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ADAPTIVE GEOMETRY WIND TURBINE BLADES FOR INCREASED PERFORMANCE AND LOAD REDUCTION

A Thesis in

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ABSTRACT

Wind energy is becoming an integral part of many nations' plans for achieving goals on renewable energy production. With wind turbines working to efficiently capture energy at different wind speeds, rotor morphing could potentially increase energy capture over wind speeds up to the rated speed. This study examines what the optimal geometry might look like at different wind speeds below the rated speed, how it might differ from one speed to another, and the increase in power and annual energy production that could be realized with the optimal geometry at each wind speed. A second study is shown that examines possible ways geometry changes used together could result in lower root bending moments while maintaining or increasing power output.

Using a blade-element theory based analysis and conducting simulations on the 1.5 MW WindPACT turbine and the 5MW NREL concept offshore turbine, variations in blade twist, collective pitch, chord, radius, and airfoil characteristics were considered. The results indicate that there are negligible benefits to changing blade collective pitch, twist, chord, and airfoil characteristics. Only radius increase has a dominant effect, with 20% increase in radius resulting in power increase of over 45% at 8 and 10 m/s and much higher percentage increases at lower speeds, for both turbines (as the power in the wind increases in proportion to the radius squared). The increase in annual energy production is in the range of 20%. However, a larger radius increases blade loading. In regards to reducing blade loading while maintaining power output, it is seen that it is possible for the 1.5MW WindPACT turbine to decrease root bending moments by over 15% with combinations in pitch and chord changes at the rated speed with negligible changes in power output.

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AEP	Annual Energy Production
a	Axial Induction Factor
a'	Tangential Induction Factor
C_d	Airfoil Drag Coefficient
C_l	Airfoil Lift Coefficient
C_n	Airfoil Normal Force Coefficient
C_P	Rotor Power Coefficient
CH	Head Loss Factor
CS	Swirl Loading Factor
dD	Differential Drag
dL	Differential Lift
dP	Differential Power
dr	Differential Spanwise Displacement
dT	Differential Thrust
F	Prandtl Total Loss Factor
F_h	Prandtl Hub Loss Factor
F_hexp	Constant for Prandtl Hub Loss
F_t	Prandtl Tip Loss Factor
F_texp	Constant for Prandtl Tip Loss
M	Blade Root Bending Moment
N_b	Number of Turbine Blades
R	Turbine Radius from Hub Center to Tip

r	Dimensional Location Along Blade
r_0	Dimensional Blade Root Location
V	Resultant Velocity
V_∞	Free Stream Velocity
X	Tip Speed Ratio
y	Nondimensional Location Along Blade
y_0	Nondimensional Blade Root Cutout
α	Blade Angle of Attack
θ	Local Blade Pitch Angle
ρ	Density of Air at Hub Height
σ	Blade Annular Solidity
φ	Velocity Inflow Angle
Ω	Rotor Rotational Speed

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Chapter 1

Introduction

Wind energy has been on the forefront of America's push for energy independence by way of renewable resources. In fact, America is already the world's largest producer of wind power with an installed capacity of 35,000MW as of the end of 2009 [1,2]. In 2008, the U.S. installed 8,400MW of wind turbine power, which it surpassed in 2009 by installing a record 9,900MW [2]. While these figures are impressive, the 35,000MWs of installed capacity represent only about 2% of total current U.S. power consumption [3]. The country is aiming for wind power to be capable of producing 20% of the nation's demand for power by 2030 [4]. Such a feat will surely require a large investment by both government and commercial interests.

1.1 Background and Motivation

With such an ambitious goal, technological advancements that increase the efficiency of wind turbines without significant cost impacts are continually sought after. Contemporary wind turbines capture approximately 48% of the power available in their stream tube when operating at peak efficiency. While this number does not seem promising, a simple momentum theory analysis can show that the most power theoretically extractable from a stream tube by a turbine is only 59.3%, so in reality these turbines are over 80% efficient [5]. However, this still leaves room for improved designs.

In order to identify where improvements in wind turbine efficiency can be made, one must first look at a wind turbine power curve. Wind turbine power curves can be broken up into three regions which can be observed on the power curve for the National Renewable Energy

Laboratory (NREL) 5MW turbine in Figure 1-1. Region I is characterized by wind speeds where no power production is occurring as it is located below the cut-in speed of the turbine. Region II is between the cut-in speed and the rated speed of the turbine. It is in this region that the turbine attempts to operate at maximum efficiency. The power captured from the wind is below the generator rating, so as much power as possible can be captured. Region III is above the rated speed of the turbine. In this region, more power than the generator can handle is produced by the rotor, and some method of shedding this extra power needs to be employed, which in modern turbines is most commonly active pitch control.

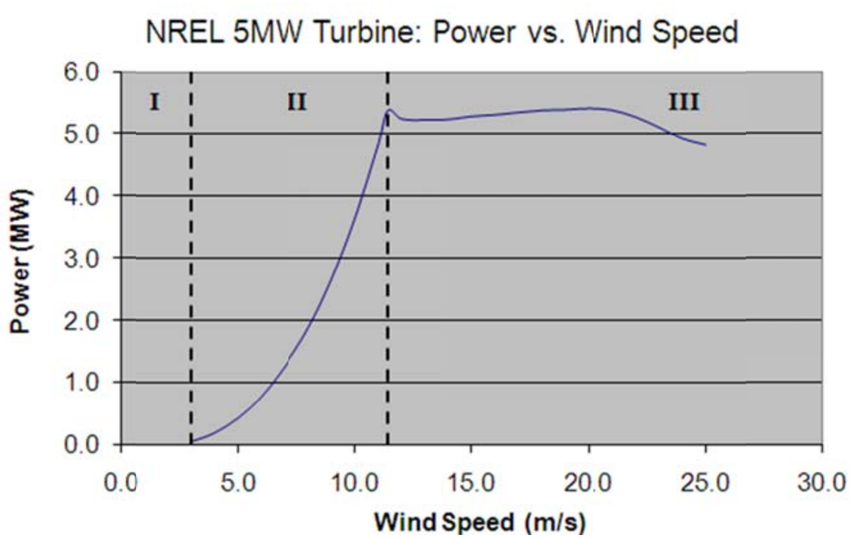

Figure 1-1: Example power curve displaying wind power regions

Since no power is produced in Region I, and more power than the generator can handle is produced in Region III, Region II is the focus of any effort to extract more power from the wind. These increases in power can take two forms. First, the overall percentage of power the rotor collects from the wind can be increased by increasing its power coefficient, or C_P. At most of Region II wind speeds, the turbine operates at the optimum tip speed ratio (which is the ratio of the blade tip speed to the speed of the free stream velocity). However, at the lowest Region II wind speeds, turbines run at off-optimal tip speed ratios due to start up considerations and the lower constraints on rotor rotational speeds [6]. Since it is operating at tip speed ratios above optimum, power production is lower than it could be. While a blade is designed to extract the most possible power at optimum tip speed ratios, a blade with a differing geometry might be more advantageous in this situation. Table 1-1 shows the power coefficients and tip speed ratios they occur at for each wind speed in Region II of the NREL 5MW turbine to be described later in Chapter 2.

Table 1-1: Region II power coefficients for NREL 5MW Turbine

Wind Speed (m/s)	Tip Speed Ratio	Power Coefficient
3.0	15	0.26
4.0	12	0.40
5.0	10	0.45
6.0	9	0.47
7.0	8	0.48
8.0	7	0.48
9.0	7	0.48
10.0	7	0.48
11.0	7	0.48
11.4	7	0.48

It can be surmised that there is a need for improvement in power generation efficiency at the lowest Region II wind speeds. Variable geometry structures are popular in aerospace applications to help a structure adapt to different aerodynamic environments. Most notably are the flaps and slats of an airplane wing which allow for high lift to be generated during the slow travel speeds of takeoff and landing, but many examples exist. Specifically, cutting edge research is being done on helicopter rotors [7,8,9,10], and research is also being conducted in the field of wind turbines. This research will be outlined in Section 1.2, the literature review.

1.2 Literature Review

Current studies have been done on turbine blades that are optimized for specific operating conditions. In addition to this, research is looking into adaptable geometry blades on both a gross blade property scale and an airfoil property scale. Most of this research is focused on alleviating loads along the blade. This survey of the literature will go into the state of these design efforts and highlight areas in need of further examination.

1.2.1 Wind Turbine Blade Optimization

One way to define an adaptive geometry blade that produces optimum power at all wind speeds would require performing a blade optimization at a set of different wind conditions and then finding a way to get those different geometries from a certain structure. Many wind turbine blade optimizations have been performed to date. However, these blade optimizations are most often performed considering the entire operating envelope of the turbine, and not necessarily at individual wind speeds.

Fuglsang et al (2002), examined the benefit of optimizing a wind turbine rotor for six different wind sites coupled with different terrain complexities. Two turbines were analyzed, a 600kW variable speed, pitch to feather turbine and a 1MW constant speed, stall controlled turbine. By using a blade cost model that they developed, increases in energy and decreases in blade cost resulted in costs of energy reductions of up to 15%. While site specific design showed the most potential for decreasing cost of energy at low wind speed sites with low turbulence, these sites could still not overcome the cost of energy at higher wind sites. Also, blades designed for one site did not see the same benefits when placed at other sites. [11]

Optimizations on the NREL 5MW Turbine which was studied in the scope of this thesis have also occurred. Xudong et al (2009), developed a blade optimization code combined with a blade aero-elastic analysis and a cost of energy algorithm. The analysis was run on three turbines, one of which was the NREL turbine in order to minimize cost of energy. The resulting blade reached a maximum chord difference of 8.2% thinner at the 40m radial station and twist values were also reduced significantly (exact value not provided) at the 30m station. Only the mid sections of the blades saw significant changes in design as described above and the optimal distributions were otherwise close to the baseline values near the hub and tip. The annual energy production of the rotor was reduced by only 0.1% whereas cost was reduced by 2.7% due to the thinner midsection of the blade. This results in a cost of energy reduction of about 2.6%. [12]

In addition to the above studies, many other blade optimization studies have been performed. They vary in every way from aerodynamic models used, to structural models used, wind profiles, wind turbines, and optimization goal. [13, 14, 15, 16] However, none of these studies examines how a blade designed for optimal power production would be shaped at different operating speeds. This investigation would prove valuable for an adaptable geometry blade aimed at extracting the most power at every wind speed.

1.2.2 Passive Twist Blades

A strong push has gone into research on blades that passively twist themselves in high wind conditions. One way to do this is through the use of carbon fiber. This strategy makes use of carbon fiber layers aligned in particular patterns which allows the blade to twist itself as it is deformed in the flapwise direction from being loaded by a wind gust. This twist affects the aerodynamic angles of attack by passively feathering and therefore reducing the angles of attack. The more the blade flaps, the more the blade twists to reduce loading. This type of control reacts much quicker than conventional blade collective pitch control, which makes it favorable for mitigating loads from transient wind events while leaving pitch control for steady state wind changes [17]. These types of blades are used to mitigate both steady and vibratory loadings on the blade.

A 2004 study by Wichita State University performed computer simulations examining the effects of a carbon blade with individual layers aligned differently to elicit different responses. The study took baseline blades of 9.2m in length from the NPS-100 100kW turbine and simulated different carbon fiber alignments in the spar cap layers of the blade build up, from +0° to +20° in 5° increments. These designs produced up to a 1.42° twist towards feather in the 20° carbon fiber alignment. It was concluded that further studies need to be performed to see if this twist was sufficient for alleviating fatigue loading, but strain values seen along the blade were not significantly greater than those of the baseline blade, which was deemed a promising result. [18]

The second manner in which twist coupling works can be exhibited in Sandia National Laboratories' research in what they call the Sweep Twist Adaptive Rotor, or STAR, program. The blade's tip is swept backwards in addition to being tapered. This puts the blade pitch axis off center with that of the rest of the blade, and allows it to twist. Prototype 27m blades were fabricated and placed on a 750kW turbine. The findings of the data agreed with the simulations that blade fatigue loadings and peak loadings were reduced. This allows a larger blade to be put on a turbine and experience minimal increases loadings, where the larger blade facilitates more energy capture at lower wind speeds. The study found that up to 10% more energy was produced than with the baseline 24m blade. [19]

In addition to these studies, General Electric has done research into advanced rotor concepts under NREL and Department of Energy funding. One of the avenues explored was a passively twisted blade that employed both of the above schemes of operation. The study found that both methods complement each other when used together. The resulting blades saw a decrease in “all key design-driver loads”. As a result, blade radius could be increased to a point where the loads were brought back to design levels. This approach realized a cost of energy reduction of 9-11%. [17]

A final Sandia report examines the general effects of twist-coupling without specifying a method by comparing energy capture and loads of different scenarios. It comes to the conclusion that blades that twist towards stall are much less favorable than blades that twist towards feather. The later see a reduction in both fatigue damage and maximum loads regardless of the powertrain type (constant or variable speed generator). However, variable speed turbines see more load reductions over the entire operating envelope than constant speed turbines which experiences lower loadings more so at low wind speeds than higher wind speeds. All of this occurs with minimal effect on energy production. Twisting towards stall not only makes the blade experience more fatigue loading, but are also subject to the stall-flutter instability. [20]

Each of these studies appears to show favorable results for a blade that has passive twist coupling. However, these blades are examined with small degrees of twist taken into account because of the limits of the materials being used. It would be interesting to see if greater twist changes would be more beneficial, a factor that this thesis takes into account. Also, these studies look into twist changes for the sole purpose of mitigating loads, which in turn allows them to make larger blades to capture more power. A study into the direct power production improvements available through twist changes is useful.

1.2.3 Variation in Swept Area

One of the most obvious ways to increase power capture from a turbine, but the one with some of the most impressive challenges to overcome, is to simply make the rotor diameter larger.

A larger rotor sweeps a larger area and has potential to collect more power, but larger blades are heavier and more expensive, both of which add cost to the system. The two trends balance to a point where the cost of energy is actually negatively affected at some point depending on the wind speeds at the site of the turbine.

Two methods for varying the area swept by the rotor have been suggested. The first is a rotor with extendable tip sections that make the rotor longer. Contained within the GE study discussed above [17] is a study on these types of extendable rotor concepts. It concluded that employing this type of blade usually requires significant hardware integration in the form of bearings, tracks, and altering existing blade designs to be able to accept these alterations and still be aerodynamically efficient. Despite these problems, simulations performed on their 750kW turbine suggested that cost of energy improvements of up to18% could be realized using this method, with an additional 3.5% improvement if control schemes were optimized [17]. Further studies by other researchers have found similar results. One study verified the findings with results indicating an 18% increase in Annual Energy Production at a particular low speed wind site in New Zealand with a 10kW turbine whose blades extend by approximately 35% [21]. These results are clearly significant.

Knight and Carver, a wind turbine blade manufacturer, with support from Department of Energy funding, actually designed and implemented a set of prototype variable length blades into a 120kW turbine. The original blades were 9m in length and were replaced by blades that varied from 8 to 12m. By having a blade that when retracted is shorter than the original blade allowed blade loadings to be decreased in high loading scenarios. This particular turbine was run to produce more power at lower wind speeds and shorten near the rated speed of the turbine, which lowered power production at these speeds but also lowered peak loadings by 2/3 over the baseline case. An increase in power production of 12.9% was realized over the 5 month test period, but no numbers for cost of energy benefits were provided. Figure 1-2 shows an image of the turbine retrofitted with the new designed blades in their extended position. [22]

Figure 1-2: Knight and Carver 8-12m extendable blades. [22]

In addition to the extendable rotor, a second popular concept is the coning rotor. This rotor cones its blades in response to higher wind speeds so they sweep less of a projected area, therefore lowering the power and loads produced. GE mentioned this type of rotor in their study, but deemed it did not merit further examination and only looked into the extendable rotor concept [17]. However, other studies have looked into this concept. A study by Cambridge University developed a new modeling tool for coning rotors using Blade Element Momentum Theory that was modified for coning rotor aerodynamics. This theory produced changes in C_P for the rotor of up to 23%, suggesting that these modifications cannot be ignored when evaluating these types of rotors. No simulations were conducted against a current baseline turbine, but instead compared against different turbine configurations with coning rotors, by examining a constant speed stall regulated turbine and a variable speed pitch regulated one. Peak loads were found to be similar but to occur at different operating conditions. [23]

These studies show that turbine blades modified to have extendable tips show promise in their ability to capture more energy and lower the cost of energy for a turbine. These studies show how specific examples work to do this, but a comprehensive study on which rotational speeds produce optimal power for specific turbine extension increments is needed. Also, these studies are for smaller size turbines so data for larger turbines is needed.

1.2.4 High Lift Devices

High lift devices have huge potential in changing airfoil characteristics by changing the flow around the airfoil that they are employed on. Many types of these devices exist, from Guerney flaps to microtabs, from vortex generators to pulse jets. However, not all of these types of devices have been examined with respect to wind turbine performance, but a report by Sandia outlines what has been done. One of the options that shows good promise, and has been the focus of much research is the microtab. A microtab is a small tab that can be deployed perpendicular from the surface of the airfoil from either the upper or lower surface. Their heights are on the order of the boundary layer thickness, around 1% of chord length. When deployed on the lower surface they increase lift, while deployment on the upper surface decreases lift production. According to the Sandia report, their use is favorable for a number of reasons. The fact that they deploy perpendicular to the airfoil surface (and therefore perpendicular to the flow) requires small activation forces relative to other methods of flow control. Their small size allows for low power requirements and fast actuation times. However, ideal placement near the trailing edge of the airfoil makes room tight for actuation devices, and air leakage into the system. [24]

When dealing with microtabs, performance enhancement depends heavily on the placement of the tabs. Case van Dam of UC Davis has completed much research into this problem [24,25,26,27]. Preliminary studies examined optimal placement of such tabs on a GU25-5(11)-8. This airfoil was chosen for its similar aerodynamic properties to wind turbine airfoils. These studies tested different placement locations very near to the trailing edge. The locations between 2 and 6% of the chord distance from the trailing edge was deemed to be the "effective zone" with the most benefits in lift observed at little drag penalty, with 5% described as the greatest compromise between lift, drag, and airfoil volume to support the hardware. At locations further from the trailing edge, lift increases were seen but with larger corresponding increases in drag. In the three dimensional simulations, solid tabs produced C_l increases of over 50%. [25] A separate study was performed that examined tab height. This study found that tab heights of 1.1%c were just as effective as larger tabs at increasing C_l but a larger drag penalty was incurred. Also, tripped boundary layer, which is used to represent a soiled blade which is common in wind turbine operation, showed decreases in performance from a clean blade, but the same increases over a tripped baseline airfoil were observed. [26]

The effects of microtabs deployed on the upper surface were examined next. These studies showed that tabs can be implemented on the upper surface to decrease lift produced by the airfoil. At 10%c from the trailing edge, a 1.1%c tab resulted in a 40% decrease in lift production at 0° angle of attack, while a 2.2%c tab resulted in a 70% decrease in lift production. As angles of attack increased, the effectiveness of these tabs diminished as the boundary layer thickness overtook them. These types of tabs could be used to reduce loadings on the blade caused by increase in flow perhaps from a wind gust. [26]

Finally, an examination into tab spacing was performed, since smaller spaced tabs would be easier to deploy and can be targeted to certain sections of a blade than a large single solid tab. All tab configurations were 1%c in height and located on the lower surface a distance of 5%c from the trailing edge. Tab width to gap width to tab height ratios of 6.56:6.56:1, 6.56:2:1, 6.56:1:1, two combinations of 4:1:1, and a solid tab were all tested. While no configuration saw the same lift increases as seen by the continuous solid tab, respectable results can be seen. In addition, non continuous tabs appear to have benefits in noise production. Table 1-3 shows the summarized results from this study, with values of 0% being equivalent to the values at the baseline configuration and 100% being the values of the improvements seen by the solid tab. [27]

Table 1-2: Results of microtab spacing simulations. [27]

Case	Solidity	$\%\Delta C_L$	$\%\Delta C_D$	$\%\Delta C_M$	%ΔL/D
Baseline GU25	0.000	0.0	0.0	0.0	0.0
6.56:6.56:1	0.500	56.3	77.1	54.1	41.9
6.56:2:1	0.766	81.4	91.7	79.7	74.6
Single Gap 4:1:1	0.800	81.4	91.0	79.7	0.47
Double Gap 4:1:1	0.800	81.4	100.0	79.7	66.8
6.56:1:1	0.868	89.3	99.2	87.8	81.7
Solid Tab	1.000	100.0	100.0	100.0	100.0

All of these papers are aimed at producing blades that experience decreased loadings. One follow up paper shows this potential by performing ADAMS simulations on a model stall regulated turbine blade at 8 m/s average wind speed and shows approximately 10% reduction in root bending moments when tabs are deployed from the lower surface of the blade [28]. However, no studies exist that attempt to increase power production from these devices. These studies by Case van Dam do point out that there might be potential to directly improve power production by employing these devices, and future work is needed to look into this [28].

1.3 Problem Statement and Thesis Overview

The above literature review shows the current direction that state of the art research is examining with respect to adaptable geometry wind turbine blades. The advancements discussed include passive twist blades that automatically lower lift produced in response to dynamic wind conditions and actively controlled microtabs with potential to increase or decrease lift by as much as 50%. Both advancements have been investigated with respect to decreasing loadings experienced by the blades. Extendable rotor blades, which have been built as prototypes and tested on existing turbines, have been proven to increase energy capture.

Besides the extendable rotor blades, none of the above technologies has been investigated with respect to direct increase in the energy captured by the turbine. An examination into this possibility needs to be performed in order to evaluate their potential. In addition, no work has been done examining adaptive chord geometries and how they could potentially impact energy production on wind turbines. The primary objective of this thesis is to examine twist distributions coupled with root pitch settings, chord variations, radial span variation, and airfoil characteristics and their impact on the power production of two different sized turbines at a range of Region II wind speeds. These turbines are those outlined in the WindPACT 1.5MW design study and NREL 5MW turbine design study referenced in Chapter 2. The results of this study are then examined to evaluate potential increases in annual energy production that they can produce. Once this objective was complete, the study was expanded to evaluate the potential of these variations to impact root bending moments of the blades while maintaining baseline power production levels.

In order to address these objectives, a MATLAB program was written utilizing Blade Element Momentum Theory, and the two turbines described above were modeled in the program to be able to analyze the effectiveness of these geometry changes. This process is outlined in Chapter 2 of the thesis. Chapter 3 presents the results for these analyses. Each turbine was modeled with changes to its twist distributions combined with root pitch changes, chord variation, radial span, and airfoil characteristics and changes in power calculated. The key results are outlined in each subsection of Section 3.1, with the full results being found in the appendices of the thesis. Section 3.2 shows these results applied to an analysis of annual energy production and how the improved power captured results in improved annual energy production numbers. Finally, Section 3.3 examines coupling the twist, chord, and radius studies with changes in blade root pitch to examine ways to maintain power production while reducing root bending moments. Chapter 4 presents a summary of these studies, and some recommendations for future work.

Chapter 2

Model Formulation and Analysis

There are a few models used to analyze wind turbine loads and performance. The most common method is to use Blade Element Momentum Theory (BEMT). This type of analysis will be detailed in the next section, as it is the tool used during this study. The National Renewable Energy Laboratory (NREL) uses this type of analysis in two of its most popular codes: WT_Perf and FAST. WT_Perf, which stands for Wind Turbine Performance, is a straight forward executable program where the user inputs aerodynamic information at different radial positions of the blade, in addition to the information on the aerodynamic conditions the turbine is experiencing [29]. Such aerodynamic information includes local blade pitch from the rotor plane, chord length, and a table of airfoil properties at different angles of attack. FAST, or Fatigue, Aerodynamics, Structures, and Turbulance, offers a much more thorough analysis than WT_Perf does. It uses BEMT for the aerodynamic solution, but combines this with a flexible blade and flexible tower structural analysis to predict loadings, displacements, and accelerations along the blades, tower, rotor and generator shafts, and even within the foundation. It can model turbines with active yaw control, active pitch control, furling mechanisms, and take user defined turbulent wind fields into account [30]. Methods based on BEMT are relatively fast to run, and offer reasonable accuracy [5].

In addition to these BEMT codes provided by NREL, other computational fluid dynamics codes exist that can be used for wind turbine applications with one example being Fluent® by Ansys®. While more accurate than BEMT methods, these methods take longer and are not much more accurate for normal wind turbine operating procedures, but are useful when modeling specific turbulent operating conditions or micro scale interactions.

2.1 Analysis Program

In order to perform the analyses needed for these studies, a simulation program was written using MATLAB. This program was based off of NREL's aforementioned WT_Perf. It was written because implementing partial span geometry changes using WT_Perf would be difficult due to the way the inputs are assigned by describing the characteristics at a few discrete spanwise positions. The custom code uses equations to accurately describe characteristics at every spanwise position, allowing for less ambiguity in the blade geometries between defined positions.

2.1.1 Blade Element Momentum Theory

BEMT combines classic momentum theory with blade element theory to get a more accurate assessment of the variation in inflow and aerodynamic characteristics along the span. It assumes that each blade element along the span of a blade can be analyzed independently from the other sections. This means that there are no three dimensional effects along the span of the blade. For the mid section of the blade, this is a fairly good assumption, but as the ends of the blade are approached this assumption is violated due to flow escaping around the ends of the

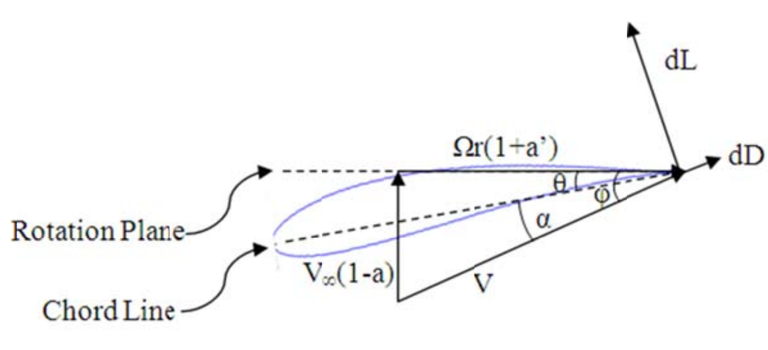

Figure 2-1: Velocity and force diagram of a wind turbine blade element

blade. Therefore, corrections, such as Prandtl's hub and tip loss models, are taken near the hub and tip of the blade to correct for this. [5].

By looking at a blade element, the aerodynamics that drive wind turbine design can be explained. Figure 2.1 shows an image of a blade element with various velocity and force components drawn on it. In this figure, V_∞ is the free stream velocity, Ωr is the rotational velocity seen by the blade section at a given radial station a distance *r* from the hub center , *a* is the axial induction factor, *a'* is the tangential induction factor, and *V* is the resultant velocity formed. The axial induction factor is the ratio of flow through the rotor plane to the free stream velocity, and is therefore a measure of how much the free stream is slowed through the rotor plane from the process of power extraction from the flow. The tangential induction factor is a measure of the rotational component added to the wake of the flow by the rotating blades, which is usually negligible at normal operating conditions. Therefore the resultant velocity seen by the airfoil can solved as follows in Eqn. 2-1.

$$V = \sqrt{[V_\infty(1-a)]^2 + [(\Omega r)(1+a')]^2} \tag{2-1}$$

The inflow angle is defined as the angle the resultant velocity of the flow makes with the rotor plane and can be solved by Eqn. 2-2:

$$\varphi = \arctan\left(\frac{V_\infty(1-a)}{\Omega r(1+a')}\right) = arctan\left(\frac{(1-a)}{yX(1+a')}\right) \tag{2-2}$$

where *X* is defined as the tip speed ratio (*ΩR/V*$_\infty$) and *y* is the nondimensional position (*r/R*) along the blade span.

Subtracting θ, the geometric pitch angle of the blade section, from φ, yields the aerodynamic angle of attack, α, for the cross section. The lift and drag coefficients, C_l and C_d, are obtained for any given angle of attack using airfoil tables. Sectional lift and drag forces are calculated below in Eqns. 2-3 and 2-4, where ρ is the density of air and *c* is the section chord length.

$$dL = \frac{1}{2}\rho c V^2 C_l dr \tag{2-3}$$

$$dD = \frac{1}{2}\rho c V^2 C_d dr \tag{2-4}$$

Once the incremental lift and drag are calculated for the section, the incremental thrust and power that each section produces can be solved using Eqns. 2-5 and 2-6 respectively.

$$dT = dL\cos\varphi + dD\sin\varphi \tag{2-5}$$

$$dP = (dL\sin\varphi - dD\cos\varphi)r\Omega \tag{2-6}$$

Finally, the full rotor thrust and power can be determined by integrating those quantities across the span of the blade (where r_0 is the blade root and R is the length of the blade) and multiplying by the number of blades (N_b) that the turbine has. This can be seen below in Eqns. 2-7 and 2-8 respectively.

$$T = N_b \int_{r_0}^{R} dT \tag{2-7}$$

$$P = N_b \int_{r_0}^{R} dP \tag{2-8}$$

The root bending moment at the connection between the blade and the hub can also be found by multiplying the incremental thrust by its distance from the hub. This formula is seen in Eqn. 2-9.

$$M = \int_{r_0}^{R} (r - r_0)dT \tag{2-9}$$

All of the above calculations are contingent on being able to solve for the axial induction factor correctly. However, there is not a closed form solution to solve for this, and an iterative process must be used until the value converges. In the program written for this analysis, this process borrows heavily from the WT_Perf program. For a given operating condition (wind speed and tip speed ratio), blade span position, and blade geometry, the process outlined hereafter can be followed.

First, a guess for the induction factor and tangential induction factor can be made, with 0 being an acceptable assumption for both. Then, equations 2-1 and 2-2 can be solved and the blade section angle of attack can be found by Eqn. 2-10:

$$\alpha = \varphi - \theta \tag{2-10}$$

With the angle of attack solved for, the section lift and drag coefficients can be picked off of a lookup chart, interpolating between values given in the table if necessary. Now, the normal coefficient for the blade section can be calculated using Eqn. 2-11, which will be used later in the analysis:

$$C_n = C_l \cos\varphi + C_d \sin\varphi \tag{2-11}$$

As stated before, Prandtl loss corrections need to be applied near the hub and tip of the blade to account for three dimensional effects that are not possible using BEMT. The process starts by calculating two factors which can be seen in Eqns. 2-12 and 2-13 below:

$$F_h exp = e^{\frac{-N_b}{2}\frac{(y-y_0)}{y_0 \sin\varphi}} \tag{2-12}$$

$$F_t exp = e^{\frac{-N_b}{2}\frac{(1-y)}{y \sin\varphi}} \tag{2-13}$$

Then these factors are used to calculate the losses at the hub and at the tip, as seen in Eqns. 2-14 and 2-15.

$$F_h = \left(\frac{2}{\pi}\right) \text{atan}\left(\frac{\sqrt{1 - F_h exp^2}}{F_h exp}\right) \tag{2-14}$$

$$F_t = \left(\frac{2}{\pi}\right) \text{atan}\left(\frac{\sqrt{1 - F_t exp^2}}{F_t exp}\right) \tag{2-15}$$

The total losses can be found using Eqn. 2-16:

$$F = F_h * F_t \tag{2-16}$$

Momentum theory cannot predict induction factors greater than about 0.4 (induction factors range from 0 to 1). When induction factors get higher than 0.4, a rotor is said to be heavily loaded and empirical formulas have been developed to calculate the induction factor, most famously is one developed by Glauert. In order to determine if the theoretical induction factor equation or the empirical equation should be used, a factor termed the head loss factor which determines how heavily the rotor is loaded needs to be calculated [29, 31]. This calculation can be seen in Eqn. 2-17:

$$CH = \frac{V^2 \sigma C_n}{{V_\infty}^2} \tag{2-17}$$

where σ is the blade annular solidity which is representative of the percentage of the rotor disk that is taken up by blades versus that which is empty space, and is calculated by Eqn. 2-18 as:

$$\sigma = \frac{N_b c}{2\pi y R} \tag{2-18}$$

In this program, *CH* is constrained to stay between the values of -2 and 2 to keep the calculations from diverging. If *CH* is less than 0.96**F*, then the theoretical formula (Eqn. 2-19) can be used to calculate the induction factor, otherwise the empirical formula (Eqn. 2-20) is used.

$$a = 0.5\left[1 - \sqrt{1 - \frac{CH}{F}}\right] \tag{2-19}$$

$$a = 0.1432 + \sqrt{-0.551 + 0.643\frac{CH}{F}} \tag{2-20}$$

A similar process is followed for the tangential induction factor *a'*. A loading factor, called *CS*, is calculated using Eqn. 2-21, and depending on the result, one of two formulas is used to calculate the tangential induction factor. If *CS* is less than 0, Eqn. 2-22 is used, otherwise Eqn. 2-23 is used.

$$CS = 4aF\frac{1-a}{X^2} \quad (2\text{-}21)$$

$$a' = 0.0 \quad (2\text{-}22)$$

$$a' = 0.5\sqrt{CS-1} \quad (2\text{-}23)$$

Finally, this process is repeated until convergence is found between two iterations. In the case of this analysis, convergence is assumed when the values from two consecutive iterations differs by 1e-6.

2.1.2 Wind Energy Analysis

In addition to the aerodynamic analysis performed by the main program, a separate program can take the data and calculate the wind energy extracted at each operating condition. Weibull distributions are used to predict the amount of time at each wind speed. The shape of a Weibull distribution for a given wind site depends on two factors: an average wind speed at hub height, and a shape factor. Rayleigh distributions are most commonly used, which make use of a shape factor of k=2. These distribution shapes were assumed for this analysis for all turbines.

This program inputs wind speed and power values from the BEMT program. It calculates the percentage of time the wind speed occurs for a given average wind speed and shape factor, and then calculates the energy produced by that wind speed per year by using Eqn. 2-24.

$$Annual\ Energy = Power\ Produced * Hours\ per\ Year * Probability\ of\ Wind\ Speed \quad (2\text{-}24)$$

Most turbines do not run for the entire year due to maintenance or wind speeds that are outside the operating range, and the Hours per Year factor can be adjusted accordingly. Since this analysis looked only at percentage increases in energy from the baseline, these factors cancel out and it was not necessary to modify the value more realistically.

This program also has a feature to limit the amount of power generated at a wind speed to the rated power of the generator. Some of the analyses ran showed potential power gains in Region II of the power curve to be more than the rated power of the generator. When performing some of the energy analyses, it was required to keep within the constraints of the generator power rating, so this option was used to ensure the generated power did not surpass the constraint.

2.1.3 Program Inputs

This program requires the user to make certain inputs to be able to be run effectively. All inputs are set to be entered in standard SI units, but English units can be entered with slight modifications to the program. There are three variables that do not depend on the turbine being simulated. The 'rho' variable represents the density of air at the hub height, and is considered to be uniform across the rotor plane. At standard sea level atmospheric operating conditions, this variable has a value of 1.225 kg/m^3. The 'atol' variable assigns the tolerance for induction factor convergence. A value of 1e-6 works well. A larger tolerance will allow the convergence to occur faster at the cost of accuracy. A smaller tolerance will make the simulation longer to run, but will give more accurate results. The 'yo' variable assigns the nondimensional root cutout value for each blade, and is set at 0.20.

The turbine specific variables are described below, however their values will be included in Section 2.2 when each turbine is described. First, the variable 'Nb' describes the number of blades the turbine has. The radius of the rotor plane, defined from the center of the hub to the blade tip, is assigned under the 'R' variable. 'Bp' describes the blade precone angle, which is the angle at which the blades are initially set relative to the rotor plane. For wind turbines, the purpose of this is to give the blades more clearance from the tower when high wind conditions bend the blades downwind. The variable is in radians, and positive in the upwind direction.

The blade geometry variables ‘theta’ and ‘c’ represent the blade planform twist distribution and chord distribution respectively. These distributions are input by way of equations written in relation to nondimensional radial span ‘y’. Piecewise functions can be used for blades that contain discontinuous geometry changes, which is most likely the case on commercial wind turbine blade designs, by making use of ‘if’ statements. One equation can be used if the nondimensional blade section is less than a certain point, and another if it is greater than that point. The twist values are defined as positive when twisted upwind from the rotor plane.

Finally, the aerodynamic conditions of operation need to be input. These parameters are kept in a matrix known as ‘Uinfo’. The matrix contains three columns and can contain as many rows as needed, with each row corresponding to a different simulation to be run. The columns of the matrix contain, from left to right, the free stream wind speed, the tip speed ratio that the rotor will be running at, and the root collective pitch setting that the blade will be set at. Like the twist distribution, the pitch setting is defined as positive in the upwind direction.

2.1.4 Program Outputs

The program is set up to provide the user with a wide variety of outputs. These outputs can be broken up into 2 different groups. These groups are gross rotor parameters, and blade level parameters. The gross rotor parameters consist of looking at values of a variable for the whole rotor (or single blade) at a variety of wind speeds or tip speed ratios. Both thrust and power output of the entire rotor can be viewed like this. Blade root bending moments for a single blade can also be viewed. These plots are useful for seeing how a rotor reacts as a whole to a range of different operating conditions.

Blade level parameters are variables that change along the span of the blade. These plots are shown with respect to the dimensional or nondimensional radial position. These types of parameters include induction factor, angle of attack, inflow angle, incremental lift and drag, and incremental thrust and power. It is useful to look at these outputs to determine how a partial span geometry change affects what is occurring at the blade level. For instance, the effects of a change of chord from 60-90% span on lift produced can be observed along the entire span of the turbine blade.

2.2 Wind Turbine Models

As part of the scope of this study, two different wind turbines were examined to see how changing blade parameters carried over from one size turbine to a different size turbine. Because of this choice, the two turbines selected to be studied were the WindPACT 1.5MW 3 bladed upwind turbine [32] and the NREL 5MW offshore concept turbine, which is also a 3 bladed upwind turbine [6]. Both of these turbines are found in NREL design reports [6,32]. The WindPACT study is the result of designing turbines that are representative of current commercial size turbines to use as research turbines. The 5MW turbine is representative of future (currently in the prototype stage) large offshore turbines. The geometries of both turbines will be described in the following two sections.

2.2.1 WindPACT 1.5MW Turbine

The WindPACT 1.5MW turbine is a 3 bladed upwind turbine. It has a radius of 35m from hub center to outer blade tip. The specifications given come from the WT_Perf sample input file that is set up to model this turbine [29]. It has a blade precone angle of 3 degrees. Its rated wind speed is at 11.8 m/s, with a cut in speed of 3 m/s and a cut out speed of 25 m/s. Its rotational speed at the rated wind speed is 20.5 rpm. Neither the WindPACT paper nor the

WT_Perf sample input file present a rotational speed operational envelope or an operating schedule of what tip speed ratio the turbine runs at for a given wind speed. The rotational speed limits for a similar 1.5MW General Electric turbine were assumed to be an acceptable estimate. These limits are stated as 11.1 rpm and 22.2 rpm [33]. All of the above specifications, as well as a few others, can be found summarized in Table 2-1.

Table 2-1: Specifications for WindPACT 1.5MW Turbine

Rated Power	1.5MW
Rated Wind Speed	11.8 m/s
Cut In Wind Speed	3 m/s
Cut Out Wind Speed	25 m/s
Rated Rotational Speed	20.5 rpm
Rotational Speed Range	22.2 – 11.1 rpm
Hub Diameter	0.05m
Blade Length	34.98m
Precone Angle	3°

For the operation schedule of tip speed ratio as a function of wind speed, it was assumed to mimic the tip speed ratios seen by the 5MW turbine, except where they needed to be modified due to fitting within the rotational speed limits or rated rotational speed at the rated wind speed. Also, the tip speed ratio for the 3 m/s case was decreased from 15 (based off of the 5MW turbine) to 14 because 15 was too fast and resulted in negative power production. Since this turbine had no simulations done above the rated speed, only power calculations at wind speeds below the rated speed are shown. This operating schedule can be seen below in Table 2-2.

In the WT_Perf sample file, a chart is given listing the aerodynamic properties of the blade at various locations along the span of the blade. For use in this program, the data points were reduced to a set of regression curves for the values of both the twist distribution and chord distribution. Table 2-3 shows the points generated from these curves. In addition, one of the studies performed was a simulation that increased the radius of the blade up to 120% of the baseline value. For these tests, the existing chord and twist distribution was extrapolated out to the extended radius. For this reason, these values are included in the table as well, which can be seen below the doubled line.

Table 2-2: Operation schedule for WindPACT 1.5MW Turbine

Wind Speed (m/s)	Tip Speed Ratio	Collective Pitch Setting (°)
3.0	14	0.0
4.0	12	0.0
5.0	10	0.0
6.0	9	0.0
7.0	8	0.0
8.0	7	0.0
9.0	7	0.0
10.0	7	0.0
11.0	6.83	0.0
11.8	6.36	0.0

Table 2-3: Blade aerodynamic properties for WindPACT 1.5MW Turbine

Radial Position (m)	Twist (deg)	Chord Length (m)	Airfoil Type
2.625	11.100	2.174	S818
4.375	11.100	2.369	S818
6.125	11.100	2.563	S818
7.875	10.794	2.757	S818
9.625	8.940	2.623	S818
11.375	7.318	2.503	S818
13.125	5.911	2.383	S818
14.875	4.704	2.263	S818
16.625	3.681	2.143	S825
18.375	2.826	2.022	S825
20.125	2.124	1.902	S825
21.875	1.559	1.782	S825
23.625	1.115	1.662	S825
25.375	0.777	1.542	S825
27.125	0.529	1.422	S826
28.875	0.355	1.302	S826
30.625	0.240	1.182	S826
32.375	0.168	1.062	S826
34.125	0.123	0.942	S826
35.875	0.090	0.822	S826
37.625	0.052	0.702	S826
39.375	-0.005	0.582	S826
41.125	-0.097	0.462	S826

The airfoil properties for the given airfoils can be commonly found, and hence are not provided in this report. Appendix A contains a MATLAB file used to simulate the WindPACT 1.5MW turbine in its range of Region II operating wind speeds

2.2.2 NREL 5MW Offshore Concept Turbine

The NREL 5MW Offshore concept turbine is also a 3 bladed upwind turbine. It was designed to represent the future generation of wind turbines for use in offshore wind generation, and was based off of two companies' turbines designed for the purpose. It has a rated speed of 11.4 m/s and has a cut-in speed of 3 m/s and a cut out speed of 25 m/s. It has a rated rotational speed of 12.1 rpm and its operational range of rotational speeds range from 6.9 rpm to 12.1 rpm. The blades of this turbine are actually not steadily preconed, but are bent at an increasing rate along the span of the blade. Since this type of configuration cannot be analyzed in any of the existing codes, a constant precone of 2.5 degrees is used. The hub diameter is 3m and the blade length is 61.5m, giving the rotor disk a radius of 63m. These specifications are summarized in Table 2-4. [6]

Table 2-4: Specifications for NREL 5MW Turbine

Rated Power	5MW
Rated Wind Speed	11.4 m/s
Cut In Wind Speed	3 m/s
Cut Out Wind Speed	25 m/s
Rated Rotational Speed	12.1 rpm
Rotational Speed Range	6.9 – 12.1 rpm
Hub Diameter	3m
Blade Length	61.5m
Precone Angle	2.5°

This turbine has an operation schedule outlined as well. This operation schedule includes tip speed ratios at each wind speed between its cut in and cut out speed. Once the rated speed is surpassed, the turbine keeps its rotational speed constant at the rated rotational speed while feathering its blades to regulate power production. The root pitch settings above the rated speed were also included in the report. [6] These specifications can be found in Table 2-5 below.

Table 2-5: Operation schedule for NREL 5MW Turbine

Wind Speed (m/s)	Tip Speed Ratio	Collective Pitch Setting (°)
3.0	15	0.0
4.0	12	0.00
5.0	10	0.00
6.0	9	0.00
7.0	8	0.00
8.0	7	0.00
9.0	7	0.00
10.0	7	0.00
11.0	7	0.00
11.4	7	0.00
12.0	6.65	3.83
13.0	6.14	6.60
14.0	5.70	8.70
15.0	5.32	10.45
16.0	4.99	12.06
17.0	4.69	13.54
18.0	4.43	14.92
19.0	4.20	16.23
20.0	3.99	17.47
21.0	3.80	18.70
22.0	3.63	19.94
23.0	3.47	21.18
24.0	3.33	22.35
25.0	3.19	23.47

Also included in the paper is an outline of the blade aerodynamic properties. As with the WindPACT turbine, these points were fitted with regression curves in a piecewise manner, and Table 2-6 was generated from these curves. As before, additional points beyond the length of the blade are also shown because these points are used in a simulation that extends the radius up to 120% of the baseline radius. These points are obtained by taking the regression curves for the outboard part of the blade and extending them to the appropriate distance. The airfoil data for these airfoils can be found in the appendices of the 5MW Turbine report. [6] The MATLAB code used to simulate the turbine operating across its operating range can be found in Appendix B.

Table 2-6: Blade aerodynamic properties for NREL 5MW Turbine

Radial Position (m)	Twist (deg)	Chord Length (m)	Airfoil Type
2.8667	13.308	3.629	Cylinder 1
5.6000	13.308	3.953	Cylinder 1
8.3333	13.308	4.277	Cylinder 2
11.7500	13.197	4.682	DU40
15.8500	11.696	4.817	DU35
19.9500	10.269	4.566	DU35
24.0500	8.917	4.316	DU30
28.1500	7.639	4.066	DU25
32.2500	6.435	3.816	DU35
36.3500	5.305	3.566	DU21
40.4500	4.250	3.316	DU21
44.5500	3.269	3.066	NACA64
48.6500	2.362	2.816	NACA64
52.7500	1.529	2.566	NACA64
56.1667	0.892	2.357	NACA64
58.9000	0.420	2.191	NACA64
61.6333	-0.020	2.024	NACA64
64.5750	-0.456	1.844	NACA64
67.7250	-0.880	1.652	NACA64
70.8750	-1.261	1.460	NACA64
74.0250	-1.598	1.268	NACA64

2.3 Validation

In order to validate that the program worked correctly, it was compared to both WT_Perf and FAST in looking at power and thrust for the rotor, and root bending moments for a single blade, for each wind speed within the operating range of the turbine. These comparisons were done solely for the 5MW turbine since the data to simulate across all wind speeds was readily available.

Since WT_Perf is purely an aerodynamic analysis and does not include structural properties as FAST does, it is expected that the MATLAB program will compare best with WT_Perf, while FAST should still offer similar results. Figure 2-2 shows the results of the power comparison, Figure 2-3 shows the results of the thrust comparison, and Figure 2-4 shows the results of the root bending moment comparison.

