of the upstream turbine. The time each condition is to be maintained is dependent on the stability of the environmental conditions. If it is forecasted that wind speeds and direction will be maintained for an extended period of time it is suggested that the sample size be extended. However, if conditions are changing then a smaller sample size may be required. The experiment should be repeated several times and the results correlated in order to inspire confidence in the results.

Applying a modification of the sensitivity test described in Chapter 4 to this data is expected to provide insight into the sensitivity of a downstream turbine's power output to the upstream turbine's characteristics. This can be accomplished by setting all inputs to the upstream turbine and the output to the downstream. The relationship between power variation downstream and various upstream parameters can then be observed and ranked. Alternatively, a combination of inputs could be drawn from up and downstream turbines while keeping the downstream power as the output.

APPENDICES

APPENDIX A

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Chapter 4: Global Sensitivity Analysis of Wind Turbine Power Output

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VITA AUCTORIS

NAME: Phillip M. McKay
PLACE OF BIRTH: North Bay, Ontario, Canada
YEAR OF BIRTH: 1985
EDUCATION: Sir Wilfrid Laurier C.I., Scarborough, Ontario
1999 – 2003, High School
University of Windsor, Windsor, Ontario
2003 – 2007, B.A.Sc. Mechanical Engineering