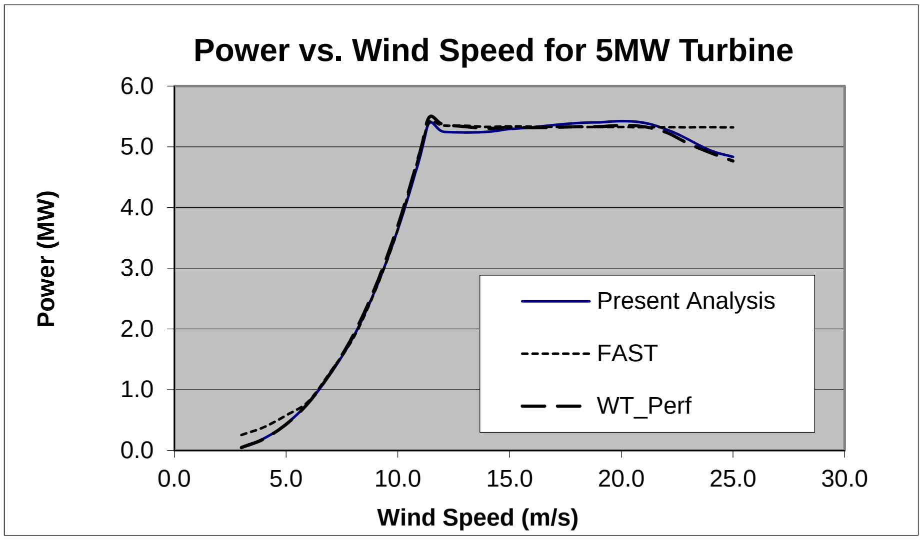

Figure 2-2: Comparison of power results from 3 different programs

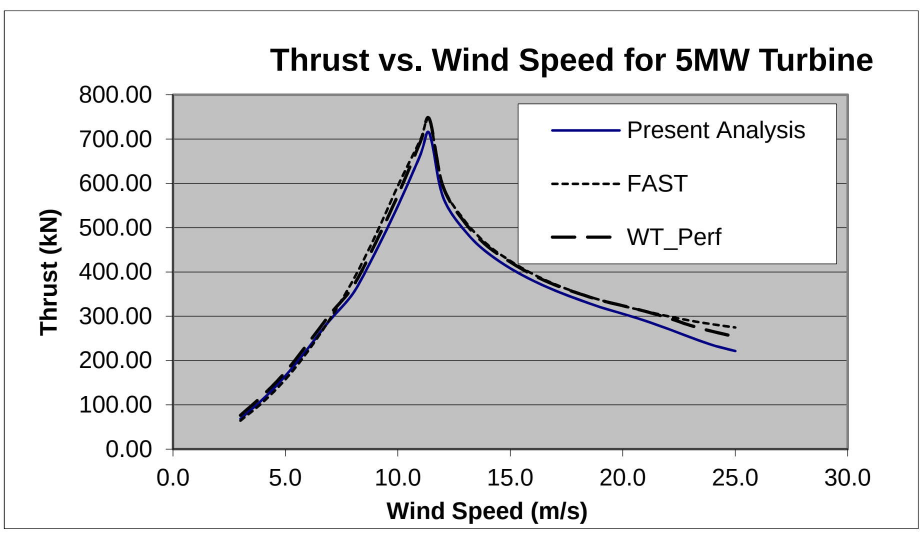

Figure 2-3: Comparison of thrust results from 3 different programs

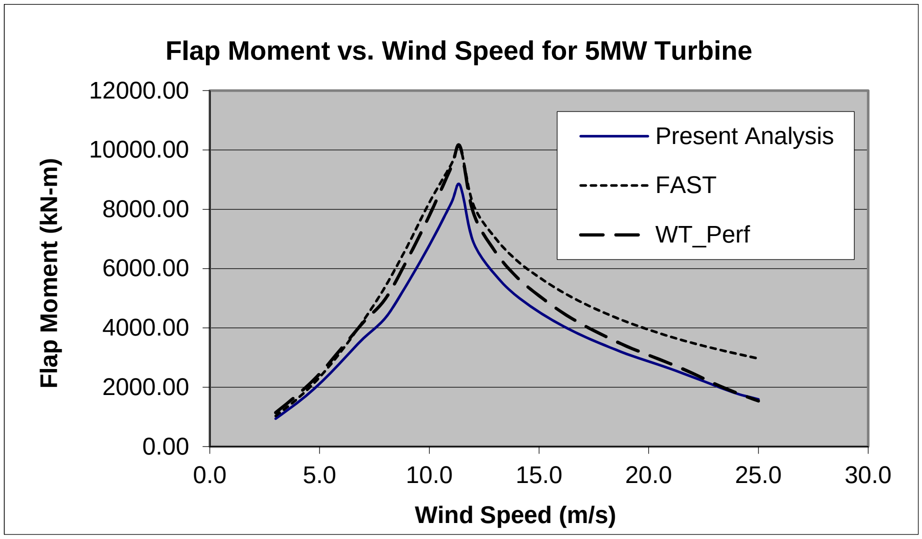

Figure 2-4: Comparison of root bending moment results from 3 different programs

From the above figures, it can be seen that the written MATLAB program is very close in agreement with WT_Perf for both the power and thrust analysis. In those two plots, FAST also has similar agreement. The root bending moment plots show some disagreement between WT_Perf and the MATLAB program. The error at the rated speed, which corresponds to the peak value on both plots, is 12.9%. However, the shapes of the two plots are very similar. Since this study most often looks at the percentage difference in values from the baseline blade configuration, this error is acceptable.

Chapter 3

Results and Discussion

In order to determine the benefit of a morphing turbine blade over the different operating wind speeds, a few parameters were examined. By looking at Eqns. 2-4, 2-6, and 2-8, it can be seen that the parameters that affect power produced by a wind turbine blade are the local pitch angle θ (through φ), the chord length, the radial span, and the lift and drag characteristics of the airfoil. By simulating these changes at different wind speeds, it is possible to see what geometries are most beneficial for producing power at the different wind speeds. This sets the foundation for designing a turbine blade that adapts its shape at different wind speeds. These simulations for both turbines are shown in Section 3.1. These results are then examined to see what effects these power increases have on the Annual Energy Production (AEP) of each turbine. These results are shown in Section 3.2.

After the above study was performed, it was seen that increasing the root pitch setting results in decreasing and power production and root bending moment. As a result, a third study was performed that examined if the above changes that resulted in an increase in power, when combined with changing the root bending moment, could result in reducing the root bending moment while maintaining or slightly increasing the power production of the turbine. The results of this study are shown in Section 3.3.

3.1 Adaptive Geometry Blades and Increased Power Production

As stated above, the four variables that can be seen by theoretical analysis to affect power production of a wind turbine blade are local pitch angle (affected by both blade twist and root pitch setting), chord length, blade span, and the airfoil properties of the airfoil used. Each of these variables was varied for each turbine and the power output was examined. The sections below each deal with one of these changing parameters, and their effect on both turbines is examined.

In order to determine how optimal geometry is affected by the turbine operating at different wind speeds, each of the investigations described above was simulated at different wind speeds. Since the potential to increase power production occurs only at the Region II wind speeds, since at Region III wind speeds the rotor is capable of producing more power than the generator can handle, each simulation was run at 4, 6, 8, and 10 m/s. These speeds occur in Region II for each turbine. Also, at the 4 and 6 m/s wind speeds, the turbines are not operating near the optimal tip speed ratios due to start up considerations, so adaptable geometry blades may potentially have a great impact at these speeds.

3.1.1 Local Pitch Angle Study

The local pitch angle at any particular element of blade is defined by both the twist distribution along the blade and the pitch setting at the blade root. The pitch angle is normally set to 0°, meaning the blade twist is at its nominal design configuration. This normally consists of a steep positive (positive angles are defined as upwind) angle towards the root of the blade, and an angle closer to zero at the blade tip.

For this study, each blade kept the same general baseline twist distribution, but it was scaled both steeper and shallower in 3° increments. For example, the root to tip nose up twist for the WindPACT 1.5MW turbine is approximately 11.1°. Therefore, the study examined profiles that were scaled to 5.1°, 8.1°, 14.1°, and 17.1°. In addition, root pitch settings were varied as well, in steps of -6°, -3°, 3°, and 6°. Finally, to insure that if the changing blade geometry changes the optimal rotational speed of the turbine, multiple turbine rotational speeds were investigated.

3.1.1.1 WindPACT 1.5MW Turbine

As stated above, the WindPACT 1.5MW Turbine has a baseline root to tip nose up twist of approximately 11.1°. Different profiles were tested that took the existing blade twist distribution and scaled it up or down in increments of 3°. Therefore, as stated above, the profiles examined for this study were 5.1°, 8.1°, 14.1°, and 17.1°. In addition to the different collective settings being tested, the simulations also occurred at various rotational speeds. For this turbine, rotational speeds were tested in increments of ±2 rpm around the baseline rotational speed, for each wind speed. Table 3-1 below shows the baseline statistics for this turbine, including the rotational speed and power produced at each tested wind speed.

Table 3-1: Baseline characteristics for WindPACT 1.5MW Turbine

Wind Speed (m/s)	Rotational Speed (rpm)	Baseline Power (MW)
4	13.10	0.038
6	14.73	0.21
8	15.28	0.57
10	19.10	1.11

When the simulations were run, rotational speeds outside of the operational range of the turbine were tested. This was done to ensure that optimal values could be found outside of the operational range of the turbine so that hardware limits are not obscuring results of the studies. Because the 4 m/s and 6 m/s wind speeds are so low, the optimal rotational speeds at these wind speeds is slower than the machinery can handle. However, because of the slow wind speeds, very little power is produced in this operational state (as can be seen from Table 3-1) and designs usually sacrifice these potential gains. Optimal values within the operational range are reported as well.

The data for this study can be broken up into three different groups. The first group is looking at the effects of changing root pitch setting (or collective pitch setting) without changing the twist distribution, the second group looks solely at scaling the twist distribution and keeping the collective constant, and the third varies both. The optimal results summary for these studies can be seen in Tables 3-2 a, b, and c, below, while the full results are available in Appendix C.

Table 3-2: Results for a) collective analysis, b) twist analysis, and c) combination of twist and collective analysis for WindPACT 1.5MW Turbine

Wind Speed (m/s)	Collective Pitch (deg)	Rotational Speed (rpm)	Power Increase
4	0	7.10	88.0%
6	0	10.73	14.3%
8	3	17.28	2.1%
10	3	21.10	2.1%

Wind Speed (m/s)	Root to Tip Twist (deg)	Rotational Speed (rpm)	Power Increase
4	14.1	9.10	76.7%
6	14.1	10.73	14.4%
8	14.1	15.28	0.4%
10	14.1	19.10	0.4%

Wind Speed (m/s)	Root to Tip Twist (deg)	Collective Pitch (deg)	Rotational Speed (rpm)	Power Increase
4	11.1	3	9.10	90.3%
6	8.1	3	12.73	16.7%
8	8.1	3	17.28	2.3%
10	8.1	3	21.10	2.5%

Within the operational range of the turbine, the maximum power at the 4m/s wind speed occurs at the lowest allowable rotational speed of 11.1 rpm and for a power increase of 85.4% with 5.1° twist with 6° collective pitch setting. When considering the minimum rpm constraint lower root to tip twist values with positive blade pitch settings appear to be beneficial for power production. However, these increases are noticeably less significant at the higher wind speeds of 8 and 10 m/s, and only appreciable at the lower wind speeds where the absolute energy extracted still remains very small.

3.1.1.2 NREL 5MW Turbine

The 5MW turbine has a slightly different twist distribution than the 1.5MW turbine does. It has a root to tip nose up twist of approximately 13.3°. Similar to the previous study, this distribution was scaled in 3 degree increments, meaning that the additional twist distributions tested had blade twists of 7.3°, 10.3°, 16.3°, and 19.3°. The same root pitch settings used before were simulated. Also, the rotational speed changes were varied by ±1 rpm since the operational range is smaller for this turbine (due to its longer blades) than for the previous turbine. Table 3-3 shows the baseline characteristics for this turbine. As with the previous study, a range of rotational speeds was examined, and if the optimal results fall outside of the operational range of the turbine, this is noted.

Table 3-3: Baseline characteristics for NREL 5MW Turbine

Wind Speed (m/s)	Rotational Speed (rpm)	Baseline Power (MW)
4	7.28	0.19
6	8.19	0.78
8	8.49	1.86
10	10.61	3.63

The summary of results for this study can be found in Table 3-4. As stated before, the results for this study can be broken up into three tables, however it can be seen that the results for the twist study would be the same as the twist/collective study results since all of the results for the latter occur at 0° collective pitch setting. Therefore only two tables are shown, one for the collective pitch only study, and one for the combination study. The results for the entire study are shown in Appendix D.

Table 3-4: Results for a) collective analysis and b) combination of twist and collective analysis for NREL 5MW Turbine

Wind Speed (m/s)	Collective Pitch (deg)	Rotational Speed (rpm)	Power Increase
4	0	5.28	20.4%
6	0	7.19	2.1%
8	0	9.49	1.8%
10	0	11.61	1.7%

Wind Speed (m/s)	Root to Tip Twist (deg)	Collective Pitch (deg)	Rotational Speed (rpm)	Power Increase
4	10.3	0	4.28	21.7%
6	10.3	0	7.19	2.7%
8	10.3	0	9.49	2.6%
10	10.3	0	11.61	2.7%

Within the operational range of the turbine, the maximum power at the 4 m/s wind speed occurs at the lowest allowable rotational speed of 6.9 rpm and at 7.3° twist with 6° tip collective. This results in a 16.8% increase in power output. This number was determined through linearly interpolating from the provided results, which was proven to be an acceptable method by comparing with actual answers. Although a slightly lower twist appears to be beneficial, the increase in power capture is very small, even compared to the previous turbine.

3.1.2 Chord Variation Study

The variable chord study was the next one to be performed. This study took the baseline chord distribution of each turbine and scaled it from 80% to 120% in 5% increments along the whole span of the blade. Again, to ensure that the changed geometry did not alter the rotational speed that the optimum value occurs at, a range of rotational speeds were simulated. In this study, they were chosen by incrementing the tip speed ratio in increments of 0.5 from the baseline. The baseline blade twist, root pitch setting, and radius were kept the same.

3.1.2.1 WindPACT 1.5MW Turbine

Table 3-5 shows the optimum results for this study on the 1.5MW turbine. It displays the combination of chord scaling factor and rotational speed that produce the optimum results at each of the tested wind speeds, and the percent increase in power that the combination produces. The full results at all each of the wind speeds can be found in Appendix E.

Table 3-5: Results for chord variation study for WindPACT 1.5MW Turbine

Wind Speed (m/s)	Chord Scaling Factor	Rotational Speed (rpm)	Power Increase
4	0.80	8.19	92.5%
6	0.80	12.28	16.8%
8	0.80	16.37	2.5%
10	0.80	20.46	2.5%

Again, the maximum power increase at 4 m/s is at 8.19 rpm, below the operating range of the turbine. The optimum within the operational range is at 11.1 rpm, where the chord scaling factor is still 0.8 and the power increase is 66.9%. From the results in Table 3-5, it is observed that a lower chord is always favored (at all wind speeds), leaving little room for an adaptive geometry blade. While it results in moderate power increase at low wind speeds (where power capture in any case remains low), the improvement at higher speeds (8 and 10 m/s) are negligible.

3.1.2.2 NREL 5MW Turbine

Table 3-6 shows the optimum results when the chord study was performed on the 5MW turbine. It shows the chord scaling factor and rotational speed that produce the highest power output and the percentage increase that amount of power is over the baseline. The full results for this study can be found in Appendix F.

Table 3-6: Results for chord variation study for NREL5MW Turbine

Wind Speed (m/s)	Chord Scaling Factor	Rotational Speed (rpm)	Power Increase
4	1.00	4.85	21.8%
6	1.00	7.28	2.1%
8	1.00	9.70	1.8%
10	1.00	12.10	1.8%

At the 4 m/s wind speed, the optimal rotational speed again is below the operating range of the hardware. The optimum occurs at lower limit of 6.9 rpm and the maximum power increase falls to 11.1% at a chord scaling factor of 0.80. As with the 1.5 MW turbine, not much improvement in energy capture appears possible with chord variation.

3.1.3 Radius Variation Study

The final gross blade property study to be performed involves both contracting and expanding the span of the blades. Each turbine's blades were varied in span from 80% to 120% in increments of 5% changes. For blades shorter than the original blade, planforms were cut short at the respective point. For planforms larger than the original blade, the twist and chord distributions are extrapolated from the trends they followed as they approached the blade tip. The specific data points used for these extrapolations can be found in Table 2-3 for the WindPACT 1.5MW Turbine and 2-6 for the NREL 5MW Turbine. Finally, as with the previous studies, various rotational speeds have been simulated to ensure that the optimal rotational speed is found. This is especially true in this study because the varying radial length directly affects the tip speed ratio that the turbine is operating at, which affects the aerodynamics of the blade. The rotational speeds are examined at every whole rpm unit, in addition to the baseline level.

3.1.3.1 WindPACT 1.5MW Turbine

Table 3-7 shows the optimal results for the varying span study on the 1.5MW Turbine. This table shows the combination of radial scaling factor and rotational speed that produce the most power and the percentage increase that power production is over the power produced by the baseline case at that wind speed, as well as the corresponding increases in thrust and root bending moment seen. The full results can be seen in Appendix G.

Table 3-7: Power results for variable radius study for WindPACT 1.5MW Turbine

Wind Speed (m/s)	Radius Scaling Factor	Rotational Speed (rpm)	Power Increase	Thrust Increase	Moment Increase
4	1.20	7.00	119.3%	-2.0%	14.4%
6	1.20	10.00	61.3%	15.0%	37.8%
8	1.20	14.00	47.1%	40.9%	71.6%
10	1.20	17.00	47.5%	37.3%	67.0%

At 4 m/s the maximum power at 120% of the nominal radius and at 7 rpm is 119.3%. If the rotational speed is constrained not to reduce below 11.1 rpm, the maximum increase in power (with the optimum radius at 120%) is 41.5% with corresponding thrust and root bending moment increases of 43.0% and 51.5% respectively. Similarly, at 6 m/s, if the minimum rotational speed is constrained to be 11.1 rpm, the maximum power increase is 58.2%, again at the largest radius factor, with corresponding increases in thrust and root bending moment of 25.8% and 74.5%.

As expected, rotors with larger radii are seen to produce more power, which can be seen in the wind power equation which solves for the amount of power available in the wind:

$$P = \frac{1}{2}\rho\pi R^2 {V_\infty}^3 \tag{3-1}$$

Equation 3-1 shows that the power available in the wind stream increases with the square of the radius. Therefore a rotor that is 20% larger will be able to tap into a source with 44% more power. Keep in mind that a rotor only captures a portion of the power available in the wind stream. If the increased rotor size allows it to become more efficient at capturing this power, increases greater than 44% can be seen.

Despite the promising results, a more encompassing look into this option is needed. In particular, it should be noted that a larger span blade increases the loadings experienced by the blade. This trend can be observed when looking at the thrust results (an indicator of blade root shear forces) and root bending moment results of this study. These results can be seen summarized in Table 3-8 and Table 3-9, which show a small portion of the results for the 10 m/s wind speed. The full results can be seen in Appendices H and I respectively.

Table 3-8: Thrust results for variable radius study for WindPACT 1.5MW Turbine

Radial Scaling Factor	Rotational Speed (rpm)				
	19.10	19.00	18.00	17.00	16.00
0.80	-41.6%	-42.0%	-46.4%	-51.4%	-56.9%
0.85	-31.9%	-32.3%	-36.9%	-42.2%	-48.2%
0.90	-21.7%	-22.1%	-26.9%	-32.4%	-38.9%
0.95	-11.2%	-11.6%	-16.3%	-22.1%	-28.9%
1.00	0.0%	-0.4%	-5.2%	-11.3%	-18.3%
1.05	11.8%	11.3%	6.2%	0.2%	-7.2%
1.10	24.2%	23.7%	18.3%	12.1%	4.4%
1.15	37.3%	36.8%	31.0%	24.4%	16.6%
1.20	51.1%	50.5%	44.2%	37.3%	29.3%

Additional blade loading needs a more robust structure to ensure against blade failure. These design changes usually result in added material, which results in added blade weight and cost, which in turn adds costs to the entire system. Therefore, economic studies need to be performed to balance the profits of increased power production with the costs of incurring increased blade loading.

Table 3-9: Root bending moment results for variable radius study for WindPACT 1.5MW Turbine

Radial Scaling Factor	Rotational Speed (rpm)				
	19.10	19.00	18.00	17.00	16.00
0.80	-54.0%	-54.2%	-57.3%	-60.9%	-65.0%
0.85	-42.9%	-43.2%	-46.7%	-50.7%	-55.4%
0.90	-30.2%	-30.6%	-34.6%	-39.1%	-44.3%
0.95	-16.0%	-16.4%	-20.8%	-26.0%	-31.8%
1.00	0.0%	-0.5%	-5.3%	-11.1%	-17.7%
1.05	18.0%	17.5%	11.9%	5.6%	-1.9%
1.10	38.1%	37.5%	31.1%	24.1%	15.8%
1.15	60.4%	59.7%	52.4%	44.5%	35.5%
1.20	85.1%	84.3%	76.0%	67.0%	57.1%

3.1.3.2 NREL 5MW Turbine

The results for the varying radius study for the NREL 5MW turbine can be found in Table 3-10. As with the previous results tables, this table shows the radial scaling factor and rotational speed combination that produces the greatest power output, and what percent that power output is over the baseline case. The full results for this study can be seen in Appendix J.

Table 3-10: Power results for variable radius study for NREL 5MW Turbine

Wind Speed (m/s)	Radius Scaling Factor	Rotational Speed (rpm)	Power Increase	Thrust Increase	Moment Increase
4	1.20	4.00	72.1%	20.8%	24.3%
6	1.20	7.00	45.3%	45.6%	61.0%
8	1.20	9.00	45.3%	65.1%	85.2%
10	1.20	11.00	45.4%	48.7%	82.6%

At the 4 m/s wind speed, if the rotational speed is constrained to a minimum of 6.9 rpm the optimal power increase occurs at that rotational speed and is 31.9% (with a radius scale factor of 1.20). The corresponding increases in thrust and root bending moment for this case are 50.1% and 70.8% respectively. As with the previous study, the greatest increases are seen at the largest radial extension. However, the same problem exists with increased blade loadings that existed in the previous study as well. Table 3-11 shows a sample of the thrust results for the 10 m/s wind speed of this study that reveal this trend. The full results can be found in Appendix K.

Table 3-11: Thrust results for variable radius study for NREL 5MW Turbine

Radial Scaling Factor	Rotational Speed (rpm)				
	12.00	11.00	10.61	10.00	9.00
0.80	-32.1%	-36.9%	-39.1%	-43.4%	-54.4%
0.85	-22.7%	-27.7%	-30.0%	-34.2%	-44.6%
0.90	-12.8%	-18.0%	-20.4%	-24.8%	-34.2%
0.95	-2.5%	-7.9%	-10.5%	-14.9%	-24.1%
1.00	8.2%	2.6%	0.0%	-4.7%	-14.1%
1.05	19.4%	13.5%	10.8%	5.9%	-3.9%
1.10	31.0%	24.8%	22.1%	17.0%	6.8%
1.15	43.1%	36.5%	33.6%	28.4%	17.9%
1.20	55.6%	48.7%	45.6%	40.3%	29.3%

Table 3-12 contains a sample of the root bending moment results for the 10 m/s wind speed of this study to demonstrate the same point. The full root bending moment results can be found in Appendix L.

Table 3-12: Root bending moment results for variable radius study for NREL 5MW Turbine

Radial Scaling Factor	Rotational Speed (rpm)				
	12.00	11.00	10.61	10.00	9.00
0.80	-46.5%	-50.5%	-52.3%	-55.5%	-63.3%
0.85	-34.8%	-39.4%	-41.4%	-45.0%	-52.9%
0.90	-21.7%	-26.8%	-29.1%	-33.2%	-41.3%
0.95	-7.1%	-12.7%	-15.4%	-19.9%	-28.7%
1.00	9.2%	2.8%	0.0%	-5.1%	-14.9%
1.05	27.2%	20.1%	16.9%	11.3%	0.3%
1.10	47.1%	39.1%	35.5%	29.4%	17.3%
1.15	69.0%	59.8%	55.9%	49.1%	35.7%
1.20	92.8%	82.6%	78.1%	70.7%	56.0%

3.1.4 Airfoil Characteristics Study

While the previous studies considered gross changes to the blade geometry (twist, chord, and radius change), this section focuses generically on the effects of devices that change the airfoil characteristics. For example, deployment of trailing-edge flaps, Gurney flaps and other such devices would change the airfoil lift and drag coefficients. Rather than specifying a certain device to be simulated, the effect of change in aerodynamic coefficients is examined in this study.

Two variations of this study were conducted: a best case scenario and a more realistic simulation. First, at each wind speed, a 20% increase in lift coefficient only (no corresponding increase in drag coefficient) over the entire span of the blade was considered to see what the absolute best possible results could be. The second, more realistic, simulation was performed with lift and drag coefficients both increased by 20% from 60–90% of the span, representative of a discrete device located and deployed solely over that section. As with the previous studies, the simulations were performed over various rotational speeds in this study, incremented in tip speed ratios of 0.5.

3.1.4.1 WindPACT 1.5MW Turbine

The optimal results for this study can be shown in Table 3-13. The table shows the rotational speed that the optimum power production occurs at for each wind speed tested. The full results can be seen in Appendix M.

Within the rotational speed limits of the turbine, the whole span simulation saw a 26.1% power increase at 4 m/s and a 10.3% power increase at 6 m/s again, both at 11.1 rpm. The partial span simulation saw a 30.8% increase in optimum power at the 4 m/s wind speed and a 10.7% increase at the 6 m/s wind speed, both again which occurred at 11.1 rpm.

Table 3-13: Results for airfoil characteristics study for WindPACT 1.5MW Turbine

Wind Speed (m/s)	1.2*Cl Whole Span		1.2*Cl and 1.2*Cd Partial Span	
	Rotational Speed (rpm)	Power Increase	Rotational Speed (rpm)	Power Increase
4	7.09	83.6%	7.09	83.2%
6	9.82	12.4%	10.64	11.2%
8	13.10	-1.4%	14.19	-2.4%
10	16.37	-1.4%	17.73	-2.4%

Surprisingly, the addition of a high lift device actually reduced the power output at higher wind speeds (8 and 10 m/s). In order to figure out the reason for this, the blade level aerodynamics were investigated. Figure 3-1 shows plots from the 10 m/s wind speed simulations that describe the phenomenon occurring in this situation.

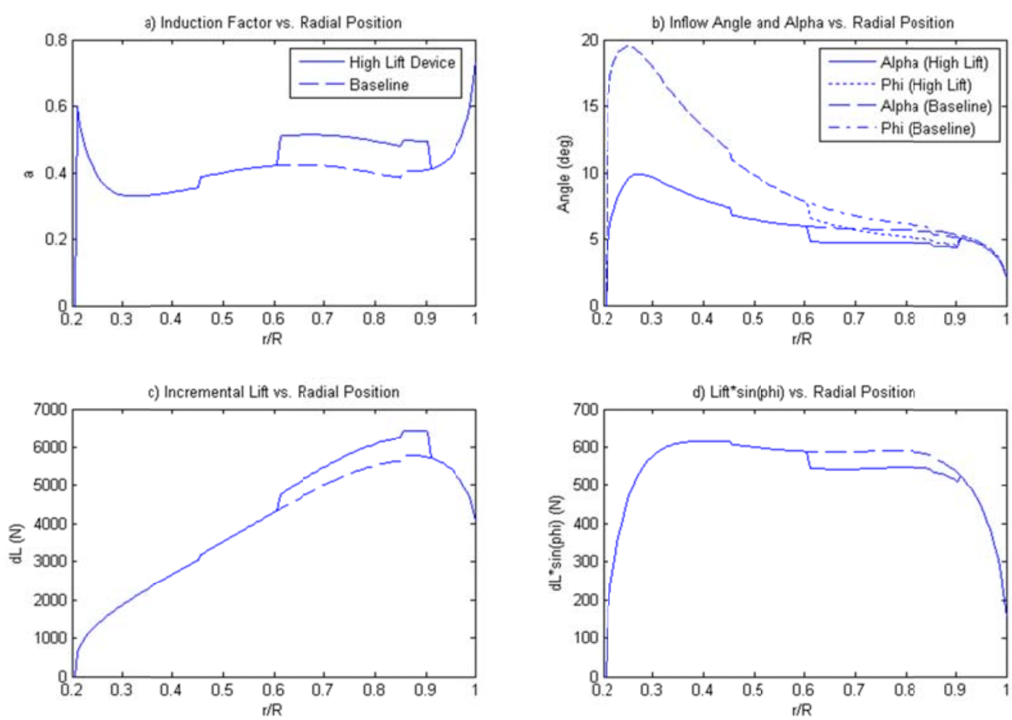

Figure 3-1: From left to right: a) Induction factor vs. radial position, b) Phi and AoA vs. radial position, c) Incremental Lift vs. radial position, and d) Power producing component of lift vs. radial position, all of the 1.5MW turbine for a free stream velocity of 10 m/s

When the lift coefficient is increased there is a corresponding increase in induction factor which, in turn, reduces the inflow angle, φ (a glance at Figure 3-1 will make this evident). Even though there is a net increase in sectional lift (although not by as much as the expected 20% due to lower local angles of attack), the reduced inflow angle reduces the power generating component of L*sin φ as a whole.

3.1.4.2 NREL 5MW Turbine

The optimal results for this study on the 5MW turbine can be seen in Table 3-14. This table shows the optimal power output and the rotational speed that it occurs at for both simulations. Appendix N contains the full results of this study.

Table 3-14: Results for airfoil characteristics study for NREL 5MW Turbine

Wind Speed (m/s)	1.2*Cl Whole Span		1.2*Cl and 1.2*Cd Partial Span	
	Rotational Speed (rpm)	Power Increase	Rotational Speed (rpm)	Power Increase
4	4.24	22.2%	4.55	19.9%
6	6.37	2.4%	6.82	0.4%
8	8.49	2.1%	9.09	0.2%
10	10.61	2.1%	11.37	0.2%

If the 6.9 rpm constraint is imposed the maximum power increases at 4 m/s are 0.4% for the whole span simulation and -1.1% (a decrease in power) for the partial span simulation. At 6 m/s the corresponding increases in power are 1.9% and 0.3% respectively, all of which occur at the minimum allowable rotational speed.

In the case of this turbine, unlike the 1.5MW turbine, there are actually positive power increases observed at the faster wind speeds of 8 and 10 m/s, although they are only minimal. While the same aerodynamic changes are occurring, the negative effects of the decreasing inflow angle are slightly less and the increases in lift act to balance this out. Figure 3-2d shows how the baseline case and the augmented airfoil property case have values for L*sin φ that closely overlap, especially when compared to the plots of the previous turbine.

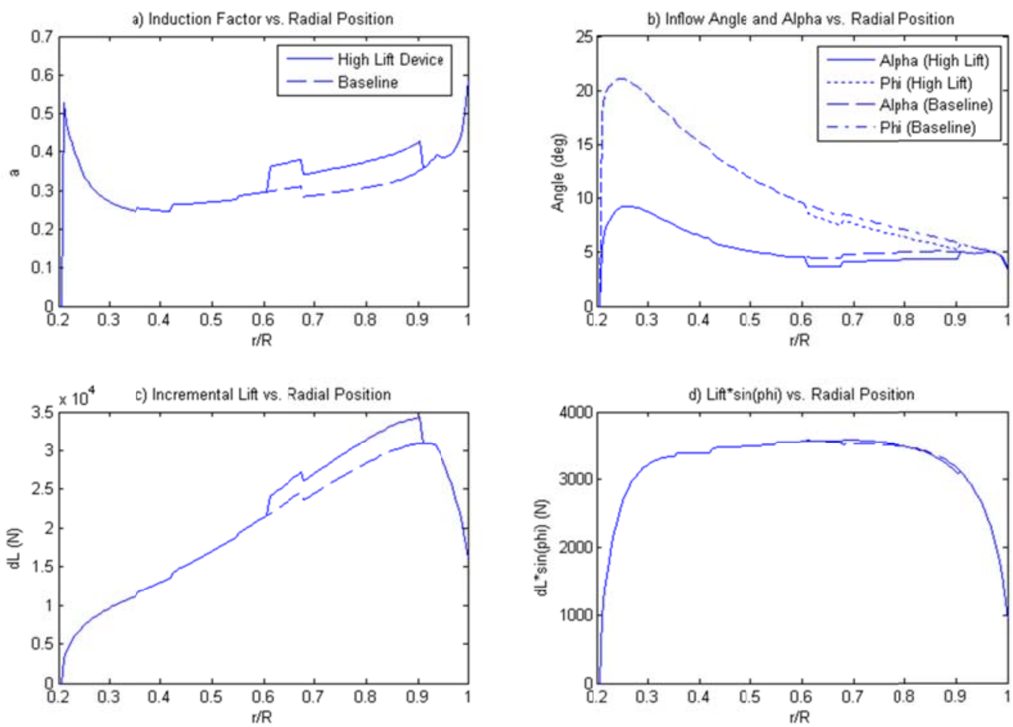

Figure 3-2: From left to right: a) Induction factor vs. radial position, b) Phi and AoA vs. radial position, c) Incremental Lift vs. radial position, and d) Power producing component of lift vs. radial position, all of the 5MW turbine for a free stream velocity of 10 m/s

3.1.5 Discussion

The results of these studies were surprising overall. Increasing the span of the blades was expected to produce favorable results in terms of increased power production, after a simple analysis of the equations involved in the procedure. After all, there are companies who already have prototypes of this type of morphing rotor built and being tested already, albeit on smaller scale wind turbines [22]. However, the other three studies did not meet expectations, with minimal increases in power production observed at the higher wind speeds (8 and 10 m/s). Some gains can be seen at the lower wind speeds, however this is somewhat due to moving the rotational speeds closer to an optimum value, and in any case the power produced at these wind speeds is relatively small anyway. However, the wind does blow at these lower speeds quite frequently. This leads into the next section where increases in energy produced by the turbine (which takes into account the probability that one wind speed is seen over another wind speed) are analyzed instead of just increases in power production.

The reason greater gains in power could not be realized deserved a second look though. For wind turbines, the Betz limit is a well known parameter that dictates via a simple momentum theory analysis that no more than 59.3% of the power available in the wind stream can be captured by a turbine [5]. This parameter is known as the power coefficient, or C_P, of the rotor. An analysis of the two turbines examined shows that the 1.5MW turbine has a rotor power coefficient of approximately 0.47, while the 5MW turbine has one of approximately 0.48.

After investigation, three large sources of losses were deemed to be Prandtl losses, airfoil drag, and having a planform that varies from the theoretically ideal planform. When Prandtl losses were not considered as part of the analysis, the turbine efficiencies rose to 0.51 and 0.52 respectively. By removing airfoil drag, the efficiencies rose to 0.54 and 0.55 respectively. This means over 90% of the power that can be captured by the turbine actually is being captured. When the ideal blade planform equations from Hanson's Wind Turbine Aerodynamics textbook [34] were applied to the turbines in lieu of the baseline blade planforms, increases of less than 0.01 over the 0.54 and 0.55 were seen. The existing planforms closely follow the ideal planforms on the outboard section of the blade, which is where most of the power production occurs. They differ greatly near the hub, where the ideal planforms go off to infinity which causes manufacturing difficulty, but very little power is produced from this section of the blade anyway. This is the main reason it was found to be hard to capture more power from the rotor changes that were implemented.

3.2 Wind Energy Analysis

While turbine power production has been examined up until this point in the study, determining whether a technological enhancement is worthwhile requires assessing the increase in turbine energy production. Energy production depends not only on power production at each wind speed but also the wind distribution seen at the site, specifically how much time the wind spends at each speed. Except for radius variation, other geometry changes (blade chord, blade twist/collective, and airfoil geometry) seem to give much larger improvement in power at the lower wind speeds. Despite the fact that the power produced at these wind speeds is relatively low, the fact that the wind blows frequently at these speeds leads to potential for significant improvements in energy capture of the turbine over the course of a year.

In order to calculate the increase in annual energy production (AEP) that each potential geometry change can provide, wind profiles for the turbines must considered. Once the baseline annual energy production is calculated by Eqn. 2-24 over all of the wind speeds in the operating range of the turbine, the increased AEP can be calculated by using the increased values of power production that each geometry change produces at each wind speed. The two numbers are then compared to establish the increase in total AEP of the wind turbine with the geometry changes in place.

3.2.1 WindPACT 1.5MW Turbine

The WindPACT 1.5MW turbine is meant to be representative of current land based commercial turbines on the market. Because of this, a wind energy resource map from the Department of Energy was consulted to determine an appropriate range of wind speeds for this turbine [35]. The Midwest contains a lot of wind class 4s and 5s, which corresponds to average wind speeds between 7.0 and 8.0 m/s. Therefore a representative wind speed of 7.5 m/s at hub height can be realistically used. By looking at a Rayleigh distribution with an average wind speed of 7.5 m/s, the following wind distribution probabilities, for bins 2 m/s in size and centered at the indicated speeds, are shown in Table 3-15. The wind blows 10.6% of the time at speeds less than 4 m/s and 18.2% of the time at speeds greater than 10 m/s.

Table 3-15: Probability of wind speeds in 2 m/s bins for a Rayleigh distribution with an average wind speed of 7.5 m/s

Wind Speed (m/s)	Probability of Occurrence
4	17.9%
6	20.2%
8	18.3%
10	13.8%
	70.2%

Since the optimum power increases are of the same order for the varying chord study, the twist/collective study, and the airfoil properties study, only the analysis for the chord study is presented, as the other studies will have similar results. The absolute optimal increases in power are analyzed in this analysis, not the values constrained by rotational speed, to show the best case AEP increases. The results for the analysis of the varying chord study can be seen in Table 3-16.

It can be seen in the results for this case that the increase in AEP is not as that large. At best case scenario for this turbine, slightly over 3% increase in AEP can be realized, despite the fact that the slower wind speeds occur quite frequently in the operation of the turbine.

Table 3-16: Percent increase in AEP produced by the optimal power increases from the 1.5MW Turbine varying chord study

Wind Speed (m/s)	Chord Scaling Factor	Percent Power Increase	Percent Increase in AEP
4	0.80	92.5%	0.96%
6	0.80	16.8%	1.09%
8	0.80	2.5%	0.40%
10	0.80	2.5%	0.58%
			3.03%

While the results for the increase in AEP based on the chord variation study did not prove very promising, the varying radius study could produce better results since it has large increases in power even at 8 and 10 m/s, which the chord study did not have. Again, the absolute optimal values were used instead of the constrained values, to look at the best case increase in AEP available. The results can be seen in Table 3-17.

Table 3-17: Percent increase in AEP produced by the optimal power increases from the 1.5MW Turbine varying radius study

Wind Speed (m/s)	Radius Scaling Factor	Percent Power Increase	Percent Increase in AEP
4	1.20	119.3%	1.24%
6	1.20	61.3%	3.96%
8	1.20	47.1%	7.48%
10	1.20	47.5%	11.08%
			23.76%

The results of this study proved more significant, with an increase in AEP of over 23%. It can still be seen that even though the power increase at 4 m/s is over 100%, that translates into an increase in AEP of only slightly greater than 1%. The majority of the increase in AEP comes from the power increases at 8 and 10 m/s.

3.2.2 NREL 5MW Turbine

The NREL 5MW turbine was designed to represent the characteristics of future offshore class turbines. Offshore sites in the United States tend to be predominantly class 6 and 7 wind zones with class 6s closest to the shore. This class is defined as having a range of wind speeds from 8.0 to 8.8 m/s, so assuming an average wind speed of 8.5 m/s at hub height is reasonable for this size of turbine [35]. Table 3-18 shows the percentages that each tested wind speed appears assuming a Rayleigh distribution with an average wind speed of 8.5 m/s and bins of 2 m/s in size centered at the speeds indicated. The wind blows for 8.3% of the time at wind speeds less than 4 m/s and for 26.6% of the time at wind speeds greater than 10 m/s.

Table 3-18: Probability of wind speeds in 2 m/s bins for a Rayleigh distribution with an average wind speed of 8.5 m/s

Wind Speed (m/s)	Probability of Occurrence
4	14.6%
6	17.6%
8	17.3%
10	14.7%
	64.2%

As with the previous turbine, the twist/collective study, the chord study, and the airfoil characteristics study all have power increases on the same order of magnitude, so the increase in AEP results is only shown for the chord study since the others will be similar. Table 3-19 shows the results of the increase in AEP when using the power increases from the variable chord study.

Table 3-19: Percent increase in AEP produced by the optimal power increases from the 5MW Turbine varying chord study

Wind Speed (m/s)	Chord Scaling Factor	Percent Power Increase	Percent Increase in AEP
4	1.00	21.8%	0.23%
6	1.00	2.1%	0.11%
8	1.00	1.8%	0.22%
10	1.00	1.8%	0.36%
			0.92%

The results of this analysis show that since the power increases for the 5MW turbine chord variation study were less than that of the 1.5MW turbine chord study, the increase in AEP is less as well. This analysis shows an increase of less than 1% in AEP. Again, the results for the 5MW radius study should be different than the chord study. The results can be seen in Table 3-20.

Table 3-20: Percent increase in AEP produced by the optimal power increases from the 5MW Turbine varying radius study

Wind Speed (m/s)	Radius Scaling Factor	Percent Power Increase	Percent Increase in AEP
4	1.20	72.1%	0.75%
6	1.20	45.3%	2.33%
8	1.20	45.3%	5.46%
10	1.20	45.4%	9.07%
			17.61%

The above results are promising, as with the 1.5MW turbine results, although slightly less. The 17% increase in AEP is relatively large compared to the results seen in the chord studies.

Therefore, even though the wind blows frequently at these lower speeds compared to the higher wind speeds in Region III of the power curve, large increases in power produced at the 4 and 6 m/s wind speeds do not necessarily correlate to large increases in AEP for the turbines. Large increases in power production at the 8 and 10 m/s wind speeds are needed to help ensure these increases in AEP are appreciable.

3.3 Adaptive Geometry Blades and Loads Reduction

The above analyses exhibited that trying to produce an increase in AEP through the use of a variable geometry blade is not feasible for most geometry changes except for a blade that increases its span. However, it was noticed that changes in pitch setting aid in reducing root bending moments in Region II of the power curve even though the main objective of the pitch controls is to limit power production. An investigation into coupling pitch changes with the radius changes was conducted. The goal of this investigation was to see if it is possible to reduce root bending moments through pitch changes while maintaining power production through increasing radius. Since the study was performed for the radius changes, it was extended to twist distributions and varying chord for completeness.

Pitch settings varied from -2° to 9° in increments of 1°. The same twist, chord, and radius variations that were used thus far were used for the study. For example, both turbines were simulated with chord variations from 80% to 120% of their baseline distributions in increments of 5%. Also, various rotational speeds were examined again, to ensure that if the optimum speed for the configuration was not the baseline speed, it could be found.

Figure 2-4 shows that peak bending moments of a turbine blade occur at the rated speed. If peak root bending moments could be lowered here, a major hurdle could potentially be eliminated for design considerations. Therefore, each simulation was carried out at the rated speed of the turbines. The study calculated tables of both the root bending moments and power production at each design point, and compared them to the baseline levels. Combinations that provided decreased bending moments while at least maintaining (if not increasing) power production were picked out. Since this study is performed at the rated speed, an increase in power is not necessary since the rotor is already producing what the generator can handle. However, at slightly slower wind speeds this could be favorable. When looking in the appendices, the design point combinations that satisfy both of the constraints above are shaded in so they can be easily picked out from the other design points.

3.3.1 Blade Twist Study

3.3.1.1 WindPACT 1.5MW Turbine

The WindPACT turbine exhibited a moderate number of design points that met the above criteria, although the best options are slightly above the operational range of rotational speeds of the turbine. In general the results of this study are favorable at higher rotational speeds, from the baseline rotational speed and above. Favorable results exist between the pitch settings of 0° and 6°. They also occur at every twist distribution tested, but tend to favor distributions that are shallower, with more results occurring there than at steeper ones. The lowest root bending moment with a corresponding positive power change exists at 4° collective pitch setting, with a rotational speed of 22.54 rpm and a root to tip twist of 8.1°. Its value is 9.8% below the baseline with a power increase of 0.5%. The full results for the study can be seen in Appendices O and P.

3.3.1.2 NREL 5MW Turbine

Favorable results for the NREL 5MW turbine in this study also exist, but the number of them is much fewer than for the previously described turbine. In fact, only five design points show improvements. These points only occur between 1° and 3° root pitch setting. Again, it seems the results are most promising at or slightly above the baseline rotational speed, occurring only between the baseline speed of 12.1 rpm and 13.82 rpm. Also, these results favor shallower twist distributions, as none of the points that meet the criteria are at distributions steeper or even at the baseline configuration. The lowest root bending moments seen in this study occur at 3° collective, at 12.96 rpm and 7.3° root to tip twist. The bending moment is reduced by 5.2% at this design point with a corresponding 0.2% increase in power possible. Full results for this study can be seen in Appendices Q and R.

3.3.2 Varying Chord Study

3.3.2.1 WindPACT 1.5MW Turbine

There are quite a few design points that meet the criteria for this WindPACT varying chord study. Results occur at or above the baseline rotational speed, with only one acceptable point found below the baseline rotational speed. Results occur from -1° to 5° collective pitch settings (with only one point occurring at the -1° setting), and at all chord scaling factors. The point with the lowest root bending moment occurs at 4° root pitch setting, 22.54 rpm, and a chord scaling factor of 1.05. It has a root bending moment decrease of 9.5% and no increase or decrease in nominal power production. There are a few other design points with decreases in root bending moment in the 9% range, and also some in the 7 and 8% range as well. It should be noted that when this study was performed at 10 m/s, root bending moment decreases on the order of up to 16% can be seen. If a full operating range bending moment reduction is desired, there is potential in this method. The full results for the 11.8 m/s simulations can be seen in Appendices S and T.

3.3.2.2 NREL 5MW Turbine

There were no useable results produced from this study on the NREL 5MW Turbine. Loads reductions and power increases did not overlap. Results for this study can be seen in Appendices U and V.

3.3.3 Varying Radius Study

3.3.3.1 WindPACT 1.5MW Turbine

The radius study results are the most promising results for the 1.5MW turbine. Not only do the results have the lowest reduction in bending moment of any of the studies done at the rated speed, the conditions where favorable points exist are the most varied. These points exist between root pitch settings of 1° and 8°, and at rotational speeds both above and below the baseline rotational speed. However, results only occur at radial scaling factors at or above baseline. The lowest root bending moment observed is at the design point located at the baseline rotational speed with 7° of root pitch and a radial scaling factor of 1.05. The root bending moment at this point is reduced from the baseline load by 14.1% with a corresponding 0.2% increase in power production. The full results for this study can be seen in Appendices W and X.

3.3.3.2 NREL 5MW Turbine

The NREL 5MW Turbine did not produce as favorable results in this study as the 1.5MW turbine did. The few design points that are favorable exist at or below the baseline rotational speed and exist between the root pitch settings of 2° and 5°. The results do occur at every radial scaling factor greater than (but not including) the baseline blade. The design point with the greatest reduction in root bending moments occurs at a root pitch setting of 2°, a rotational speed of 11 rpm, and a radial scaling factor of 1.05. It shows a reduction in root bending moment of 6.3% with an increase in power of 0.1%. The full results from this study can be seen in Appendices Y and Z.

Chapter 4

Summary and Conclusions

In the push for more environmentally friendly ways to produce the energy that the world needs, wind turbines are poised to make up a significant portion of this expanding market. However, many improvements in wind turbine technology are being examined in order to make these machines more productive, safer, and have a longer design life. One way to design blades to be more productive and to have a longer design life is through adaptive blade technology which will allow more energy to be captured and lower blade loads to be experienced. These changes result in a lower cost of energy to be produced which results in turbines being more economical in more situations. While research has gone into blade geometry changes that result in reduced loads being produced, not much (besides extendable radius blades) has gone into technology that directly increases energy production.

This thesis provided an investigation into what types of adaptable geometry blades have potential for extracting increased energy from the wind flow. A tool using Blade Element Momentum Theory was produced in order to simulate different geometry changes on two research turbine models and was created and evaluated against existing tools. Parametric studies were performed on design variables of two turbine designs to evaluate these variables' effects on power production and energy production. Finally, a study was performed combining the results of the power study with the results of a root bending moment study to see what blade configurations can maintain turbine power production while reducing blade root bending moments.

4.1 Modeling Summary

These studies utilized a modeling tool that was developed using Blade Element Momentum theory to calculate the aerodynamic forces experienced by the blades. These forces are then in turn used to calculate the power, thrust, and root bending moments that the blades produce. The blades are assumed rigid structures in this analysis. Prandtl's losses are assumed around the hub and tip in order to more accurately predict the aerodynamic conditions that exist at these areas. Characteristics specific to certain turbines can be input, including functions for describing chord and twist distributions, as well as radial spans and precone angles. In addition, inputs related to the aerodynamic operation of the turbine can be entered, such as tip speed ratios and pitch settings available at each wind speed. The input files were generated to test two different turbine configurations, the WindPACT study 1.5MW turbine, and the result of an NREL study on 5MW turbine configurations.

This modeling tool was verified against existing programs that are used to predict wind turbine performance. The 5MW turbine configuration was simulated at each wind speed in its operational envelope, and the results compared to those compiled from industry models WT_Perf and FAST, both distributed by NREL. The results for power and thrust production compared well with FAST which is a more complex code, and exceptionally well with WT_Perf which utilizes the same Blade Element Momentum theory. Results for root bending moment also compared well, but with a slightly higher level of error. However, since the study only compared relative increases or decreases in root bending moments instead of actual values, this error was deemed acceptable.

4.2 Results Summary

Both of these turbines were the subject of parametric studies to investigate how certain geometric changes can affect the power produced and forces generated by a wind turbine blade. For the first set of studies, power output levels of these different geometry changes were examined at Region II wind speeds of 4, 6, 8, and 10 m/s. Each change was also simulated at a range of rotational speeds to ensure that if the geometry change altered the rotational speed at which optimal results occurred, the new optimums would be found. Also, each change that was examined made use of the baseline blade distributions and scaling them larger or smaller while keeping the other characteristics as unchanged as possible.

The first two studies for each turbine regarded twist distributions coupled with collective pitch changes, and chord distribution variations. Each of these studies produced results of the same order of magnitude for both turbines, with the results for the 1.5MW turbine being overall more favorable than those for the 5MW turbine. At the slower wind speeds of 4 m/s, the 1.5MW turbine saw an absolute maximum power increase of 92.5% possible during the chord study, while the 5MW turbine saw an absolute maximum power increase at 4 m/s of 21.8% which also occurred during the same study. At the higher wind speeds of 8 and 10 m/s, both turbines only saw increases in power production around the order of 2%. While there appears to be potential in the results of the lower wind speeds, the higher wind speeds appear to have negligible increases.

The radius study produced much more favorable results. Again, the 1.5MW turbine produced overall more favorable results at the lower wind speeds, with an overall optimum power increase of 119.3% at 4 m/s. The 5MW turbine only experienced an overall maximum power increase of 72.1% at the 4 m/s wind speed. At the faster wind speeds of 8 and 10 m/s, power increases on the order of 45 to 47% were seen. All of these optimal results occurred at the largest radius tested. These results are much more favorable than the chord and twist studies. However, it was found that increases in power correspond to increases in blade loadings which result in blades that are more expensive to design and fabricate.

Finally, the airfoil characteristic study was performed on both turbines. In this study, each turbine performed differently in different aspects. Overall at the lower wind speeds, the 1.5MW turbine again proved to perform better, with an 83.6% increase in power during the full span increase in lift coefficient and an 83.2% increase in power during the partial span increases in lift and drag coefficient at the 4 m/s wind speed. The 5MW turbine saw more moderate increases, with 22.2% and 19.9% increases respectively. However, at the faster wind speeds, the 5MW turbine saw the modest increases of 2.1% and 0.2% at both 8 and 10 m/s, while the 1.5MW turbine actually saw decreases in power production of -1.4% and -2.4% respectively. This decrease comes from the increased lift produced by the blade sections affecting the aerodynamic inflow angles. So while lift is increased, the portion of the lift vector that is directed in the power producing direction at the blade element level is decreased.

Since wind turbine economics depend not only on power production at each wind speed, but how often those wind speeds occur, a study was performed on annual energy production of the two simulated wind turbines. The study utilized the results from the previous studies, as well as wind speed distributions calculated from Rayleigh distributions around average hub height wind speeds that each turbine would experience where it was operated. For power increases experienced on the scale of those from the chord studies, the 1.5MW turbine would produce approximately 3% more energy throughout the year, and the 5MW turbine would produce slightly less than 1% more energy. Compared to the radius study, these results are relatively low. When the results of the radius study are applied to this energy analysis, the 1.5MW turbine produces an increase in AEP of 23.76% and the 5MW turbine produces an increase of 17.61%.

After these studies were performed, a separate endeavor was taken on that examined the combination of pitch control with the geometry changes of twist value, chord variation, and radial expansion. This was done because it was noticed that adding positive pitch to the baseline blades decreased the bending moments produced, as well as the power produced. If the losses of power could be mitigated by the previous geometry changes while still realizing losses in bending moments, this would be very beneficial. At the rated speed of each turbine (where peak bending moments occur for each blade), each study produced root bending moment decreases of close to 10% or more for the 1.5MW turbine while at least maintaining power production. In fact, the radius study for this turbine saw bending moment decreases on the order of 14%. Larger decreases were available in some cases at speeds lower than the rated speed, showing promise for load reduction across the entire operating range. The 5MW turbine saw more modest results; the twist and radius studies saw bending moment reductions of 5 and 6% respectively, while the chord study could not produce a single result with negative changes in root bending moment while maintaining power production.

4.3 Conclusions

This thesis has reviewed how much potential gain can be expected from different geometry changes on two classes of wind turbine blades. By reviewing changes to twist distributions, root pitch settings, chord distributions, radial span, and airfoil characteristics at a variation of different Region II wind speeds, geometries that are optimal at each air speed could be determined. From here, a scheme for an adaptive geometry rotor that is optimal at all wind speeds could be designed to directly increase energy production and therefore potentially decrease the cost of energy that the turbine generates.

While changes in radial span produce the greatest potential for increasing energy production throughout the year, with gains as high as 23%, each change investigated by this study has potential, which is demonstrated by the wind energy analysis study. It is up to the designer of the turbine to determine if the additional energy capture can be realized at a low enough cost to be economically beneficial. In addition, when combined with changes in pitch, it was proven that radial changes make it possible in most scenarios to reduce root bending moments on the blade while maintaining power production, and it is even able to increase power production if the turbine is running within the right portion of the operational envelope. While much more work is needed to refine these concepts in order to come up with a useable geometry, the ground work has been laid for this type of adaptive geometry blades to make an impact on wind turbine cost of energy.

4.4 Future Work

The area of adaptive geometry wind turbine blades requires much more work to be performed before morphing blades are ready to be fabricated and placed on operating wind turbines in the field. First of all, this study only examined scaled changes to the existing wind turbine blade geometry. For instance, the blade chord distribution was scaled between 80% and 120%. A future study would look at completely different chord distributions or twist distributions, such as a blade with reverse twist for example. Along the same lines, the changes employed in the airfoil characteristic study were simply applied to the existing blade geometry. Better results might be had if such changes were integrated into blade design from the first stages and not simply added on to an existing blade design. Once favorable distributions are found at the different wind speeds, hardware that facilitates these changes, whether passively through carbon fiber layering or actively though tracks and bearings, would need to be designed and tested for system strength and load bearing capability.

Once blade geometries are found that are beneficial to increasing annual energy production, proper control schemes for these implementations are needed. For instance, it would need to be determined how much to extend a blade for each wind speed, or to retract when a certain wind speed is reached. Retracting the blade early would result in reduced loadings for the blade, but also reduction of possible power production, while delaying retraction as long as possible would result in maximum power capture but also extreme loads that need to be designed around. When microtabs would be deployed to reduce loads instead of utilizing blade pitch is another example of the types of control schemes that would need to be researched. Once these types of studies are accomplished and the research in this field matures, adaptable geometry wind turbine blades will begin to be implemented and significantly lower the cost of energy they provide.

Finally, some effort needs to go into developing cost models for these morphed blades. Variable geometry blades require significant cost increases over standard blades. In the case of an active morphing blade, the addition of tracks, bearings, and other components used to change the shape of the blade drive costs upwards. Also, assembly of these types of blades is usually more complicated which increases costs as well. For passively morphing blades, such as those that use carbon fiber to tailor certain blade characteristics, these materials are usually more expensive than the fiberglass and aluminum used in standard blades. Once a design is decided upon that requires the use of a morphing turbine blade change its performance, the cost of the blade is needed to ensure that not only is more energy collected, but the increase in energy profits offsets the increase in blade cost.

Bibliography

[1] *AWEA Year End 2009 Market Report*. Rep. American Wind Energy Association, Jan. 2010. Web. 11 June 2010. <http://www.awea.org/publications/reports/4Q09.pdf>.

[2] Gardner, Timothy. "US Wind Power Capacity up in '09, but Jobs Stalled." *Reuters.com*. 26 Jan. 2010. Web. 11 June 2010. <http://www.reuters.com/article/idUSN2211296320100126?type=marketsNews>.

[3] Behr, Peter. "Predicting Wind Power's Growth -- an Art That Needs More Science." *NYTimes.com*. The New York Times, 28 Apr. 2010. Web. 11 June 2010. <http://www.nytimes.com/cwire/2010/04/28/28climatewire-predicting-wind-powers-growth----an-art-that-29171.html>.

[4] *20% Wind Energy by 2030, Increasing Wind Energy's Contribution to U.S. Electricity Supply*. Tech. no. DOE/GO-102008-2567. Department of Energy, Oct. 2008. Web. 11 June 2010. <http://www.20percentwind.org/20percent_wind_energy_report_revOct08.pdf>.

[5] Leishman, J. Gordon. *Principles of Helicopter Aerodynamics*. Cambridge: Cambridge UP, 2006.

[6] Jonkman, J., S. Butterfield, W. Musial, and G. Scott. "Definition of a 5-MW Reference Wind Turbine for Offshore System Development." *National Renewable Energy Laboratory*. Feb 2009. NREL, Web. 25 Feb 2009.

[7] Prabhakar, T., F. Gandhi, F. Steiner, and D. McLaughlin, "A Centrifugal Force Actuated Variable Span Morphing Helicopter Rotor," *63rd Annual AHS International Forum and Technology Display*, Virginia Beach, VA, May 1-3, 2007. Also at *the AHS International/Korean Society for Aeronautical and Space Sciences International Forum on Rotorcraft Multidisciplinary Technology*, Seoul, Korea, 15-17 October, 2007.

[8] Bae, E.-S., F. Gandhi, and M. Maughmer, "Optimally Scheduled Deployments of Miniature Trailing-Edge Effectors for Rotorcraft Power Reduction," *Proceedings of the 65th Annual AHS International Forum and Technology Display*, Grapevine, Texas, 27-19May, 2009.

[9] Leon, O., E. Hayden, and F. Gandhi, "Rotorcraft Operating Envelope Expansion Using Extendable Chord Sections," *Proceedings of the 65th Annual AHS International Forum and Technology Display*, Grapevine, Texas, 27-29 May, 2009.

[10] Mistry, M., and F. Gandhi, "Performance Improvement with Variable Rotor Span and RPM," *Proceedings of the 66th Annual AHS International Forum and Technology Display*, Phoenix, Arizona, 11-13 May, 2010.

[11] Fuglsang, P., et al. "Site Specific Design Optimization of Wind Turbines." *Wind Energy* 5.4 (2002): 261-79.

[12] Xudong, W., et al. 'Blade Optimization for Wind Turbines', European Wind Energy Conference & Exhibition EWEC 2009, Marseille, France,16–19 March, 2009.

[13] Benini, Ernesto, and Andrea Toffolo. "Optimal Design of Horizontal-Axis Wind Turbines Using Blade Element Theory and Evolutionary Computation." *Journal of Solar Energy Engineering* 124.4 (2002): 357-63.

[14] Fuglsang, P., and H. A. Madsen. "Optimization Method for Wind Turbine Rotors." *Journal of Wind Engineering and Industrial Aerodynamics* 80.1-2 (1999): 191-206.

[15] Fuglsang, P., and K. Thomson. "Site-Specific Design Optimization of 1.5–2.0 MW Wind Turbines." *Journal of Solar Energy Engineering* 123.4 (2001): 296-303.

[16] Jureczko, M., A. Mezyk, and M. Pawlak. "Optimisation of Wind Turbine Blades." *Journal of Materials Processing Technology* 167.2-3 (2005): 463-71.

[17] *Advanced Wind Turbine Program Next Generation Wind Turbine Development Program*. Rep. no. NREL/SR-500-38752. Tehachapi, CA: GE Wind Energy, LLC, 2006.

[18] Locke, James, and Ulyses Valencia. *Design Studies for Twist-Coupled Wind Turbine Blades*. Rep. no. SAND2004-0522. Albuquerque, NM: Sandia National Laboratories, 2004.

[19] *Sweep-Twist Adaptive Rotor Blade: Final Project Report*. Rep. no. SAND2009-8037. Albuquerque, NM: Sandia National Laboratories, 2010.

[20] Don, Lobitz W., el al. *The Use of Twist-Coupled Blades to Enhance the Performance of Horizontal Axis Wind Turbines*. Rep. no. SAND2001-1303. Albuquerque, NM: Sandia National Laboratories, 2001.

[21] Imraan, Mustahib, Rajnish N. Sharma, and Richard G. J. Flay. "Telescopic Wind Turbines to Capture Energy at Low Wind Speeds." *Proceedings of the ASME 2009 3rd International Conference of Energy Sustainability*. San Francisco, CA, 2009.

[22] *Variable Length Wind Turbine Blade*. Rep. no. DE-FG36-03GO13171. National City, CA: Energy Unlimited, 2006.

[23] Crawford, Curran, and Jim Platts. "Updating and Optimization of a Coning Rotor Concept." *Journal of Solar Energy Engineering* 130.3 (2008).

[24] Johnson, Scott J., C.P. van Dam, and Dale E. Berg. *Active Load Control Techniques for Wind Turbines*. Rep. no. SAND2008-4809. Albuquerque, NM: Sandia National Laboratories, 2008.

[25] Nakafuji, D.T. Yen, C.P. van Dam, R.L. Smith, and S.D. Collins. "Active Load Control for Airfoils Using Microtabs." *Journal of Solar Energy Engineering* 123.4 (2001): 282-89.

[26] Baker, J.P., K.J. Standish, and, C.P. van Dam. "Two-Dimensional Wind Tunnel and Computational Investigation of a Microtab Modified S809 Airfoil," AIAA Paper 2005-1186, Wind Energy Symposium, Reno, Nevada, 2005.

[27] Mayda, E.A., C.P. van Dam,, and D.T. YenNakafuji. "Computational Investigation of Finite Width Microtabs for Aerodynamic Load Control," AIAA Paper 2005-1185, Wind Energy Symposium, Reno, Nevada, 2005.

[28] Zayas, J.R., et al. "Active Aerodynamic Load Control for Wind Turbine Blades." *Proceedings of the European Wind Energy Conference*. Athens, 2006.

[29] Buhl Jr., Marshall L. "WT_Perf User's Guide." *NWTC Design Codes*. 17 Dec 2004. NREL, Web. 10 Jan 2010. <http://wind.nrel.gov/designcodes/simulators/wtperf/WT_Perf.pdf>.

[30] Jonkman, Jason M., and Marshal L. Buhl, Jr. *FAST User's Guide*. Rep. no. NREL/EL-500-38230. National Renewable Energy Lab, Aug. 2005. Web. 5 June 2010. <http://wind.nrel.gov/designcodes/simulators/fast/FAST.pdf>.

[31] Moriarty, P. J., and A. C. Hansen. "AeroDyn Theory Manual." *NWTC Design Codes*. Jan 2005. NREL, Web. 10 Jan 2010. <http://www.nrel.gov/docs/fy05osti/36881.pdf>.

[32] Malcolm, D. J., and A. C. Hansen. "WindPACT Turbine Rotor Design Study." *National Renewable Energy Laboratory*. Apr 2006. NREL, Web. 31 Mar 2009. <http://www.nrel.gov/docs/fy06osti/32495.pdf>.

[33] "1.5MW Wind Turbine Technical Specifications." *GE Energy*. General Electric, Web. 10 Jan 2010. <http://www.gepower.com/prod_serv/products/wind_turbines/en/15mw/specs.htm>.

[34] Hansen, Martin O. L. *Aerodynamics of Wind Turbines*. London: Earthscan, 2008.

[35] "United States - 50 Meter Wind Resource Map." *Wind Powering America: State and United States Wind Resource Maps*. Web. 29 Jan 2010. <http://www.windpoweringamerica.gov/wind_maps.asp>.

Appendix A

Example MATLAB File for WindPACT 1.5MW Turbine

```
% This program is written to calculate the rotor thrust, rotor power,
% and blade bending moments for a given turbine.  This particular Mfile
% is set up to run the WindPACT 1.5MW Turbine.  The program is a BEMT
% based code, which borrows from NREL's WT_Perf program.  It was
written
% by Leonardo Albanese.

clear all
close all

rho=1.225;                      %Assigns density in SI units
Nb=3;                           %Assigns number of blades
R=35;                           %Assigns blade radius in meters
Bp=3*(pi/180);                  %Assigns Precone Angle
a_tol=1e-6;                     %Assigns the tolerance for inflow ratio
convergance

Uinfo=[3 14 0
    4 12 0
    5 10 0
    6 9 0
    7 8 0
    8 7 0
    9 7 0
    10 7 0
    11 6.83 0
    11.8 6.36 0];

yo=0.2;                         %Assigns root cutout value
yit=(1-yo)/150;                 %Sets interval step value of y
ya=yo:yit:1;                    %Creates array with dimensionless radius
values

q=0;
while q<length(Uinfo)
    q=q+1;
    V=Uinfo(q,1);
    X=Uinfo(q,2);
    coll=Uinfo(q,3);

i=1;
while i<(length(ya)-1)                                    %Calculates
the induction ratio, and therefore inflow angle (phi) and AoA ratio at
each radial position
    i=i+1;
```

```
    y=ya(i);                                                    %Selects value
of radial position to use in this iteration
    if y<0.21735                                                %Calculates
twist at this radial position
        theta=((11.1)+coll)*(pi/180);
    else
        theta=(((-20.904*y^3+63.463*y^2-
64.867*y+22.414))+coll)*(pi/180);
    end
    if y<0.225                                                   %Calculates
chord at this radial position
        c=35*(0.111*y+0.0538);
    else
        c=35*(-0.0686*y+0.0938);
    end
    thetaa(q,i)=theta*180/pi;                                   %Stores theta
value into a global array
    ca(i)=c;                                                    %Stores chord
value into a global array
    sig=Nb*c/(2*pi*y*R);                                        %Calucates
solidity at this radial position

    %Calculates induction factor
    a=0.0;                                                      %Initial value
of axial induction factor
    del_a=0.0;                                                  %Initial value
of delta a
    del_a_O=0.0;                                                %Stores
previous a
    a_step=0.25;                                                %Iteration
step size of a
    del_a_test=1;                                               %The delta a
that is tested against

    aprime=0.0;                                                 %Same but for
tangential induction factor
    del_aprime=0.0;
    del_aprime_O=0.0;
    aprime_step=0.25;

    ItSLSC=0;                                                   %Stores
Iterations Since Last Sign Change of a
    iter=1;
    while (iter<5000 && abs(del_a_test)>=a_tol)          %Stops
performing loop when iterations get too high or the del_a is below the
specified tolerance
        Vi_tan=X*V*y*(1+aprime);
        Vi_norm=V*(1-a);
        Vi=sqrt(Vi_tan^2+Vi_norm^2);

        phi=atan(Vi_norm/Vi_tan);                               %Calculates
inflow angle phi
        alpha=(phi-theta)*180/pi;                               %Calculates
angle of attack alpha
```

```
        fhub=(Nb/2)*((y-yo)/(yo*sin(phi)));             %Calculates
Prandtl Losses at hub and tip
        Fhexp=exp(-fhub);
        Fhub=(2/pi)*atan(sqrt(1-Fhexp^2)/Fhexp);
        ftip=(Nb/2)*((1-y)/(y*sin(phi)));
        Ftexp=exp(-ftip);
        Ftip=(2/pi)*atan(sqrt(1-Ftexp^2)/Ftexp);
        F=Fhub*Ftip;

        [Cl Cd]=airfoildat(y,alpha);                    %Calls Cl and
Cd of radial station from an interpolation program
        Cn=Cl*cos(phi)+Cd*sin(phi);                     %Calculates Cn
to be used below

        CH=Vi^2*sig*Cn/(V^2);                           %Calculates
head loss factor which determines which indcution factor formula to use
        CH=min(max(-2.0,CH),2.0);                       %Keeps CH
within certain bounds
        if (CH<0.96*F)
            a_new=0.5*(1-sqrt(1-CH/F));
        else
            a_new=0.1432+sqrt(-0.55106+0.6427*CH/F);
        end

        del_a=a_new-a;
        if ((del_a_O ~= 0.0) && (del_a/del_a_O < 0.0))   %Changes step
size of iterations accordingly
            a_step=0.5*a_step;
            ItSLSC=0;
        elseif (ItSLSC == 10)
            a_step=2.0*a_step;
            ItSLSC=0;
        else
            ItSLSC=ItSLSC+1;
        end

        del_a_test=a_step*del_a;
        a=a+del_a_test;
        del_a_O=del_a_test;

        swrlarg=1.0+4.0*a*F*(1.0-a)/(X^2);
        if (swrlarg < 0.0)
            aprime=0.0;
        else
            aprime=0.5*(sqrt(swrlarg)-1.0);
        end
        iter=iter+1;
    end

    indrat(q,i)=a;            %Stores value of 'a' into a global array
    phia(q,i)=phi*180/pi;     %Stores phi value into a global array
    alphaa(q,i)=alpha;        %Stores angle of attack in a global array
```

```
    Clar(q,i)=Cl;
    dL=1/2*rho*(Vi^2)*c*yit*R*Cl*R/4;
    dLa(q,i)=dL;
    Cdar(q,i)=Cd;
    dD=1/2*rho*(Vi^2)*c*yit*R*Cd*R/4;
    dDa(q,i)=dD;

    Qty1(q,i)=dL*sin(phi);
    Qty2(q,i)=dD*cos(phi);
    Qty(q,i)=Qty1(q,i)-Qty2(q,i);

    dCt(q,i)=sig*(X^2)*(Cl*cos(phi)+Cd*sin(phi))*(y^2)*cos(Bp);
%Calculates local Ct at each radial position
    dCp(q,i)=sig*(X^3)*(Cl*sin(phi)-Cd*cos(phi))*(y^3)*cos(Bp);
%Calculates local Cp at each radial position
    dCm(q,i)=sig*(X^2)*(Cl*cos(phi)+Cd*sin(phi))*(y^2)*(y-
1.5/R)*cos(Bp); %Calculates local Cm at each radial position
end

%Sums the dCts, dCms, and dCps to get total Ct, Cm, and Cp values
Ct=0;
Cp=0;
Cm=0;
l=1;
while l<(length(ya)-2)
    l=l+1;
    dCt1=((dCt(q,l)+dCt(q,l+1))/2)*(1/(length(ya)-1));
    Ct=dCt1+Ct;
    dCp1=((dCp(q,l)+dCp(q,l+1))/2)*(1/(length(ya)-1));
    Cp=dCp1+Cp;
    dCm1=((dCm(q,l)+dCm(q,l+1))/2)*(1/(length(ya)-1));
    Cm=dCm1+Cm;
end
Cta(q)=Ct;
Cpa(q)=Cp;
P(q)=Cp*1/2*rho*(V)^3*pi*R^2;
T(q)=Ct*1/2*rho*(V)^2*pi*R^2;
M(q)=Cm*1/2*rho*(V)^2*pi*(R^3)/Nb;
end


[E]=windenergy(Uinfo(:,1)',P);
%Calls windenergy program to calculate energies
TotalE=sum(E)

yar=ya(2:length(ya));


plot(Uinfo(:,1),P/1e6),xlabel('Wind Speed (m/s)'),ylabel('Power
(MW)'),title('Power Output vs. Wind Speed')
axis([0,25,0,2]
```

```
% This function is used to calculate energy produced annually from a
% power rating.  It takes a velocity vector and corresponding power
% vector from the main program, calculates the probability of that wind
% speed using a Weibull Probability Function, and multiplies by the
% number of hours in a year and the power produced at that wind speed.
% It is set up for the WindPACT 1.5MW Turbine and uses an average hub
% height wind speed of 7.5m/s.  It was written by Leonardo Albanese.

function [E]=windenergy(V,P)

[w,l]=size(P);

Vavg=7.5;
k=2.0;
A=Vavg/(exp(gammaln(1+1/k)));

RP=1.5e6;
for i=1:w
for j=1:l
    W(i,j)=wblpdf(V(j),A,k);
    if P(i,j)<RP
        Usepwr(i,j)=P(i,j);
    else
        Usepwr(i,j)=RP;
    end
    E(i,j)=W(i,j)*Usepwr(i,j)*8760;
end
end
```

Appendix B

Example MATLAB File for NREL 5MW Turbine

```
% This program is written to calculate the rotor thrust, rotor power,
% and blade bending moments for a given turbine.  This particular Mfile
% is set up to run the NREL 5MW Turbine.  The program is a BEMT based
% code, which borrows from NREL's WT_Perf program.  It was written
% by Leonardo Albanese.

clear all
close all

rho=1.225;                     %Assigns density in SI units
Nb=3;                          %Assigns number of blades
R=63;                          %Assigns blade radius in meters
Bp=2.5*(pi/180);               %Assigns Precone Angle
a_tol=1e-6;                    %Assigns the tolerance for inflow ratio
convergance

%Contains the TSR and Collective Pitch (deg) settings for each Wind
Speed
Uinfo=[3 15 0
    4 12 0
    5 10 0
    6 9 0
    7 8 0
    8 7 0
    9 7 0
    10 7 0
    11 7 0
    11.4 7 0               %Rated turbine speed
    12 6.65 3.83           %Blades feather and rotor runs at constant
rotational speed
    13 6.14 6.60
    14 5.70 8.70
    15 5.32 10.45
    16 4.99 12.06
    17 4.69 13.54
    18 4.43 14.92
    19 4.20 16.23
    20 3.99 17.47
    21 3.80 18.70
    22 3.63 19.94
    23 3.47 21.18
    24 3.33 22.35
    25 3.19 23.47];

yo=0.2;                        %Assigns root cutout value
```

```
yit=(1-yo)/150;               %Sets interval step value of y
ya=yo:yit:1;                  %Creates array with dimensionless radius
values

q=0;
while q<length(Uinfo)
    q=q+1;
    V=Uinfo(q,1);
    X=Uinfo(q,2);
    coll=Uinfo(q,3);

i=1;
while i<(length(ya)-1)                                      %Calculates
the induction ratio, and therefore inflow angle (phi) and AoA ratio at
each radial position
    i=i+1;
    y=ya(i);                                                %Selects value
of radial position to use in this iteration
    if y<0.181819                                           %Calculates
twist at this radial position
        theta=(((13.308))+coll)*(pi/180);
    else
        theta=(((8.768*y^2-26.905*y+17.91))+coll)*(pi/180);
    end
    if y<0.22                                               %Calculates
chord at this radial position
        c=63*(0.1168*y+0.0522);
    else
        c=63*(-0.061*y+0.0918);
    end
    thetaa(q,i)=theta*180/pi;                               %Stores theta
value into a global array
    ca(i)=c;                                                %Stores chord
value into a global array
    sig=Nb*c/(2*pi*y*R);                                    %Calucates
solidity at this radial position

    %Calculates induction factor
    a=0.0;                                                  %Initial value
of axial induction factor
    del_a=0.0;                                              %Initial value
of delta a
    del_a_O=0.0;                                            %Stores
previous a
    a_step=0.25;                                            %Iteration
step size of a
    del_a_test=1;                                           %The delta a
that is tested against

    aprime=0.0;                                             %Same but for
tangential induction factor
    del_aprime=0.0;
    del_aprime_O=0.0;
    aprime_step=0.25;
```

```
    ItSLSC=0;                                                    %Stores
Iterations Since Last Sign Change of a
    iter=1;
    while (iter<5000 && abs(del_a_test)>=a_tol)                  %Stops
performing loop when iterations get too high or the del_a is below the
specified tolerance
        Vi_tan=X*V*y*(1+aprime);
        Vi_norm=V*(1-a);
        Vi=sqrt(Vi_tan^2+Vi_norm^2);

        phi=atan(Vi_norm/Vi_tan);                                %Calculates
inflow angle phi
        alpha=(phi-theta)*180/pi;                                %Calculates
angle of attack alpha

        fhub=(Nb/2)*((y-yo)/(yo*sin(phi)));                      %Calculates
Prandtl Losses at hub and tip
        Fhexp=exp(-fhub);
        Fhub=(2/pi)*atan(sqrt(1-Fhexp^2)/Fhexp);
        ftip=(Nb/2)*((1-y)/(y*sin(phi)));
        Ftexp=exp(-ftip);
        Ftip=(2/pi)*atan(sqrt(1-Ftexp^2)/Ftexp);
        F=Fhub*Ftip;

        [Cl Cd]=airfoildat(y,alpha);                             %Calls Cl and
Cd of radial station from an interpolation program
        Cn=Cl*cos(phi)+Cd*sin(phi);                              %Calculates Cn
to be used below

        CH=Vi^2*sig*Cn/(V^2);                                    %Calculates
head loss factor which determines which indcution factor formula to use
        CH=min(max(-2.0,CH),2.0);                                %Keeps CH
within certain bounds
        if (CH<0.96*F)
            a_new=0.5*(1-sqrt(1-CH/F));
        else
            a_new=0.1432+sqrt(-0.55106+0.6427*CH/F);
        end

        del_a=a_new-a;
        if ((del_a_O ~= 0.0) && (del_a/del_a_O < 0.0))           %Changes step
size of iterations accordingly
            a_step=0.5*a_step;
            ItSLSC=0;
        elseif (ItSLSC == 10)
            a_step=2.0*a_step;
            ItSLSC=0;
        else
            ItSLSC=ItSLSC+1;
        end

        del_a_test=a_step*del_a;
```

```
        a=a+del_a_test;
        del_a_O=del_a_test;

        swrlarg=1.0+4.0*a*F*(1.0-a)/(X^2);
        if (swrlarg < 0.0)
            aprime=0.0;
        else
            aprime=0.5*(sqrt(swrlarg)-1.0);
        end
        iter=iter+1;
    end

    indrat(q,i)=a;            %Stores value of 'a' into a global array
    phia(q,i)=phi*180/pi;     %Stores phi value into a global array
    alphaa(q,i)=alpha;        %Stores angle of attack in a global array

    Clar(q,i)=Cl;
    dL=1/2*rho*(Vi^2)*c*yit*R*Cl*R/4;
    dLa(q,i)=dL;
    Cdar(q,i)=Cd;
    dD=1/2*rho*(Vi^2)*c*yit*R*Cd*R/4;
    dDa(q,i)=dD;
    Qty1(q,i)=dL*sin(phi);
    Qty2(q,i)=dD*cos(phi);
    Qty(q,i)=Qty1(q,i)-Qty2(q,i);

    dCt(q,i)=sig*(X^2)*(Cl*cos(phi)+Cd*sin(phi))*(y^2)*cos(Bp);
%Calculates local Ct at each radial position
    dCp(q,i)=sig*(X^3)*(Cl*sin(phi)-Cd*cos(phi))*(y^3)*cos(Bp);
%Calculates local Cp at each radial position
    dCm(q,i)=sig*(X^2)*(Cl*cos(phi)+Cd*sin(phi))*(y^2)*(y-
1.5/R)*cos(Bp);   %Calculates local Cm at each radial position
end

%Sums the dCts, dCms, and dCps to get total Ct, Cm, and Cp values
Ct=0;
Cp=0;
Cm=0;
l=1;
while l<(length(ya)-2)
    l=l+1;
    dCt1=((dCt(q,l)+dCt(q,l+1))/2)*(1/(length(ya)-1));
    Ct=dCt1+Ct;
    dCp1=((dCp(q,l)+dCp(q,l+1))/2)*(1/(length(ya)-1));
    Cp=dCp1+Cp;
    dCm1=((dCm(q,l)+dCm(q,l+1))/2)*(1/(length(ya)-1));
    Cm=dCm1+Cm;
end
Cta(q)=Ct;
Cpa(q)=Cp;
P(q)=Cp*1/2*rho*(V)^3*pi*R^2;
T(q)=Ct*1/2*rho*(V)^2*pi*R^2;
M(q)=Cm*1/2*rho*(V)^2*pi*(R^3)/Nb;
end
```

```
[E]=windenergy(Uinfo(:,1)',P);
TotalE=sum(E);

yar=ya(2:length(ya));

plot(Uinfo(:,1),E/1e6),xlabel('Wind Speed (m/s)'),ylabel('Power
(MW)'),title('Power Output vs. Wind Speed')
axis([0,25,0,6]),%grid on

yar=ya(2:length(ya));
```

```
% This function is used to calculate energy produced annually from a
% power rating.  It takes a velocity vector and corresponding power
% vector from the main program, calculates the probability of that wind
% speed using a Weibull Probability Function, and multiplies by the
% number of hours in a year and the power produced at that wind speed.
% It is set up for the NREL 5MW Turbine and uses an average hub
% hieght wind speed of 8.5m/s.  It was written by Leonardo Albanese.

function [E]=windenergy(V,P)

[w,l]=size(P);

Vavg=8.5;
k=2.0;
A=Vavg/(exp(gammaln(1+1/k)));

RP=5e6;
for i=1:w
for j=1:l
    W(i,j)=wblpdf(V(j),A,k);
    if P(i,j)<RP
        Usepwr(i,j)=P(i,j);
    else
        Usepwr(i,j)=RP;
    end
    E(i,j)=W(i,j)*Usepwr(i,j)*8760;
end
end
```

Appendix C

Power Results for WindPACT 1.5MW Turbine Twist and Collective Pitch Study

1.5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 10 m/s

Rotational Speed: 17.10 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
			Percentage Difference from Baseline Pitch/Collective		
5.1	-31.7%	-17.2%	-5.8%	-3.1%	-9.5%
8.1	-24.7%	-11.8%	-2.6%	-2.9%	-11.2%
11.1	-18.8%	-7.8%	-1.4%	-3.7%	-13.3%
14.1	-13.7%	-5.5%	-1.3%	-5.2%	-16.1%
17.1	-10.4%	-4.8%	-1.7%	-7.4%	-19.2%

Baseline

Rotational Speed: 19.10 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
			Percentage Difference from Baseline Pitch/Collective		
5.1	-28.9%	-14.0%	-2.6%	1.7%	-4.6%
8.1	-23.0%	-10.4%	-1.1%	1.5%	-6.6%
11.1	-18.9%	-8.6%	0.0%	0.6%	-9.1%
14.1	-17.1%	-7.0%	0.4%	-1.2%	-12.2%
17.1	-15.5%	-5.8%	-0.2%	-3.5%	-15.9%

Rotational Speed: 21.10 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
			Percentage Difference from Baseline Pitch/Collective		
5.1	-33.6%	-17.6%	-7.0%	1.7%	-1.7%
8.1	-30.6%	-15.4%	-5.0%	2.5%	-3.6%
11.1	-28.0%	-13.3%	-3.5%	2.1%	-6.3%
14.1	-25.4%	-11.4%	-2.7%	0.7%	-9.9%
17.1	-23.0%	-10.1%	-2.7%	-1.6%	-14.3%

Rotational Speed:		23.10 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-46.1%	-26.2%	-12.5%	-1.4%	-0.2%		
	8.1	-42.0%	-23.4%	-10.2%	0.4%	-2.0%		
	11.1	-38.7%	-21.0%	-8.1%	0.9%	-4.8%		
	14.1	-35.7%	-18.6%	-6.7%	0.1%	-8.9%		
	17.1	-33.0%	-16.6%	-6.4%	-2.1%	-13.9%		

1.5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 8 m/s

Rotational Speed:		13.28 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-34.1%	-18.7%	-8.4%	-5.6%	-11.2%		
	8.1	-26.7%	-13.3%	-5.0%	-4.8%	-12.7%		
	11.1	-20.2%	-8.9%	-3.2%	-5.4%	-14.6%		
	14.1	-14.6%	-5.9%	-3.0%	-6.7%	-17.2%		
	17.1	-10.3%	-4.8%	-3.5%	-8.8%	-20.2%		

Baseline

Rotational Speed:		15.28 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-28.9%	-14.0%	-2.6%	1.7%	-4.5%		
	8.1	-23.0%	-10.4%	-1.1%	1.6%	-6.6%		
	11.1	-18.9%	-8.6%	0.0%	0.6%	-9.1%		
	14.1	-17.1%	-7.0%	0.4%	-1.2%	-12.2%		
	17.1	-15.5%	-5.8%	-0.2%	-3.5%	-15.9%		

Rotational Speed:		17.28 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-36.4%	-19.5%	-8.3%	1.2%	-1.2%		
	8.1	-33.4%	-17.1%	-6.3%	2.3%	-3.1%		
	11.1	-30.4%	-15.0%	-4.5%	2.1%	-5.8%		
	14.1	-27.7%	-13.1%	-3.6%	0.8%	-9.5%		
	17.1	-25.3%	-11.6%	-3.5%	-1.5%	-14.1%		

Rotational Speed:		19.28 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-53.5%	-31.5%	-15.7%	-3.5%	0.1%		
	8.1	-49.2%	-28.3%	-13.1%	-1.4%	-1.6%		
	11.1	-45.6%	-25.5%	-10.8%	-0.5%	-4.5%		
	14.1	-42.3%	-22.8%	-9.2%	-1.0%	-8.8%		
	17.1	-39.2%	-20.4%	-8.7%	-3.1%	-14.3%		

1.5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 6 m/s

Rotational Speed:		10.73 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-20.1%	-3.5%	10.4%	13.7%	5.6%		
	8.1	-12.5%	2.1%	13.4%	13.2%	3.6%		
	11.1	-6.2%	5.7%	14.3%	12.1%	0.9%		
	14.1	-1.5%	7.2%	14.4%	10.2%	-2.5%		
	17.1	0.4%	8.0%	13.6%	7.5%	-6.2%		

Rotational Speed:		12.73 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-25.0%	-6.6%	5.6%	15.8%	12.2%		
	8.1	-21.6%	-4.0%	7.9%	16.7%	10.0%		
	11.1	-18.6%	-1.6%	9.7%	16.4%	6.9%		
	14.1	-15.5%	0.5%	10.7%	14.8%	2.8%		
	17.1	-12.9%	2.1%	10.7%	12.1%	-2.3%		

Baseline

Rotational Speed:		14.73 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-51.5%	-24.9%	-5.8%	8.8%	14.1%		
	8.1	-46.3%	-20.9%	-2.7%	11.4%	12.3%		
	11.1	-42.0%	-17.6%	0.0%	12.5%	8.9%		
	14.1	-37.9%	-14.3%	2.1%	12.0%	3.9%		
	17.1	-34.2%	-11.5%	2.7%	9.6%	-2.6%		

Rotational Speed:		16.73 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-90.9%	-50.4%	-21.6%	-0.6%	12.4%		
	8.1	-83.4%	-44.5%	-17.2%	2.9%	11.2%		
	11.1	-76.9%	-39.6%	-13.4%	4.9%	7.6%		
	14.1	-70.7%	-35.0%	-10.1%	4.7%	1.4%		
	17.1	-65.2%	-30.9%	-8.7%	2.2%	-7.0%		

1.5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 4 m/s

Rotational Speed: 7.10 RPM

Percentage Difference from Baseline Pitch/Collective

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
5.1	31.3%	58.6%	81.4%	86.6%	73.4%
8.1	43.8%	67.9%	86.5%	86.0%	70.1%
11.1	54.3%	74.3%	88.0%	84.1%	65.6%
14.1	62.5%	76.8%	88.2%	81.0%	60.2%
17.1	66.0%	78.2%	87.0%	76.7%	54.1%

Rotational Speed: 9.10 RPM

Percentage Difference from Baseline Pitch/Collective

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
5.1	5.7%	41.6%	66.2%	86.5%	87.1%
8.1	12.9%	46.8%	70.4%	89.6%	83.7%
11.1	19.1%	51.2%	74.2%	90.3%	78.4%
14.1	24.6%	55.5%	76.7%	88.5%	70.9%
17.1	29.6%	59.0%	77.2%	84.4%	61.7%

Rotational Speed: 11.10 RPM

Percentage Difference from Baseline Pitch/Collective

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
5.1	-82.2%	-16.3%	30.4%	64.4%	85.4%
8.1	-69.9%	-6.7%	37.5%	70.2%	83.5%
11.1	-59.2%	1.3%	43.7%	73.4%	77.4%
14.1	-49.2%	8.7%	49.1%	73.1%	67.3%
17.1	-40.3%	15.3%	51.3%	69.0%	53.6%

Baseline								
Rotational Speed:		13.10 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	5.1	-132.7%	-100.9%	-20.6%	35.1%	71.9%		
	8.1	-121.8%	-87.1%	-9.4%	43.1%	71.9%		
	11.1	-111.8%	-74.7%	0.0%	48.5%	64.6%		
	14.1	-101.8%	-62.9%	8.2%	48.2%	50.9%		
	17.1	-92.5%	-52.4%	12.1%	42.1%	31.5%		

Appendix D

Power Results for NREL 5MW Turbine Twist and Collective Pitch Study

5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 10 m/s

Rotational Speed: 9.61 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
			Percentage Difference from Baseline Pitch/Collective		
7.30	-39.0%	-16.9%	-4.8%	-7.0%	-18.8%
10.30	-31.5%	-7.8%	-3.6%	-9.5%	-23.8%
13.30	-18.9%	-3.3%	-5.1%	-13.7%	-30.5%
16.30	-8.3%	-3.6%	-7.5%	-18.6%	-37.2%
19.30	-5.4%	-5.3%	-11.2%	-25.0%	-45.4%

Baseline

Rotational Speed: 10.61 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
			Percentage Difference from Baseline Pitch/Collective		
7.30	-24.0%	-7.3%	0.9%	-2.0%	-16.3%
10.30	-14.3%	-4.2%	1.3%	-5.3%	-22.6%
13.30	-9.2%	-2.1%	0.0%	-10.7%	-30.9%
16.30	-7.1%	-1.6%	-3.0%	-16.7%	-39.2%
19.30	-5.7%	-2.8%	-7.9%	-24.6%	-49.5%

Rotational Speed: 11.61 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
			Percentage Difference from Baseline Pitch/Collective		
7.30	-22.3%	-10.6%	1.0%	0.7%	-15.3%
10.30	-18.3%	-6.9%	2.7%	-3.0%	-22.8%
13.30	-14.3%	-3.5%	1.7%	-9.2%	-32.8%
16.30	-11.2%	-2.1%	-1.5%	-16.3%	-43.0%
19.30	-8.8%	-2.7%	-7.0%	-25.8%	-55.7%

Rotational Speed:	12.61 RPM						
			Percentage Difference from Baseline Pitch/Collective				
Root to Tip	Pitch Setting						
Nose Up Twist	-6°	-3°	0°	3°	6°		
7.30	-30.7%	-14.1%	-1.4%	2.0%	-15.3%		
10.30	-25.6%	-9.8%	1.4%	-1.7%	-24.1%		
13.30	-20.4%	-5.9%	1.4%	-8.7%	-36.1%		
16.30	-16.3%	-4.0%	-1.6%	-17.0%	-48.6%		
19.30	-13.1%	-4.4%	-7.7%	-28.4%	-64.1%		

5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 8 m/s

Rotational Speed:	7.49 RPM						
			Percentage Difference from Baseline Pitch/Collective				
Root to Tip	Pitch Setting						
Nose Up Twist	-6°	-3°	0°	3°	6°		
7.30	-42.3%	-20.5%	-8.3%	-8.7%	-19.7%		
10.30	-34.9%	-12.2%	-5.5%	-10.9%	-24.3%		
13.30	-26.9%	-5.0%	-6.7%	-14.8%	-30.6%		
16.30	-16.3%	-4.8%	-9.0%	-19.2%	-37.0%		
19.30	-8.3%	-6.4%	-12.5%	-25.3%	-44.6%		

Baseline

Rotational Speed:	8.49 RPM						
			Percentage Difference from Baseline Pitch/Collective				
Root to Tip	Pitch Setting						
Nose Up Twist	-6°	-3°	0°	3°	6°		
7.30	-23.9%	-7.3%	0.9%	-2.0%	-16.3%		
10.30	-14.3%	-4.2%	1.3%	-5.3%	-22.6%		
13.30	-9.2%	-2.2%	0.0%	-10.7%	-30.8%		
16.30	-7.1%	-1.7%	-3.0%	-16.7%	-39.2%		
19.30	-5.7%	-2.8%	-7.9%	-24.6%	-49.4%		

Rotational Speed:	9.49 RPM					
			Percentage Difference from Baseline Pitch/Collective			
Root to Tip	Pitch Setting					
Nose Up Twist	-6°	-3°	0°	3°	6°	
7.30	-24.2%	-11.5%	0.5%	1.1%	-15.1%	
10.30	-20.0%	-7.5%	2.6%	-2.5%	-22.9%	
13.30	-15.8%	-3.9%	1.8%	-8.9%	-33.4%	
16.30	-12.4%	-2.5%	-1.3%	-16.3%	-44.2%	
19.30	-9.8%	-3.0%	-7.1%	-26.3%	-57.5%	

Rotational Speed:	10.49 RPM					
			Percentage Difference from Baseline Pitch/Collective			
Root to Tip	Pitch Setting					
Nose Up Twist	-6°	-3°	0°	3°	6°	
7.30	-35.6%	-16.3%	-2.9%	2.3%	-15.6%	
10.30	-29.7%	-11.8%	0.3%	-1.4%	-25.2%	
13.30	-23.9%	-7.5%	0.7%	-8.8%	-38.3%	
16.30	-19.3%	-5.5%	-2.2%	-17.8%	-52.0%	
19.30	-15.6%	-5.8%	-8.6%	-30.3%	-69.3%	

5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 6 m/s

Rotational Speed:	6.19 RPM					
			Percentage Difference from Baseline Pitch/Collective			
Root to Tip	Pitch Setting					
Nose Up Twist	-6°	-3°	0°	3°	6°	
7.30	-26.2%	-8.2%	0.3%	-2.9%	-16.6%	
10.30	-16.1%	-3.3%	0.5%	-6.0%	-22.5%	
13.30	-8.1%	-1.6%	-0.9%	-11.1%	-30.4%	
16.30	-5.9%	-1.6%	-3.6%	-16.9%	-38.2%	
19.30	-4.8%	-3.0%	-8.3%	-24.3%	-47.8%	

Rotational Speed: 7.19 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
	Percentage Difference from Baseline Pitch/Collective				
7.30	-24.9%	-11.7%	0.5%	1.6%	-14.9%
10.30	-20.7%	-7.6%	2.7%	-2.1%	-22.9%
13.30	-16.3%	-3.9%	2.1%	-8.6%	-33.6%
16.30	-12.7%	-2.4%	-1.1%	-16.2%	-44.7%
19.30	-10.0%	-2.9%	-6.8%	-26.3%	-58.4%

Baseline

Rotational Speed: 8.19 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
	Percentage Difference from Baseline Pitch/Collective				
7.30	-40.9%	-19.0%	-4.3%	2.7%	-16.0%
10.30	-34.2%	-14.0%	-0.8%	-1.0%	-26.4%
13.30	-27.7%	-9.3%	0.0%	-8.9%	-41.0%
16.30	-22.5%	-7.0%	-2.8%	-18.8%	-56.1%
19.30	-18.4%	-7.2%	-9.6%	-32.5%	-75.4%

Rotational Speed: 9.19 RPM

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
	Percentage Difference from Baseline Pitch/Collective				
7.30	-61.3%	-30.4%	-10.5%	1.6%	-19.6%
10.30	-51.8%	-23.8%	-6.0%	-2.3%	-33.4%
13.30	-42.8%	-17.5%	-4.6%	-12.2%	-52.8%
16.30	-35.9%	-14.3%	-7.6%	-25.0%	-73.6%
19.30	-30.3%	-14.5%	-15.9%	-43.2%	-100.6%

5MW Power Analysis: Twist vs. Collective Analysis at Different Rotational Speeds at 4 m/s

Rotational Speed: 4.28 RPM

Percentage Difference from Baseline Pitch/Collective

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
7.30	9.8%	15.9%	21.0%	21.3%	16.7%
10.30	9.2%	16.8%	21.7%	17.0%	4.1%
13.30	8.2%	17.0%	20.0%	7.1%	-17.4%
16.30	6.4%	16.6%	16.4%	-5.2%	-41.7%
19.30	-1.2%	15.5%	10.4%	-22.0%	-73.6%

Rotational Speed: 5.28 RPM

Percentage Difference from Baseline Pitch/Collective

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
7.30	-2.0%	7.7%	15.9%	22.8%	21.8%
10.30	-5.7%	9.3%	19.8%	21.3%	5.9%
13.30	-9.6%	10.3%	20.4%	9.1%	-26.8%
16.30	-12.9%	10.1%	16.9%	-9.0%	-66.5%
19.30	-16.9%	8.5%	9.2%	-35.6%	-121.8%

Rotational Speed: 6.28 RPM

Percentage Difference from Baseline Pitch/Collective

Root to Tip Nose Up Twist	Pitch Setting -6°	-3°	0°	3°	6°
7.30	-23.2%	-7.6%	4.8%	15.4%	20.3%
10.30	-28.8%	-5.7%	10.7%	18.3%	0.7%
13.30	-36.6%	-4.2%	12.4%	3.5%	-47.8%
16.30	-44.0%	-4.4%	8.6%	-22.6%	-111.3%
19.30	-51.3%	-6.7%	-1.9%	-63.4%	-196.4%

Baseline								
Rotational Speed:		7.28 RPM						
				Percentage Difference from Baseline Pitch/Collective				
	Root to Tip	Pitch Setting						
	Nose Up Twist	-6°	-3°	0°	3°	6°		
	7.30	-53.1%	-28.6%	-9.5%	4.9%	13.7%		
	10.30	-62.0%	-26.4%	-1.8%	9.3%	-11.2%		
	13.30	-68.3%	-24.9%	0.0%	-9.5%	-83.3%		
	16.30	-73.3%	-26.0%	-6.0%	-47.0%	-176.6%		
	19.30	-77.5%	-30.0%	-21.4%	-108.3%	-299.3%		

Appendix E

Power Results for WindPACT 1.5MW Turbine Chord Study

Wind Speed:	10 m/s												
			Percentage Difference from Baseline										
Chord Scale	RPM						Baseline						
Factor	27.28	25.92	24.56	23.19	21.83	20.46	19.10	17.73	16.37	15.01	13.64	12.28	10.91
0.80	-9.7%	-6.0%	-2.9%	-0.2%	2.1%	2.5%	0.1%	-5.2%	-13.7%	-25.3%	-39.4%	-54.7%	-69.7%
0.85	-12.7%	-8.6%	-5.1%	-2.2%	0.4%	2.2%	1.2%	-3.1%	-10.6%	-21.9%	-36.1%	-52.0%	-67.7%
0.90	-15.7%	-11.3%	-7.4%	-4.2%	-1.4%	1.0%	1.5%	-1.4%	-8.0%	-18.8%	-33.0%	-49.3%	-65.7%
0.95	-18.7%	-14.0%	-9.8%	-6.3%	-3.2%	-0.6%	1.1%	-0.4%	-5.9%	-15.9%	-30.0%	-46.6%	-63.7%
1.00	-21.7%	-16.8%	-12.2%	-8.3%	-5.0%	-2.2%	0.0%	0.1%	-4.2%	-13.4%	-27.1%	-44.0%	-61.7%
1.05	-24.7%	-19.5%	-14.7%	-10.4%	-6.9%	-3.9%	-1.3%	-0.2%	-3.0%	-11.1%	-24.4%	-41.4%	-59.8%
1.10	-27.6%	-22.2%	-17.1%	-12.6%	-8.8%	-5.5%	-2.8%	-1.0%	-2.3%	-9.2%	-21.8%	-38.9%	-57.8%
1.15	-30.6%	-24.8%	-19.6%	-14.7%	-10.6%	-7.2%	-4.2%	-2.1%	-2.1%	-7.6%	-19.5%	-36.4%	-55.8%
1.20	-33.5%	-27.4%	-21.9%	-16.9%	-12.5%	-8.8%	-5.7%	-3.2%	-2.4%	-6.4%	-17.3%	-34.1%	-53.8%

Wind Speed:	8 m/s												
			Percentage Difference from Baseline										
Chord Scale	RPM						Baseline						
Factor	21.83	20.74	19.64	18.55	17.46	16.37	15.28	14.19	13.10	12.00	10.91	9.82	8.73
0.80	-9.7%	-6.0%	-2.9%	-0.2%	2.1%	2.5%	0.1%	-5.2%	-13.7%	-25.3%	-39.4%	-54.7%	-69.7%
0.85	-12.7%	-8.6%	-5.1%	-2.2%	0.4%	2.2%	1.2%	-3.1%	-10.6%	-21.9%	-36.1%	-52.0%	-67.7%
0.90	-15.7%	-11.3%	-7.4%	-4.2%	-1.4%	1.0%	1.6%	-1.4%	-8.0%	-18.8%	-33.0%	-49.3%	-65.7%
0.95	-18.7%	-14.0%	-9.8%	-6.2%	-3.2%	-0.6%	1.1%	-0.4%	-5.9%	-15.9%	-30.0%	-46.6%	-63.7%
1.00	-21.7%	-16.8%	-12.2%	-8.3%	-5.0%	-2.2%	0.0%	0.1%	-4.2%	-13.4%	-27.1%	-44.0%	-61.7%
1.05	-24.7%	-19.5%	-14.7%	-10.4%	-6.9%	-3.9%	-1.3%	-0.2%	-3.0%	-11.1%	-24.4%	-41.4%	-59.8%
1.10	-27.6%	-22.2%	-17.1%	-12.6%	-8.8%	-5.5%	-2.7%	-1.0%	-2.3%	-9.2%	-21.8%	-38.9%	-57.8%
1.15	-30.6%	-24.8%	-19.6%	-14.7%	-10.6%	-7.2%	-4.2%	-2.1%	-2.1%	-7.6%	-19.5%	-36.4%	-55.8%
1.20	-33.5%	-27.4%	-21.9%	-16.9%	-12.5%	-8.8%	-5.7%	-3.2%	-2.4%	-6.4%	-17.3%	-34.1%	-53.8%

Wind Speed:	6 m/s												
			Percentage Difference from Baseline										
Chord Scale	RPM						Baseline						
Factor	19.64	18.83	18.01	17.19	16.37	15.55	14.73	13.91	13.10	12.28	11.46	10.64	9.82
0.80	-18.5%	-12.4%	-6.9%	-1.8%	2.9%	7.1%	10.6%	13.7%	16.3%	16.8%	14.1%	8.0%	-1.6%
0.85	-23.7%	-17.1%	-11.0%	-5.6%	-0.5%	4.2%	8.1%	11.5%	14.4%	16.5%	15.4%	10.5%	1.8%
0.90	-28.9%	-21.7%	-15.2%	-9.3%	-3.9%	1.1%	5.5%	9.2%	12.4%	15.1%	15.7%	12.3%	4.8%
0.95	-34.1%	-26.4%	-19.4%	-13.1%	-7.4%	-2.0%	2.8%	6.8%	10.3%	13.3%	15.2%	13.6%	7.3%
1.00	-39.3%	-31.1%	-23.6%	-16.9%	-10.8%	-5.2%	0.0%	4.5%	8.2%	11.4%	14.0%	14.1%	9.2%
1.05	-44.6%	-35.8%	-27.9%	-20.7%	-14.1%	-8.3%	-2.8%	2.1%	6.1%	9.6%	12.4%	13.8%	10.6%
1.10	-49.8%	-40.6%	-32.1%	-24.4%	-17.5%	-11.3%	-5.6%	-0.4%	4.0%	7.7%	10.8%	12.8%	11.4%
1.15	-55.0%	-45.3%	-36.3%	-28.2%	-20.9%	-14.3%	-8.3%	-2.8%	1.8%	5.8%	9.2%	11.6%	11.6%
1.20	-60.3%	-50.0%	-40.6%	-32.0%	-24.3%	-17.3%	-11.0%	-5.3%	-0.2%	3.9%	7.5%	10.3%	11.3%

Wind Speed:	4 m/s												
			Percentage Difference from Baseline										
Chord Scale	RPM	Baseline											
Factor	13.64	13.10	12.55	12.00	11.46	10.91	10.37	9.82	9.28	8.73	8.19	7.64	7.09
0.80	23.2%	34.2%	44.3%	53.4%	61.8%	69.6%	76.5%	82.3%	87.4%	91.7%	92.5%	88.0%	77.9%
0.85	13.8%	25.8%	36.7%	46.6%	55.6%	64.0%	71.6%	78.1%	83.7%	88.5%	91.9%	90.1%	82.0%
0.90	4.3%	17.2%	29.0%	39.7%	49.4%	58.3%	66.6%	73.8%	79.9%	85.2%	89.6%	90.7%	85.1%
0.95	-5.2%	8.6%	21.3%	32.8%	43.2%	52.6%	61.4%	69.4%	76.0%	81.8%	86.6%	89.8%	87.1%
1.00	-14.7%	0.0%	13.5%	25.8%	37.0%	47.0%	56.2%	64.8%	72.1%	78.3%	83.6%	87.8%	87.9%
1.05	-24.2%	-8.6%	5.7%	18.9%	30.7%	41.5%	51.2%	60.2%	68.2%	74.8%	80.5%	85.3%	87.4%
1.10	-33.8%	-17.3%	-2.1%	11.9%	24.5%	35.9%	46.2%	55.6%	64.1%	71.3%	77.4%	82.6%	85.9%
1.15	-43.3%	-25.9%	-9.9%	4.9%	18.3%	30.4%	41.2%	51.1%	60.1%	67.8%	74.3%	79.9%	83.9%
1.20	-52.9%	-34.5%	-17.7%	-2.1%	12.0%	24.8%	36.3%	46.6%	56.1%	64.4%	71.2%	77.1%	81.8%

Appendix F

Power Results for NREL 5MW Turbine Chord Study

Wind Speed: 10 m/s

Percentage Difference from Baseline

Chord Scale Factor	RPM 15.16	14.40	13.64	12.88	12.13	11.37	Baseline 10.61	9.85	9.09	8.34	7.58	6.82	6.06
0.80	-0.9%	0.2%	0.6%	0.3%	-0.9%	-3.2%	-7.2%	-12.2%	-19.0%	-30.3%	-44.9%	-58.1%	-69.2%
0.85	-1.5%	0.1%	0.9%	1.1%	0.4%	-1.4%	-4.8%	-9.6%	-15.8%	-26.6%	-41.9%	-55.6%	-67.4%
0.90	-2.3%	-0.4%	0.9%	1.5%	1.2%	0.0%	-2.9%	-7.3%	-13.1%	-23.2%	-38.9%	-53.2%	-65.5%
0.95	-3.3%	-1.2%	0.4%	1.4%	1.7%	0.9%	-1.2%	-5.3%	-10.7%	-19.9%	-36.0%	-50.8%	-63.7%
1.00	-4.4%	-2.2%	-0.3%	1.1%	1.8%	1.5%	0.0%	-3.7%	-8.7%	-17.0%	-33.2%	-48.4%	-61.8%
1.05	-5.5%	-3.2%	-1.1%	0.5%	1.5%	1.7%	0.8%	-2.3%	-6.9%	-14.3%	-30.3%	-46.0%	-60.0%
1.10	-6.7%	-4.2%	-2.1%	-0.3%	1.0%	1.7%	1.2%	-1.2%	-5.4%	-12.0%	-27.5%	-43.7%	-58.3%
1.15	-7.9%	-5.3%	-3.1%	-1.2%	0.4%	1.3%	1.4%	-0.3%	-4.1%	-10.0%	-24.6%	-41.4%	-56.5%
1.20	-9.2%	-6.5%	-4.1%	-2.1%	-0.4%	0.8%	1.2%	0.2%	-3.1%	-8.3%	-21.8%	-39.2%	-54.8%

Wind Speed: 8 m/s

Percentage Difference from Baseline

Chord Scale Factor	RPM 12.13	11.52	10.91	10.31	9.70	9.09	Baseline 8.49	7.88	7.28	6.67	6.06	5.46	4.85
0.80	-0.9%	0.2%	0.6%	0.3%	-0.9%	-3.2%	-7.2%	-12.2%	-19.0%	-30.2%	-44.9%	-58.1%	-69.2%
0.85	-1.5%	0.1%	0.9%	1.1%	0.4%	-1.4%	-4.8%	-9.6%	-15.8%	-26.6%	-41.9%	-55.6%	-67.4%
0.90	-2.3%	-0.4%	0.9%	1.5%	1.2%	0.0%	-2.9%	-7.3%	-13.1%	-23.2%	-38.9%	-53.2%	-65.5%
0.95	-3.3%	-1.2%	0.4%	1.4%	1.7%	0.9%	-1.2%	-5.3%	-10.7%	-19.9%	-36.0%	-50.8%	-63.7%
1.00	-4.4%	-2.2%	-0.3%	1.1%	1.8%	1.5%	0.0%	-3.7%	-8.7%	-17.0%	-33.2%	-48.4%	-61.8%
1.05	-5.5%	-3.2%	-1.1%	0.5%	1.5%	1.7%	0.8%	-2.3%	-6.9%	-14.3%	-30.3%	-46.0%	-60.0%
1.10	-6.7%	-4.3%	-2.1%	-0.3%	1.0%	1.7%	1.2%	-1.2%	-5.4%	-12.0%	-27.5%	-43.7%	-58.3%
1.15	-7.9%	-5.3%	-3.1%	-1.2%	0.4%	1.3%	1.4%	-0.3%	-4.1%	-10.0%	-24.6%	-41.4%	-56.5%
1.20	-9.2%	-6.5%	-4.1%	-2.1%	-0.4%	0.8%	1.2%	0.2%	-3.1%	-8.3%	-21.8%	-39.2%	-54.8%

Wind Speed: 6 m/s

Percentage Difference from Baseline

Chord Scale Factor	RPM 10.91	10.46	10.00	9.55	9.09	8.64	Baseline 8.19	7.73	7.28	6.82	6.37	5.91	5.46
0.80	-9.8%	-6.9%	-4.4%	-2.3%	-0.6%	0.5%	0.9%	0.6%	-0.6%	-2.9%	-6.9%	-12.0%	-18.7%
0.85	-11.3%	-8.2%	-5.5%	-3.2%	-1.2%	0.3%	1.2%	1.4%	0.7%	-1.1%	-4.6%	-9.3%	-15.6%
0.90	-12.8%	-9.6%	-6.8%	-4.2%	-2.0%	-0.2%	1.1%	1.7%	1.5%	0.3%	-2.6%	-7.0%	-12.9%
0.95	-14.5%	-11.1%	-8.1%	-5.4%	-3.0%	-0.9%	0.7%	1.7%	2.0%	1.2%	-0.9%	-5.1%	-10.5%
1.00	-16.2%	-12.6%	-9.5%	-6.6%	-4.1%	-1.9%	0.0%	1.4%	2.1%	1.8%	0.3%	-3.4%	-8.4%
1.05	-18.0%	-14.2%	-10.9%	-7.9%	-5.2%	-2.9%	-0.9%	0.8%	1.8%	2.0%	1.1%	-2.0%	-6.6%
1.10	-19.8%	-15.9%	-12.3%	-9.2%	-6.4%	-4.0%	-1.8%	0.0%	1.3%	2.0%	1.5%	-0.9%	-5.1%
1.15	-21.6%	-17.5%	-13.8%	-10.6%	-7.6%	-5.1%	-2.8%	-0.9%	0.6%	1.6%	1.6%	-0.1%	-3.8%
1.20	-23.5%	-19.2%	-15.4%	-11.9%	-8.9%	-6.2%	-3.9%	-1.8%	-0.1%	1.1%	1.5%	0.5%	-2.8%

Wind Speed:	4 m/s												
			Percentage Difference from Baseline										
Chord Scale	RPM	Baseline											
Factor	7.58	7.28	6.97	6.67	6.37	6.06	5.76	5.46	5.15	4.85	4.55	4.24	3.94
0.80	3.9%	7.7%	11.1%	14.1%	16.6%	18.6%	19.9%	20.4%	20.0%	18.6%	15.9%	11.1%	5.1%
0.85	1.9%	5.9%	9.5%	12.8%	15.6%	17.9%	19.8%	20.8%	21.0%	20.2%	18.1%	13.9%	8.2%
0.90	-0.3%	4.0%	7.9%	11.3%	14.3%	17.0%	19.2%	20.7%	21.4%	21.2%	19.7%	16.3%	11.0%
0.95	-2.5%	2.0%	6.1%	9.7%	13.0%	15.8%	18.2%	20.2%	21.4%	21.7%	20.8%	18.2%	13.3%
1.00	-4.7%	0.0%	4.3%	8.1%	11.5%	14.5%	17.1%	19.4%	21.0%	21.8%	21.5%	19.7%	15.3%
1.05	-7.0%	-2.1%	2.4%	6.4%	10.0%	13.1%	15.9%	18.3%	20.3%	21.5%	21.8%	20.6%	17.0%
1.10	-9.4%	-4.3%	0.4%	4.6%	8.4%	11.7%	14.6%	17.2%	19.3%	20.9%	21.7%	21.1%	18.3%
1.15	-11.8%	-6.4%	-1.6%	2.9%	6.8%	10.2%	13.3%	16.0%	18.3%	20.1%	21.3%	21.3%	19.3%
1.20	-14.2%	-8.7%	-3.6%	1.0%	5.1%	8.7%	11.9%	14.7%	17.2%	19.2%	20.6%	21.2%	20.0%

Appendix G

Power Results for WindPACT 1.5MW Turbine Radius Study

Wind Speed: 10 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 25.00	24.00	23.00	22.00	21.00	20.00	Baseline 19.10	19.00	18.00	17.00	16.00	15.00	14.00
0.80	-41.9%	-40.7%	-39.6%	-38.7%	-38.1%	-38.0%	-38.9%	-39.0%	-41.8%	-46.1%	-51.9%	-58.8%	-66.4%
0.85	-35.0%	-33.4%	-32.0%	-30.8%	-29.8%	-29.2%	-29.4%	-29.5%	-31.6%	-35.6%	-41.3%	-48.6%	-57.0%
0.90	-27.9%	-26.0%	-24.2%	-22.6%	-21.2%	-20.2%	-19.8%	-19.9%	-21.2%	-24.6%	-30.1%	-37.5%	-46.6%
0.95	-20.8%	-18.3%	-16.1%	-14.1%	-12.4%	-10.9%	-10.0%	-10.0%	-10.5%	-13.2%	-18.3%	-25.8%	-35.2%
1.00	-13.7%	-10.5%	-7.8%	-5.4%	-3.3%	-1.4%	0.0%	0.1%	0.4%	-1.7%	-6.2%	-13.4%	-23.1%
1.05	-6.6%	-2.8%	0.6%	3.5%	6.1%	8.4%	10.3%	10.5%	11.5%	10.2%	6.3%	-0.5%	-10.3%
1.10	0.5%	4.9%	9.0%	12.6%	15.7%	18.5%	20.7%	21.0%	22.8%	22.4%	19.0%	12.8%	3.1%
1.15	7.4%	12.6%	17.4%	21.8%	25.6%	28.9%	31.5%	31.8%	34.3%	34.8%	32.2%	26.4%	17.1%
1.20	14.2%	20.2%	25.8%	31.0%	35.5%	39.4%	42.6%	42.9%	45.9%	47.5%	45.7%	40.3%	31.5%

Wind Speed: 8 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 21.00	20.00	19.00	18.00	17.00	16.00	Baseline 15.28	15.00	14.00	13.00	12.00	11.00	10.00
0.80	-43.6%	-41.9%	-40.4%	-39.1%	-38.2%	-38.0%	-38.9%	-39.6%	-43.8%	-50.3%	-58.8%	-68.3%	-77.6%
0.85	-37.1%	-35.0%	-33.1%	-31.4%	-30.0%	-29.2%	-29.4%	-29.9%	-33.4%	-39.7%	-48.6%	-59.2%	-70.3%
0.90	-30.7%	-27.9%	-25.5%	-23.4%	-21.5%	-20.2%	-19.8%	-20.0%	-22.6%	-28.5%	-37.5%	-49.0%	-61.6%
0.95	-24.3%	-20.8%	-17.7%	-15.1%	-12.8%	-10.9%	-10.0%	-9.9%	-11.6%	-16.8%	-25.8%	-37.8%	-51.9%
1.00	-17.9%	-13.7%	-9.8%	-6.6%	-3.8%	-1.4%	0.0%	0.3%	-0.3%	-4.8%	-13.4%	-25.8%	-41.1%
1.05	-11.6%	-6.6%	-1.9%	2.1%	5.5%	8.4%	10.3%	10.9%	11.2%	7.5%	-0.5%	-13.1%	-29.4%
1.10	-5.5%	0.5%	5.9%	10.9%	15.0%	18.5%	20.7%	21.5%	22.9%	20.1%	12.8%	0.2%	-16.7%
1.15	0.5%	7.4%	13.8%	19.7%	24.7%	28.9%	31.5%	32.5%	34.9%	33.2%	26.4%	14.2%	-3.3%
1.20	6.1%	14.2%	21.6%	28.4%	34.5%	39.4%	42.6%	43.7%	47.1%	46.4%	40.2%	28.6%	10.8%

Wind Speed: 6 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 19.00	18.00	17.00	16.00	15.00	Baseline 14.73	14.00	13.00	12.00	11.00	10.00	9.00	8.00
0.80	-49.2%	-45.4%	-41.9%	-38.9%	-36.4%	-35.8%	-34.2%	-32.6%	-32.1%	-35.1%	-42.9%	-54.9%	-68.8%
0.85	-45.0%	-40.2%	-35.9%	-32.0%	-28.8%	-28.0%	-26.1%	-23.7%	-22.5%	-24.1%	-31.3%	-43.7%	-59.4%
0.90	-41.2%	-35.3%	-30.0%	-25.2%	-21.0%	-20.1%	-17.6%	-14.7%	-12.6%	-12.9%	-19.1%	-31.6%	-48.7%
0.95	-38.0%	-30.7%	-24.2%	-18.5%	-13.2%	-11.9%	-8.9%	-5.3%	-2.4%	-1.5%	-6.5%	-18.7%	-36.9%
1.00	-35.4%	-26.5%	-18.7%	-11.7%	-5.4%	-3.9%	0.0%	4.4%	8.0%	10.1%	6.4%	-5.2%	-24.1%
1.05	-33.6%	-23.0%	-13.5%	-5.1%	2.3%	4.2%	9.0%	14.4%	18.8%	21.9%	19.6%	8.9%	-10.4%
1.10	-32.8%	-20.1%	-8.7%	1.3%	10.0%	12.2%	17.9%	24.5%	29.8%	34.1%	33.2%	23.5%	4.1%
1.15	-33.1%	-18.0%	-4.5%	7.3%	17.7%	20.2%	26.9%	34.9%	41.2%	46.3%	47.1%	38.4%	19.3%
1.20	-34.5%	-16.8%	-1.0%	13.0%	25.1%	28.1%	35.8%	45.2%	52.7%	58.8%	61.3%	53.6%	35.1%

Wind Speed:	4 m/s										
			Percentage Difference from Baseline								
Radius Scale	RPM	Baseline									
Factor	14.00	13.10	13.00	12.00	11.00	10.00	9.00	8.00	7.00	6.00	5.00
0.80	-42.9%	-34.5%	-33.6%	-25.6%	-18.7%	-13.4%	-9.2%	-7.5%	-16.2%	-38.6%	-66.6%
0.85	-40.4%	-29.7%	-28.6%	-18.6%	-10.0%	-3.1%	2.3%	5.5%	-0.6%	-23.4%	-55.7%
0.90	-39.0%	-25.7%	-24.3%	-11.9%	-1.4%	7.5%	14.2%	19.0%	15.5%	-6.8%	-42.8%
0.95	-38.9%	-22.6%	-20.9%	-5.7%	7.1%	18.1%	26.6%	32.9%	31.8%	10.7%	-28.3%
1.00	-40.4%	-20.7%	-18.6%	0.0%	15.5%	28.7%	39.3%	47.1%	48.6%	29.1%	-12.2%
1.05	-43.8%	-20.0%	-17.6%	4.9%	23.6%	39.3%	52.2%	61.6%	65.8%	48.3%	5.3%
1.10	-49.2%	-20.9%	-18.0%	8.8%	31.3%	49.8%	65.3%	76.7%	83.3%	68.1%	24.2%
1.15	-56.9%	-23.4%	-20.0%	11.7%	38.3%	60.2%	78.4%	92.1%	101.2%	88.4%	44.2%
1.20	-67.4%	-28.0%	-23.9%	13.2%	44.6%	70.3%	91.5%	107.9%	119.3%	109.1%	65.2%

Appendix H

Thrust Results for WindPACT 1.5MW Turbine Radius Study

Wind Speed: 10 m/s

Percentage Difference from Baseline

Radius Scale	RPM						Baseline						
Factor	25.00	24.00	23.00	22.00	21.00	20.00	19.10	19.00	18.00	17.00	16.00	15.00	14.00
0.80	-25.5%	-27.8%	-30.1%	-32.6%	-35.2%	-38.2%	-41.6%	-42.0%	-46.4%	-51.4%	-56.9%	-62.6%	-68.0%
0.85	-14.5%	-17.1%	-19.8%	-22.5%	-25.4%	-28.6%	-31.9%	-32.3%	-36.9%	-42.2%	-48.2%	-54.7%	-61.1%
0.90	-2.7%	-5.7%	-8.7%	-11.8%	-15.0%	-18.4%	-21.7%	-22.1%	-26.9%	-32.4%	-38.9%	-45.9%	-53.3%
0.95	10.1%	6.6%	3.1%	-0.4%	-3.9%	-7.6%	-11.2%	-11.6%	-16.3%	-22.1%	-28.9%	-36.5%	-44.7%
1.00	23.8%	19.8%	15.8%	11.9%	7.9%	3.9%	0.0%	-0.4%	-5.2%	-11.3%	-18.3%	-26.4%	-35.3%
1.05	38.5%	33.9%	29.4%	24.9%	20.5%	16.0%	11.8%	11.3%	6.2%	0.2%	-7.2%	-15.7%	-25.2%
1.10	54.2%	49.0%	43.9%	38.8%	33.8%	28.8%	24.2%	23.7%	18.3%	12.1%	4.4%	-4.5%	-14.6%
1.15	70.7%	65.1%	59.3%	53.6%	48.0%	42.4%	37.3%	36.8%	31.0%	24.4%	16.6%	7.2%	-3.3%
1.20	88.3%	82.1%	75.7%	69.3%	63.0%	56.7%	51.1%	50.5%	44.2%	37.3%	29.3%	19.5%	8.4%

Wind Speed: 8 m/s

Percentage Difference from Baseline

Radius Scale	RPM						Baseline						
Factor	21.00	20.00	19.00	18.00	17.00	16.00	15.28	15.00	14.00	13.00	12.00	11.00	10.00
0.80	-22.6%	-25.5%	-28.3%	-31.3%	-34.5%	-38.2%	-41.6%	-43.0%	-48.8%	-55.5%	-62.6%	-69.3%	-75.4%
0.85	-11.2%	-14.5%	-17.8%	-21.1%	-24.7%	-28.6%	-31.9%	-33.4%	-39.5%	-46.7%	-54.7%	-62.6%	-70.0%
0.90	1.2%	-2.7%	-6.5%	-10.3%	-14.2%	-18.4%	-21.7%	-23.2%	-29.6%	-37.2%	-45.9%	-55.1%	-63.8%
0.95	14.6%	10.1%	5.7%	1.4%	-3.0%	-7.6%	-11.2%	-12.6%	-19.1%	-27.1%	-36.5%	-46.7%	-56.9%
1.00	28.9%	23.8%	18.8%	13.9%	8.9%	3.9%	0.0%	-1.6%	-8.1%	-16.4%	-26.4%	-37.6%	-49.1%
1.05	44.2%	38.5%	32.8%	27.2%	21.6%	16.0%	11.8%	10.1%	3.4%	-5.3%	-15.7%	-27.7%	-40.7%
1.10	60.5%	54.2%	47.8%	41.3%	35.1%	28.8%	24.3%	22.4%	15.3%	6.5%	-4.5%	-17.3%	-31.4%
1.15	77.8%	70.8%	63.7%	56.4%	49.4%	42.4%	37.3%	35.4%	27.8%	18.8%	7.2%	-6.2%	-21.4%
1.20	96.1%	88.3%	80.5%	72.5%	64.5%	56.8%	51.1%	49.0%	40.9%	31.4%	19.5%	5.4%	-10.8%

Wind Speed: 6 m/s

Percentage Difference from Baseline

Radius Scale	RPM					Baseline							
Factor	19.00	18.00	17.00	16.00	15.00	14.73	14.00	13.00	12.00	11.00	10.00	9.00	8.00
0.80	-23.3%	-26.5%	-29.8%	-33.1%	-36.4%	-37.2%	-39.6%	-43.2%	-47.3%	-52.9%	-60.1%	-68.0%	-75.6%
0.85	-11.8%	-15.6%	-19.3%	-23.2%	-27.0%	-28.0%	-30.8%	-34.7%	-39.0%	-44.8%	-52.3%	-61.3%	-70.2%
0.90	0.6%	-3.7%	-8.0%	-12.5%	-16.9%	-18.1%	-21.2%	-25.6%	-30.3%	-36.1%	-44.1%	-53.8%	-64.2%
0.95	14.0%	9.0%	4.1%	-0.9%	-6.0%	-7.4%	-11.0%	-15.9%	-21.1%	-27.0%	-35.3%	-45.8%	-57.5%
1.00	28.5%	22.7%	17.1%	11.5%	5.7%	4.2%	0.0%	-5.6%	-11.3%	-17.6%	-26.2%	-37.2%	-50.0%
1.05	44.0%	37.5%	31.0%	24.7%	18.3%	16.5%	11.7%	5.4%	-1.0%	-7.8%	-16.5%	-28.0%	-42.0%
1.10	60.7%	53.3%	45.9%	38.8%	31.6%	29.7%	24.3%	17.1%	10.0%	2.6%	-6.3%	-18.4%	-33.3%
1.15	78.5%	70.1%	61.8%	53.8%	45.8%	43.6%	37.7%	29.5%	21.6%	13.5%	4.1%	-8.4%	-24.1%
1.20	97.5%	88.1%	78.8%	69.7%	60.8%	58.4%	51.8%	42.7%	33.8%	25.0%	15.0%	2.0%	-14.4%

Wind Speed:	4 m/s										
			Percentage Difference from Baseline								
Radius Scale	RPM	Baseline									
Factor	14.00	13.10	13.00	12.00	11.00	10.00	9.00	8.00	7.00	6.00	5.00
0.80	-32.3%	-35.8%	-36.2%	-40.1%	-44.2%	-48.2%	-52.2%	-57.0%	-64.4%	-74.0%	-82.9%
0.85	-22.0%	-26.2%	-26.6%	-31.2%	-35.9%	-40.5%	-45.2%	-50.3%	-57.9%	-68.5%	-79.1%
0.90	-10.9%	-15.7%	-16.3%	-21.6%	-26.9%	-32.3%	-37.6%	-43.2%	-51.0%	-62.4%	-74.8%
0.95	1.2%	-4.4%	-5.1%	-11.2%	-17.2%	-23.4%	-29.5%	-35.7%	-43.8%	-55.8%	-70.0%
1.00	14.2%	7.8%	7.0%	0.0%	-6.9%	-13.9%	-20.8%	-27.7%	-36.0%	-48.8%	-64.6%
1.05	28.2%	20.9%	20.1%	12.0%	4.2%	-3.6%	-11.6%	-19.3%	-28.1%	-41.4%	-58.7%
1.10	43.3%	34.9%	34.0%	24.9%	16.0%	7.2%	-1.7%	-10.4%	-19.8%	-33.6%	-52.3%
1.15	59.3%	49.9%	48.9%	38.6%	28.5%	18.8%	8.8%	-1.0%	-11.1%	-25.4%	-45.3%
1.20	76.5%	65.9%	64.8%	53.2%	41.9%	31.0%	20.0%	9.0%	-2.0%	-16.9%	-37.9%

Appendix I

Root Bending Moment Results for WindPACT 1.5MW Turbine Radius Study

Wind Speed: 10 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 25.00	24.00	23.00	22.00	21.00	20.00	Baseline 19.10	19.00	18.00	17.00	16.00	15.00	14.00
0.80	-41.0%	-43.0%	-45.0%	-47.1%	-49.2%	-51.5%	-54.0%	-54.2%	-57.3%	-60.9%	-65.0%	-69.3%	-73.6%
0.85	-27.4%	-29.9%	-32.4%	-34.9%	-37.5%	-40.2%	-42.9%	-43.2%	-46.7%	-50.7%	-55.4%	-60.5%	-65.8%
0.90	-11.8%	-14.9%	-17.9%	-21.0%	-24.1%	-27.2%	-30.2%	-30.6%	-34.6%	-39.1%	-44.3%	-50.2%	-56.6%
0.95	6.1%	2.3%	-1.4%	-5.1%	-8.8%	-12.5%	-16.0%	-16.4%	-20.8%	-26.0%	-31.8%	-38.4%	-45.8%
1.00	26.5%	21.9%	17.4%	12.9%	8.5%	4.1%	0.0%	-0.5%	-5.3%	-11.1%	-17.7%	-25.0%	-33.3%
1.05	49.6%	44.1%	38.6%	33.3%	28.0%	22.8%	18.0%	17.5%	11.9%	5.6%	-1.9%	-10.1%	-19.3%
1.10	75.6%	69.0%	62.4%	56.1%	49.8%	43.6%	38.1%	37.5%	31.1%	24.1%	15.8%	6.6%	-3.7%
1.15	104.5%	96.8%	89.1%	81.5%	74.1%	66.9%	60.4%	59.7%	52.4%	44.5%	35.5%	25.1%	13.7%
1.20	136.6%	127.7%	118.8%	109.8%	101.1%	92.7%	85.1%	84.3%	76.0%	67.0%	57.1%	45.6%	32.9%

Wind Speed: 8 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 21.00	20.00	19.00	18.00	17.00	16.00	Baseline 15.28	15.00	14.00	13.00	12.00	11.00	10.00
0.80	-38.4%	-41.0%	-43.5%	-46.0%	-48.7%	-51.5%	-54.0%	-55.0%	-59.1%	-63.9%	-69.3%	-74.6%	-79.6%
0.85	-24.3%	-27.4%	-30.5%	-33.6%	-36.9%	-40.2%	-42.9%	-44.0%	-48.7%	-54.2%	-60.5%	-67.1%	-73.5%
0.90	-7.8%	-11.8%	-15.6%	-19.5%	-23.3%	-27.2%	-30.2%	-31.5%	-36.8%	-43.0%	-50.2%	-58.2%	-66.0%
0.95	11.0%	6.1%	1.4%	-3.2%	-7.8%	-12.5%	-16.0%	-17.4%	-23.3%	-30.2%	-38.4%	-47.7%	-57.2%
1.00	32.4%	26.5%	20.8%	15.2%	9.6%	4.1%	0.0%	-1.6%	-8.0%	-16.0%	-25.0%	-35.5%	-46.9%
1.05	56.6%	49.6%	42.7%	35.9%	29.3%	22.8%	18.0%	16.1%	8.9%	0.1%	-10.1%	-21.8%	-34.9%
1.10	83.7%	75.6%	67.3%	59.2%	51.4%	43.6%	38.1%	35.9%	27.7%	18.1%	6.6%	-6.4%	-21.3%
1.15	114.1%	104.5%	94.9%	85.3%	76.0%	66.9%	60.4%	57.9%	48.6%	37.9%	25.1%	10.6%	-5.9%
1.20	147.9%	136.6%	125.5%	114.3%	103.3%	92.7%	85.1%	82.2%	71.6%	59.7%	45.6%	29.5%	11.2%

Wind Speed: 6 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 19.00	18.00	17.00	16.00	15.00	Baseline 14.73	14.00	13.00	12.00	11.00	10.00	9.00	8.00
0.80	-38.7%	-41.6%	-44.6%	-47.5%	-50.3%	-51.1%	-53.2%	-56.1%	-59.2%	-63.2%	-68.2%	-74.2%	-80.1%
0.85	-24.4%	-28.0%	-31.7%	-35.4%	-39.0%	-39.9%	-42.4%	-46.0%	-49.7%	-54.2%	-59.8%	-66.8%	-74.2%
0.90	-7.8%	-12.4%	-16.8%	-21.4%	-25.8%	-27.0%	-30.1%	-34.4%	-38.8%	-43.8%	-50.2%	-58.1%	-67.1%
0.95	11.2%	5.6%	0.2%	-5.3%	-10.8%	-12.2%	-16.0%	-21.2%	-26.4%	-32.0%	-39.3%	-48.2%	-58.7%
1.00	32.9%	26.2%	19.5%	13.0%	6.4%	4.7%	0.0%	-6.2%	-12.4%	-18.9%	-27.0%	-37.0%	-49.0%
1.05	57.6%	49.4%	41.5%	33.6%	25.9%	23.7%	18.1%	10.6%	3.3%	-4.3%	-13.2%	-24.4%	-37.8%
1.10	85.5%	75.7%	66.1%	56.8%	47.7%	45.2%	38.4%	29.5%	20.8%	12.1%	2.2%	-10.3%	-25.3%
1.15	116.8%	105.2%	93.8%	82.8%	72.0%	69.1%	61.2%	50.6%	40.3%	30.3%	19.2%	5.2%	-11.4%
1.20	151.8%	138.1%	124.7%	111.7%	99.0%	95.7%	86.6%	74.0%	62.0%	50.3%	37.8%	22.4%	4.0%

Wind Speed:	4 m/s										
			Percentage Difference from Baseline								
Radius Scale	RPM	Baseline									
Factor	14.00	13.10	13.00	12.00	11.00	10.00	9.00	8.00	7.00	6.00	5.00
0.80	-46.7%	-49.9%	-50.2%	-53.7%	-57.3%	-60.6%	-64.0%	-67.7%	-72.7%	-79.5%	-86.4%
0.85	-34.2%	-38.2%	-38.6%	-43.0%	-47.3%	-51.6%	-55.8%	-60.1%	-65.8%	-73.7%	-82.3%
0.90	-19.6%	-24.6%	-25.1%	-30.5%	-35.9%	-41.2%	-46.3%	-51.5%	-57.9%	-66.8%	-77.3%
0.95	-2.8%	-9.0%	-9.6%	-16.3%	-22.7%	-29.2%	-35.5%	-41.7%	-48.9%	-58.9%	-71.5%
1.00	16.4%	8.9%	8.1%	0.0%	-7.8%	-15.6%	-23.2%	-30.6%	-38.7%	-50.0%	-64.6%
1.05	38.3%	29.2%	28.2%	18.5%	9.0%	-0.2%	-9.4%	-18.1%	-27.4%	-40.0%	-56.6%
1.10	63.0%	52.2%	51.0%	39.3%	28.0%	17.1%	6.1%	-4.2%	-14.9%	-28.9%	-47.5%
1.15	90.8%	77.9%	76.5%	62.6%	49.2%	36.3%	23.5%	11.3%	-1.0%	-16.6%	-37.3%
1.20	122.0%	106.7%	105.1%	88.7%	72.9%	57.8%	42.9%	28.5%	14.4%	-2.9%	-25.8%

Appendix J

Power Results for NREL 5MW Turbine Radius Study

Wind Speed: 10 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 16.00	15.00	14.00	13.00	12.00	11.00	Baseline 10.61	10.00	9.00	8.00	7.00	6.00	5.00
0.80	-37.8%	-36.7%	-35.8%	-35.4%	-36.1%	-38.5%	-39.7%	-42.8%	-54.4%	-65.5%	-75.6%	-84.6%	-92.0%
0.85	-30.3%	-28.7%	-27.5%	-26.8%	-27.1%	-29.4%	-30.6%	-33.2%	-43.2%	-57.2%	-69.4%	-80.3%	-89.3%
0.90	-22.6%	-20.6%	-18.9%	-17.9%	-17.8%	-19.6%	-21.0%	-23.6%	-31.3%	-47.5%	-62.3%	-75.2%	-86.1%
0.95	-14.9%	-12.3%	-10.1%	-8.6%	-8.2%	-9.4%	-10.7%	-13.5%	-20.1%	-36.5%	-54.2%	-69.4%	-82.4%
1.00	-7.2%	-3.9%	-1.1%	0.9%	1.8%	1.0%	0.0%	-2.8%	-9.4%	-23.5%	-44.8%	-62.9%	-78.2%
1.05	0.5%	4.6%	8.0%	10.7%	12.0%	11.6%	10.8%	8.4%	1.6%	-10.4%	-34.2%	-55.6%	-73.4%
1.10	7.9%	13.0%	17.2%	20.6%	22.6%	22.6%	22.0%	20.0%	13.0%	2.0%	-22.6%	-47.4%	-67.9%
1.15	15.0%	21.2%	26.4%	30.6%	33.3%	33.9%	33.4%	31.7%	25.0%	14.1%	-8.9%	-38.2%	-61.9%
1.20	21.7%	29.3%	35.6%	40.7%	44.2%	45.4%	45.1%	43.7%	37.5%	26.3%	5.7%	-27.8%	-55.2%

Wind Speed: 8 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 14.00	13.00	12.00	11.00	10.00	9.00	Baseline 8.49	8.00	7.00	6.00	5.00	4.00	3.00
0.80	-40.0%	-38.2%	-36.7%	-35.6%	-35.6%	-37.8%	-39.7%	-42.8%	-57.2%	-70.7%	-82.6%	-92.0%	-97.8%
0.85	-33.2%	-30.8%	-28.7%	-27.3%	-26.8%	-28.6%	-30.6%	-33.2%	-47.1%	-63.5%	-77.7%	-89.3%	-96.9%
0.90	-26.4%	-23.2%	-20.6%	-18.6%	-17.7%	-18.9%	-21.0%	-23.6%	-34.9%	-55.2%	-72.1%	-86.1%	-95.8%
0.95	-19.7%	-15.6%	-12.3%	-9.7%	-8.2%	-8.9%	-10.7%	-13.5%	-22.9%	-45.5%	-65.8%	-82.4%	-94.4%
1.00	-13.2%	-8.1%	-3.9%	-0.5%	1.5%	1.4%	0.0%	-2.8%	-11.7%	-34.8%	-58.7%	-78.2%	-92.5%
1.05	-7.1%	-0.7%	4.6%	8.7%	11.5%	11.9%	10.8%	8.4%	-0.6%	-22.2%	-50.7%	-73.4%	-90.4%
1.10	-1.5%	6.5%	13.0%	18.1%	21.8%	22.8%	22.0%	20.0%	10.8%	-8.3%	-41.6%	-67.9%	-87.8%
1.15	3.6%	13.3%	21.2%	27.6%	32.2%	33.9%	33.4%	31.7%	22.6%	5.4%	-31.3%	-61.9%	-84.9%
1.20	8.0%	19.6%	29.2%	37.0%	42.7%	45.3%	45.1%	43.6%	35.0%	18.2%	-19.8%	-55.2%	-81.6%

Wind Speed: 6 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 14.00	13.00	12.00	11.00	10.00	9.00	Baseline 8.19	8.00	7.00	6.00	5.00	4.00	3.00
0.80	-54.1%	-49.1%	-44.8%	-41.3%	-38.6%	-36.5%	-35.4%	-35.2%	-36.6%	-42.7%	-61.8%	-78.7%	-92.0%
0.85	-51.6%	-45.0%	-39.5%	-34.9%	-31.3%	-28.5%	-27.0%	-26.7%	-27.4%	-33.0%	-52.6%	-73.1%	-89.3%
0.90	-50.1%	-41.6%	-34.5%	-28.6%	-24.0%	-20.3%	-18.2%	-17.9%	-17.9%	-23.4%	-42.1%	-66.7%	-86.0%
0.95	-49.7%	-39.0%	-30.1%	-22.6%	-16.6%	-12.0%	-9.2%	-8.7%	-8.1%	-13.2%	-29.5%	-59.4%	-82.3%
1.00	-50.9%	-37.5%	-26.3%	-16.9%	-9.4%	-3.6%	0.0%	0.7%	2.1%	-2.5%	-16.8%	-51.1%	-78.1%
1.05	-54.0%	-37.2%	-23.3%	-11.8%	-2.4%	4.9%	9.4%	10.2%	12.5%	8.7%	-4.9%	-41.7%	-73.3%
1.10	-59.3%	-38.4%	-21.3%	-7.2%	4.3%	13.3%	18.8%	19.9%	23.2%	20.4%	6.8%	-30.8%	-67.9%
1.15	-67.0%	-41.5%	-20.5%	-3.4%	10.6%	21.6%	28.4%	29.7%	34.2%	32.1%	18.6%	-19.2%	-61.8%
1.20	-77.4%	-46.8%	-21.2%	-0.5%	16.3%	29.6%	37.9%	39.6%	45.3%	44.1%	30.9%	-5.8%	-55.1%

Wind Speed:		4 m/s									
				Percentage Difference from Baseline							
	Radius Scale	RPM			Baseline						
	Factor	10.00	9.00	8.00	7.28	7.00	6.00	5.00	4.00	3.00	2.00	1.00
	0.80	-52.3%	-42.1%	-34.1%	-29.6%	-28.2%	-24.1%	-22.8%	-31.5%	-65.0%	-90.4%	-99.4%
	0.85	-51.4%	-38.1%	-27.7%	-21.9%	-20.0%	-14.6%	-12.3%	-20.0%	-56.3%	-87.2%	-99.3%
	0.90	-52.2%	-35.1%	-21.8%	-14.3%	-11.8%	-4.9%	-1.4%	-8.5%	-46.3%	-83.3%	-99.1%
	0.95	-55.2%	-33.3%	-16.5%	-6.9%	-3.8%	5.1%	9.9%	3.6%	-34.7%	-78.9%	-98.9%
	1.00	-60.6%	-33.0%	-11.9%	0.0%	4.0%	15.1%	21.6%	16.4%	-21.9%	-73.9%	-98.6%
	1.05	-69.0%	-34.6%	-8.4%	6.3%	11.3%	25.3%	33.6%	29.8%	-6.8%	-68.1%	-98.2%
	1.10	-80.7%	-38.3%	-6.0%	12.0%	18.0%	35.3%	45.9%	43.7%	9.8%	-61.6%	-97.6%
	1.15	-96.3%	-44.7%	-5.1%	16.8%	24.1%	45.2%	58.3%	57.7%	26.2%	-54.4%	-97.0%
	1.20	-116.3%	-54.0%	-6.0%	20.5%	29.3%	54.8%	70.9%	72.1%	41.6%	-46.3%	-96.2%

Appendix K

Thrust Results for NREL 5MW Turbine Radius Study

Wind Speed: 10 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM						Baseline						
	16.00	15.00	14.00	13.00	12.00	11.00	10.61	10.00	9.00	8.00	7.00	6.00	5.00
0.80	-20.9%	-23.2%	-25.6%	-28.5%	-32.1%	-36.9%	-39.1%	-43.4%	-54.4%	-62.9%	-70.8%	-78.4%	-85.4%
0.85	-10.7%	-13.2%	-15.8%	-18.9%	-22.7%	-27.7%	-30.0%	-34.2%	-44.6%	-56.2%	-65.2%	-74.1%	-82.3%
0.90	0.0%	-2.6%	-5.5%	-8.9%	-12.8%	-18.0%	-20.4%	-24.8%	-34.2%	-48.5%	-59.2%	-69.3%	-78.7%
0.95	11.3%	8.4%	5.3%	1.7%	-2.5%	-7.9%	-10.5%	-14.9%	-24.1%	-39.3%	-52.5%	-64.0%	-74.9%
1.00	23.0%	19.9%	16.5%	12.7%	8.2%	2.6%	0.0%	-4.7%	-14.1%	-28.4%	-45.3%	-58.3%	-70.7%
1.05	35.2%	31.9%	28.3%	24.2%	19.4%	13.5%	10.8%	5.9%	-3.9%	-17.3%	-37.2%	-52.1%	-66.0%
1.10	47.9%	44.4%	40.5%	36.1%	31.0%	24.8%	22.1%	17.0%	6.8%	-6.6%	-27.9%	-45.4%	-61.0%
1.15	61.0%	57.2%	53.1%	48.5%	43.1%	36.5%	33.6%	28.4%	17.9%	4.2%	-16.7%	-38.2%	-55.6%
1.20	74.4%	70.5%	66.2%	61.3%	55.6%	48.7%	45.6%	40.3%	29.3%	15.2%	-5.0%	-30.4%	-49.7%

Wind Speed: 8 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM						Baseline						
	14.00	13.00	12.00	11.00	10.00	9.00	8.49	8.00	7.00	6.00	5.00	4.00	3.00
0.80	-25.4%	-27.9%	-30.8%	-34.3%	-39.0%	-45.1%	-49.0%	-54.2%	-65.0%	-73.3%	-81.2%	-88.4%	-94.0%
0.85	-13.7%	-16.3%	-19.4%	-23.0%	-27.7%	-33.9%	-37.8%	-42.4%	-55.9%	-66.4%	-76.1%	-84.9%	-92.2%
0.90	-1.0%	-3.9%	-7.1%	-10.9%	-15.7%	-22.0%	-26.0%	-30.5%	-44.0%	-58.4%	-70.0%	-80.9%	-90.1%
0.95	12.7%	9.5%	5.9%	1.9%	-2.9%	-9.3%	-13.4%	-18.0%	-30.5%	-49.1%	-63.1%	-76.1%	-87.5%
1.00	27.2%	23.8%	19.9%	15.6%	10.5%	4.1%	0.0%	-4.7%	-17.0%	-37.9%	-55.1%	-70.7%	-84.4%
1.05	42.7%	39.0%	34.8%	30.1%	24.8%	18.2%	14.1%	9.4%	-3.2%	-23.7%	-46.0%	-64.4%	-80.7%
1.10	59.1%	55.1%	50.6%	45.6%	39.9%	33.0%	28.9%	24.1%	11.4%	-8.0%	-35.8%	-57.1%	-76.4%
1.15	76.4%	72.1%	67.4%	62.0%	55.8%	48.7%	44.4%	39.6%	26.7%	7.7%	-24.2%	-49.0%	-71.5%
1.20	94.6%	90.1%	85.0%	79.2%	72.7%	65.1%	60.6%	55.8%	42.8%	23.6%	-10.6%	-39.9%	-66.0%

Wind Speed: 6 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM						Baseline						
	14.00	13.00	12.00	11.00	10.00	9.00	8.19	8.00	7.00	6.00	5.00	4.00	3.00
0.80	-27.7%	-29.6%	-31.7%	-34.0%	-36.7%	-39.9%	-43.3%	-44.2%	-50.4%	-60.2%	-72.1%	-81.5%	-89.9%
0.85	-16.8%	-18.8%	-21.1%	-23.7%	-26.6%	-30.0%	-33.5%	-34.4%	-40.7%	-50.0%	-65.0%	-76.5%	-86.9%
0.90	-5.0%	-7.2%	-9.7%	-12.5%	-15.7%	-19.4%	-23.0%	-24.0%	-30.3%	-39.7%	-56.4%	-70.7%	-83.4%
0.95	7.6%	5.2%	2.5%	-0.5%	-4.0%	-8.1%	-11.9%	-12.9%	-19.2%	-28.8%	-45.2%	-64.0%	-79.3%
1.00	20.9%	18.4%	15.5%	12.2%	8.4%	4.1%	0.0%	-1.0%	-7.6%	-17.3%	-32.9%	-56.3%	-74.6%
1.05	34.9%	32.4%	29.3%	25.8%	21.7%	17.0%	12.6%	11.5%	4.6%	-5.1%	-20.6%	-47.6%	-69.1%
1.10	49.7%	47.1%	43.9%	40.2%	35.8%	30.7%	26.0%	24.8%	17.6%	7.7%	-8.0%	-37.6%	-62.8%
1.15	65.2%	62.5%	59.2%	55.3%	50.7%	45.2%	40.2%	38.9%	31.2%	21.2%	5.2%	-25.3%	-55.7%
1.20	81.4%	78.7%	75.3%	71.2%	66.4%	60.6%	55.1%	53.7%	45.6%	35.2%	19.1%	-10.6%	-47.9%

Wind Speed:	4 m/s									
			Percentage Difference from Baseline							
Radius Scale	RPM			Baseline						
Factor	10.00	9.00	8.00	7.28	7.00	6.00	5.00	4.00	3.00	2.00	1.00
0.80	-34.0%	-36.2%	-39.0%	-41.2%	-42.2%	-46.3%	-52.7%	-64.5%	-79.3%	-91.0%	-97.9%
0.85	-24.0%	-26.5%	-29.5%	-32.0%	-33.1%	-37.5%	-43.9%	-55.3%	-73.9%	-88.3%	-97.3%
0.90	-13.4%	-16.1%	-19.3%	-22.0%	-23.2%	-28.0%	-34.6%	-46.1%	-67.7%	-85.2%	-96.6%
0.95	-2.1%	-4.9%	-8.4%	-11.4%	-12.7%	-17.9%	-24.8%	-36.4%	-60.5%	-81.5%	-95.9%
1.00	9.9%	6.9%	3.2%	0.0%	-1.4%	-7.0%	-14.3%	-26.1%	-51.9%	-77.3%	-95.0%
1.05	22.5%	19.4%	15.5%	12.1%	10.6%	4.5%	-3.2%	-15.2%	-40.9%	-72.4%	-93.9%
1.10	35.7%	32.6%	28.6%	24.9%	23.3%	16.8%	8.4%	-3.8%	-28.7%	-66.8%	-92.6%
1.15	49.8%	46.4%	42.3%	38.4%	36.8%	29.8%	20.8%	8.3%	-16.5%	-60.5%	-91.2%
1.20	65.4%	60.9%	56.6%	52.7%	50.9%	43.4%	33.9%	20.8%	-4.2%	-53.4%	-89.5%

Appendix L

Root Bending Moment Results for NREL 5MW Turbine Radius Study

Wind Speed: 10 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 16.00	15.00	14.00	13.00	12.00	11.00	Baseline 10.61	10.00	9.00	8.00	7.00	6.00	5.00
0.80	-36.2%	-38.4%	-40.7%	-43.3%	-46.5%	-50.5%	-52.3%	-55.5%	-63.3%	-70.0%	-76.4%	-82.6%	-88.3%
0.85	-22.8%	-25.4%	-28.2%	-31.2%	-34.8%	-39.4%	-41.4%	-45.0%	-52.9%	-62.2%	-70.1%	-77.7%	-84.8%
0.90	-7.7%	-10.8%	-14.1%	-17.7%	-21.7%	-26.8%	-29.1%	-33.2%	-41.3%	-53.1%	-62.7%	-71.9%	-80.7%
0.95	9.3%	5.6%	1.8%	-2.4%	-7.1%	-12.7%	-15.4%	-19.9%	-28.7%	-41.7%	-54.0%	-65.2%	-75.8%
1.00	28.3%	23.9%	19.4%	14.6%	9.2%	2.8%	0.0%	-5.1%	-14.9%	-28.1%	-44.1%	-57.4%	-70.2%
1.05	49.3%	44.2%	39.0%	33.4%	27.2%	20.1%	16.9%	11.3%	0.3%	-13.4%	-32.7%	-48.5%	-63.7%
1.10	72.4%	66.6%	60.6%	54.2%	47.1%	39.1%	35.5%	29.4%	17.3%	2.3%	-19.1%	-38.4%	-56.1%
1.15	97.8%	91.1%	84.3%	77.0%	69.0%	59.8%	55.9%	49.1%	35.7%	19.4%	-2.8%	-27.0%	-47.7%
1.20	125.5%	118.0%	110.1%	101.8%	92.8%	82.6%	78.1%	70.7%	56.0%	38.0%	15.0%	-14.2%	-38.1%

Wind Speed: 8 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 14.00	13.00	12.00	11.00	10.00	9.00	Baseline 8.49	8.00	7.00	6.00	5.00	4.00	3.00
0.80	-33.0%	-35.7%	-38.4%	-41.3%	-44.8%	-49.4%	-52.3%	-55.5%	-65.2%	-73.2%	-81.1%	-88.3%	-94.3%
0.85	-19.0%	-22.2%	-25.5%	-29.0%	-33.0%	-38.1%	-41.4%	-45.0%	-55.6%	-66.2%	-75.8%	-84.8%	-92.5%
0.90	-3.1%	-6.9%	-10.8%	-15.0%	-19.6%	-25.4%	-29.1%	-33.2%	-44.0%	-57.9%	-69.7%	-80.6%	-90.3%
0.95	14.7%	10.2%	5.6%	0.7%	-4.7%	-11.2%	-15.4%	-19.9%	-31.4%	-48.3%	-62.5%	-75.8%	-87.7%
1.00	34.5%	29.3%	23.9%	18.2%	12.0%	4.5%	0.0%	-5.1%	-17.7%	-36.9%	-54.2%	-70.2%	-84.4%
1.05	56.5%	50.5%	44.2%	37.6%	30.4%	22.0%	16.9%	11.3%	-2.8%	-22.9%	-44.7%	-63.7%	-80.6%
1.10	80.7%	73.8%	66.6%	59.0%	50.7%	41.2%	35.5%	29.4%	13.8%	-7.2%	-33.9%	-56.2%	-76.1%
1.15	107.3%	99.4%	91.1%	82.5%	73.1%	62.2%	55.9%	49.1%	32.0%	9.7%	-21.7%	-47.7%	-71.1%
1.20	136.4%	127.3%	117.9%	108.1%	97.4%	85.2%	78.1%	70.6%	51.8%	27.5%	-7.9%	-38.1%	-65.3%

Wind Speed: 6 m/s

Percentage Difference from Baseline

Radius Scale Factor	RPM 14.00	13.00	12.00	11.00	10.00	9.00	Baseline 8.19	8.00	7.00	6.00	5.00	4.00	3.00
0.80	-33.8%	-36.3%	-39.0%	-41.7%	-44.6%	-47.7%	-50.4%	-51.1%	-55.6%	-62.2%	-72.7%	-81.7%	-90.1%
0.85	-19.9%	-23.0%	-26.2%	-29.5%	-33.0%	-36.7%	-39.9%	-40.7%	-45.8%	-53.3%	-65.7%	-76.8%	-87.1%
0.90	-4.2%	-7.9%	-11.7%	-15.7%	-19.9%	-24.3%	-28.1%	-29.0%	-34.9%	-43.3%	-56.9%	-70.9%	-83.6%
0.95	13.4%	9.0%	4.5%	-0.2%	-5.1%	-10.3%	-14.8%	-15.9%	-22.6%	-32.0%	-46.2%	-64.2%	-79.4%
1.00	33.1%	27.9%	22.6%	17.0%	11.3%	5.2%	0.0%	-1.3%	-9.0%	-19.4%	-34.6%	-56.4%	-74.7%
1.05	54.8%	48.8%	42.6%	36.2%	29.5%	22.5%	16.4%	14.9%	6.1%	-5.5%	-22.1%	-47.4%	-69.1%
1.10	78.8%	71.9%	64.7%	57.3%	49.6%	41.5%	34.5%	32.8%	22.7%	9.9%	-8.6%	-37.3%	-62.8%
1.15	105.1%	97.1%	88.9%	80.4%	71.6%	62.3%	54.3%	52.4%	41.0%	26.6%	6.3%	-25.4%	-55.6%
1.20	133.9%	124.8%	115.4%	105.7%	95.6%	85.1%	76.0%	73.8%	61.0%	44.9%	22.6%	-11.2%	-47.4%

Wind Speed:	4 m/s										
			Percentage Difference from Baseline								
Radius Scale	RPM			Baseline							
Factor	10.00	9.00	8.00	7.28	7.00	6.00	5.00	4.00	3.00	2.00	1.00
0.80	-41.1%	-44.3%	-47.6%	-50.2%	-51.2%	-55.1%	-59.8%	-67.6%	-80.5%	-91.5%	-98.1%
0.85	-28.7%	-32.6%	-36.7%	-39.8%	-41.0%	-45.7%	-51.2%	-59.9%	-75.4%	-88.9%	-97.6%
0.90	-14.7%	-19.4%	-24.3%	-28.0%	-29.5%	-35.0%	-41.5%	-51.3%	-69.3%	-85.9%	-97.1%
0.95	0.9%	-4.6%	-10.4%	-14.7%	-16.5%	-23.1%	-30.6%	-41.7%	-62.4%	-82.4%	-96.4%
1.00	18.4%	11.9%	5.1%	0.0%	-2.0%	-9.7%	-18.5%	-30.9%	-54.1%	-78.3%	-95.6%
1.05	37.8%	30.2%	22.3%	16.3%	14.0%	5.0%	-5.0%	-19.0%	-43.9%	-73.5%	-94.6%
1.10	59.2%	50.4%	41.2%	34.4%	31.6%	21.3%	9.8%	-5.8%	-32.4%	-68.1%	-93.5%
1.15	82.6%	72.5%	62.0%	54.1%	51.0%	39.2%	26.0%	8.6%	-20.1%	-61.9%	-92.1%
1.20	108.2%	96.7%	84.7%	75.7%	72.1%	58.7%	43.8%	24.3%	-7.2%	-54.9%	-90.5%

Appendix M

Power Results for WindPACT 1.5MW Turbine Airfoil Characteristic Study

Wind Speed:	10 m/s												
			Percentage Difference from Baseline										
	RPM						Baseline						
Case	27.28	25.92	24.56	23.19	21.83	20.46	19.10	17.73	16.37	15.01	13.64	12.28	10.91
1.2Cl Whole Span	-30.6%	-24.9%	-19.7%	-15.0%	-10.9%	-7.5%	-4.5%	-2.2%	-1.4%	-5.2%	-15.8%	-32.1%	-51.3%
1.2Cl and 1.2Cd Partial	-28.2%	-22.6%	-17.5%	-12.9%	-9.0%	-5.8%	-3.3%	-2.4%	-4.1%	-11.9%	-23.9%	-39.8%	-57.4%

Wind Speed:	8 m/s												
			Percentage Difference from Baseline										
	RPM						Baseline						
Case	21.83	20.74	19.64	18.55	17.46	16.37	15.28	14.19	13.10	12.00	10.91	9.82	8.73
1.2Cl Whole Span	-30.6%	-24.9%	-19.7%	-15.0%	-10.9%	-7.5%	-4.5%	-2.2%	-1.4%	-5.2%	-15.8%	-32.1%	-51.3%
1.2Cl and 1.2Cd Partial	-28.2%	-22.6%	-17.5%	-12.9%	-9.0%	-5.8%	-3.3%	-2.4%	-4.1%	-11.9%	-23.8%	-39.8%	-57.4%

Wind Speed:	6 m/s												
			Percentage Difference from Baseline										
	RPM						Baseline						
Case	19.64	18.83	18.01	17.19	16.37	15.55	14.73	13.91	13.10	12.28	11.46	10.64	9.82
1.2Cl Whole Span	-54.7%	-45.1%	-36.3%	-28.2%	-20.9%	-14.4%	-8.5%	-3.1%	1.6%	5.5%	8.8%	11.4%	12.4%
1.2Cl and 1.2Cd Partial	-51.0%	-41.6%	-33.0%	-25.2%	-18.2%	-11.8%	-6.0%	-0.7%	3.7%	7.4%	10.2%	11.2%	9.2%

Wind Speed:	4 m/s												
			Percentage Difference from Baseline										
	RPM	Baseline											
Case	13.64	13.10	12.55	12.00	11.46	10.91	10.37	9.82	9.28	8.73	8.19	7.64	7.09
1.2Cl Whole Span	-42.6%	-25.4%	-9.6%	5.0%	18.3%	30.3%	41.0%	50.7%	59.6%	67.4%	73.8%	79.3%	83.6%
1.2Cl and 1.2Cd Partial	-36.1%	-19.3%	-3.8%	10.3%	23.2%	34.8%	45.3%	54.9%	63.5%	70.9%	76.9%	81.5%	83.2%

Appendix N

Power Results for NREL 5MW Turbine Airfoil Characteristic Study

Wind Speed:	10 m/s												
			Percentage Difference from Baseline										
	RPM						Baseline						
Case	15.16	14.40	13.64	12.88	12.13	11.37	10.61	9.85	9.09	8.34	7.58	6.82	6.06
1.2Cl Whole Span	-7.0%	-4.6%	-2.5%	-0.7%	0.7%	1.8%	2.1%	1.0%	-2.3%	-7.4%	-20.6%	-37.3%	-52.3%
1.2 Cl and 1.2Cd Partial	-8.0%	-5.6%	-3.6%	-1.9%	-0.6%	0.2%	-0.1%	-2.1%	-6.5%	-14.2%	-29.4%	-43.7%	-58.3%

Wind Speed:	8 m/s												
			Percentage Difference from Baseline										
	RPM						Baseline						
Case	12.13	11.52	10.91	10.31	9.70	9.09	8.49	7.88	7.28	6.67	6.06	5.46	4.85
1.2Cl Whole Span	-7.0%	-4.6%	-2.5%	-0.7%	0.7%	1.8%	2.1%	1.0%	-2.3%	-7.4%	-20.6%	-37.3%	-52.3%
1.2 Cl and 1.2Cd Partial	-8.0%	-5.6%	-3.6%	-1.9%	-0.6%	0.2%	-0.1%	-2.1%	-6.5%	-14.2%	-29.4%	-43.7%	-58.3%

Wind Speed:	6 m/s												
			Percentage Difference from Baseline										
	RPM						Baseline						
Case	10.91	10.46	10.00	9.55	9.09	8.64	8.19	7.73	7.28	6.82	6.37	5.91	5.46
1.2Cl Whole Span	-19.7%	-15.9%	-12.5%	-9.4%	-6.7%	-4.3%	-2.2%	-0.4%	1.0%	2.1%	2.4%	1.3%	-2.0%
1.2 Cl and 1.2Cd Partial	-21.1%	-17.2%	-13.7%	-10.5%	-7.8%	-5.3%	-3.3%	-1.6%	-0.3%	0.4%	0.2%	-1.9%	-6.2%

Wind Speed:	4 m/s												
			Percentage Difference from Baseline										
	RPM	Baseline											
Case	7.58	7.28	6.97	6.67	6.37	6.06	5.76	5.46	5.15	4.85	4.55	4.24	3.94
1.2Cl Whole Span	-9.1%	-4.2%	0.4%	4.5%	8.1%	11.4%	14.2%	16.7%	18.8%	20.6%	21.8%	22.2%	20.9%
1.2 Cl and 1.2Cd Partial	-11.0%	-5.8%	-1.1%	3.0%	6.8%	10.1%	13.0%	15.4%	17.5%	19.0%	19.9%	19.6%	17.1%

Appendix O

Root Bending Moment Results for WindPACT 1.5MW Turbine Twist vs. Pitch Parametric Study at 11.8 m/s

Pitch Setting:	-2°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	71.0%	61.3%	51.9%	42.4%	32.8%	22.8%	8.6%	-0.2%	-15.1%	-30.5%	-45.0%	-58.0%	-70.1%
8.10	66.8%	57.5%	48.5%	39.6%	30.5%	21.4%	8.1%	-0.2%	-14.7%	-30.1%	-44.8%	-57.9%	-70.1%
11.10	63.0%	54.1%	45.4%	36.9%	28.3%	19.8%	7.4%	-0.4%	-14.4%	-29.7%	-44.5%	-57.8%	-70.1%
14.10	59.3%	50.7%	42.4%	34.2%	25.9%	17.8%	6.3%	-0.9%	-14.3%	-29.4%	-44.2%	-57.6%	-70.1%
17.10	55.8%	47.4%	39.4%	31.5%	23.5%	15.7%	4.8%	-1.9%	-14.3%	-29.1%	-43.9%	-57.4%	-70.0%

Pitch Setting:	-1°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	60.8%	52.1%	43.7%	35.3%	26.9%	18.1%	5.4%	-2.7%	-15.9%	-30.4%	-44.6%	-57.5%	-69.7%
8.10	56.8%	48.5%	40.4%	32.5%	24.6%	16.5%	4.8%	-3.0%	-15.7%	-30.1%	-44.3%	-57.4%	-69.7%
11.10	53.2%	45.2%	37.5%	29.9%	22.4%	14.7%	3.8%	-3.4%	-15.6%	-29.8%	-44.1%	-57.3%	-69.7%
14.10	49.7%	42.0%	34.5%	27.3%	20.0%	12.7%	2.5%	-4.3%	-15.6%	-29.6%	-43.8%	-57.1%	-69.7%
17.10	46.1%	38.8%	31.5%	24.5%	17.6%	10.5%	0.9%	-5.6%	-15.9%	-29.3%	-43.5%	-56.9%	-69.6%

Pitch Setting:	0°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	50.9%	43.2%	35.8%	28.4%	21.0%	13.3%	2.1%	-5.6%	-17.5%	-30.8%	-44.4%	-57.1%	-69.4%
8.10	47.1%	39.7%	32.7%	25.7%	18.8%	11.6%	1.2%	-6.1%	-17.5%	-30.5%	-44.1%	-57.0%	-69.4%
11.10	43.7%	36.7%	29.8%	23.2%	16.6%	9.8%	0.0%	-6.8%	-17.6%	-30.3%	-43.9%	-56.8%	-69.3%
14.10	40.2%	33.6%	26.9%	20.5%	14.2%	7.7%	-1.5%	-8.0%	-18.0%	-30.2%	-43.6%	-56.6%	-69.3%
17.10	36.6%	30.3%	24.0%	17.8%	11.7%	5.5%	-3.3%	-9.4%	-18.6%	-30.1%	-43.4%	-56.4%	-69.2%

Pitch Setting:	1°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	41.4%	34.7%	28.2%	21.8%	15.4%	8.7%	-1.8%	-8.8%	-19.7%	-31.6%	-44.4%	-56.8%	-69.1%
8.10	37.7%	31.5%	25.2%	19.2%	13.2%	6.8%	-2.9%	-9.5%	-19.9%	-31.5%	-44.2%	-56.7%	-69.0%
11.10	34.4%	28.5%	22.5%	16.7%	10.9%	4.9%	-4.3%	-10.5%	-20.2%	-31.4%	-44.0%	-56.5%	-69.0%
14.10	30.9%	25.4%	19.7%	14.1%	8.5%	2.6%	-6.1%	-11.8%	-20.8%	-31.5%	-43.8%	-56.3%	-68.9%
17.10	27.3%	22.1%	16.7%	11.3%	6.0%	0.2%	-8.2%	-13.4%	-21.8%	-31.6%	-43.6%	-56.1%	-68.8%

Pitch Setting:	2°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	32.2%	26.6%	21.0%	15.5%	9.9%	3.7%	-6.0%	-12.3%	-22.2%	-33.1%	-44.7%	-56.6%	-68.8%
8.10	28.7%	23.5%	18.2%	13.0%	7.7%	1.7%	-7.4%	-13.3%	-22.6%	-33.1%	-44.6%	-56.5%	-68.7%
11.10	25.4%	20.6%	15.6%	10.5%	5.3%	-0.5%	-9.0%	-14.5%	-23.2%	-33.2%	-44.4%	-56.4%	-68.7%
14.10	22.0%	17.4%	12.7%	7.8%	2.7%	-3.0%	-11.0%	-16.0%	-24.1%	-33.4%	-44.3%	-56.2%	-68.6%
17.10	18.3%	14.0%	9.7%	5.0%	0.0%	-5.5%	-13.2%	-17.8%	-25.2%	-33.8%	-44.2%	-56.0%	-68.5%

Pitch Setting: 3°

			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	23.5%	18.9%	14.3%	9.4%	4.2%	-1.6%	-10.5%	-16.3%	-25.1%	-34.9%	-45.6%	-56.7%	-68.5%
8.10	20.2%	16.0%	11.6%	6.9%	1.7%	-3.9%	-12.1%	-17.4%	-25.7%	-35.1%	-45.5%	-56.6%	-68.5%
11.10	17.0%	13.0%	8.9%	4.2%	-0.9%	-6.3%	-14.0%	-18.8%	-26.4%	-35.4%	-45.4%	-56.4%	-68.4%
14.10	13.4%	9.7%	5.9%	1.3%	-3.7%	-8.8%	-16.1%	-20.6%	-27.5%	-35.8%	-45.4%	-56.3%	-68.3%
17.10	9.7%	6.2%	2.5%	-1.7%	-6.5%	-11.5%	-18.3%	-22.6%	-28.9%	-36.4%	-45.5%	-56.2%	-68.2%

Pitch Setting: 4°

			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	15.4%	11.7%	7.6%	3.1%	-2.0%	-7.4%	-15.3%	-20.4%	-28.3%	-37.1%	-46.8%	-57.0%	-68.4%
8.10	12.3%	8.7%	4.7%	0.2%	-4.7%	-9.8%	-17.1%	-21.8%	-29.1%	-37.4%	-46.8%	-56.9%	-68.3%
11.10	8.9%	5.5%	1.6%	-2.6%	-7.4%	-12.3%	-19.1%	-23.4%	-30.0%	-37.8%	-46.8%	-56.8%	-68.3%
14.10	5.2%	1.9%	-1.8%	-5.7%	-10.2%	-15.0%	-21.3%	-25.3%	-31.3%	-38.4%	-46.9%	-56.7%	-68.2%
17.10	1.2%	-1.9%	-5.4%	-9.0%	-13.1%	-17.7%	-23.7%	-27.3%	-32.8%	-39.3%	-47.2%	-56.6%	-68.1%

Pitch Setting: 5°

			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	7.4%	4.0%	0.2%	-3.9%	-8.4%	-13.3%	-20.2%	-24.7%	-31.7%	-39.5%	-48.2%	-57.6%	-68.3%
8.10	3.9%	0.6%	-3.1%	-7.0%	-11.3%	-15.9%	-22.3%	-26.3%	-32.7%	-40.0%	-48.3%	-57.5%	-68.3%
11.10	0.1%	-3.0%	-6.4%	-10.1%	-14.1%	-18.5%	-24.4%	-28.1%	-33.8%	-40.6%	-48.5%	-57.5%	-68.2%
14.10	-4.0%	-6.9%	-10.0%	-13.4%	-17.0%	-21.2%	-26.7%	-30.1%	-35.3%	-41.4%	-48.8%	-57.5%	-68.2%
17.10	-8.4%	-10.9%	-13.7%	-16.8%	-20.1%	-23.9%	-29.1%	-32.2%	-36.9%	-42.4%	-49.1%	-57.5%	-68.1%

Pitch Setting: 6°

			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-1.5%	-4.6%	-7.9%	-11.4%	-15.3%	-19.5%	-25.5%	-29.3%	-35.4%	-42.2%	-49.9%	-58.5%	-68.5%
8.10	-5.5%	-8.4%	-11.4%	-14.7%	-18.2%	-22.1%	-27.6%	-31.0%	-36.5%	-42.8%	-50.2%	-58.5%	-68.4%
11.10	-9.6%	-12.2%	-14.9%	-17.9%	-21.1%	-24.8%	-29.9%	-32.9%	-37.8%	-43.6%	-50.5%	-58.5%	-68.4%
14.10	-14.0%	-16.3%	-18.7%	-21.3%	-24.2%	-27.5%	-32.2%	-35.1%	-39.4%	-44.6%	-50.9%	-58.6%	-68.3%
17.10	-18.7%	-20.5%	-22.5%	-24.9%	-27.4%	-30.2%	-34.6%	-37.2%	-41.2%	-45.7%	-51.4%	-58.7%	-68.2%

Pitch Setting: 7°

			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-11.4%	-13.7%	-16.4%	-19.2%	-22.4%	-25.8%	-30.8%	-34.0%	-39.2%	-45.1%	-51.9%	-59.6%	-68.8%
8.10	-15.7%	-17.8%	-20.1%	-22.6%	-25.4%	-28.5%	-33.0%	-35.9%	-40.4%	-45.9%	-52.3%	-59.7%	-68.7%
11.10	-20.0%	-21.8%	-23.8%	-26.0%	-28.4%	-31.2%	-35.3%	-37.9%	-41.9%	-46.8%	-52.7%	-59.8%	-68.7%
14.10	-24.7%	-26.0%	-27.6%	-29.5%	-31.6%	-34.0%	-37.7%	-40.1%	-43.6%	-47.9%	-53.2%	-59.9%	-68.7%
17.10	-29.5%	-30.4%	-31.6%	-33.1%	-34.9%	-36.9%	-40.1%	-42.3%	-45.5%	-49.2%	-54.0%	-60.1%	-68.6%

Pitch Setting: 8°

			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-21.9%	-23.5%	-25.2%	-27.3%	-29.6%	-32.3%	-36.2%	-38.8%	-43.1%	-48.2%	-54.1%	-60.9%	-69.3%
8.10	-26.5%	-27.7%	-29.1%	-30.8%	-32.8%	-35.1%	-38.6%	-40.9%	-44.6%	-49.1%	-54.6%	-61.0%	-69.3%
11.10	-31.0%	-31.8%	-32.9%	-34.2%	-35.9%	-37.8%	-40.9%	-42.9%	-46.1%	-50.1%	-55.1%	-61.2%	-69.3%
14.10	-35.8%	-36.2%	-36.8%	-37.8%	-39.1%	-40.7%	-43.3%	-45.1%	-47.9%	-51.3%	-55.8%	-61.5%	-69.3%
17.10	-40.6%	-40.7%	-40.9%	-41.5%	-42.4%	-43.6%	-45.7%	-47.3%	-49.8%	-52.8%	-56.6%	-61.8%	-69.3%

Pitch Setting:	9°												
		Percentage Difference from Baseline											
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-32.8%	-33.5%	-34.4%	-35.5%	-37.0%	-38.9%	-41.8%	-43.8%	-47.2%	-51.4%	-56.5%	-62.4%	-70.0%
8.10	-37.5%	-37.9%	-38.4%	-39.2%	-40.2%	-41.7%	-44.2%	-45.9%	-48.7%	-52.4%	-57.0%	-62.6%	-70.0%
11.10	-42.1%	-42.1%	-42.3%	-42.7%	-43.4%	-44.5%	-46.5%	-48.0%	-50.4%	-53.5%	-57.7%	-62.9%	-70.0%
14.10	-47.0%	-46.5%	-46.4%	-46.4%	-46.7%	-47.4%	-49.0%	-50.2%	-52.3%	-54.9%	-58.4%	-63.2%	-70.1%
17.10	-52.0%	-51.0%	-50.5%	-50.1%	-50.0%	-50.4%	-51.5%	-52.4%	-54.2%	-56.4%	-59.4%	-63.7%	-70.1%

Appendix P

Power Results for WindPACT 1.5MW Turbine Twist vs. Pitch Parametric Study at 11.8 m/s

Pitch Setting:	-2°											
			Percentage Difference from Baseline									
Root to Tip	RPM						Baseline					
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-34.6%	-27.4%	-21.1%	-15.7%	-11.2%	-8.8%	-11.5%	-15.0%	-26.0%	-41.8%	-58.8%	-74.4%	-87.6%
8.10	-30.8%	-24.2%	-18.4%	-13.3%	-9.2%	-6.1%	-6.9%	-10.1%	-20.9%	-37.1%	-55.3%	-72.1%	-86.3%
11.10	-27.6%	-21.5%	-16.1%	-11.4%	-7.3%	-4.5%	-3.8%	-6.4%	-16.7%	-32.7%	-51.8%	-69.7%	-85.0%
14.10	-24.6%	-18.8%	-13.8%	-9.5%	-5.8%	-3.2%	-2.7%	-4.1%	-13.0%	-28.4%	-48.0%	-67.2%	-83.6%
17.10	-22.2%	-16.8%	-12.2%	-8.3%	-5.1%	-2.7%	-2.4%	-3.7%	-10.4%	-24.5%	-44.3%	-64.4%	-82.1%

Pitch Setting:	-1°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-27.8%	-21.8%	-16.5%	-11.8%	-7.9%	-5.0%	-7.5%	-11.7%	-22.4%	-37.6%	-54.2%	-70.1%	-84.4%
8.10	-24.5%	-18.9%	-14.0%	-9.7%	-6.0%	-3.1%	-3.5%	-7.5%	-18.0%	-33.1%	-50.7%	-67.7%	-83.1%
11.10	-21.6%	-16.3%	-11.7%	-7.7%	-4.3%	-1.7%	-1.5%	-4.5%	-14.3%	-29.2%	-47.2%	-65.4%	-81.7%
14.10	-18.9%	-13.9%	-9.7%	-6.2%	-3.2%	-0.8%	-1.0%	-3.3%	-11.3%	-25.5%	-43.7%	-62.7%	-80.3%
17.10	-17.2%	-12.6%	-8.8%	-5.6%	-2.9%	-0.8%	-0.9%	-3.5%	-9.7%	-22.3%	-40.2%	-60.0%	-78.7%

Pitch Setting:	0°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-22.0%	-16.7%	-12.2%	-8.2%	-4.8%	-1.9%	-4.0%	-9.1%	-19.8%	-34.1%	-50.3%	-66.2%	-81.4%
8.10	-18.9%	-14.0%	-9.9%	-6.2%	-2.9%	-0.4%	-1.0%	-5.6%	-15.9%	-30.1%	-46.9%	-63.9%	-80.0%
11.10	-16.2%	-11.6%	-7.7%	-4.4%	-1.6%	0.7%	0.0%	-3.5%	-12.8%	-26.6%	-43.6%	-61.5%	-78.6%
14.10	-13.9%	-9.8%	-6.2%	-3.3%	-0.9%	1.0%	0.1%	-3.2%	-10.5%	-23.4%	-40.3%	-58.8%	-77.1%
17.10	-13.1%	-9.3%	-5.9%	-3.2%	-1.0%	0.5%	-0.3%	-3.7%	-9.9%	-20.9%	-37.2%	-56.2%	-75.5%

Pitch Setting:	1°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-16.7%	-12.2%	-8.2%	-4.8%	-1.8%	0.6%	-1.9%	-7.2%	-17.9%	-31.5%	-47.1%	-62.9%	-78.5%
8.10	-13.8%	-9.7%	-6.0%	-2.8%	0.0%	1.8%	0.1%	-4.4%	-14.5%	-27.9%	-43.9%	-60.5%	-77.1%
11.10	-11.2%	-7.5%	-4.1%	-1.4%	0.9%	2.4%	0.3%	-3.3%	-12.1%	-24.8%	-40.8%	-58.1%	-75.6%
14.10	-9.7%	-6.4%	-3.4%	-0.8%	1.1%	1.9%	-0.1%	-3.5%	-10.7%	-22.2%	-37.8%	-55.5%	-74.1%
17.10	-9.7%	-6.5%	-3.7%	-1.3%	0.3%	0.7%	-1.4%	-4.3%	-10.9%	-20.4%	-35.1%	-53.0%	-72.4%

Pitch Setting:	2°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-11.8%	-8.0%	-4.5%	-1.4%	1.0%	2.2%	-1.0%	-6.2%	-16.7%	-29.7%	-44.6%	-60.0%	-75.8%
8.10	-9.0%	-5.6%	-2.4%	0.4%	2.4%	2.7%	-0.1%	-4.3%	-13.8%	-26.5%	-41.5%	-57.7%	-74.4%
11.10	-6.8%	-3.8%	-1.1%	1.3%	2.7%	2.5%	-0.5%	-4.0%	-12.0%	-23.9%	-38.7%	-55.3%	-72.9%
14.10	-6.2%	-3.4%	-1.0%	1.2%	2.0%	1.3%	-1.6%	-4.7%	-11.5%	-21.9%	-36.1%	-52.9%	-71.3%
17.10	-7.2%	-4.4%	-2.1%	-0.1%	0.3%	-0.5%	-3.4%	-6.0%	-12.3%	-20.8%	-33.8%	-50.5%	-69.6%

Pitch Setting: 3°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-7.1%	-3.9%	-0.9%	1.6%	2.8%	2.4%	-1.3%	-6.3%	-16.1%	-28.5%	-42.6%	-57.6%	-73.4%
8.10	-4.4%	-1.6%	0.9%	2.8%	3.2%	2.3%	-1.4%	-5.2%	-13.8%	-25.8%	-39.8%	-55.4%	-71.9%
11.10	-3.1%	-0.6%	1.5%	2.7%	2.6%	1.3%	-2.3%	-5.6%	-12.7%	-23.7%	-37.4%	-53.1%	-70.5%
14.10	-3.5%	-1.1%	0.8%	1.5%	1.0%	-0.5%	-3.9%	-6.8%	-13.0%	-22.2%	-35.2%	-50.8%	-68.9%
17.10	-5.5%	-3.1%	-1.5%	-0.8%	-1.4%	-2.8%	-6.2%	-8.8%	-14.0%	-21.9%	-33.4%	-48.7%	-67.1%

Pitch Setting: 4°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-2.5%	0.0%	2.0%	3.0%	2.8%	1.3%	-2.7%	-7.3%	-16.3%	-27.9%	-41.4%	-55.7%	-71.3%
8.10	-0.4%	1.6%	2.8%	3.0%	2.2%	0.5%	-3.5%	-7.0%	-14.7%	-25.6%	-38.9%	-53.5%	-69.8%
11.10	-0.2%	1.4%	2.1%	1.9%	0.8%	-1.1%	-4.9%	-8.0%	-14.3%	-24.0%	-36.7%	-51.4%	-68.4%
14.10	-1.9%	-0.6%	0.0%	-0.3%	-1.4%	-3.3%	-7.0%	-9.7%	-15.1%	-23.1%	-34.9%	-49.3%	-66.7%
17.10	-5.4%	-4.0%	-3.4%	-3.5%	-4.4%	-6.2%	-9.6%	-12.1%	-16.6%	-23.6%	-33.6%	-47.4%	-65.1%

Pitch Setting: 5°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	0.7%	2.0%	2.5%	2.2%	1.2%	-0.8%	-5.0%	-9.0%	-17.3%	-28.0%	-40.6%	-54.3%	-69.5%
8.10	1.2%	1.9%	1.9%	1.2%	-0.1%	-2.3%	-6.4%	-9.6%	-16.4%	-26.1%	-38.4%	-52.2%	-68.0%
11.10	-0.3%	0.1%	0.0%	-0.7%	-2.2%	-4.4%	-8.1%	-11.1%	-16.6%	-25.0%	-36.6%	-50.3%	-66.6%
14.10	-3.7%	-3.2%	-3.2%	-3.7%	-5.0%	-7.1%	-10.7%	-13.2%	-17.9%	-24.9%	-35.2%	-48.5%	-65.0%
17.10	-8.8%	-7.7%	-7.4%	-7.7%	-8.6%	-10.3%	-13.6%	-15.9%	-19.9%	-25.8%	-34.4%	-46.9%	-63.4%

Pitch Setting: 6°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	0.5%	0.8%	0.5%	-0.3%	-1.7%	-3.9%	-8.1%	-11.5%	-18.9%	-28.7%	-40.3%	-53.4%	-68.0%
8.10	-0.8%	-0.8%	-1.2%	-2.2%	-3.8%	-5.9%	-9.9%	-12.8%	-18.6%	-27.3%	-38.5%	-51.4%	-66.6%
11.10	-3.9%	-3.8%	-4.1%	-5.0%	-6.4%	-8.5%	-12.1%	-14.7%	-19.5%	-26.8%	-37.0%	-49.7%	-65.1%
14.10	-8.7%	-8.2%	-8.3%	-8.8%	-9.9%	-11.6%	-14.9%	-17.2%	-21.3%	-27.2%	-36.0%	-48.2%	-63.6%
17.10	-15.1%	-13.9%	-13.3%	-13.4%	-14.0%	-15.3%	-18.1%	-20.1%	-23.6%	-28.5%	-35.8%	-46.9%	-62.1%

Pitch Setting: 7°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-2.9%	-2.9%	-3.4%	-4.4%	-5.9%	-7.9%	-11.8%	-14.8%	-21.1%	-29.9%	-40.6%	-52.8%	-66.8%
8.10	-5.8%	-5.8%	-6.2%	-7.1%	-8.5%	-10.5%	-13.9%	-16.6%	-21.5%	-29.1%	-39.1%	-51.0%	-65.4%
11.10	-10.2%	-9.9%	-10.0%	-10.6%	-11.7%	-13.4%	-16.6%	-18.8%	-22.9%	-29.0%	-38.0%	-49.6%	-64.0%
14.10	-16.3%	-15.3%	-14.9%	-15.1%	-15.7%	-17.0%	-19.7%	-21.6%	-25.1%	-30.0%	-37.5%	-48.3%	-62.6%
17.10	-23.9%	-22.1%	-20.9%	-20.3%	-20.4%	-21.1%	-23.1%	-24.8%	-27.7%	-31.7%	-37.8%	-47.3%	-61.3%

Pitch Setting: 8°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
5.10	-9.1%	-8.9%	-9.1%	-9.8%	-11.0%	-12.8%	-16.1%	-18.7%	-23.9%	-31.7%	-41.4%	-52.6%	-65.9%
8.10	-13.3%	-12.9%	-12.8%	-13.3%	-14.2%	-15.8%	-18.6%	-20.8%	-24.9%	-31.3%	-40.2%	-51.1%	-64.6%
11.10	-19.0%	-17.9%	-17.4%	-17.4%	-18.0%	-19.1%	-21.5%	-23.4%	-26.8%	-31.8%	-39.5%	-49.8%	-63.3%
14.10	-26.1%	-24.4%	-23.1%	-22.5%	-22.5%	-23.1%	-24.9%	-26.4%	-29.2%	-33.2%	-39.5%	-48.8%	-62.0%
17.10	-34.5%	-31.9%	-29.8%	-28.4%	-27.7%	-27.6%	-28.6%	-29.8%	-32.1%	-35.2%	-40.2%	-48.2%	-60.9%

Pitch Setting:		9°												
				Percentage Difference from Baseline										
	Root to Tip	RPM						Baseline						
	Nose Up Twist	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
	5.10	-17.4%	-16.7%	-16.3%	-16.5%	-17.1%	-18.3%	-20.9%	-23.0%	-27.2%	-33.9%	-42.6%	-52.8%	-65.4%
	8.10	-22.9%	-21.7%	-20.9%	-20.6%	-20.9%	-21.7%	-23.8%	-25.5%	-28.8%	-34.0%	-41.7%	-51.5%	-64.1%
	11.10	-29.5%	-27.6%	-26.3%	-25.4%	-25.1%	-25.5%	-27.0%	-28.3%	-31.0%	-35.0%	-41.5%	-50.6%	-62.9%
	14.10	-37.6%	-34.8%	-32.7%	-31.1%	-30.1%	-29.9%	-30.6%	-31.6%	-33.7%	-36.8%	-41.8%	-49.8%	-61.8%
	17.10	-47.0%	-43.0%	-40.0%	-37.5%	-35.7%	-34.7%	-34.6%	-35.1%	-36.7%	-39.1%	-43.0%	-49.6%	-60.8%

Appendix Q

Root Bending Moment Results for NREL 5MW Turbine Twist vs. Pitch Parametric Study at 11.4 m/s

Pitch Setting: -2°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	63.7%	56.7%	49.7%	42.6%	35.2%	27.4%	19.1%	8.2%	-7.1%	-19.8%	-31.9%	-43.9%	-55.5%
10.30	55.3%	49.1%	42.9%	36.7%	30.2%	23.2%	15.6%	6.9%	-5.9%	-20.7%	-32.7%	-44.3%	-55.6%
13.30	46.7%	41.3%	35.8%	30.3%	24.6%	18.3%	11.4%	3.3%	-6.2%	-20.6%	-33.5%	-44.9%	-55.8%
16.30	39.0%	34.2%	29.4%	24.4%	19.3%	13.7%	7.2%	-0.3%	-8.7%	-19.2%	-34.0%	-45.4%	-56.2%
19.30	30.0%	26.0%	21.8%	17.5%	13.0%	8.0%	2.2%	-4.7%	-12.2%	-20.9%	-33.1%	-46.0%	-56.6%

Pitch Setting: -1°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	51.7%	45.9%	40.1%	34.2%	28.0%	21.6%	14.4%	5.2%	-8.1%	-21.6%	-33.1%	-44.5%	-55.7%
10.30	43.9%	38.8%	33.7%	28.5%	23.1%	17.4%	10.7%	2.6%	-7.8%	-22.0%	-33.9%	-45.0%	-55.8%
13.30	35.5%	31.1%	26.7%	22.1%	17.4%	12.2%	5.9%	-1.4%	-9.8%	-20.9%	-34.7%	-45.6%	-56.2%
16.30	27.7%	23.9%	20.1%	16.0%	11.8%	7.1%	1.4%	-5.3%	-12.9%	-21.6%	-34.5%	-46.2%	-56.5%
19.30	18.4%	15.3%	12.1%	8.7%	4.9%	0.8%	-4.0%	-9.9%	-16.6%	-24.2%	-33.4%	-46.7%	-57.0%

Pitch Setting: 0°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	40.4%	35.8%	31.0%	26.2%	21.2%	15.8%	9.4%	1.3%	-9.9%	-23.2%	-34.5%	-45.3%	-55.9%
10.30	33.0%	29.0%	24.9%	20.6%	16.2%	11.1%	5.1%	-2.1%	-10.8%	-22.8%	-35.4%	-45.8%	-56.2%
13.30	24.6%	21.3%	17.7%	14.0%	9.9%	5.4%	0.0%	-6.4%	-13.9%	-22.9%	-35.6%	-46.5%	-56.6%
16.30	16.5%	13.7%	10.7%	7.4%	3.7%	-0.3%	-4.9%	-10.6%	-17.2%	-24.8%	-34.7%	-47.1%	-57.0%
19.30	6.5%	4.5%	2.1%	-0.6%	-3.6%	-7.0%	-10.8%	-15.5%	-21.2%	-27.8%	-35.5%	-47.1%	-57.6%

Pitch Setting: 1°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	30.0%	26.3%	22.6%	18.7%	14.4%	9.4%	3.6%	-3.4%	-12.6%	-24.5%	-36.2%	-46.2%	-56.3%
10.30	22.8%	19.7%	16.4%	12.8%	8.8%	4.2%	-1.1%	-7.3%	-14.7%	-24.5%	-36.7%	-46.9%	-56.7%
13.30	14.0%	11.4%	8.6%	5.4%	1.8%	-2.1%	-6.7%	-11.9%	-18.3%	-26.0%	-36.2%	-47.7%	-57.2%
16.30	5.1%	3.1%	0.8%	-1.8%	-4.8%	-8.2%	-12.0%	-16.4%	-21.9%	-28.5%	-36.4%	-48.0%	-57.7%
19.30	-5.8%	-6.9%	-8.4%	-10.3%	-12.5%	-15.1%	-18.2%	-21.7%	-26.2%	-31.7%	-38.3%	-47.2%	-58.2%

Pitch Setting: 2°

Percentage Difference from Baseline

Root to Tip	RPM						Baseline						
Nose Up Twist	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	20.4%	17.5%	14.4%	10.9%	6.9%	2.4%	-2.8%	-8.7%	-16.2%	-26.3%	-37.7%	-47.5%	-56.9%
10.30	12.7%	10.2%	7.3%	4.2%	0.6%	-3.3%	-7.8%	-13.0%	-19.1%	-27.1%	-37.7%	-48.2%	-57.4%
13.30	2.6%	0.7%	-1.5%	-4.0%	-6.9%	-10.1%	-13.7%	-18.1%	-23.1%	-29.5%	-37.8%	-48.8%	-57.9%
16.30	-7.2%	-8.4%	-9.8%	-11.7%	-13.9%	-16.4%	-19.4%	-22.8%	-27.0%	-32.3%	-39.1%	-48.4%	-58.5%
19.30	-18.8%	-19.0%	-19.6%	-20.5%	-21.9%	-23.6%	-25.7%	-28.4%	-31.6%	-35.9%	-41.4%	-48.5%	-58.9%

Pitch Setting: 3°

Percentage Difference from Baseline

Root to Tip Nose Up Twist	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	10.3%	7.8%	5.0%	2.0%	-1.4%	-5.2%	-9.6%	-14.6%	-20.7%	-28.9%	-39.0%	-48.9%	-57.7%
10.30	1.2%	-0.7%	-2.9%	-5.4%	-8.2%	-11.3%	-14.9%	-19.2%	-24.1%	-30.4%	-39.3%	-49.5%	-58.3%
13.30	-10.0%	-11.0%	-12.4%	-14.1%	-16.1%	-18.4%	-21.2%	-24.4%	-28.5%	-33.5%	-40.2%	-49.6%	-58.9%
16.30	-20.5%	-20.7%	-21.2%	-22.1%	-23.3%	-25.0%	-27.0%	-29.5%	-32.6%	-36.6%	-42.1%	-49.6%	-59.4%
19.30	-32.8%	-31.9%	-31.4%	-31.3%	-31.6%	-32.3%	-33.5%	-35.2%	-37.4%	-40.4%	-44.7%	-50.6%	-59.4%

Pitch Setting: 4°

Percentage Difference from Baseline

Root to Tip Nose Up Twist	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-1.6%	-3.4%	-5.4%	-7.7%	-10.3%	-13.2%	-16.6%	-20.8%	-25.7%	-32.1%	-40.7%	-50.3%	-58.7%
10.30	-11.7%	-12.7%	-14.0%	-15.5%	-17.4%	-19.7%	-22.3%	-25.5%	-29.5%	-34.5%	-41.5%	-50.6%	-59.3%
13.30	-23.6%	-23.7%	-24.0%	-24.6%	-25.6%	-27.1%	-28.9%	-31.2%	-34.1%	-37.9%	-43.1%	-50.8%	-60.0%
16.30	-34.8%	-33.8%	-33.2%	-33.0%	-33.1%	-33.7%	-34.8%	-36.3%	-38.4%	-41.4%	-45.4%	-51.4%	-60.2%
19.30	-47.5%	-45.4%	-43.7%	-42.4%	-41.6%	-41.3%	-41.5%	-42.2%	-43.4%	-45.3%	-48.4%	-53.0%	-59.9%

Pitch Setting: 5°

Percentage Difference from Baseline

Root to Tip Nose Up Twist	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-14.8%	-15.6%	-16.6%	-17.9%	-19.6%	-21.6%	-24.1%	-27.2%	-31.1%	-36.0%	-43.0%	-51.6%	-59.9%
10.30	-25.6%	-25.5%	-25.6%	-26.2%	-27.1%	-28.3%	-30.0%	-32.2%	-35.1%	-39.0%	-44.2%	-51.9%	-60.5%
13.30	-38.2%	-36.9%	-36.1%	-35.6%	-35.5%	-35.9%	-36.7%	-38.0%	-39.9%	-42.7%	-46.6%	-52.5%	-60.9%
16.30	-49.7%	-47.4%	-45.6%	-44.2%	-43.2%	-42.8%	-42.8%	-43.3%	-44.5%	-46.3%	-49.2%	-53.7%	-60.9%
19.30	-62.9%	-59.4%	-56.4%	-53.9%	-51.9%	-50.5%	-49.5%	-49.2%	-49.5%	-50.5%	-52.4%	-55.7%	-61.2%

Pitch Setting: 6°

Percentage Difference from Baseline

Root to Tip Nose Up Twist	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-28.8%	-28.4%	-28.4%	-28.6%	-29.3%	-30.3%	-31.8%	-33.8%	-36.6%	-40.4%	-45.8%	-53.1%	-61.1%
10.30	-40.2%	-38.8%	-37.8%	-37.2%	-37.0%	-37.2%	-37.9%	-39.0%	-40.9%	-43.7%	-47.6%	-53.7%	-61.6%
13.30	-53.3%	-50.7%	-48.6%	-46.9%	-45.7%	-45.0%	-44.7%	-45.0%	-45.9%	-47.6%	-50.4%	-54.8%	-61.8%
16.30	-65.3%	-61.6%	-58.4%	-55.7%	-53.6%	-51.9%	-50.9%	-50.4%	-50.6%	-51.4%	-53.3%	-56.5%	-62.1%
19.30	-78.9%	-73.9%	-69.5%	-65.6%	-62.4%	-59.8%	-57.8%	-56.4%	-55.7%	-55.7%	-56.6%	-58.8%	-62.8%

Pitch Setting: 7°

Percentage Difference from Baseline

Root to Tip Nose Up Twist	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-43.6%	-41.9%	-40.6%	-39.7%	-39.2%	-39.2%	-39.6%	-40.6%	-42.3%	-45.1%	-49.1%	-55.0%	-62.3%
10.30	-55.5%	-52.7%	-50.4%	-48.5%	-47.1%	-46.2%	-45.9%	-46.0%	-46.8%	-48.5%	-51.4%	-55.9%	-62.6%
13.30	-69.2%	-65.1%	-61.5%	-58.5%	-56.1%	-54.2%	-52.8%	-52.1%	-52.1%	-52.7%	-54.5%	-57.6%	-63.0%
16.30	-81.6%	-76.3%	-71.6%	-67.5%	-64.1%	-61.3%	-59.1%	-57.6%	-56.7%	-56.6%	-57.4%	-59.6%	-63.6%
19.30	-95.3%	-88.9%	-83.0%	-77.7%	-73.1%	-69.2%	-66.1%	-63.6%	-61.9%	-61.0%	-61.0%	-62.1%	-64.9%

Pitch Setting: 8°

Percentage Difference from Baseline

Root to Tip Nose Up Twist	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-59.3%	-56.1%	-53.3%	-51.1%	-49.4%	-48.3%	-47.6%	-47.6%	-48.2%	-49.8%	-52.8%	-57.3%	-63.5%
10.30	-71.8%	-67.3%	-63.4%	-60.2%	-57.5%	-55.5%	-54.0%	-53.1%	-52.9%	-53.6%	-55.4%	-58.6%	-63.9%
13.30	-85.7%	-80.1%	-75.0%	-70.4%	-66.7%	-63.6%	-61.1%	-59.3%	-58.2%	-57.9%	-58.6%	-60.7%	-64.6%
16.30	-98.0%	-91.4%	-85.3%	-79.8%	-74.9%	-70.8%	-67.4%	-64.8%	-63.0%	-61.9%	-61.8%	-62.9%	-65.6%
19.30	-111.9%	-104.0%	-96.7%	-90.1%	-84.1%	-78.9%	-74.5%	-70.9%	-68.2%	-66.3%	-65.4%	-65.5%	-67.2%

Pitch Setting:		9°												
				Percentage Difference from Baseline										
	Root to Tip	RPM						Baseline						
	Nose Up Twist	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
	7.30	-75.3%	-70.9%	-66.7%	-63.0%	-59.9%	-57.5%	-55.8%	-54.7%	-54.3%	-54.8%	-56.6%	-59.9%	-65.0%
	10.30	-87.7%	-82.2%	-77.1%	-72.4%	-68.2%	-64.9%	-62.2%	-60.3%	-59.1%	-58.7%	-59.4%	-61.6%	-65.7%
	13.30	-101.7%	-94.9%	-88.7%	-82.9%	-77.6%	-73.1%	-69.4%	-66.6%	-64.5%	-63.2%	-62.9%	-63.9%	-66.6%
	16.30	-114.6%	-106.4%	-98.9%	-92.2%	-86.1%	-80.5%	-75.9%	-72.1%	-69.2%	-67.2%	-66.2%	-66.3%	-68.0%
	19.30	-128.7%	-119.3%	-110.5%	-102.5%	-95.3%	-88.8%	-83.1%	-78.3%	-74.5%	-71.7%	-69.9%	-69.1%	-69.8%

Appendix R

Power Results for NREL 5MW Turbine Twist vs. Pitch Parametric Study at 11.4 m/s

Pitch Setting:	-2°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-22.2%	-17.8%	-13.8%	-10.3%	-7.6%	-6.0%	-4.2%	-7.9%	-20.6%	-33.6%	-47.2%	-60.2%	-72.0%
10.30	-16.3%	-12.6%	-9.2%	-6.3%	-3.8%	-2.5%	-1.6%	-2.5%	-13.0%	-28.5%	-43.6%	-57.0%	-69.3%
13.30	-11.4%	-8.2%	-5.4%	-3.1%	-1.2%	-0.2%	-0.4%	-2.2%	-7.0%	-22.4%	-39.9%	-54.0%	-66.6%
16.30	-10.0%	-7.0%	-4.5%	-2.4%	-0.8%	-0.1%	-1.0%	-3.3%	-7.3%	-16.0%	-35.9%	-51.6%	-64.6%
19.30	-12.4%	-9.2%	-6.5%	-4.3%	-2.9%	-2.4%	-3.3%	-5.7%	-9.4%	-15.2%	-29.0%	-48.7%	-62.7%

Pitch Setting:	-1°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-15.8%	-12.2%	-9.0%	-6.2%	-3.7%	-2.0%	-1.2%	-4.1%	-16.6%	-29.9%	-43.4%	-56.8%	-69.1%
10.30	-10.5%	-7.5%	-4.8%	-2.5%	-0.5%	1.0%	0.4%	-2.0%	-9.7%	-25.4%	-39.9%	-53.9%	-66.6%
13.30	-7.1%	-4.5%	-2.3%	-0.4%	1.0%	1.7%	0.3%	-2.6%	-7.4%	-18.5%	-35.7%	-51.1%	-64.1%
16.30	-7.8%	-5.2%	-2.9%	-1.2%	-0.1%	0.1%	-1.3%	-4.4%	-8.8%	-15.5%	-31.3%	-48.8%	-62.3%
19.30	-12.6%	-9.6%	-7.1%	-5.2%	-4.1%	-3.9%	-4.9%	-7.5%	-11.6%	-16.9%	-26.0%	-46.3%	-60.5%

Pitch Setting:	0°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-10.2%	-7.2%	-4.6%	-2.2%	-0.1%	1.4%	0.9%	-2.4%	-13.1%	-27.6%	-40.4%	-53.6%	-66.4%
10.30	-5.7%	-3.2%	-1.1%	0.8%	2.3%	2.7%	1.3%	-2.1%	-8.4%	-22.4%	-37.1%	-51.0%	-64.1%
13.30	-4.3%	-2.1%	-0.3%	1.1%	1.8%	1.5%	0.0%	-3.7%	-8.7%	-17.0%	-33.2%	-48.4%	-61.8%
16.30	-7.3%	-5.0%	-3.1%	-1.9%	-1.3%	-1.7%	-3.0%	-6.1%	-10.7%	-16.8%	-28.3%	-45.8%	-60.1%
19.30	-15.4%	-12.3%	-9.9%	-8.1%	-7.2%	-7.1%	-7.9%	-10.1%	-14.0%	-19.2%	-26.4%	-42.0%	-58.4%

Pitch Setting:	1°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-5.0%	-2.6%	-0.4%	1.5%	2.8%	3.0%	1.5%	-2.2%	-10.9%	-25.1%	-38.4%	-51.1%	-64.0%
10.30	-1.9%	0.1%	1.8%	2.8%	3.1%	2.5%	0.6%	-3.0%	-8.8%	-20.2%	-35.5%	-48.7%	-61.9%
13.30	-3.3%	-1.6%	-0.3%	0.3%	0.3%	-0.5%	-2.3%	-5.4%	-10.5%	-17.6%	-30.9%	-46.1%	-59.9%
16.30	-9.5%	-7.3%	-5.7%	-4.8%	-4.6%	-5.1%	-6.4%	-8.8%	-13.1%	-18.8%	-27.6%	-43.5%	-58.3%
19.30	-21.0%	-17.7%	-15.0%	-13.2%	-12.1%	-11.8%	-12.4%	-13.9%	-17.0%	-21.8%	-28.1%	-39.4%	-56.7%

Pitch Setting:	2°												
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-0.3%	1.4%	2.7%	3.4%	3.4%	2.5%	0.4%	-3.2%	-10.1%	-23.2%	-37.2%	-49.3%	-61.8%
10.30	0.1%	1.2%	1.9%	2.0%	1.5%	0.4%	-1.7%	-5.0%	-10.3%	-19.3%	-33.7%	-47.2%	-59.9%
13.30	-5.6%	-4.2%	-3.3%	-3.0%	-3.3%	-4.2%	-5.9%	-8.6%	-12.8%	-19.1%	-29.7%	-44.9%	-58.0%
16.30	-15.2%	-12.8%	-11.1%	-10.1%	-9.7%	-10.0%	-11.0%	-12.9%	-16.0%	-21.3%	-28.6%	-41.8%	-56.5%
19.30	-29.9%	-25.9%	-22.7%	-20.3%	-18.7%	-18.0%	-18.0%	-19.0%	-20.9%	-24.7%	-30.3%	-38.9%	-54.4%

Pitch Setting: 3°												
			Percentage Difference from Baseline									
Root to Tip	RPM						Baseline					
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	1.5%	2.2%	2.4%	2.2%	1.5%	0.2%	-2.0%	-5.5%	-11.2%	-22.1%	-35.9%	-48.2%	-60.1%
10.30	-2.4%	-1.6%	-1.3%	-1.5%	-2.2%	-3.4%	-5.3%	-8.3%	-12.7%	-19.9%	-32.5%	-46.4%	-58.4%
13.30	-12.0%	-10.3%	-9.2%	-8.7%	-8.8%	-9.4%	-10.7%	-12.8%	-16.1%	-21.3%	-29.8%	-43.6%	-56.7%
16.30	-24.5%	-21.5%	-19.1%	-17.4%	-16.5%	-16.3%	-16.7%	-18.0%	-20.2%	-24.1%	-30.3%	-40.8%	-55.2%
19.30	-42.2%	-37.0%	-32.7%	-29.4%	-26.9%	-25.4%	-24.6%	-24.8%	-25.8%	-28.2%	-32.9%	-40.0%	-53.1%

Pitch Setting: 4°													
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-1.7%	-1.2%	-1.2%	-1.5%	-2.4%	-3.7%	-5.7%	-8.8%	-13.5%	-22.0%	-34.9%	-47.7%	-58.9%
10.30	-9.1%	-8.0%	-7.4%	-7.3%	-7.7%	-8.6%	-10.1%	-12.4%	-16.1%	-21.8%	-32.1%	-45.6%	-57.5%
13.30	-22.1%	-19.6%	-17.7%	-16.5%	-15.8%	-15.9%	-16.5%	-17.9%	-20.4%	-24.4%	-31.1%	-42.8%	-56.0%
16.30	-37.2%	-32.9%	-29.5%	-26.8%	-24.9%	-23.7%	-23.4%	-23.8%	-25.2%	-27.9%	-32.7%	-41.0%	-54.5%
19.30	-57.6%	-50.8%	-45.0%	-40.3%	-36.6%	-33.8%	-32.1%	-31.3%	-31.4%	-32.7%	-35.8%	-41.7%	-52.1%

Pitch Setting: 5°													
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-8.8%	-8.0%	-7.5%	-7.5%	-8.0%	-8.9%	-10.5%	-13.0%	-16.9%	-23.4%	-34.5%	-47.1%	-58.3%
10.30	-19.4%	-17.4%	-16.0%	-15.1%	-14.8%	-15.0%	-15.9%	-17.5%	-20.3%	-24.7%	-32.6%	-44.9%	-57.1%
13.30	-35.4%	-31.5%	-28.5%	-26.1%	-24.4%	-23.5%	-23.3%	-23.9%	-25.3%	-28.3%	-33.3%	-42.7%	-55.6%
16.30	-53.0%	-46.9%	-41.9%	-37.8%	-34.6%	-32.3%	-30.9%	-30.4%	-30.8%	-32.3%	-35.7%	-42.3%	-53.8%
19.30	-76.2%	-67.0%	-59.3%	-52.8%	-47.5%	-43.4%	-40.4%	-38.4%	-37.5%	-37.8%	-39.6%	-43.9%	-52.0%

Pitch Setting: 6°													
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-19.4%	-17.5%	-16.2%	-15.4%	-15.1%	-15.4%	-16.3%	-18.0%	-20.9%	-26.1%	-35.0%	-46.7%	-58.0%
10.30	-32.8%	-29.4%	-26.7%	-24.7%	-23.3%	-22.6%	-22.6%	-23.4%	-25.1%	-28.4%	-34.4%	-44.8%	-56.8%
13.30	-51.6%	-45.9%	-41.2%	-37.3%	-34.3%	-32.2%	-30.9%	-30.4%	-30.9%	-32.6%	-36.4%	-43.5%	-55.1%
16.30	-71.8%	-63.3%	-56.3%	-50.4%	-45.6%	-41.9%	-39.2%	-37.5%	-36.9%	-37.4%	-39.5%	-44.2%	-53.6%
19.30	-97.8%	-85.9%	-75.5%	-66.9%	-59.7%	-54.0%	-49.5%	-46.1%	-44.1%	-43.3%	-43.8%	-46.5%	-52.9%

Pitch Setting: 7°													
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-33.1%	-29.8%	-27.1%	-25.1%	-23.7%	-23.0%	-23.0%	-23.8%	-25.7%	-29.4%	-36.4%	-46.8%	-57.9%
10.30	-49.2%	-43.8%	-39.5%	-35.9%	-33.2%	-31.3%	-30.2%	-29.9%	-30.6%	-32.7%	-37.2%	-45.4%	-56.6%
13.30	-71.0%	-62.8%	-55.8%	-50.1%	-45.5%	-41.9%	-39.3%	-37.6%	-37.1%	-37.6%	-40.0%	-45.2%	-55.1%
16.30	-93.7%	-82.4%	-72.7%	-64.5%	-57.9%	-52.5%	-48.3%	-45.3%	-43.4%	-42.8%	-43.6%	-46.8%	-54.0%
19.30	-121.7%	-107.0%	-94.0%	-82.7%	-73.2%	-65.4%	-59.2%	-54.5%	-51.1%	-49.1%	-48.5%	-49.9%	-54.4%

Pitch Setting: 8°													
			Percentage Difference from Baseline										
Root to Tip	RPM						Baseline						
Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
7.30	-50.3%	-44.6%	-40.0%	-36.4%	-33.6%	-31.7%	-30.6%	-30.3%	-31.1%	-33.4%	-38.8%	-47.5%	-57.9%
10.30	-69.1%	-61.1%	-54.3%	-48.7%	-44.3%	-40.9%	-38.5%	-37.1%	-36.6%	-37.5%	-40.5%	-46.7%	-56.6%
13.30	-93.5%	-82.5%	-72.8%	-64.6%	-57.9%	-52.6%	-48.4%	-45.4%	-43.6%	-43.1%	-44.1%	-47.8%	-55.4%
16.30	-117.9%	-103.8%	-91.4%	-80.5%	-71.4%	-64.0%	-58.1%	-53.6%	-50.4%	-48.6%	-48.2%	-50.0%	-55.1%
19.30	-147.6%	-129.8%	-114.1%	-100.1%	-88.1%	-77.9%	-69.8%	-63.4%	-58.5%	-55.2%	-53.5%	-53.5%	-56.4%

Pitch Setting:		9°												
				Percentage Difference from Baseline										
	Root to Tip	RPM						Baseline						
	Nose Up Twis	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
	7.30	-70.0%	-62.3%	-55.4%	-49.6%	-44.9%	-41.4%	-38.9%	-37.5%	-37.1%	-38.1%	-41.8%	-48.7%	-58.1%
	10.30	-90.8%	-80.6%	-71.5%	-63.5%	-56.8%	-51.6%	-47.6%	-44.8%	-43.2%	-42.8%	-44.3%	-48.9%	-57.2%
	13.30	-117.3%	-103.6%	-91.6%	-81.0%	-71.8%	-64.2%	-58.3%	-53.8%	-50.7%	-48.9%	-48.6%	-50.8%	-56.5%
	16.30	-144.2%	-126.7%	-111.3%	-98.1%	-86.6%	-76.7%	-68.7%	-62.5%	-57.8%	-54.7%	-53.2%	-53.5%	-57.1%
	19.30	-175.4%	-154.5%	-135.6%	-118.8%	-104.2%	-91.7%	-81.2%	-72.8%	-66.3%	-61.6%	-58.7%	-57.5%	-58.9%

Appendix S

Root Bending Moment Results for WindPACT 1.5MW Turbine Chord vs. Pitch Parametric Study at 11.8 m/s

Pitch Setting: -2°

					Percentage Difference from Baseline								
Chord Scale	RPM						Baseline						
Factor	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	42.4%	34.8%	27.2%	19.6%	12.0%	3.3%	-9.6%	-18.4%	-31.4%	-44.1%	-56.0%	-66.5%	-76.2%
0.85	47.7%	39.8%	32.0%	24.1%	16.3%	7.7%	-4.8%	-13.6%	-27.1%	-40.5%	-53.2%	-64.4%	-74.7%
0.90	52.9%	44.7%	36.6%	28.5%	20.5%	11.9%	-0.4%	-9.0%	-22.9%	-36.9%	-50.3%	-62.2%	-73.2%
0.95	58.0%	49.4%	41.1%	32.7%	24.4%	15.9%	3.7%	-4.5%	-18.6%	-33.3%	-47.4%	-60.0%	-71.6%
1.00	63.0%	54.1%	45.4%	36.9%	28.3%	19.8%	7.4%	-0.4%	-14.4%	-29.7%	-44.5%	-57.8%	-70.1%
1.05	67.9%	58.6%	49.7%	40.9%	32.1%	23.3%	10.9%	3.4%	-10.3%	-26.1%	-41.6%	-55.6%	-68.5%
1.10	72.7%	63.1%	53.8%	44.8%	35.8%	26.8%	14.4%	6.8%	-6.3%	-22.6%	-38.7%	-53.4%	-67.0%
1.15	77.4%	67.5%	57.9%	48.6%	39.5%	30.2%	17.8%	10.1%	-2.5%	-19.0%	-35.8%	-51.1%	-65.4%
1.20	82.0%	71.8%	61.9%	52.4%	43.0%	33.5%	21.2%	13.3%	1.1%	-15.4%	-32.8%	-48.9%	-63.8%

Pitch Setting: -1°

					Percentage Difference from Baseline								
Chord Scale	RPM						Baseline						
Factor	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	34.3%	27.5%	20.9%	14.2%	7.4%	-0.6%	-12.4%	-20.0%	-31.8%	-43.9%	-55.6%	-66.1%	-75.9%
0.85	39.2%	32.1%	25.2%	18.3%	11.4%	3.8%	-8.0%	-15.6%	-27.6%	-40.4%	-52.7%	-63.9%	-74.4%
0.90	43.9%	36.6%	29.4%	22.3%	15.1%	7.8%	-3.8%	-11.3%	-23.5%	-36.9%	-49.8%	-61.7%	-72.8%
0.95	48.6%	40.9%	33.5%	26.2%	18.8%	11.3%	0.1%	-7.3%	-19.5%	-33.3%	-46.9%	-59.5%	-71.3%
1.00	53.2%	45.2%	37.5%	29.9%	22.4%	14.7%	3.8%	-3.4%	-15.6%	-29.8%	-44.1%	-57.3%	-69.7%
1.05	57.7%	49.4%	41.4%	33.5%	25.9%	18.0%	7.2%	0.2%	-11.8%	-26.3%	-41.2%	-55.0%	-68.1%
1.10	62.0%	53.5%	45.2%	37.1%	29.2%	21.2%	10.5%	3.5%	-8.2%	-22.8%	-38.3%	-52.8%	-66.6%
1.15	66.3%	57.5%	48.9%	40.6%	32.5%	24.3%	13.6%	6.5%	-4.7%	-19.4%	-35.4%	-50.6%	-65.0%
1.20	70.4%	61.5%	52.6%	44.1%	35.7%	27.4%	16.5%	9.5%	-1.4%	-16.0%	-32.5%	-48.3%	-63.4%

Pitch Setting: 0°

					Percentage Difference from Baseline								
Chord Scale	RPM						Baseline						
Factor	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	26.5%	20.6%	14.7%	8.9%	2.4%	-4.8%	-15.7%	-22.4%	-32.8%	-44.1%	-55.3%	-65.7%	-75.6%
0.85	31.0%	24.8%	18.7%	12.6%	6.4%	-0.6%	-11.5%	-18.3%	-28.8%	-40.6%	-52.4%	-63.5%	-74.1%
0.90	35.3%	28.8%	22.5%	16.2%	10.0%	3.2%	-7.5%	-14.3%	-25.0%	-37.1%	-49.6%	-61.3%	-72.5%
0.95	39.6%	32.8%	26.2%	19.7%	13.3%	6.6%	-3.6%	-10.5%	-21.3%	-33.7%	-46.7%	-59.1%	-70.9%
1.00	43.7%	36.7%	29.8%	23.2%	16.6%	9.8%	0.0%	-6.8%	-17.6%	-30.3%	-43.9%	-56.8%	-69.3%
1.05	47.7%	40.5%	33.4%	26.5%	19.7%	12.8%	3.3%	-3.4%	-14.1%	-26.9%	-41.0%	-54.6%	-67.7%
1.10	51.6%	44.2%	36.8%	29.8%	22.8%	15.8%	6.3%	-0.1%	-10.7%	-23.6%	-38.2%	-52.3%	-66.1%
1.15	55.3%	47.8%	40.3%	32.9%	25.7%	18.6%	9.1%	3.0%	-7.5%	-20.4%	-35.3%	-50.1%	-64.6%
1.20	59.0%	51.4%	43.7%	36.1%	28.7%	21.4%	11.7%	5.8%	-4.4%	-17.2%	-32.5%	-47.9%	-62.9%

Pitch Setting: 1°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	19.1%	13.9%	8.8%	3.2%	-2.9%	-9.6%	-19.2%	-25.3%	-34.5%	-44.5%	-55.2%	-65.4%	-75.3%
0.85	23.1%	17.6%	12.4%	7.0%	1.1%	-5.6%	-15.2%	-21.4%	-30.8%	-41.2%	-52.4%	-63.2%	-73.8%
0.90	27.0%	21.4%	15.8%	10.4%	4.7%	-1.8%	-11.4%	-17.6%	-27.2%	-37.9%	-49.6%	-60.9%	-72.2%
0.95	30.8%	25.0%	19.2%	13.6%	7.9%	1.6%	-7.7%	-14.0%	-23.7%	-34.6%	-46.8%	-58.7%	-70.6%
1.00	34.4%	28.5%	22.5%	16.7%	10.9%	4.9%	-4.3%	-10.5%	-20.2%	-31.4%	-44.0%	-56.5%	-69.0%
1.05	37.9%	31.9%	25.8%	19.7%	13.8%	7.8%	-1.1%	-7.2%	-16.9%	-28.3%	-41.2%	-54.3%	-67.4%
1.10	41.3%	35.2%	28.9%	22.7%	16.6%	10.5%	1.8%	-4.0%	-13.7%	-25.2%	-38.4%	-52.0%	-65.8%
1.15	44.7%	38.4%	32.0%	25.6%	19.3%	13.0%	4.5%	-1.1%	-10.7%	-22.2%	-35.7%	-49.8%	-64.2%
1.20	47.9%	41.5%	35.0%	28.4%	22.0%	15.5%	7.0%	1.6%	-7.7%	-19.2%	-32.9%	-47.6%	-62.5%

Pitch Setting: 2°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	12.0%	7.3%	2.4%	-2.9%	-8.5%	-14.6%	-23.1%	-28.4%	-36.7%	-45.6%	-55.4%	-65.2%	-75.1%
0.85	15.5%	10.9%	6.1%	0.9%	-4.7%	-10.7%	-19.3%	-24.8%	-33.1%	-42.5%	-52.6%	-63.0%	-73.5%
0.90	18.9%	14.3%	9.5%	4.4%	-1.1%	-7.1%	-15.7%	-21.2%	-29.7%	-39.3%	-49.9%	-60.8%	-71.9%
0.95	22.2%	17.5%	12.6%	7.6%	2.2%	-3.7%	-12.3%	-17.8%	-26.4%	-36.2%	-47.1%	-58.6%	-70.3%
1.00	25.4%	20.6%	15.6%	10.5%	5.3%	-0.5%	-9.0%	-14.5%	-23.2%	-33.2%	-44.4%	-56.4%	-68.7%
1.05	28.6%	23.6%	18.5%	13.2%	8.1%	2.4%	-6.0%	-11.3%	-20.0%	-30.2%	-41.7%	-54.1%	-67.1%
1.10	31.6%	26.5%	21.3%	16.0%	10.7%	5.2%	-3.1%	-8.4%	-17.0%	-27.3%	-39.1%	-51.9%	-65.4%
1.15	34.5%	29.3%	24.0%	18.6%	13.1%	7.6%	-0.3%	-5.6%	-14.1%	-24.5%	-36.5%	-49.8%	-63.8%
1.20	37.4%	32.0%	26.7%	21.2%	15.5%	10.0%	2.2%	-2.9%	-11.3%	-21.7%	-33.9%	-47.6%	-62.2%

Pitch Setting: 3°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	4.6%	0.3%	-4.5%	-9.4%	-14.4%	-19.8%	-27.3%	-32.0%	-39.1%	-47.2%	-55.9%	-65.1%	-74.9%
0.85	8.1%	4.0%	-0.7%	-5.6%	-10.7%	-16.1%	-23.7%	-28.5%	-35.8%	-44.1%	-53.2%	-63.0%	-73.3%
0.90	11.2%	7.3%	2.8%	-2.1%	-7.2%	-12.6%	-20.3%	-25.1%	-32.6%	-41.2%	-50.6%	-60.8%	-71.6%
0.95	14.1%	10.3%	6.0%	1.2%	-3.9%	-9.4%	-17.1%	-21.9%	-29.5%	-38.2%	-48.0%	-58.6%	-70.0%
1.00	17.0%	13.0%	8.9%	4.2%	-0.9%	-6.3%	-14.0%	-18.8%	-26.4%	-35.4%	-45.4%	-56.4%	-68.4%
1.05	19.7%	15.6%	11.5%	7.0%	2.0%	-3.3%	-11.0%	-15.8%	-23.5%	-32.5%	-42.9%	-54.3%	-66.8%
1.10	22.3%	18.2%	14.0%	9.6%	4.7%	-0.6%	-8.2%	-13.0%	-20.7%	-29.8%	-40.3%	-52.1%	-65.2%
1.15	24.9%	20.7%	16.3%	11.9%	7.1%	2.0%	-5.5%	-10.3%	-17.9%	-27.1%	-37.8%	-50.0%	-63.6%
1.20	27.4%	23.1%	18.7%	14.2%	9.4%	4.3%	-3.0%	-7.8%	-15.3%	-24.4%	-35.4%	-47.8%	-62.0%

Pitch Setting: 4°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-3.7%	-7.5%	-11.6%	-16.0%	-20.5%	-25.1%	-31.6%	-35.7%	-41.9%	-49.0%	-56.9%	-65.3%	-74.7%
0.85	-0.1%	-3.9%	-7.9%	-12.3%	-17.0%	-21.7%	-28.3%	-32.4%	-38.8%	-46.1%	-54.3%	-63.2%	-73.1%
0.90	3.2%	-0.5%	-4.5%	-8.9%	-13.6%	-18.4%	-25.1%	-29.3%	-35.8%	-43.3%	-51.8%	-61.0%	-71.5%
0.95	6.2%	2.6%	-1.3%	-5.7%	-10.4%	-15.3%	-22.0%	-26.3%	-32.9%	-40.5%	-49.3%	-58.9%	-69.9%
1.00	8.9%	5.5%	1.6%	-2.6%	-7.4%	-12.3%	-19.1%	-23.4%	-30.0%	-37.8%	-46.8%	-56.8%	-68.3%
1.05	11.4%	8.1%	4.4%	0.2%	-4.5%	-9.5%	-16.3%	-20.5%	-27.3%	-35.1%	-44.4%	-54.7%	-66.7%
1.10	13.7%	10.4%	6.8%	2.8%	-1.8%	-6.8%	-13.6%	-17.9%	-24.6%	-32.5%	-42.0%	-52.6%	-65.0%
1.15	15.9%	12.6%	9.1%	5.2%	0.8%	-4.2%	-11.0%	-15.3%	-22.0%	-30.0%	-39.6%	-50.5%	-63.4%
1.20	18.1%	14.7%	11.2%	7.4%	3.2%	-1.8%	-8.6%	-12.8%	-19.5%	-27.5%	-37.3%	-48.4%	-61.8%

Pitch Setting: 5°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-12.5%	-15.7%	-19.1%	-22.7%	-26.6%	-30.6%	-36.2%	-39.6%	-45.0%	-51.1%	-58.1%	-65.7%	-74.6%
0.85	-9.0%	-12.2%	-15.6%	-19.3%	-23.3%	-27.4%	-33.0%	-36.6%	-42.1%	-48.4%	-55.6%	-63.6%	-73.0%
0.90	-5.8%	-9.0%	-12.4%	-16.0%	-20.1%	-24.3%	-30.1%	-33.6%	-39.3%	-45.7%	-53.2%	-61.6%	-71.4%
0.95	-2.7%	-5.9%	-9.3%	-13.0%	-17.0%	-21.3%	-27.2%	-30.8%	-36.5%	-43.1%	-50.9%	-59.5%	-69.8%
1.00	0.1%	-3.0%	-6.4%	-10.1%	-14.1%	-18.5%	-24.4%	-28.1%	-33.8%	-40.6%	-48.5%	-57.5%	-68.2%
1.05	2.8%	-0.3%	-3.7%	-7.3%	-11.3%	-15.7%	-21.8%	-25.4%	-31.2%	-38.1%	-46.2%	-55.5%	-66.6%
1.10	5.2%	2.2%	-1.1%	-4.7%	-8.7%	-13.1%	-19.2%	-22.9%	-28.7%	-35.6%	-43.9%	-53.5%	-65.1%
1.15	7.4%	4.5%	1.3%	-2.3%	-6.2%	-10.6%	-16.7%	-20.4%	-26.3%	-33.3%	-41.6%	-51.5%	-63.5%
1.20	9.5%	6.6%	3.5%	0.0%	-3.8%	-8.2%	-14.4%	-18.1%	-23.9%	-31.0%	-39.4%	-49.5%	-61.9%

Pitch Setting: 6°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-21.7%	-24.2%	-26.8%	-29.7%	-32.8%	-36.2%	-40.8%	-43.7%	-48.2%	-53.5%	-59.6%	-66.5%	-74.7%
0.85	-18.4%	-21.0%	-23.6%	-26.5%	-29.7%	-33.2%	-37.9%	-40.9%	-45.5%	-50.9%	-57.2%	-64.4%	-73.1%
0.90	-15.3%	-17.9%	-20.6%	-23.5%	-26.7%	-30.3%	-35.2%	-38.1%	-42.8%	-48.4%	-54.9%	-62.5%	-71.5%
0.95	-12.4%	-15.0%	-17.7%	-20.6%	-23.9%	-27.5%	-32.5%	-35.5%	-40.3%	-46.0%	-52.7%	-60.5%	-69.9%
1.00	-9.6%	-12.2%	-14.9%	-17.9%	-21.1%	-24.8%	-29.9%	-32.9%	-37.8%	-43.6%	-50.5%	-58.5%	-68.4%
1.05	-7.0%	-9.6%	-12.3%	-15.3%	-18.5%	-22.2%	-27.3%	-30.5%	-35.3%	-41.3%	-48.3%	-56.6%	-66.8%
1.10	-4.5%	-7.1%	-9.8%	-12.8%	-16.0%	-19.7%	-24.9%	-28.1%	-33.0%	-39.0%	-46.1%	-54.6%	-65.2%
1.15	-2.2%	-4.7%	-7.4%	-10.4%	-13.6%	-17.3%	-22.6%	-25.8%	-30.7%	-36.7%	-44.0%	-52.7%	-63.7%
1.20	0.0%	-2.5%	-5.2%	-8.1%	-11.4%	-15.0%	-20.3%	-23.6%	-28.5%	-34.5%	-41.9%	-50.9%	-62.1%

Pitch Setting: 7°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-31.1%	-32.8%	-34.7%	-36.8%	-39.1%	-41.8%	-45.5%	-47.9%	-51.6%	-56.1%	-61.3%	-67.4%	-74.9%
0.85	-28.1%	-29.9%	-31.8%	-33.9%	-36.3%	-39.0%	-42.9%	-45.3%	-49.1%	-53.7%	-59.1%	-65.4%	-73.3%
0.90	-25.3%	-27.0%	-29.0%	-31.2%	-33.6%	-36.3%	-40.3%	-42.7%	-46.6%	-51.3%	-56.9%	-63.5%	-71.8%
0.95	-22.6%	-24.3%	-26.3%	-28.5%	-31.0%	-33.7%	-37.8%	-40.3%	-44.2%	-49.0%	-54.8%	-61.6%	-70.2%
1.00	-20.0%	-21.8%	-23.8%	-26.0%	-28.4%	-31.2%	-35.3%	-37.9%	-41.9%	-46.8%	-52.7%	-59.8%	-68.7%
1.05	-17.5%	-19.3%	-21.3%	-23.5%	-26.0%	-28.8%	-33.0%	-35.6%	-39.7%	-44.6%	-50.6%	-57.9%	-67.2%
1.10	-15.2%	-16.9%	-18.9%	-21.2%	-23.7%	-26.5%	-30.7%	-33.4%	-37.5%	-42.4%	-48.6%	-56.1%	-65.6%
1.15	-13.0%	-14.7%	-16.7%	-18.9%	-21.4%	-24.2%	-28.5%	-31.2%	-35.3%	-40.3%	-46.6%	-54.2%	-64.1%
1.20	-10.9%	-12.5%	-14.5%	-16.8%	-19.3%	-22.1%	-26.4%	-29.1%	-33.3%	-38.3%	-44.6%	-52.4%	-62.6%

Pitch Setting: 8°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-40.8%	-41.6%	-42.7%	-44.0%	-45.6%	-47.4%	-50.3%	-52.1%	-55.1%	-58.7%	-63.2%	-68.5%	-75.2%
0.85	-38.2%	-39.0%	-40.1%	-41.4%	-43.0%	-44.9%	-47.8%	-49.7%	-52.8%	-56.5%	-61.1%	-66.6%	-73.7%
0.90	-35.7%	-36.5%	-37.6%	-38.9%	-40.6%	-42.5%	-45.4%	-47.4%	-50.5%	-54.3%	-59.1%	-64.8%	-72.2%
0.95	-33.3%	-34.1%	-35.2%	-36.5%	-38.2%	-40.1%	-43.1%	-45.1%	-48.3%	-52.2%	-57.1%	-63.0%	-70.8%
1.00	-31.0%	-31.8%	-32.9%	-34.2%	-35.9%	-37.8%	-40.9%	-42.9%	-46.1%	-50.1%	-55.1%	-61.2%	-69.3%
1.05	-28.8%	-29.6%	-30.6%	-32.0%	-33.6%	-35.6%	-38.7%	-40.8%	-44.0%	-48.0%	-53.2%	-59.5%	-67.8%
1.10	-26.6%	-27.5%	-28.5%	-29.8%	-31.5%	-33.5%	-36.6%	-38.7%	-42.0%	-46.0%	-51.2%	-57.7%	-66.3%
1.15	-24.6%	-25.4%	-26.4%	-27.7%	-29.4%	-31.4%	-34.6%	-36.7%	-40.0%	-44.1%	-49.4%	-56.0%	-64.9%
1.20	-22.6%	-23.4%	-24.4%	-25.7%	-27.4%	-29.4%	-32.6%	-34.7%	-38.1%	-42.2%	-47.5%	-54.3%	-63.4%

Pitch Setting:	9°												
			Percentage Difference from Baseline										
Chord Scale	RPM						Baseline						
Factor	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-50.6%	-50.7%	-50.9%	-51.3%	-52.1%	-53.2%	-55.1%	-56.4%	-58.7%	-61.6%	-65.2%	-69.8%	-75.8%
0.85	-48.4%	-48.4%	-48.6%	-49.1%	-49.8%	-50.9%	-52.9%	-54.2%	-56.5%	-59.5%	-63.3%	-68.0%	-74.3%
0.90	-46.2%	-46.2%	-46.4%	-46.9%	-47.6%	-48.7%	-50.7%	-52.1%	-54.4%	-57.5%	-61.4%	-66.3%	-72.9%
0.95	-44.1%	-44.1%	-44.3%	-44.7%	-45.5%	-46.6%	-48.6%	-50.0%	-52.4%	-55.5%	-59.5%	-64.6%	-71.5%
1.00	-42.1%	-42.1%	-42.3%	-42.7%	-43.4%	-44.5%	-46.5%	-48.0%	-50.4%	-53.5%	-57.7%	-62.9%	-70.0%
1.05	-40.2%	-40.1%	-40.3%	-40.7%	-41.4%	-42.5%	-44.6%	-46.0%	-48.5%	-51.7%	-55.8%	-61.2%	-68.6%
1.10	-38.3%	-38.2%	-38.4%	-38.8%	-39.5%	-40.6%	-42.6%	-44.1%	-46.6%	-49.8%	-54.1%	-59.6%	-67.2%
1.15	-36.5%	-36.4%	-36.6%	-36.9%	-37.6%	-38.7%	-40.7%	-42.2%	-44.8%	-48.0%	-52.3%	-57.9%	-65.8%
1.20	-34.8%	-34.6%	-34.8%	-35.1%	-35.8%	-36.9%	-38.9%	-40.4%	-43.0%	-46.2%	-50.6%	-56.3%	-64.4%

Appendix T

Power Results for WindPACT 1.5MW Turbine Chord vs. Pitch Parametric Study at 11.8 m/s

Pitch Setting: -2°

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
	Percentage Difference from Baseline												
0.80	-13.8%	-9.3%	-5.3%	-2.1%	-0.4%	-0.8%	-7.7%	-15.4%	-29.1%	-45.3%	-61.9%	-76.5%	-88.5%
0.85	-17.2%	-12.3%	-8.0%	-4.3%	-1.8%	-1.2%	-5.5%	-12.3%	-25.6%	-42.0%	-59.4%	-74.8%	-87.6%
0.90	-20.6%	-15.4%	-10.7%	-6.6%	-3.5%	-2.2%	-4.1%	-9.7%	-22.3%	-38.8%	-56.8%	-73.1%	-86.7%
0.95	-24.1%	-18.4%	-13.4%	-9.0%	-5.3%	-3.2%	-3.5%	-7.7%	-19.3%	-35.7%	-54.3%	-71.4%	-85.9%
1.00	-27.6%	-21.5%	-16.1%	-11.4%	-7.3%	-4.5%	-3.8%	-6.4%	-16.7%	-32.7%	-51.8%	-69.7%	-85.0%
1.05	-31.1%	-24.5%	-18.7%	-13.7%	-9.3%	-6.0%	-4.6%	-5.9%	-14.3%	-29.8%	-49.2%	-68.0%	-84.1%
1.10	-34.7%	-27.6%	-21.4%	-16.0%	-11.4%	-7.7%	-5.4%	-6.0%	-12.5%	-27.1%	-46.7%	-66.3%	-83.1%
1.15	-38.3%	-30.7%	-24.1%	-18.4%	-13.4%	-9.3%	-6.4%	-6.4%	-11.1%	-24.6%	-44.3%	-64.5%	-82.2%
1.20	-42.0%	-33.8%	-26.8%	-20.7%	-15.4%	-11.0%	-7.4%	-6.9%	-10.3%	-22.3%	-41.8%	-62.7%	-81.2%

Pitch Setting: -1°

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
	Percentage Difference from Baseline												
0.80	-9.3%	-5.5%	-2.3%	0.6%	2.2%	0.4%	-6.7%	-13.7%	-26.5%	-41.7%	-57.8%	-72.8%	-85.9%
0.85	-12.3%	-8.2%	-4.6%	-1.4%	0.9%	1.0%	-4.4%	-10.7%	-23.0%	-38.4%	-55.1%	-70.9%	-84.8%
0.90	-15.3%	-10.9%	-6.9%	-3.5%	-0.7%	0.7%	-2.7%	-8.1%	-19.8%	-35.2%	-52.5%	-69.1%	-83.8%
0.95	-18.5%	-13.6%	-9.3%	-5.6%	-2.4%	-0.4%	-1.8%	-6.1%	-16.9%	-32.1%	-49.8%	-67.2%	-82.8%
1.00	-21.6%	-16.3%	-11.7%	-7.7%	-4.3%	-1.7%	-1.5%	-4.5%	-14.3%	-29.2%	-47.2%	-65.4%	-81.7%
1.05	-24.7%	-19.0%	-14.1%	-9.9%	-6.2%	-3.2%	-1.9%	-3.6%	-12.0%	-26.4%	-44.6%	-63.5%	-80.7%
1.10	-27.9%	-21.7%	-16.5%	-11.9%	-8.0%	-4.7%	-2.6%	-3.3%	-10.1%	-23.8%	-42.1%	-61.6%	-79.6%
1.15	-31.0%	-24.5%	-18.8%	-14.0%	-9.9%	-6.3%	-3.4%	-3.6%	-8.7%	-21.3%	-39.6%	-59.7%	-78.5%
1.20	-34.1%	-27.3%	-21.2%	-16.1%	-11.7%	-7.9%	-4.5%	-4.2%	-7.7%	-19.1%	-37.2%	-57.8%	-77.4%

Pitch Setting: 0°

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
	Percentage Difference from Baseline												
0.80	-5.3%	-2.2%	0.5%	2.8%	3.2%	0.8%	-6.6%	-13.1%	-24.7%	-39.0%	-54.4%	-69.5%	-83.3%
0.85	-8.0%	-4.5%	-1.5%	1.1%	2.9%	1.9%	-4.1%	-10.0%	-21.4%	-35.7%	-51.7%	-67.5%	-82.1%
0.90	-10.7%	-6.8%	-3.5%	-0.7%	1.7%	2.3%	-2.2%	-7.4%	-18.2%	-32.5%	-48.9%	-65.5%	-81.0%
0.95	-13.5%	-9.2%	-5.6%	-2.5%	0.1%	1.8%	-0.8%	-5.2%	-15.4%	-29.5%	-46.2%	-63.5%	-79.8%
1.00	-16.2%	-11.6%	-7.7%	-4.4%	-1.6%	0.7%	0.0%	-3.5%	-12.8%	-26.6%	-43.6%	-61.5%	-78.6%
1.05	-18.9%	-14.1%	-9.8%	-6.3%	-3.2%	-0.7%	0.2%	-2.3%	-10.5%	-23.8%	-41.0%	-59.5%	-77.4%
1.10	-21.6%	-16.6%	-12.0%	-8.2%	-4.9%	-2.1%	-0.2%	-1.6%	-8.6%	-21.3%	-38.5%	-57.5%	-76.2%
1.15	-24.3%	-19.0%	-14.1%	-10.0%	-6.5%	-3.6%	-1.1%	-1.4%	-7.0%	-18.9%	-36.0%	-55.5%	-75.0%
1.20	-26.9%	-21.4%	-16.3%	-11.9%	-8.2%	-5.0%	-2.1%	-1.7%	-5.8%	-16.8%	-33.6%	-53.5%	-73.8%

Pitch Setting: 1°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-2.1%	0.7%	2.8%	3.6%	2.7%	-0.1%	-7.1%	-13.1%	-23.9%	-37.0%	-51.7%	-66.6%	-80.8%
0.85	-4.3%	-1.3%	1.2%	3.1%	3.2%	1.4%	-4.6%	-10.1%	-20.6%	-33.8%	-48.9%	-64.4%	-79.5%
0.90	-6.6%	-3.3%	-0.5%	1.8%	3.1%	2.3%	-2.4%	-7.4%	-17.5%	-30.6%	-46.2%	-62.3%	-78.2%
0.95	-8.9%	-5.4%	-2.3%	0.2%	2.3%	2.6%	-0.8%	-5.1%	-14.6%	-27.7%	-43.4%	-60.2%	-76.9%
1.00	-11.2%	-7.5%	-4.1%	-1.4%	0.9%	2.4%	0.3%	-3.3%	-12.1%	-24.8%	-40.8%	-58.1%	-75.6%
1.05	-13.5%	-9.7%	-6.1%	-3.0%	-0.5%	1.5%	0.9%	-1.9%	-9.8%	-22.2%	-38.2%	-56.0%	-74.3%
1.10	-15.9%	-11.8%	-8.0%	-4.6%	-2.0%	0.3%	1.1%	-0.9%	-7.7%	-19.7%	-35.7%	-53.9%	-73.0%
1.15	-18.2%	-13.8%	-9.9%	-6.3%	-3.4%	-1.0%	0.8%	-0.3%	-6.0%	-17.4%	-33.2%	-51.9%	-71.7%
1.20	-20.5%	-15.9%	-11.8%	-8.0%	-4.9%	-2.3%	0.1%	-0.2%	-4.6%	-15.2%	-30.9%	-49.8%	-70.3%

Pitch Setting: 2°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	0.7%	2.8%	3.4%	2.7%	0.9%	-2.1%	-8.5%	-13.9%	-23.8%	-35.9%	-49.7%	-64.1%	-78.5%
0.85	-1.1%	1.4%	3.1%	3.2%	2.2%	-0.2%	-5.9%	-10.9%	-20.5%	-32.7%	-46.9%	-61.9%	-77.1%
0.90	-3.0%	-0.3%	2.1%	3.2%	2.8%	1.1%	-3.7%	-8.2%	-17.4%	-29.7%	-44.1%	-59.7%	-75.7%
0.95	-4.9%	-2.1%	0.5%	2.5%	3.0%	2.0%	-1.9%	-5.9%	-14.6%	-26.7%	-41.3%	-57.5%	-74.3%
1.00	-6.8%	-3.8%	-1.1%	1.3%	2.7%	2.5%	-0.5%	-4.0%	-12.0%	-23.9%	-38.7%	-55.3%	-72.9%
1.05	-8.8%	-5.6%	-2.8%	-0.1%	1.9%	2.5%	0.5%	-2.4%	-9.7%	-21.3%	-36.1%	-53.2%	-71.5%
1.10	-10.7%	-7.4%	-4.4%	-1.6%	0.7%	2.1%	1.1%	-1.2%	-7.6%	-18.8%	-33.6%	-51.1%	-70.1%
1.15	-12.7%	-9.2%	-6.0%	-3.1%	-0.6%	1.2%	1.4%	-0.4%	-5.8%	-16.5%	-31.2%	-49.0%	-68.6%
1.20	-14.7%	-10.9%	-7.6%	-4.6%	-1.9%	0.2%	1.3%	0.2%	-4.4%	-14.4%	-28.9%	-46.9%	-67.2%

Pitch Setting: 3°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	2.1%	2.4%	1.9%	0.4%	-1.8%	-4.9%	-10.8%	-15.5%	-24.3%	-35.5%	-48.3%	-62.1%	-76.5%
0.85	1.4%	2.5%	2.6%	1.7%	-0.1%	-2.8%	-8.2%	-12.6%	-21.0%	-32.4%	-45.4%	-59.8%	-75.0%
0.90	0.1%	2.0%	2.8%	2.5%	1.2%	-1.1%	-5.9%	-9.9%	-18.0%	-29.3%	-42.7%	-57.5%	-73.5%
0.95	-1.5%	0.9%	2.4%	2.8%	2.1%	0.3%	-3.9%	-7.6%	-15.2%	-26.4%	-40.0%	-55.3%	-72.0%
1.00	-3.1%	-0.6%	1.5%	2.7%	2.6%	1.3%	-2.3%	-5.6%	-12.7%	-23.7%	-37.4%	-53.1%	-70.5%
1.05	-4.8%	-2.1%	0.3%	2.1%	2.7%	1.9%	-1.0%	-3.9%	-10.4%	-21.0%	-34.9%	-50.9%	-69.0%
1.10	-6.4%	-3.6%	-1.1%	1.1%	2.4%	2.2%	0.0%	-2.5%	-8.4%	-18.6%	-32.4%	-48.8%	-67.5%
1.15	-8.1%	-5.1%	-2.5%	-0.2%	1.7%	2.2%	0.7%	-1.4%	-6.7%	-16.3%	-30.1%	-46.7%	-66.0%
1.20	-9.7%	-6.6%	-3.9%	-1.5%	0.7%	1.9%	1.1%	-0.6%	-5.2%	-14.1%	-27.8%	-44.6%	-64.5%

Pitch Setting: 4°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	0.5%	0.0%	-1.2%	-3.0%	-5.4%	-8.5%	-13.9%	-17.9%	-25.6%	-35.7%	-47.5%	-60.5%	-74.7%
0.85	1.0%	1.0%	0.3%	-1.2%	-3.3%	-6.1%	-11.2%	-15.0%	-22.4%	-32.5%	-44.7%	-58.2%	-73.1%
0.90	1.1%	1.6%	1.3%	0.2%	-1.6%	-4.1%	-8.8%	-12.4%	-19.5%	-29.5%	-42.0%	-55.9%	-71.5%
0.95	0.7%	1.7%	1.9%	1.2%	-0.2%	-2.5%	-6.7%	-10.1%	-16.8%	-26.7%	-39.3%	-53.6%	-69.9%
1.00	-0.2%	1.4%	2.1%	1.9%	0.8%	-1.1%	-4.9%	-8.0%	-14.3%	-24.0%	-36.7%	-51.4%	-68.4%
1.05	-1.4%	0.7%	1.9%	2.2%	1.6%	0.0%	-3.3%	-6.2%	-12.1%	-21.4%	-34.2%	-49.2%	-66.8%
1.10	-2.8%	-0.4%	1.4%	2.2%	2.0%	0.9%	-2.0%	-4.7%	-10.1%	-19.0%	-31.8%	-47.1%	-65.2%
1.15	-4.2%	-1.7%	0.5%	1.8%	2.2%	1.5%	-1.0%	-3.3%	-8.3%	-16.7%	-29.5%	-45.0%	-63.7%
1.20	-5.6%	-3.0%	-0.6%	1.2%	2.0%	1.8%	-0.2%	-2.2%	-6.7%	-14.6%	-27.2%	-42.9%	-62.1%

Pitch Setting: 5°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-3.6%	-4.3%	-5.6%	-7.4%	-9.8%	-12.7%	-17.5%	-21.0%	-27.5%	-36.4%	-47.3%	-59.4%	-73.1%
0.85	-2.2%	-2.7%	-3.7%	-5.3%	-7.5%	-10.2%	-14.8%	-18.1%	-24.5%	-33.3%	-44.5%	-57.1%	-71.5%
0.90	-1.3%	-1.4%	-2.1%	-3.4%	-5.4%	-8.0%	-12.3%	-15.6%	-21.7%	-30.4%	-41.8%	-54.8%	-69.9%
0.95	-0.6%	-0.5%	-0.9%	-1.9%	-3.7%	-6.1%	-10.1%	-13.2%	-19.0%	-27.7%	-39.2%	-52.5%	-68.2%
1.00	-0.3%	0.1%	0.0%	-0.7%	-2.2%	-4.4%	-8.1%	-11.1%	-16.6%	-25.0%	-36.6%	-50.3%	-66.6%
1.05	-0.4%	0.4%	0.7%	0.2%	-1.0%	-2.9%	-6.4%	-9.2%	-14.4%	-22.5%	-34.1%	-48.1%	-65.0%
1.10	-0.7%	0.4%	1.0%	0.8%	0.0%	-1.7%	-4.9%	-7.5%	-12.4%	-20.2%	-31.7%	-46.0%	-63.3%
1.15	-1.4%	0.2%	1.1%	1.3%	0.7%	-0.7%	-3.6%	-5.9%	-10.6%	-18.0%	-29.4%	-43.9%	-61.7%
1.20	-2.3%	-0.3%	0.9%	1.4%	1.2%	0.1%	-2.5%	-4.6%	-9.0%	-16.0%	-27.2%	-41.9%	-60.1%

Pitch Setting: 6°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-9.6%	-10.2%	-11.2%	-12.8%	-14.8%	-17.4%	-21.5%	-24.6%	-30.0%	-37.7%	-47.5%	-58.8%	-71.9%
0.85	-7.8%	-8.2%	-9.1%	-10.4%	-12.3%	-14.8%	-18.9%	-21.8%	-27.1%	-34.8%	-44.8%	-56.4%	-70.2%
0.90	-6.2%	-6.5%	-7.1%	-8.4%	-10.1%	-12.5%	-16.4%	-19.2%	-24.4%	-32.0%	-42.1%	-54.2%	-68.5%
0.95	-4.9%	-5.0%	-5.5%	-6.5%	-8.1%	-10.4%	-14.1%	-16.9%	-21.8%	-29.3%	-39.5%	-51.9%	-66.8%
1.00	-3.9%	-3.8%	-4.1%	-5.0%	-6.4%	-8.5%	-12.1%	-14.7%	-19.5%	-26.8%	-37.0%	-49.7%	-65.1%
1.05	-3.2%	-2.9%	-3.0%	-3.6%	-4.9%	-6.8%	-10.2%	-12.7%	-17.3%	-24.4%	-34.6%	-47.6%	-63.5%
1.10	-2.7%	-2.1%	-2.1%	-2.5%	-3.6%	-5.3%	-8.6%	-10.9%	-15.3%	-22.1%	-32.3%	-45.4%	-61.8%
1.15	-2.4%	-1.6%	-1.4%	-1.6%	-2.5%	-4.0%	-7.1%	-9.3%	-13.5%	-19.9%	-30.0%	-43.4%	-60.2%
1.20	-2.3%	-1.3%	-0.8%	-0.9%	-1.5%	-2.9%	-5.7%	-7.9%	-11.9%	-18.0%	-27.9%	-41.3%	-58.6%

Pitch Setting: 7°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-17.2%	-17.4%	-18.0%	-19.0%	-20.5%	-22.6%	-26.0%	-28.6%	-33.0%	-39.6%	-48.2%	-58.5%	-70.9%
0.85	-15.1%	-15.2%	-15.7%	-16.6%	-18.0%	-20.0%	-23.4%	-25.9%	-30.3%	-36.8%	-45.5%	-56.2%	-69.2%
0.90	-13.3%	-13.2%	-13.6%	-14.4%	-15.7%	-17.6%	-20.9%	-23.3%	-27.7%	-34.1%	-43.0%	-54.0%	-67.4%
0.95	-11.7%	-11.5%	-11.7%	-12.4%	-13.6%	-15.4%	-18.7%	-21.0%	-25.2%	-31.5%	-40.4%	-51.7%	-65.7%
1.00	-10.2%	-9.9%	-10.0%	-10.6%	-11.7%	-13.4%	-16.6%	-18.8%	-22.9%	-29.0%	-38.0%	-49.6%	-64.0%
1.05	-9.0%	-8.6%	-8.6%	-9.0%	-10.0%	-11.6%	-14.6%	-16.8%	-20.8%	-26.7%	-35.7%	-47.4%	-62.3%
1.10	-8.0%	-7.4%	-7.3%	-7.6%	-8.5%	-9.9%	-12.8%	-15.0%	-18.9%	-24.5%	-33.4%	-45.3%	-60.7%
1.15	-7.2%	-6.4%	-6.1%	-6.4%	-7.1%	-8.4%	-11.2%	-13.3%	-17.0%	-22.4%	-31.2%	-43.3%	-59.0%
1.20	-6.5%	-5.6%	-5.2%	-5.3%	-5.9%	-7.1%	-9.7%	-11.7%	-15.3%	-20.5%	-29.1%	-41.3%	-57.4%

Pitch Setting: 8°

Percentage Difference from Baseline

Chord Scale Factor	RPM 30.59	28.98	27.37	25.76	24.15	22.54	Baseline 20.50	19.32	17.71	16.10	14.49	12.88	11.10
0.80	-26.4%	-25.8%	-25.7%	-26.0%	-26.9%	-28.3%	-30.9%	-32.9%	-36.5%	-41.9%	-49.4%	-58.6%	-70.2%
0.85	-24.3%	-23.6%	-23.3%	-23.6%	-24.4%	-25.7%	-28.3%	-30.2%	-33.9%	-39.2%	-46.8%	-56.4%	-68.5%
0.90	-22.3%	-21.5%	-21.2%	-21.4%	-22.1%	-23.4%	-25.9%	-27.8%	-31.4%	-36.6%	-44.3%	-54.1%	-66.7%
0.95	-20.6%	-19.6%	-19.2%	-19.3%	-20.0%	-21.2%	-23.6%	-25.5%	-29.0%	-34.1%	-41.9%	-52.0%	-65.0%
1.00	-19.0%	-17.9%	-17.4%	-17.4%	-18.0%	-19.1%	-21.5%	-23.4%	-26.8%	-31.8%	-39.5%	-49.8%	-63.3%
1.05	-17.5%	-16.4%	-15.8%	-15.7%	-16.2%	-17.2%	-19.6%	-21.4%	-24.7%	-29.5%	-37.2%	-47.7%	-61.6%
1.10	-16.2%	-15.0%	-14.3%	-14.1%	-14.5%	-15.5%	-17.7%	-19.5%	-22.8%	-27.5%	-35.1%	-45.7%	-60.0%
1.15	-15.1%	-13.8%	-13.0%	-12.7%	-13.0%	-13.9%	-16.0%	-17.7%	-20.9%	-25.5%	-33.0%	-43.7%	-58.3%
1.20	-14.1%	-12.7%	-11.8%	-11.4%	-11.6%	-12.4%	-14.4%	-16.1%	-19.2%	-23.6%	-30.9%	-41.7%	-56.7%

Pitch Setting:		9°											
				Percentage Difference from Baseline									
	Chord Scale	RPM						Baseline					
	Factor	30.59	28.98	27.37	25.76	24.15	22.54	20.50	19.32	17.71	16.10	14.49	12.88	11.10
	0.80	-36.8%	-35.3%	-34.3%	-33.8%	-33.8%	-34.4%	-36.1%	-37.5%	-40.3%	-44.5%	-50.9%	-59.2%	-69.8%
	0.85	-34.7%	-33.2%	-32.1%	-31.5%	-31.4%	-31.9%	-33.6%	-35.0%	-37.8%	-42.0%	-48.5%	-56.9%	-68.1%
	0.90	-32.9%	-31.2%	-30.0%	-29.3%	-29.2%	-29.7%	-31.3%	-32.6%	-35.4%	-39.5%	-46.0%	-54.8%	-66.4%
	0.95	-31.1%	-29.3%	-28.1%	-27.3%	-27.1%	-27.5%	-29.1%	-30.4%	-33.1%	-37.2%	-43.7%	-52.6%	-64.6%
	1.00	-29.5%	-27.6%	-26.3%	-25.4%	-25.1%	-25.5%	-27.0%	-28.3%	-31.0%	-35.0%	-41.5%	-50.6%	-62.9%
	1.05	-28.0%	-26.0%	-24.6%	-23.7%	-23.3%	-23.6%	-25.0%	-26.4%	-28.9%	-32.9%	-39.3%	-48.5%	-61.3%
	1.10	-26.7%	-24.6%	-23.1%	-22.1%	-21.6%	-21.9%	-23.2%	-24.5%	-27.0%	-30.9%	-37.2%	-46.5%	-59.6%
	1.15	-25.4%	-23.2%	-21.6%	-20.6%	-20.1%	-20.2%	-21.5%	-22.7%	-25.2%	-29.0%	-35.1%	-44.6%	-58.0%
	1.20	-24.3%	-22.0%	-20.3%	-19.2%	-18.6%	-18.7%	-19.9%	-21.1%	-23.5%	-27.2%	-33.2%	-42.7%	-56.4%

Appendix U

Root Bending Moment Results for NREL 5MW Turbine Chord vs. Pitch Parametric Study at 11.4 m/s

Pitch Setting: -2°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	30.8%	26.0%	21.0%	15.8%	9.8%	3.0%	-4.6%	-12.9%	-23.4%	-36.2%	-46.2%	-55.6%	-64.6%
0.85	35.1%	30.0%	25.0%	19.7%	13.9%	7.4%	-0.2%	-8.5%	-18.8%	-32.3%	-43.0%	-52.9%	-62.4%
0.90	39.1%	33.9%	28.7%	23.5%	17.7%	11.3%	3.9%	-4.4%	-14.4%	-28.5%	-39.8%	-50.2%	-60.2%
0.95	43.0%	37.7%	32.3%	26.9%	21.3%	15.0%	7.8%	-0.4%	-10.2%	-24.6%	-36.6%	-47.5%	-58.0%
1.00	46.7%	41.3%	35.8%	30.3%	24.6%	18.3%	11.4%	3.3%	-6.2%	-20.6%	-33.5%	-44.9%	-55.8%
1.05	50.3%	44.8%	39.2%	33.5%	27.8%	21.6%	14.7%	6.8%	-2.5%	-16.4%	-30.3%	-42.2%	-53.7%
1.10	53.9%	48.1%	42.4%	36.6%	30.8%	24.6%	17.8%	10.1%	1.0%	-12.2%	-27.2%	-39.6%	-51.5%
1.15	57.3%	51.4%	45.6%	39.7%	33.7%	27.5%	20.7%	13.1%	4.2%	-8.2%	-24.2%	-36.9%	-49.3%
1.20	60.6%	54.6%	48.6%	42.6%	36.5%	30.3%	23.5%	16.0%	7.3%	-4.5%	-21.2%	-34.3%	-47.1%

Pitch Setting: -1°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	21.4%	17.4%	13.2%	8.6%	3.4%	-2.6%	-9.3%	-16.8%	-25.2%	-36.7%	-47.1%	-56.2%	-64.8%
0.85	25.1%	21.0%	16.9%	12.4%	7.4%	1.5%	-5.1%	-12.6%	-21.1%	-32.7%	-43.9%	-53.5%	-62.7%
0.90	28.7%	24.5%	20.3%	15.9%	11.1%	5.4%	-1.2%	-8.7%	-17.2%	-28.7%	-40.8%	-50.9%	-60.5%
0.95	32.2%	27.9%	23.5%	19.1%	14.4%	9.0%	2.5%	-4.9%	-13.4%	-24.7%	-37.7%	-48.2%	-58.3%
1.00	35.5%	31.1%	26.7%	22.1%	17.4%	12.2%	5.9%	-1.4%	-9.8%	-20.9%	-34.7%	-45.6%	-56.2%
1.05	38.7%	34.2%	29.7%	25.0%	20.2%	15.2%	9.1%	2.0%	-6.4%	-17.2%	-31.6%	-43.0%	-54.0%
1.10	41.8%	37.2%	32.6%	27.8%	23.0%	17.9%	12.1%	5.2%	-3.1%	-13.6%	-28.5%	-40.5%	-51.9%
1.15	44.8%	40.1%	35.4%	30.5%	25.6%	20.5%	14.9%	8.1%	0.0%	-10.2%	-25.5%	-37.9%	-49.7%
1.20	47.7%	42.9%	38.1%	33.2%	28.2%	23.0%	17.4%	10.9%	2.9%	-6.9%	-22.4%	-35.4%	-47.6%

Pitch Setting: 0°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	11.8%	8.5%	4.8%	0.7%	-3.7%	-8.7%	-14.5%	-20.9%	-28.2%	-37.3%	-48.1%	-56.8%	-65.1%
0.85	15.4%	12.0%	8.4%	4.5%	0.1%	-4.8%	-10.6%	-17.1%	-24.5%	-33.5%	-45.0%	-54.2%	-63.0%
0.90	18.6%	15.3%	11.8%	7.9%	3.7%	-1.2%	-6.8%	-13.3%	-20.8%	-29.9%	-41.9%	-51.6%	-60.8%
0.95	21.7%	18.4%	14.9%	11.1%	6.9%	2.2%	-3.3%	-9.8%	-17.3%	-26.4%	-38.7%	-49.1%	-58.7%
1.00	24.6%	21.3%	17.7%	14.0%	9.9%	5.4%	0.0%	-6.4%	-13.9%	-22.9%	-35.6%	-46.5%	-56.6%
1.05	27.5%	24.0%	20.5%	16.7%	12.7%	8.3%	3.0%	-3.2%	-10.7%	-19.6%	-32.4%	-44.0%	-54.5%
1.10	30.2%	26.7%	23.0%	19.3%	15.3%	10.9%	5.9%	-0.2%	-7.6%	-16.4%	-29.2%	-41.5%	-52.4%
1.15	32.8%	29.2%	25.5%	21.7%	17.7%	13.4%	8.5%	2.6%	-4.6%	-13.3%	-26.0%	-39.1%	-50.3%
1.20	35.3%	31.7%	27.9%	24.1%	20.0%	15.7%	11.0%	5.3%	-1.8%	-10.4%	-22.8%	-36.6%	-48.2%

Pitch Setting: 1°

Percentage Difference from Baseline

Chord Scale	RPM						Baseline						
Factor	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	1.6%	-1.2%	-4.3%	-7.7%	-11.4%	-15.5%	-20.1%	-25.5%	-31.7%	-39.1%	-48.8%	-57.6%	-65.5%
0.85	5.1%	2.3%	-0.7%	-4.1%	-7.8%	-11.8%	-16.5%	-21.9%	-28.2%	-35.7%	-45.6%	-55.1%	-63.4%
0.90	8.3%	5.6%	2.6%	-0.7%	-4.4%	-8.4%	-13.0%	-18.4%	-24.7%	-32.3%	-42.5%	-52.6%	-61.3%
0.95	11.3%	8.6%	5.7%	2.5%	-1.2%	-5.2%	-9.8%	-15.1%	-21.5%	-29.1%	-39.3%	-50.1%	-59.3%
1.00	14.0%	11.4%	8.6%	5.4%	1.8%	-2.1%	-6.7%	-11.9%	-18.3%	-26.0%	-36.2%	-47.7%	-57.2%
1.05	16.6%	14.0%	11.2%	8.1%	4.6%	0.7%	-3.7%	-8.9%	-15.3%	-22.9%	-33.2%	-45.2%	-55.1%
1.10	19.0%	16.5%	13.7%	10.6%	7.2%	3.4%	-0.9%	-6.1%	-12.4%	-20.0%	-30.2%	-42.8%	-53.1%
1.15	21.3%	18.8%	16.0%	13.0%	9.7%	5.9%	1.6%	-3.5%	-9.6%	-17.1%	-27.3%	-40.4%	-51.1%
1.20	23.5%	20.9%	18.2%	15.2%	11.9%	8.2%	4.1%	-0.9%	-7.0%	-14.4%	-24.4%	-38.0%	-49.1%

Pitch Setting: 2°

Percentage Difference from Baseline

Chord Scale	RPM						Baseline						
Factor	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-9.5%	-11.6%	-14.0%	-16.6%	-19.5%	-22.6%	-26.3%	-30.5%	-35.5%	-41.7%	-49.6%	-58.6%	-66.1%
0.85	-6.1%	-8.2%	-10.5%	-13.1%	-16.1%	-19.3%	-22.9%	-27.2%	-32.3%	-38.5%	-46.6%	-56.1%	-64.0%
0.90	-3.0%	-5.0%	-7.3%	-9.9%	-12.8%	-16.1%	-19.7%	-24.0%	-29.1%	-35.4%	-43.6%	-53.7%	-62.0%
0.95	-0.1%	-2.0%	-4.3%	-6.9%	-9.8%	-13.0%	-16.6%	-21.0%	-26.1%	-32.4%	-40.7%	-51.2%	-60.0%
1.00	2.6%	0.7%	-1.5%	-4.0%	-6.9%	-10.1%	-13.7%	-18.1%	-23.2%	-29.5%	-37.8%	-48.8%	-58.0%
1.05	5.2%	3.3%	1.2%	-1.3%	-4.1%	-7.4%	-11.0%	-15.3%	-20.3%	-26.7%	-35.0%	-46.3%	-56.0%
1.10	7.5%	5.7%	3.6%	1.2%	-1.6%	-4.7%	-8.4%	-12.6%	-17.6%	-23.9%	-32.3%	-43.8%	-54.0%
1.15	9.7%	8.0%	6.0%	3.6%	0.9%	-2.3%	-5.9%	-10.0%	-15.1%	-21.3%	-29.6%	-41.3%	-52.0%
1.20	11.8%	10.1%	8.1%	5.8%	3.1%	0.1%	-3.5%	-7.6%	-12.6%	-18.8%	-26.9%	-38.9%	-50.1%

Pitch Setting: 3°

Percentage Difference from Baseline

Chord Scale	RPM						Baseline						
Factor	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-21.4%	-22.6%	-24.0%	-25.7%	-27.7%	-30.1%	-32.7%	-36.0%	-39.8%	-44.7%	-51.1%	-59.4%	-66.8%
0.85	-18.3%	-19.4%	-20.9%	-22.6%	-24.6%	-27.0%	-29.7%	-32.9%	-36.8%	-41.8%	-48.3%	-56.9%	-64.8%
0.90	-15.3%	-16.5%	-17.9%	-19.6%	-21.6%	-24.0%	-26.7%	-30.0%	-34.0%	-38.9%	-45.5%	-54.5%	-62.8%
0.95	-12.6%	-13.7%	-15.1%	-16.8%	-18.8%	-21.1%	-23.9%	-27.2%	-31.2%	-36.2%	-42.8%	-52.0%	-60.8%
1.00	-10.0%	-11.0%	-12.4%	-14.1%	-16.1%	-18.4%	-21.2%	-24.4%	-28.5%	-33.5%	-40.2%	-49.6%	-58.9%
1.05	-7.5%	-8.5%	-9.8%	-11.5%	-13.5%	-15.8%	-18.6%	-21.8%	-25.9%	-30.9%	-37.6%	-47.1%	-57.0%
1.10	-5.2%	-6.1%	-7.4%	-9.0%	-11.0%	-13.4%	-16.1%	-19.4%	-23.4%	-28.4%	-35.0%	-44.7%	-55.1%
1.15	-3.0%	-3.9%	-5.2%	-6.7%	-8.7%	-11.0%	-13.7%	-17.0%	-21.0%	-26.0%	-32.6%	-42.3%	-53.2%
1.20	-1.0%	-1.8%	-3.0%	-4.5%	-6.4%	-8.7%	-11.5%	-14.7%	-18.7%	-23.6%	-30.2%	-40.0%	-51.3%

Pitch Setting: 4°

Percentage Difference from Baseline

Chord Scale	RPM						Baseline						
Factor	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-33.8%	-34.0%	-34.4%	-35.2%	-36.2%	-37.6%	-39.4%	-41.6%	-44.5%	-48.2%	-53.2%	-60.2%	-67.6%
0.85	-31.1%	-31.2%	-31.6%	-32.4%	-33.4%	-34.8%	-36.6%	-38.9%	-41.8%	-45.5%	-50.6%	-57.8%	-65.7%
0.90	-28.5%	-28.6%	-29.0%	-29.7%	-30.7%	-32.1%	-33.9%	-36.2%	-39.2%	-42.9%	-48.0%	-55.4%	-63.8%
0.95	-26.0%	-26.1%	-26.4%	-27.1%	-28.1%	-29.5%	-31.4%	-33.6%	-36.6%	-40.4%	-45.6%	-53.1%	-61.9%
1.00	-23.6%	-23.7%	-24.0%	-24.6%	-25.6%	-27.1%	-28.9%	-31.2%	-34.1%	-37.9%	-43.1%	-50.8%	-60.0%
1.05	-21.4%	-21.4%	-21.6%	-22.3%	-23.3%	-24.7%	-26.5%	-28.8%	-31.7%	-35.6%	-40.8%	-48.5%	-58.1%
1.10	-19.3%	-19.2%	-19.4%	-20.0%	-21.0%	-22.4%	-24.2%	-26.5%	-29.4%	-33.3%	-38.4%	-46.2%	-56.2%
1.15	-17.2%	-17.1%	-17.3%	-17.9%	-18.8%	-20.2%	-22.0%	-24.3%	-27.2%	-31.1%	-36.2%	-44.0%	-54.3%
1.20	-15.3%	-15.1%	-15.3%	-15.8%	-16.7%	-18.0%	-19.8%	-22.1%	-25.0%	-28.9%	-34.0%	-41.8%	-52.5%

Pitch Setting: 5°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-46.7%	-45.7%	-45.1%	-44.8%	-44.9%	-45.4%	-46.2%	-47.5%	-49.4%	-52.1%	-55.8%	-61.4%	-68.4%
0.85	-44.4%	-43.4%	-42.7%	-42.4%	-42.4%	-42.9%	-43.7%	-45.0%	-46.9%	-49.7%	-53.4%	-59.1%	-66.5%
0.90	-42.2%	-41.2%	-40.4%	-40.0%	-40.0%	-40.5%	-41.3%	-42.6%	-44.5%	-47.3%	-51.1%	-56.9%	-64.6%
0.95	-40.2%	-39.0%	-38.2%	-37.8%	-37.7%	-38.1%	-39.0%	-40.3%	-42.2%	-45.0%	-48.8%	-54.7%	-62.8%
1.00	-38.2%	-36.9%	-36.1%	-35.6%	-35.5%	-35.9%	-36.7%	-38.0%	-39.9%	-42.7%	-46.6%	-52.5%	-60.9%
1.05	-36.2%	-35.0%	-34.0%	-33.5%	-33.4%	-33.8%	-34.6%	-35.9%	-37.8%	-40.6%	-44.4%	-50.4%	-59.0%
1.10	-34.4%	-33.1%	-32.1%	-31.5%	-31.4%	-31.7%	-32.5%	-33.7%	-35.6%	-38.4%	-42.3%	-48.3%	-57.1%
1.15	-32.6%	-31.2%	-30.2%	-29.6%	-29.4%	-29.7%	-30.4%	-31.7%	-33.6%	-36.4%	-40.2%	-46.2%	-55.3%
1.20	-30.9%	-29.5%	-28.4%	-27.7%	-27.5%	-27.7%	-28.5%	-29.7%	-31.6%	-34.4%	-38.2%	-44.1%	-53.4%

Pitch Setting: 6°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-59.9%	-57.8%	-56.0%	-54.7%	-53.7%	-53.2%	-53.1%	-53.5%	-54.5%	-56.2%	-58.9%	-63.0%	-69.2%
0.85	-58.2%	-55.9%	-54.1%	-52.6%	-51.6%	-51.0%	-50.9%	-51.3%	-52.2%	-54.0%	-56.7%	-60.9%	-67.3%
0.90	-56.5%	-54.1%	-52.2%	-50.7%	-49.6%	-48.9%	-48.8%	-49.1%	-50.1%	-51.8%	-54.6%	-58.8%	-65.5%
0.95	-54.9%	-52.4%	-50.4%	-48.8%	-47.6%	-46.9%	-46.7%	-47.1%	-48.0%	-49.7%	-52.5%	-56.8%	-63.6%
1.00	-53.3%	-50.7%	-48.6%	-46.9%	-45.7%	-45.0%	-44.7%	-45.0%	-45.9%	-47.6%	-50.4%	-54.8%	-61.8%
1.05	-51.8%	-49.1%	-46.9%	-45.2%	-43.9%	-43.1%	-42.8%	-43.1%	-44.0%	-45.6%	-48.5%	-52.8%	-60.0%
1.10	-50.4%	-47.6%	-45.3%	-43.5%	-42.1%	-41.2%	-40.9%	-41.2%	-42.1%	-43.7%	-46.5%	-50.9%	-58.2%
1.15	-49.0%	-46.1%	-43.7%	-41.8%	-40.4%	-39.5%	-39.1%	-39.3%	-40.2%	-41.8%	-44.6%	-49.0%	-56.4%
1.20	-47.6%	-44.7%	-42.2%	-40.2%	-38.7%	-37.8%	-37.4%	-37.6%	-38.4%	-40.0%	-42.8%	-47.1%	-54.6%

Pitch Setting: 7°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-73.6%	-70.1%	-67.1%	-64.6%	-62.6%	-61.1%	-60.0%	-59.5%	-59.6%	-60.4%	-62.2%	-65.1%	-70.0%
0.85	-72.4%	-68.8%	-65.7%	-63.0%	-60.9%	-59.3%	-58.2%	-57.6%	-57.7%	-58.4%	-60.2%	-63.1%	-68.3%
0.90	-71.3%	-67.5%	-64.2%	-61.5%	-59.2%	-57.5%	-56.3%	-55.7%	-55.7%	-56.5%	-58.2%	-61.2%	-66.5%
0.95	-70.2%	-66.3%	-62.8%	-60.0%	-57.6%	-55.8%	-54.6%	-53.9%	-53.9%	-54.6%	-56.3%	-59.4%	-64.8%
1.00	-69.2%	-65.1%	-61.5%	-58.5%	-56.1%	-54.2%	-52.8%	-52.1%	-52.1%	-52.7%	-54.5%	-57.6%	-63.0%
1.05	-68.2%	-63.9%	-60.2%	-57.1%	-54.6%	-52.6%	-51.2%	-50.4%	-50.3%	-50.9%	-52.7%	-55.8%	-61.3%
1.10	-67.2%	-62.8%	-59.0%	-55.8%	-53.1%	-51.0%	-49.6%	-48.7%	-48.6%	-49.2%	-50.9%	-54.0%	-59.6%
1.15	-66.3%	-61.7%	-57.8%	-54.5%	-51.7%	-49.5%	-48.0%	-47.1%	-46.9%	-47.5%	-49.2%	-52.3%	-57.9%
1.20	-65.4%	-60.7%	-56.6%	-53.2%	-50.3%	-48.1%	-46.5%	-45.5%	-45.3%	-45.9%	-47.5%	-50.6%	-56.3%

Pitch Setting: 8°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-87.8%	-83.0%	-78.6%	-74.8%	-71.7%	-69.1%	-67.1%	-65.6%	-64.8%	-64.7%	-65.6%	-67.6%	-71.2%
0.85	-87.2%	-82.3%	-77.7%	-73.7%	-70.4%	-67.6%	-65.5%	-64.0%	-63.1%	-63.0%	-63.8%	-65.8%	-69.6%
0.90	-86.7%	-81.5%	-76.7%	-72.6%	-69.1%	-66.2%	-64.0%	-62.4%	-61.4%	-61.3%	-62.0%	-64.1%	-67.9%
0.95	-86.2%	-80.8%	-75.8%	-71.5%	-67.9%	-64.9%	-62.5%	-60.8%	-59.8%	-59.6%	-60.3%	-62.4%	-66.3%
1.00	-85.7%	-80.1%	-75.0%	-70.4%	-66.7%	-63.6%	-61.1%	-59.3%	-58.2%	-57.9%	-58.6%	-60.7%	-64.6%
1.05	-85.2%	-79.5%	-74.1%	-69.4%	-65.5%	-62.3%	-59.7%	-57.8%	-56.7%	-56.3%	-57.0%	-59.0%	-63.0%
1.10	-84.7%	-78.8%	-73.3%	-68.5%	-64.4%	-61.0%	-58.4%	-56.4%	-55.2%	-54.8%	-55.4%	-57.4%	-61.5%
1.15	-84.3%	-78.2%	-72.5%	-67.5%	-63.3%	-59.8%	-57.0%	-55.0%	-53.7%	-53.3%	-53.8%	-55.8%	-59.9%
1.20	-83.8%	-77.6%	-71.8%	-66.6%	-62.2%	-58.7%	-55.8%	-53.7%	-52.3%	-51.8%	-52.3%	-54.3%	-58.3%

Pitch Setting:	9°												
			Percentage Difference from Baseline										
Chord Scale	RPM						Baseline						
Factor	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-101.5%	-95.6%	-90.4%	-85.5%	-81.0%	-77.2%	-74.2%	-71.8%	-70.1%	-69.2%	-69.1%	-70.2%	-72.7%
0.85	-101.5%	-95.4%	-89.9%	-84.8%	-80.1%	-76.1%	-72.9%	-70.4%	-68.6%	-67.6%	-67.5%	-68.6%	-71.2%
0.90	-101.6%	-95.3%	-89.5%	-84.2%	-79.3%	-75.1%	-71.7%	-69.1%	-67.2%	-66.1%	-65.9%	-67.0%	-69.6%
0.95	-101.7%	-95.1%	-89.1%	-83.5%	-78.4%	-74.1%	-70.6%	-67.8%	-65.8%	-64.6%	-64.4%	-65.5%	-68.1%
1.00	-101.7%	-94.9%	-88.7%	-82.9%	-77.6%	-73.1%	-69.4%	-66.6%	-64.5%	-63.2%	-62.9%	-63.9%	-66.6%
1.05	-101.8%	-94.7%	-88.3%	-82.3%	-76.9%	-72.1%	-68.4%	-65.3%	-63.1%	-61.8%	-61.4%	-62.4%	-65.1%
1.10	-101.8%	-94.5%	-87.9%	-81.8%	-76.1%	-71.2%	-67.3%	-64.2%	-61.9%	-60.4%	-60.0%	-61.0%	-63.7%
1.15	-101.9%	-94.4%	-87.6%	-81.2%	-75.4%	-70.3%	-66.3%	-63.0%	-60.6%	-59.1%	-58.6%	-59.5%	-62.2%
1.20	-101.9%	-94.2%	-87.2%	-80.7%	-74.7%	-69.5%	-65.3%	-61.9%	-59.4%	-57.8%	-57.3%	-58.1%	-60.8%

Appendix V

Power Results for NREL 5MW Turbine Chord vs. Pitch Parametric Study at 11.4 m/s

Pitch Setting: -2°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-3.7%	-1.5%	0.4%	1.6%	1.2%	-0.6%	-3.8%	-8.8%	-19.7%	-36.2%	-51.0%	-62.8%	-73.2%
0.85	-5.5%	-3.0%	-0.9%	0.8%	1.3%	0.3%	-2.2%	-6.4%	-15.8%	-32.6%	-48.2%	-60.5%	-71.5%
0.90	-7.4%	-4.7%	-2.3%	-0.4%	0.8%	0.6%	-1.1%	-4.5%	-12.3%	-29.0%	-45.3%	-58.3%	-69.9%
0.95	-9.4%	-6.4%	-3.8%	-1.7%	-0.1%	0.4%	-0.5%	-3.1%	-9.4%	-25.7%	-42.6%	-56.1%	-68.2%
1.00	-11.4%	-8.2%	-5.4%	-3.1%	-1.2%	-0.2%	-0.4%	-2.2%	-7.0%	-22.4%	-39.9%	-54.0%	-66.6%
1.05	-13.4%	-10.1%	-7.1%	-4.5%	-2.4%	-1.0%	-0.8%	-1.7%	-5.3%	-19.0%	-37.2%	-51.8%	-65.0%
1.10	-15.5%	-11.9%	-8.7%	-6.0%	-3.7%	-1.9%	-1.3%	-1.6%	-4.1%	-15.7%	-34.4%	-49.8%	-63.3%
1.15	-17.6%	-13.8%	-10.4%	-7.5%	-5.0%	-3.0%	-2.0%	-1.9%	-3.4%	-12.8%	-31.6%	-47.7%	-61.7%
1.20	-19.7%	-15.7%	-12.1%	-9.0%	-6.3%	-4.2%	-2.8%	-2.5%	-3.2%	-10.3%	-28.8%	-45.7%	-60.1%

Pitch Setting: -1°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-1.5%	0.4%	1.6%	2.1%	1.3%	-1.4%	-5.2%	-10.2%	-18.2%	-33.0%	-47.9%	-60.3%	-71.1%
0.85	-2.8%	-0.7%	1.0%	2.0%	2.0%	0.1%	-3.2%	-7.8%	-14.9%	-29.2%	-44.7%	-58.0%	-69.4%
0.90	-4.1%	-1.9%	0.0%	1.5%	2.1%	1.2%	-1.6%	-5.7%	-12.0%	-25.4%	-41.6%	-55.7%	-67.6%
0.95	-5.6%	-3.2%	-1.1%	0.6%	1.7%	1.7%	-0.5%	-4.0%	-9.4%	-21.9%	-38.6%	-53.4%	-65.9%
1.00	-7.1%	-4.5%	-2.3%	-0.4%	1.0%	1.7%	0.3%	-2.6%	-7.4%	-18.5%	-35.7%	-51.1%	-64.1%
1.05	-8.7%	-6.0%	-3.6%	-1.5%	0.2%	1.3%	0.8%	-1.7%	-5.7%	-15.5%	-32.9%	-48.9%	-62.4%
1.10	-10.4%	-7.4%	-4.9%	-2.7%	-0.8%	0.5%	0.8%	-1.0%	-4.5%	-12.7%	-30.3%	-46.6%	-60.7%
1.15	-12.0%	-8.9%	-6.2%	-3.8%	-1.9%	-0.4%	0.5%	-0.7%	-3.5%	-10.3%	-27.7%	-44.4%	-59.0%
1.20	-13.7%	-10.5%	-7.6%	-5.1%	-3.0%	-1.3%	-0.1%	-0.6%	-2.8%	-8.3%	-25.3%	-42.3%	-57.3%

Pitch Setting: 0°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-0.9%	0.2%	0.6%	0.3%	-0.9%	-3.2%	-7.2%	-12.2%	-19.0%	-30.3%	-44.9%	-58.1%	-69.2%
0.85	-1.5%	0.1%	0.9%	1.1%	0.4%	-1.4%	-4.8%	-9.6%	-15.9%	-26.7%	-41.9%	-55.6%	-67.4%
0.90	-2.3%	-0.4%	0.9%	1.5%	1.2%	0.0%	-2.9%	-7.3%	-13.1%	-23.2%	-39.0%	-53.2%	-65.5%
0.95	-3.3%	-1.2%	0.4%	1.4%	1.7%	0.9%	-1.2%	-5.3%	-10.8%	-20.0%	-36.1%	-50.8%	-63.7%
1.00	-4.3%	-2.1%	-0.3%	1.1%	1.8%	1.5%	0.0%	-3.7%	-8.7%	-17.0%	-33.2%	-48.4%	-61.8%
1.05	-5.5%	-3.2%	-1.1%	0.5%	1.5%	1.7%	0.8%	-2.3%	-6.9%	-14.4%	-30.4%	-46.1%	-60.0%
1.10	-6.7%	-4.2%	-2.1%	-0.3%	1.0%	1.7%	1.2%	-1.2%	-5.4%	-12.1%	-27.5%	-43.7%	-58.3%
1.15	-7.9%	-5.3%	-3.1%	-1.2%	0.4%	1.3%	1.4%	-0.3%	-4.1%	-10.0%	-24.7%	-41.5%	-56.5%
1.20	-9.1%	-6.5%	-4.1%	-2.1%	-0.4%	0.8%	1.2%	0.2%	-3.1%	-8.3%	-21.9%	-39.2%	-54.8%

Pitch Setting: 1°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-3.4%	-2.8%	-2.9%	-3.6%	-4.8%	-6.9%	-9.9%	-14.7%	-20.7%	-29.6%	-43.3%	-56.0%	-67.5%
0.85	-2.9%	-2.0%	-1.7%	-2.0%	-3.0%	-4.8%	-7.5%	-11.9%	-17.7%	-26.2%	-40.1%	-53.5%	-65.6%
0.90	-2.7%	-1.5%	-0.9%	-0.9%	-1.6%	-3.0%	-5.5%	-9.5%	-15.0%	-23.1%	-37.0%	-50.9%	-63.7%
0.95	-2.9%	-1.4%	-0.5%	-0.1%	-0.5%	-1.6%	-3.7%	-7.3%	-12.6%	-20.2%	-33.9%	-48.5%	-61.8%
1.00	-3.3%	-1.6%	-0.3%	0.3%	0.3%	-0.5%	-2.3%	-5.4%	-10.5%	-17.6%	-30.9%	-46.1%	-59.9%
1.05	-3.9%	-2.0%	-0.5%	0.5%	0.8%	0.3%	-1.1%	-3.8%	-8.5%	-15.1%	-27.9%	-43.7%	-58.0%
1.10	-4.7%	-2.5%	-0.8%	0.4%	1.0%	0.8%	-0.2%	-2.5%	-6.8%	-13.0%	-25.1%	-41.5%	-56.1%
1.15	-5.5%	-3.2%	-1.3%	0.1%	1.0%	1.1%	0.5%	-1.5%	-5.3%	-11.1%	-22.4%	-39.3%	-54.2%
1.20	-6.4%	-4.0%	-1.9%	-0.3%	0.8%	1.2%	0.9%	-0.7%	-4.0%	-9.4%	-19.9%	-37.1%	-52.4%

Pitch Setting: 2°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-9.0%	-8.5%	-8.5%	-9.0%	-10.1%	-11.8%	-14.2%	-17.7%	-23.0%	-30.4%	-41.8%	-54.6%	-66.0%
0.85	-7.7%	-7.0%	-6.8%	-7.1%	-8.0%	-9.5%	-11.7%	-15.1%	-20.1%	-27.3%	-38.6%	-52.1%	-64.0%
0.90	-6.7%	-5.7%	-5.4%	-5.5%	-6.2%	-7.5%	-9.5%	-12.7%	-17.4%	-24.4%	-35.6%	-49.7%	-62.0%
0.95	-6.0%	-4.8%	-4.2%	-4.1%	-4.6%	-5.7%	-7.6%	-10.5%	-15.0%	-21.6%	-32.6%	-47.2%	-60.0%
1.00	-5.6%	-4.2%	-3.3%	-3.0%	-3.3%	-4.2%	-5.9%	-8.6%	-12.8%	-19.1%	-29.7%	-44.9%	-58.0%
1.05	-5.5%	-3.8%	-2.7%	-2.2%	-2.3%	-3.0%	-4.4%	-6.9%	-10.7%	-16.8%	-26.9%	-42.5%	-56.1%
1.10	-5.5%	-3.6%	-2.3%	-1.6%	-1.4%	-2.0%	-3.2%	-5.4%	-8.9%	-14.7%	-24.3%	-40.1%	-54.2%
1.15	-5.7%	-3.6%	-2.1%	-1.2%	-0.8%	-1.1%	-2.1%	-4.1%	-7.3%	-12.8%	-21.7%	-37.8%	-52.3%
1.20	-6.1%	-3.8%	-2.1%	-1.0%	-0.4%	-0.5%	-1.3%	-3.0%	-6.0%	-11.1%	-19.4%	-35.5%	-50.5%

Pitch Setting: 3°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-17.5%	-16.5%	-16.0%	-16.0%	-16.6%	-17.6%	-19.4%	-22.0%	-26.0%	-32.2%	-41.4%	-53.8%	-64.7%
0.85	-15.7%	-14.6%	-13.9%	-13.9%	-14.3%	-15.3%	-16.9%	-19.4%	-23.2%	-29.1%	-38.4%	-51.2%	-62.7%
0.90	-14.3%	-12.9%	-12.1%	-11.9%	-12.2%	-13.1%	-14.6%	-17.0%	-20.7%	-26.3%	-35.4%	-48.7%	-60.6%
0.95	-13.0%	-11.5%	-10.6%	-10.2%	-10.4%	-11.2%	-12.6%	-14.8%	-18.3%	-23.7%	-32.5%	-46.1%	-58.7%
1.00	-12.0%	-10.3%	-9.2%	-8.7%	-8.8%	-9.4%	-10.7%	-12.8%	-16.1%	-21.3%	-29.8%	-43.6%	-56.7%
1.05	-11.2%	-9.3%	-8.1%	-7.4%	-7.4%	-7.9%	-9.0%	-11.0%	-14.1%	-19.1%	-27.2%	-41.1%	-54.8%
1.10	-10.6%	-8.5%	-7.1%	-6.3%	-6.1%	-6.5%	-7.6%	-9.3%	-12.3%	-17.0%	-24.8%	-38.7%	-52.9%
1.15	-10.1%	-7.9%	-6.4%	-5.4%	-5.1%	-5.3%	-6.2%	-7.9%	-10.7%	-15.1%	-22.6%	-36.3%	-51.0%
1.20	-9.9%	-7.5%	-5.8%	-4.6%	-4.2%	-4.3%	-5.1%	-6.6%	-9.2%	-13.4%	-20.4%	-34.0%	-49.2%

Pitch Setting: 4°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-28.4%	-26.5%	-25.1%	-24.3%	-24.0%	-24.4%	-25.3%	-27.1%	-30.0%	-34.5%	-42.0%	-53.0%	-63.9%
0.85	-26.6%	-24.5%	-22.9%	-22.0%	-21.7%	-22.0%	-22.9%	-24.5%	-27.3%	-31.7%	-39.1%	-50.4%	-61.9%
0.90	-24.9%	-22.7%	-21.0%	-20.0%	-19.6%	-19.8%	-20.6%	-22.1%	-24.8%	-29.1%	-36.3%	-47.8%	-59.9%
0.95	-23.4%	-21.1%	-19.3%	-18.1%	-17.6%	-17.7%	-18.5%	-20.0%	-22.5%	-26.6%	-33.7%	-45.3%	-58.0%
1.00	-22.1%	-19.6%	-17.7%	-16.5%	-15.8%	-15.9%	-16.5%	-17.9%	-20.4%	-24.4%	-31.1%	-42.8%	-56.0%
1.05	-21.0%	-18.3%	-16.3%	-14.9%	-14.2%	-14.2%	-14.8%	-16.1%	-18.4%	-22.2%	-28.8%	-40.4%	-54.1%
1.10	-19.9%	-17.2%	-15.1%	-13.6%	-12.8%	-12.6%	-13.1%	-14.4%	-16.5%	-20.3%	-26.4%	-38.0%	-52.3%
1.15	-19.1%	-16.2%	-14.0%	-12.4%	-11.5%	-11.2%	-11.6%	-12.8%	-14.8%	-18.4%	-24.3%	-35.6%	-50.4%
1.20	-18.3%	-15.3%	-13.0%	-11.3%	-10.3%	-10.0%	-10.3%	-11.3%	-13.3%	-16.7%	-22.3%	-33.3%	-48.6%

Pitch Setting: 5°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-41.5%	-38.2%	-35.7%	-33.7%	-32.5%	-31.9%	-31.9%	-32.8%	-34.5%	-37.9%	-43.5%	-52.8%	-63.7%
0.85	-39.7%	-36.4%	-33.6%	-31.6%	-30.2%	-29.5%	-29.5%	-30.3%	-32.0%	-35.2%	-40.8%	-50.2%	-61.7%
0.90	-38.2%	-34.6%	-31.8%	-29.6%	-28.1%	-27.4%	-27.3%	-28.0%	-29.6%	-32.8%	-38.2%	-47.7%	-59.6%
0.95	-36.7%	-33.0%	-30.0%	-27.8%	-26.2%	-25.3%	-25.2%	-25.9%	-27.4%	-30.4%	-35.7%	-45.2%	-57.6%
1.00	-35.4%	-31.5%	-28.5%	-26.1%	-24.4%	-23.5%	-23.3%	-23.9%	-25.3%	-28.3%	-33.3%	-42.7%	-55.6%
1.05	-34.2%	-30.2%	-27.0%	-24.5%	-22.7%	-21.7%	-21.5%	-22.0%	-23.4%	-26.2%	-31.0%	-40.3%	-53.6%
1.10	-33.1%	-29.0%	-25.6%	-23.0%	-21.2%	-20.1%	-19.8%	-20.2%	-21.6%	-24.2%	-28.9%	-38.0%	-51.7%
1.15	-32.1%	-27.9%	-24.4%	-21.7%	-19.8%	-18.6%	-18.2%	-18.6%	-19.9%	-22.4%	-26.9%	-35.8%	-49.8%
1.20	-31.2%	-26.8%	-23.3%	-20.5%	-18.5%	-17.2%	-16.8%	-17.1%	-18.3%	-20.7%	-25.1%	-33.6%	-47.8%

Pitch Setting: 6°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-56.5%	-51.7%	-47.6%	-44.3%	-41.8%	-40.1%	-39.1%	-38.9%	-39.7%	-41.8%	-45.9%	-53.1%	-63.4%
0.85	-55.2%	-50.1%	-45.8%	-42.4%	-39.7%	-37.9%	-36.9%	-36.6%	-37.3%	-39.3%	-43.4%	-50.6%	-61.3%
0.90	-53.9%	-48.6%	-44.2%	-40.6%	-37.8%	-35.9%	-34.7%	-34.4%	-35.1%	-37.0%	-40.9%	-48.2%	-59.2%
0.95	-52.7%	-47.2%	-42.6%	-38.9%	-36.0%	-34.0%	-32.7%	-32.4%	-32.9%	-34.7%	-38.6%	-45.8%	-57.2%
1.00	-51.6%	-45.9%	-41.2%	-37.3%	-34.3%	-32.2%	-30.9%	-30.4%	-30.9%	-32.6%	-36.4%	-43.5%	-55.1%
1.05	-50.6%	-44.7%	-39.8%	-35.8%	-32.7%	-30.5%	-29.1%	-28.6%	-29.1%	-30.7%	-34.3%	-41.2%	-53.1%
1.10	-49.7%	-43.6%	-38.6%	-34.4%	-31.2%	-28.9%	-27.4%	-26.9%	-27.3%	-28.8%	-32.3%	-39.0%	-51.2%
1.15	-48.9%	-42.6%	-37.4%	-33.1%	-29.8%	-27.4%	-25.9%	-25.3%	-25.6%	-27.1%	-30.4%	-36.9%	-49.2%
1.20	-48.1%	-41.7%	-36.3%	-31.9%	-28.5%	-26.0%	-24.4%	-23.7%	-24.0%	-25.4%	-28.6%	-34.9%	-47.3%

Pitch Setting: 7°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-73.8%	-66.7%	-60.8%	-56.0%	-52.0%	-49.0%	-46.8%	-45.5%	-45.2%	-46.1%	-48.9%	-54.3%	-63.2%
0.85	-73.0%	-65.6%	-59.5%	-54.4%	-50.2%	-47.0%	-44.8%	-43.4%	-43.0%	-43.8%	-46.5%	-51.9%	-61.1%
0.90	-72.3%	-64.6%	-58.2%	-52.9%	-48.6%	-45.2%	-42.8%	-41.4%	-40.9%	-41.7%	-44.2%	-49.6%	-59.1%
0.95	-71.6%	-63.7%	-57.0%	-51.5%	-47.0%	-43.5%	-41.0%	-39.5%	-38.9%	-39.6%	-42.1%	-47.4%	-57.1%
1.00	-71.0%	-62.8%	-55.8%	-50.1%	-45.5%	-41.9%	-39.3%	-37.6%	-37.1%	-37.6%	-40.0%	-45.2%	-55.1%
1.05	-70.5%	-61.9%	-54.7%	-48.9%	-44.1%	-40.3%	-37.6%	-35.9%	-35.3%	-35.8%	-38.0%	-43.2%	-53.1%
1.10	-70.0%	-61.2%	-53.7%	-47.7%	-42.7%	-38.9%	-36.0%	-34.3%	-33.6%	-34.0%	-36.2%	-41.2%	-51.2%
1.15	-69.6%	-60.4%	-52.8%	-46.6%	-41.5%	-37.5%	-34.6%	-32.7%	-31.9%	-32.3%	-34.4%	-39.2%	-49.2%
1.20	-69.2%	-59.8%	-51.9%	-45.5%	-40.3%	-36.2%	-33.2%	-31.2%	-30.4%	-30.7%	-32.7%	-37.4%	-47.4%

Pitch Setting: 8°

Percentage Difference from Baseline

Chord Scale Factor	RPM 17.28	16.42	15.55	14.69	13.82	12.96	Baseline 12.10	11.23	10.37	9.50	8.64	7.78	6.90
0.80	-93.4%	-84.0%	-75.7%	-68.7%	-63.1%	-58.5%	-55.0%	-52.6%	-51.1%	-50.9%	-52.3%	-56.3%	-63.5%
0.85	-93.4%	-83.6%	-74.9%	-67.6%	-61.7%	-56.9%	-53.2%	-50.6%	-49.1%	-48.8%	-50.1%	-54.1%	-61.4%
0.90	-93.4%	-83.2%	-74.1%	-66.5%	-60.3%	-55.4%	-51.5%	-48.8%	-47.2%	-46.8%	-48.0%	-51.9%	-59.4%
0.95	-93.4%	-82.8%	-73.4%	-65.5%	-59.1%	-53.9%	-49.9%	-47.1%	-45.4%	-44.9%	-46.0%	-49.8%	-57.4%
1.00	-93.5%	-82.5%	-72.8%	-64.6%	-57.9%	-52.6%	-48.4%	-45.4%	-43.6%	-43.1%	-44.1%	-47.8%	-55.4%
1.05	-93.5%	-82.2%	-72.2%	-63.7%	-56.7%	-51.2%	-46.9%	-43.9%	-42.0%	-41.3%	-42.2%	-45.9%	-53.5%
1.10	-93.6%	-81.9%	-71.6%	-62.8%	-55.7%	-50.0%	-45.5%	-42.4%	-40.4%	-39.7%	-40.5%	-44.0%	-51.6%
1.15	-93.7%	-81.7%	-71.0%	-62.0%	-54.6%	-48.8%	-44.2%	-40.9%	-38.9%	-38.1%	-38.8%	-42.1%	-49.8%
1.20	-93.9%	-81.5%	-70.5%	-61.3%	-53.7%	-47.7%	-42.9%	-39.5%	-37.4%	-36.5%	-37.2%	-40.4%	-48.0%

Pitch Setting:		9°												
				Percentage Difference from Baseline										
	Chord Scale	RPM						Baseline						
	Factor	17.28	16.42	15.55	14.69	13.82	12.96	12.10	11.23	10.37	9.50	8.64	7.78	6.90
	0.80	-113.9%	-102.3%	-92.1%	-83.1%	-75.2%	-68.8%	-63.8%	-60.0%	-57.4%	-56.0%	-56.1%	-58.8%	-64.2%
	0.85	-114.8%	-102.6%	-91.9%	-82.5%	-74.3%	-67.5%	-62.3%	-58.3%	-55.6%	-54.1%	-54.1%	-56.7%	-62.2%
	0.90	-115.6%	-102.9%	-91.8%	-82.0%	-73.4%	-66.4%	-60.9%	-56.7%	-53.9%	-52.3%	-52.2%	-54.7%	-60.2%
	0.95	-116.4%	-103.2%	-91.7%	-81.5%	-72.6%	-65.3%	-59.6%	-55.2%	-52.2%	-50.5%	-50.4%	-52.7%	-58.3%
	1.00	-117.3%	-103.6%	-91.6%	-81.0%	-71.8%	-64.2%	-58.3%	-53.8%	-50.7%	-48.9%	-48.6%	-50.8%	-56.5%
	1.05	-118.1%	-103.9%	-91.5%	-80.6%	-71.1%	-63.2%	-57.1%	-52.4%	-49.2%	-47.3%	-46.9%	-48.9%	-54.6%
	1.10	-118.9%	-104.3%	-91.5%	-80.2%	-70.4%	-62.2%	-55.9%	-51.1%	-47.7%	-45.7%	-45.3%	-47.2%	-52.9%
	1.15	-119.7%	-104.6%	-91.4%	-79.9%	-69.8%	-61.3%	-54.8%	-49.8%	-46.3%	-44.2%	-43.7%	-45.5%	-51.1%
	1.20	-120.6%	-105.0%	-91.4%	-79.5%	-69.1%	-60.5%	-53.8%	-48.6%	-45.0%	-42.8%	-42.2%	-43.9%	-49.4%

Appendix W

Root Bending Moment Results for WindPACT 1.5MW Turbine Radius vs. Pitch Parametric Study at 11.8 m/s

Pitch Setting: -2°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-42.0%	-44.9%	-48.1%	-51.9%	-54.1%	-56.3%	-60.8%	-65.3%	-69.6%	-73.6%	-77.3%	-80.7%	-83.7%
0.85	-27.9%	-31.4%	-35.0%	-39.0%	-41.4%	-44.0%	-49.5%	-55.0%	-60.4%	-65.6%	-70.4%	-74.8%	-78.8%
0.90	-11.7%	-15.8%	-20.0%	-24.5%	-26.9%	-29.7%	-36.1%	-42.7%	-49.4%	-55.9%	-62.0%	-67.7%	-72.8%
0.95	6.6%	2.1%	-2.9%	-8.1%	-10.7%	-13.7%	-20.6%	-28.4%	-36.4%	-44.3%	-51.9%	-59.0%	-65.5%
1.00	27.3%	22.1%	16.5%	10.5%	7.4%	4.3%	-3.0%	-11.8%	-21.3%	-30.8%	-40.0%	-48.8%	-56.9%
1.05	50.9%	44.6%	38.3%	31.4%	27.8%	24.3%	16.4%	7.0%	-3.9%	-15.0%	-26.1%	-36.8%	-46.7%
1.10	77.4%	69.9%	62.5%	55.0%	50.9%	46.6%	38.0%	27.9%	16.0%	3.0%	-10.1%	-22.8%	-34.8%
1.15	107.0%	98.2%	89.5%	81.0%	76.5%	71.7%	61.8%	51.0%	38.2%	23.4%	8.3%	-6.7%	-21.0%
1.20	139.9%	129.8%	119.6%	109.7%	104.7%	99.5%	88.3%	76.4%	62.6%	46.4%	29.0%	11.7%	-5.1%

Pitch Setting: -1°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-44.0%	-46.6%	-49.4%	-52.7%	-54.6%	-56.7%	-60.9%	-65.1%	-69.3%	-73.3%	-77.0%	-80.4%	-83.5%
0.85	-30.6%	-33.7%	-36.9%	-40.6%	-42.6%	-44.9%	-49.8%	-55.0%	-60.2%	-65.2%	-70.0%	-74.5%	-78.5%
0.90	-15.4%	-18.8%	-22.7%	-26.7%	-29.0%	-31.4%	-36.9%	-43.0%	-49.3%	-55.6%	-61.6%	-67.3%	-72.4%
0.95	1.9%	-2.1%	-6.3%	-11.1%	-13.6%	-16.2%	-22.2%	-29.1%	-36.6%	-44.1%	-51.5%	-58.6%	-65.1%
1.00	21.5%	16.7%	12.0%	6.7%	3.8%	0.8%	-5.8%	-13.3%	-21.8%	-30.8%	-39.7%	-48.3%	-56.4%
1.05	43.7%	38.1%	32.4%	26.7%	23.4%	20.0%	12.7%	4.4%	-5.0%	-15.4%	-25.9%	-36.3%	-46.1%
1.10	68.5%	61.9%	55.3%	48.7%	45.3%	41.5%	33.1%	24.0%	13.7%	2.1%	-10.2%	-22.3%	-34.1%
1.15	96.1%	88.6%	80.8%	73.1%	69.3%	65.2%	56.0%	45.8%	34.5%	21.8%	7.8%	-6.4%	-20.3%
1.20	126.9%	118.0%	109.2%	100.2%	95.7%	91.3%	81.4%	69.8%	57.4%	43.5%	28.0%	11.6%	-4.6%

Pitch Setting: 0°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-45.9%	-48.3%	-51.0%	-54.0%	-55.6%	-57.4%	-61.1%	-65.2%	-69.1%	-73.1%	-76.8%	-80.2%	-83.3%
0.85	-33.4%	-36.0%	-39.0%	-42.4%	-44.3%	-46.2%	-50.5%	-55.2%	-60.2%	-65.0%	-69.8%	-74.2%	-78.3%
0.90	-19.0%	-22.0%	-25.3%	-29.2%	-31.3%	-33.5%	-38.3%	-43.7%	-49.5%	-55.5%	-61.3%	-66.9%	-72.1%
0.95	-2.7%	-6.2%	-9.9%	-14.2%	-16.6%	-19.1%	-24.5%	-30.5%	-37.1%	-44.2%	-51.3%	-58.2%	-64.7%
1.00	15.8%	11.6%	7.3%	2.7%	0.0%	-2.9%	-8.9%	-15.7%	-23.1%	-31.2%	-39.6%	-48.0%	-55.9%
1.05	36.6%	31.7%	26.7%	21.4%	18.6%	15.4%	8.5%	1.0%	-7.3%	-16.4%	-26.2%	-36.0%	-45.6%
1.10	59.8%	54.1%	48.3%	42.3%	39.1%	35.7%	28.0%	19.6%	10.4%	0.2%	-10.8%	-22.4%	-33.7%
1.15	85.7%	79.0%	72.3%	65.4%	61.8%	58.0%	49.7%	40.1%	29.9%	18.7%	6.4%	-6.8%	-20.1%
1.20	114.4%	106.6%	98.8%	91.0%	86.9%	82.6%	73.5%	63.0%	51.5%	39.1%	25.5%	10.8%	-4.6%

Pitch Setting: 1°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-48.1%	-50.2%	-52.7%	-55.4%	-56.9%	-58.4%	-61.8%	-65.4%	-69.2%	-72.9%	-76.6%	-80.0%	-83.2%
0.85	-36.1%	-38.5%	-41.3%	-44.4%	-46.1%	-47.9%	-51.7%	-55.9%	-60.4%	-65.0%	-69.6%	-74.0%	-78.0%
0.90	-22.5%	-25.3%	-28.4%	-31.9%	-33.9%	-35.9%	-40.2%	-44.9%	-50.1%	-55.6%	-61.2%	-66.7%	-71.8%
0.95	-7.1%	-10.3%	-13.9%	-17.8%	-19.9%	-22.2%	-27.1%	-32.5%	-38.4%	-44.7%	-51.4%	-58.0%	-64.4%
1.00	10.3%	6.6%	2.5%	-2.0%	-4.3%	-6.9%	-12.4%	-18.5%	-25.1%	-32.2%	-40.0%	-47.9%	-55.6%
1.05	29.7%	25.4%	20.8%	15.7%	13.0%	10.2%	4.1%	-2.8%	-10.2%	-18.3%	-26.9%	-36.2%	-45.4%
1.10	51.5%	46.5%	41.2%	35.4%	32.3%	29.2%	22.4%	14.7%	6.4%	-2.6%	-12.4%	-22.8%	-33.7%
1.15	75.6%	69.8%	63.8%	57.3%	53.8%	50.1%	42.5%	34.2%	24.8%	14.8%	3.9%	-7.8%	-20.3%
1.20	102.3%	95.6%	88.8%	81.4%	77.4%	73.3%	64.7%	55.5%	45.2%	34.0%	21.9%	8.8%	-5.1%

Pitch Setting: 2°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-50.3%	-52.3%	-54.5%	-57.0%	-58.3%	-59.7%	-62.7%	-65.9%	-69.3%	-72.9%	-76.4%	-79.8%	-83.0%
0.85	-39.1%	-41.3%	-43.8%	-46.6%	-48.1%	-49.7%	-53.2%	-56.9%	-60.9%	-65.2%	-69.5%	-73.8%	-77.8%
0.90	-26.2%	-28.9%	-31.8%	-34.9%	-36.6%	-38.4%	-42.3%	-46.6%	-51.2%	-56.1%	-61.3%	-66.5%	-71.6%
0.95	-11.7%	-14.8%	-18.1%	-21.7%	-23.6%	-25.6%	-30.0%	-34.8%	-40.1%	-45.7%	-51.7%	-58.0%	-64.2%
1.00	4.7%	1.1%	-2.7%	-6.9%	-9.1%	-11.3%	-16.2%	-21.6%	-27.5%	-33.9%	-40.8%	-48.1%	-55.5%
1.05	23.0%	18.8%	14.4%	9.7%	7.2%	4.6%	-0.8%	-6.9%	-13.5%	-20.7%	-28.5%	-36.8%	-45.5%
1.10	43.3%	38.6%	33.5%	28.1%	25.2%	22.3%	16.2%	9.5%	2.1%	-6.0%	-14.7%	-24.0%	-34.0%
1.15	65.9%	60.4%	54.6%	48.4%	45.2%	41.9%	34.9%	27.5%	19.3%	10.4%	0.6%	-9.8%	-21.0%
1.20	90.9%	84.5%	77.9%	70.9%	67.2%	63.5%	55.6%	47.2%	38.2%	28.4%	17.6%	5.9%	-6.6%

Pitch Setting: 3°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-52.8%	-54.6%	-56.5%	-58.7%	-59.9%	-61.1%	-63.8%	-66.7%	-69.8%	-73.1%	-76.4%	-79.7%	-82.8%
0.85	-42.2%	-44.3%	-46.6%	-49.1%	-50.4%	-51.8%	-54.8%	-58.2%	-61.8%	-65.6%	-69.6%	-73.7%	-77.7%
0.90	-30.2%	-32.7%	-35.3%	-38.1%	-39.6%	-41.2%	-44.6%	-48.4%	-52.5%	-57.0%	-61.7%	-66.6%	-71.5%
0.95	-16.7%	-19.5%	-22.6%	-25.8%	-27.5%	-29.3%	-33.2%	-37.4%	-42.1%	-47.1%	-52.5%	-58.3%	-64.2%
1.00	-1.5%	-4.8%	-8.3%	-12.0%	-14.0%	-16.0%	-20.3%	-25.1%	-30.3%	-36.0%	-42.2%	-48.7%	-55.6%
1.05	15.5%	11.6%	7.6%	3.3%	1.1%	-1.2%	-6.1%	-11.4%	-17.2%	-23.6%	-30.5%	-38.0%	-45.8%
1.10	34.5%	29.9%	25.2%	20.3%	17.8%	15.2%	9.7%	3.8%	-2.7%	-9.7%	-17.5%	-25.9%	-34.8%
1.15	55.6%	50.2%	44.7%	39.1%	36.2%	33.3%	27.0%	20.4%	13.3%	5.4%	-3.1%	-12.5%	-22.5%
1.20	78.8%	72.6%	66.2%	59.8%	56.5%	53.1%	46.1%	38.7%	30.8%	22.1%	12.7%	2.3%	-8.9%

Pitch Setting: 4°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-55.3%	-56.9%	-58.7%	-60.6%	-61.6%	-62.7%	-65.1%	-67.7%	-70.4%	-73.4%	-76.5%	-79.7%	-82.7%
0.85	-45.5%	-47.4%	-49.4%	-51.6%	-52.8%	-54.0%	-56.7%	-59.6%	-62.8%	-66.3%	-69.9%	-73.8%	-77.6%
0.90	-34.5%	-36.6%	-39.0%	-41.5%	-42.8%	-44.2%	-47.2%	-50.5%	-54.1%	-58.1%	-62.4%	-66.8%	-71.5%
0.95	-22.0%	-24.5%	-27.2%	-30.1%	-31.6%	-33.2%	-36.6%	-40.3%	-44.3%	-48.8%	-53.7%	-58.8%	-64.3%
1.00	-7.9%	-11.0%	-14.1%	-17.4%	-19.1%	-20.9%	-24.7%	-28.9%	-33.4%	-38.4%	-43.9%	-49.8%	-56.0%
1.05	7.8%	4.1%	0.5%	-3.3%	-5.3%	-7.3%	-11.5%	-16.2%	-21.3%	-26.8%	-32.9%	-39.6%	-46.7%
1.10	25.2%	21.0%	16.6%	12.3%	10.0%	7.8%	3.0%	-2.2%	-7.8%	-14.0%	-20.7%	-28.2%	-36.3%
1.15	44.3%	39.6%	34.5%	29.4%	26.9%	24.3%	18.9%	13.1%	6.9%	0.0%	-7.4%	-15.6%	-24.6%
1.20	65.2%	59.9%	54.3%	48.4%	45.4%	42.4%	36.3%	29.9%	22.9%	15.5%	7.2%	-1.8%	-11.8%

Pitch Setting: 5°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-58.0%	-59.4%	-60.9%	-62.6%	-63.5%	-64.5%	-66.5%	-68.8%	-71.3%	-73.9%	-76.8%	-79.7%	-82.7%
0.85	-49.0%	-50.6%	-52.4%	-54.3%	-55.3%	-56.4%	-58.7%	-61.3%	-64.1%	-67.2%	-70.5%	-74.0%	-77.6%
0.90	-38.8%	-40.8%	-42.8%	-45.0%	-46.1%	-47.3%	-49.9%	-52.8%	-56.0%	-59.5%	-63.3%	-67.4%	-71.6%
0.95	-27.4%	-29.7%	-32.1%	-34.5%	-35.8%	-37.2%	-40.1%	-43.3%	-46.9%	-50.8%	-55.1%	-59.8%	-64.7%
1.00	-14.6%	-17.3%	-20.1%	-23.0%	-24.4%	-26.0%	-29.2%	-32.8%	-36.8%	-41.1%	-45.9%	-51.2%	-56.8%
1.05	-0.4%	-3.5%	-6.8%	-10.1%	-11.8%	-13.6%	-17.2%	-21.2%	-25.5%	-30.4%	-35.7%	-41.6%	-48.0%
1.10	15.2%	11.7%	7.9%	4.1%	2.1%	0.1%	-4.0%	-8.4%	-13.2%	-18.6%	-24.4%	-30.9%	-38.1%
1.15	32.2%	28.3%	24.1%	19.7%	17.4%	15.1%	10.4%	5.5%	0.2%	-5.6%	-12.1%	-19.2%	-27.1%
1.20	50.8%	46.4%	41.8%	36.8%	34.2%	31.6%	26.2%	20.7%	14.9%	8.5%	1.4%	-6.4%	-15.1%

Pitch Setting: 6°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-60.8%	-62.0%	-63.3%	-64.7%	-65.5%	-66.3%	-68.1%	-70.1%	-72.2%	-74.6%	-77.2%	-79.9%	-82.7%
0.85	-52.6%	-54.0%	-55.5%	-57.1%	-58.0%	-58.9%	-60.9%	-63.1%	-65.5%	-68.3%	-71.2%	-74.4%	-77.7%
0.90	-43.3%	-45.0%	-46.8%	-48.6%	-49.6%	-50.6%	-52.8%	-55.3%	-58.0%	-61.1%	-64.4%	-68.1%	-72.0%
0.95	-33.0%	-34.9%	-37.0%	-39.1%	-40.2%	-41.4%	-43.8%	-46.5%	-49.6%	-53.0%	-56.8%	-60.9%	-65.4%
1.00	-21.5%	-23.8%	-26.1%	-28.6%	-29.9%	-31.2%	-33.9%	-36.9%	-40.3%	-44.1%	-48.2%	-52.8%	-57.9%
1.05	-9.0%	-11.5%	-14.2%	-17.0%	-18.5%	-20.0%	-23.1%	-26.4%	-30.0%	-34.2%	-38.8%	-43.9%	-49.6%
1.10	4.7%	1.9%	-1.1%	-4.2%	-5.9%	-7.6%	-11.1%	-14.8%	-18.8%	-23.3%	-28.4%	-34.0%	-40.3%
1.15	19.6%	16.5%	13.2%	9.7%	7.8%	5.9%	1.9%	-2.3%	-6.7%	-11.5%	-17.1%	-23.2%	-30.0%
1.20	35.8%	32.3%	28.7%	24.8%	22.7%	20.6%	16.1%	11.4%	6.5%	1.2%	-4.7%	-11.5%	-18.9%

Pitch Setting: 7°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-63.6%	-64.6%	-65.7%	-66.9%	-67.5%	-68.2%	-69.8%	-71.5%	-73.4%	-75.5%	-77.8%	-80.2%	-82.8%
0.85	-56.2%	-57.4%	-58.6%	-60.0%	-60.7%	-61.5%	-63.1%	-65.0%	-67.2%	-69.5%	-72.1%	-75.0%	-78.0%
0.90	-47.9%	-49.3%	-50.7%	-52.3%	-53.1%	-54.0%	-55.8%	-57.8%	-60.2%	-62.8%	-65.8%	-69.0%	-72.5%
0.95	-38.8%	-40.3%	-42.0%	-43.7%	-44.7%	-45.6%	-47.7%	-49.9%	-52.5%	-55.4%	-58.6%	-62.3%	-66.3%
1.00	-28.8%	-30.5%	-32.3%	-34.3%	-35.4%	-36.4%	-38.7%	-41.2%	-44.0%	-47.2%	-50.7%	-54.8%	-59.2%
1.05	-17.9%	-19.7%	-21.8%	-24.0%	-25.2%	-26.4%	-28.9%	-31.7%	-34.7%	-38.1%	-42.1%	-46.5%	-51.4%
1.10	-6.0%	-8.1%	-10.3%	-12.8%	-14.1%	-15.4%	-18.3%	-21.3%	-24.6%	-28.3%	-32.6%	-37.4%	-42.8%
1.15	6.7%	4.5%	2.0%	-0.6%	-2.0%	-3.5%	-6.7%	-10.1%	-13.7%	-17.7%	-22.2%	-27.5%	-33.3%
1.20	20.5%	18.0%	15.3%	12.4%	10.9%	9.3%	5.9%	2.1%	-1.9%	-6.3%	-11.1%	-16.7%	-23.1%

Pitch Setting: 8°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-66.4%	-67.3%	-68.2%	-69.1%	-69.7%	-70.2%	-71.5%	-73.0%	-74.6%	-76.4%	-78.4%	-80.7%	-83.0%
0.85	-59.9%	-60.8%	-61.8%	-62.9%	-63.5%	-64.1%	-65.5%	-67.1%	-68.9%	-70.9%	-73.2%	-75.7%	-78.5%
0.90	-52.6%	-53.7%	-54.8%	-56.0%	-56.7%	-57.4%	-58.9%	-60.5%	-62.5%	-64.7%	-67.3%	-70.1%	-73.3%
0.95	-44.7%	-45.8%	-47.1%	-48.4%	-49.1%	-49.9%	-51.6%	-53.4%	-55.5%	-57.9%	-60.7%	-63.8%	-67.3%
1.00	-36.1%	-37.3%	-38.6%	-40.1%	-40.9%	-41.8%	-43.6%	-45.6%	-47.8%	-50.4%	-53.5%	-56.9%	-60.8%
1.05	-26.8%	-28.1%	-29.6%	-31.1%	-32.0%	-32.9%	-34.9%	-37.1%	-39.5%	-42.3%	-45.5%	-49.3%	-53.5%
1.10	-16.9%	-18.3%	-19.8%	-21.5%	-22.4%	-23.4%	-25.5%	-27.9%	-30.5%	-33.5%	-36.9%	-40.9%	-45.5%
1.15	-6.3%	-7.7%	-9.3%	-11.1%	-12.1%	-13.1%	-15.4%	-18.0%	-20.8%	-24.0%	-27.7%	-31.9%	-36.9%
1.20	4.9%	3.5%	1.9%	0.0%	-1.1%	-2.2%	-4.6%	-7.3%	-10.4%	-13.8%	-17.7%	-22.2%	-27.6%

Pitch Setting:	9°												
			Percentage Difference from Baseline										
Radius Scale	RPM				Baseline								
Factor	24.00	23.00	22.00	21.00	20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-69.4%	-70.0%	-70.7%	-71.4%	-71.9%	-72.3%	-73.3%	-74.5%	-75.9%	-77.5%	-79.2%	-81.2%	-83.3%
0.85	-63.6%	-64.3%	-65.0%	-65.9%	-66.3%	-66.8%	-67.9%	-69.2%	-70.7%	-72.4%	-74.3%	-76.5%	-79.0%
0.90	-57.4%	-58.1%	-58.9%	-59.8%	-60.3%	-60.8%	-62.0%	-63.3%	-64.9%	-66.8%	-68.9%	-71.3%	-74.1%
0.95	-50.7%	-51.4%	-52.2%	-53.2%	-53.7%	-54.3%	-55.5%	-56.9%	-58.6%	-60.6%	-62.9%	-65.5%	-68.6%
1.00	-43.6%	-44.2%	-45.1%	-46.0%	-46.6%	-47.2%	-48.5%	-50.0%	-51.8%	-53.8%	-56.3%	-59.2%	-62.5%
1.05	-36.0%	-36.6%	-37.4%	-38.4%	-38.9%	-39.6%	-40.9%	-42.5%	-44.4%	-46.5%	-49.1%	-52.2%	-55.8%
1.10	-28.1%	-28.6%	-29.3%	-30.2%	-30.8%	-31.4%	-32.8%	-34.5%	-36.4%	-38.7%	-41.4%	-44.7%	-48.5%
1.15	-19.8%	-20.2%	-20.8%	-21.6%	-22.2%	-22.8%	-24.2%	-26.0%	-28.0%	-30.4%	-33.2%	-36.6%	-40.7%
1.20	-11.1%	-11.4%	-11.9%	-12.6%	-13.1%	-13.7%	-15.1%	-16.9%	-19.0%	-21.4%	-24.4%	-27.9%	-32.2%

Appendix X

Power Results for WindPACT 1.5MW Turbine Radius vs. Pitch Parametric Study at 11.8 m/s

Pitch Setting: -2°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-40.9%	-41.4%	-42.7%	-45.3%	-47.2%	-49.6%	-55.3%	-62.0%	-69.0%	-75.7%	-81.7%	-86.8%	-91.1%
0.85	-32.7%	-32.5%	-33.2%	-35.0%	-36.6%	-38.7%	-44.2%	-51.3%	-59.2%	-67.2%	-74.8%	-81.5%	-87.1%
0.90	-24.3%	-23.7%	-23.5%	-24.6%	-25.7%	-27.4%	-32.6%	-39.6%	-48.1%	-57.3%	-66.5%	-74.9%	-82.1%
0.95	-15.7%	-14.5%	-14.0%	-14.1%	-14.8%	-16.0%	-20.4%	-27.3%	-36.0%	-46.1%	-56.7%	-66.9%	-75.9%
1.00	-7.0%	-5.2%	-4.1%	-3.8%	-3.9%	-4.5%	-7.9%	-14.3%	-23.1%	-33.8%	-45.6%	-57.5%	-68.5%
1.05	1.7%	4.2%	6.0%	6.8%	6.9%	6.9%	4.8%	-0.8%	-9.6%	-20.6%	-33.3%	-46.8%	-59.8%
1.10	10.5%	13.7%	16.2%	17.9%	18.1%	18.2%	17.5%	12.9%	4.6%	-6.6%	-20.0%	-34.8%	-49.7%
1.15	19.4%	23.2%	26.6%	28.9%	29.7%	30.0%	30.0%	26.9%	19.4%	8.2%	-5.7%	-21.7%	-38.4%
1.20	28.4%	32.9%	36.9%	40.2%	41.4%	42.2%	42.6%	40.9%	34.5%	23.6%	9.3%	-7.5%	-25.8%

Pitch Setting: -1°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-39.1%	-39.5%	-40.8%	-43.5%	-45.4%	-47.6%	-52.8%	-59.0%	-65.7%	-72.4%	-78.7%	-84.3%	-89.0%
0.85	-30.6%	-30.5%	-31.1%	-33.1%	-34.7%	-36.8%	-42.0%	-48.4%	-55.8%	-63.6%	-71.3%	-78.3%	-84.5%
0.90	-22.0%	-21.3%	-21.4%	-22.5%	-23.8%	-25.5%	-30.4%	-37.0%	-44.8%	-53.5%	-62.5%	-71.1%	-78.8%
0.95	-13.1%	-11.9%	-11.4%	-11.8%	-12.6%	-14.0%	-18.4%	-24.8%	-33.0%	-42.4%	-52.5%	-62.7%	-72.1%
1.00	-4.0%	-2.4%	-1.3%	-1.1%	-1.5%	-2.4%	-6.0%	-12.1%	-20.3%	-30.2%	-41.3%	-52.9%	-64.1%
1.05	5.2%	7.4%	9.1%	10.0%	9.9%	9.3%	6.6%	1.1%	-7.0%	-17.3%	-29.1%	-41.9%	-54.9%
1.10	14.6%	17.3%	19.6%	21.2%	21.6%	21.4%	19.3%	14.7%	6.9%	-3.5%	-16.0%	-29.9%	-44.4%
1.15	24.3%	27.4%	30.3%	32.6%	33.3%	33.7%	32.3%	28.5%	21.3%	11.0%	-2.0%	-16.8%	-32.8%
1.20	34.0%	37.8%	41.2%	44.1%	45.3%	46.1%	45.8%	42.3%	36.1%	26.0%	12.8%	-2.9%	-20.2%

Pitch Setting: 0°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-37.5%	-37.9%	-39.5%	-42.2%	-44.0%	-46.1%	-50.9%	-56.7%	-63.1%	-69.6%	-76.0%	-81.8%	-86.9%
0.85	-28.9%	-28.7%	-29.6%	-31.8%	-33.5%	-35.4%	-40.3%	-46.3%	-53.2%	-60.6%	-68.2%	-75.4%	-81.9%
0.90	-20.0%	-19.4%	-19.6%	-21.2%	-22.5%	-24.3%	-29.0%	-35.1%	-42.4%	-50.6%	-59.2%	-67.8%	-75.8%
0.95	-10.8%	-9.8%	-9.4%	-10.3%	-11.4%	-12.9%	-17.2%	-23.2%	-30.7%	-39.5%	-49.1%	-59.0%	-68.6%
1.00	-1.4%	0.1%	1.0%	0.8%	0.0%	-1.2%	-5.0%	-10.8%	-18.4%	-27.6%	-38.0%	-49.1%	-60.2%
1.05	8.4%	10.2%	11.7%	12.1%	11.7%	10.8%	7.5%	2.1%	-5.4%	-14.8%	-25.9%	-38.1%	-50.6%
1.10	18.4%	20.6%	22.5%	23.7%	23.6%	23.1%	20.2%	15.4%	8.1%	-1.5%	-13.0%	-26.1%	-40.0%
1.15	28.6%	31.2%	33.6%	35.5%	35.8%	35.6%	33.5%	28.9%	22.1%	12.5%	0.6%	-13.3%	-28.4%
1.20	39.0%	42.1%	45.0%	47.4%	48.2%	48.4%	47.0%	42.9%	36.4%	27.1%	14.9%	0.4%	-15.9%

Pitch Setting: 1°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-36.3%	-37.0%	-38.6%	-41.4%	-43.1%	-45.0%	-49.6%	-54.9%	-60.9%	-67.2%	-73.6%	-79.5%	-84.9%
0.85	-27.4%	-27.7%	-28.8%	-31.1%	-32.7%	-34.6%	-39.2%	-44.7%	-51.2%	-58.2%	-65.6%	-72.8%	-79.5%
0.90	-18.2%	-18.1%	-18.8%	-20.6%	-21.9%	-23.7%	-28.2%	-33.8%	-40.6%	-48.3%	-56.5%	-64.9%	-73.0%
0.95	-8.7%	-8.1%	-8.5%	-9.8%	-11.0%	-12.4%	-16.6%	-22.3%	-29.3%	-37.4%	-46.5%	-56.0%	-65.5%
1.00	1.1%	2.1%	2.2%	1.3%	0.3%	-1.0%	-4.7%	-10.2%	-17.3%	-25.8%	-35.5%	-46.0%	-56.8%
1.05	11.2%	12.6%	13.2%	12.7%	11.9%	10.8%	7.5%	2.4%	-4.7%	-13.5%	-23.7%	-35.1%	-47.2%
1.10	21.7%	23.5%	24.5%	24.4%	23.9%	23.0%	20.0%	15.2%	8.4%	-0.5%	-11.2%	-23.3%	-36.6%
1.15	32.5%	34.6%	36.2%	36.5%	36.2%	35.4%	32.9%	28.4%	22.0%	13.0%	2.0%	-10.8%	-25.1%
1.20	43.5%	46.1%	48.1%	48.9%	48.8%	48.3%	46.0%	42.0%	35.8%	27.1%	15.8%	2.4%	-12.7%

Pitch Setting: 2°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-35.9%	-36.8%	-38.4%	-40.9%	-42.6%	-44.5%	-48.7%	-53.7%	-59.3%	-65.3%	-71.5%	-77.5%	-83.0%
0.85	-26.8%	-27.5%	-28.8%	-31.0%	-32.4%	-34.2%	-38.6%	-43.8%	-49.7%	-56.4%	-63.4%	-70.5%	-77.2%
0.90	-17.4%	-17.9%	-19.0%	-20.8%	-22.1%	-23.7%	-27.8%	-33.2%	-39.5%	-46.6%	-54.4%	-62.5%	-70.5%
0.95	-7.6%	-7.8%	-8.7%	-10.3%	-11.5%	-12.9%	-16.6%	-22.0%	-28.5%	-36.0%	-44.5%	-53.6%	-62.8%
1.00	2.7%	2.6%	2.0%	0.5%	-0.5%	-1.8%	-5.3%	-10.2%	-16.9%	-24.8%	-33.8%	-43.7%	-54.1%
1.05	13.3%	13.5%	13.0%	11.8%	10.8%	9.6%	6.4%	1.8%	-4.7%	-12.9%	-22.4%	-33.0%	-44.4%
1.10	24.3%	24.8%	24.5%	23.4%	22.6%	21.4%	18.4%	14.0%	7.9%	-0.4%	-10.3%	-21.5%	-33.9%
1.15	35.6%	36.5%	36.4%	35.5%	34.7%	33.7%	30.8%	26.6%	20.7%	12.7%	2.4%	-9.4%	-22.6%
1.20	47.0%	48.5%	48.7%	48.0%	47.2%	46.3%	43.5%	39.5%	33.8%	26.1%	15.7%	3.3%	-10.7%

Pitch Setting: 3°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-36.2%	-37.2%	-38.8%	-41.0%	-42.5%	-44.3%	-48.3%	-52.9%	-58.1%	-63.8%	-69.8%	-75.7%	-81.2%
0.85	-27.1%	-28.1%	-29.5%	-31.6%	-32.9%	-34.5%	-38.4%	-43.3%	-48.9%	-55.0%	-61.7%	-68.6%	-75.3%
0.90	-17.7%	-18.6%	-19.9%	-21.8%	-23.0%	-24.5%	-28.1%	-33.0%	-38.9%	-45.5%	-52.8%	-60.6%	-68.4%
0.95	-7.9%	-8.7%	-9.9%	-11.7%	-12.9%	-14.2%	-17.6%	-22.2%	-28.3%	-35.3%	-43.2%	-51.7%	-60.6%
1.00	2.4%	1.7%	0.5%	-1.2%	-2.3%	-3.6%	-6.8%	-11.2%	-17.1%	-24.5%	-32.8%	-42.0%	-51.9%
1.05	13.2%	12.5%	11.4%	9.7%	8.7%	7.4%	4.3%	0.1%	-5.6%	-13.0%	-21.8%	-31.7%	-42.4%
1.10	24.3%	23.8%	22.7%	21.0%	20.0%	18.8%	15.7%	11.7%	6.2%	-1.0%	-10.2%	-20.6%	-32.1%
1.15	35.8%	35.5%	34.4%	32.8%	31.8%	30.6%	27.5%	23.5%	18.2%	11.2%	2.0%	-9.0%	-21.2%
1.20	47.7%	47.5%	46.6%	45.0%	44.0%	42.7%	39.8%	35.7%	30.6%	23.7%	14.7%	3.3%	-9.7%

Pitch Setting: 4°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-37.0%	-38.2%	-39.7%	-41.8%	-43.1%	-44.6%	-48.2%	-52.6%	-57.4%	-62.7%	-68.4%	-74.1%	-79.7%
0.85	-28.3%	-29.4%	-30.9%	-32.8%	-34.0%	-35.3%	-38.8%	-43.3%	-48.5%	-54.2%	-60.4%	-67.0%	-73.6%
0.90	-19.1%	-20.2%	-21.6%	-23.5%	-24.6%	-25.9%	-29.1%	-33.4%	-38.8%	-45.0%	-51.8%	-59.1%	-66.6%
0.95	-9.4%	-10.5%	-12.0%	-13.8%	-14.9%	-16.2%	-19.3%	-23.3%	-28.7%	-35.2%	-42.5%	-50.4%	-58.8%
1.00	0.7%	-0.5%	-1.9%	-3.7%	-4.9%	-6.1%	-9.1%	-13.0%	-18.1%	-24.7%	-32.5%	-41.0%	-50.3%
1.05	11.2%	10.0%	8.5%	6.7%	5.6%	4.3%	1.3%	-2.4%	-7.4%	-13.8%	-21.9%	-31.1%	-41.0%
1.10	22.1%	20.9%	19.4%	17.5%	16.3%	15.1%	12.1%	8.4%	3.6%	-2.7%	-10.8%	-20.4%	-31.1%
1.15	33.3%	32.3%	30.7%	28.7%	27.5%	26.3%	23.3%	19.5%	14.8%	8.7%	0.7%	-9.2%	-20.6%
1.20	44.9%	43.9%	42.4%	40.4%	39.2%	37.8%	34.8%	31.0%	26.3%	20.3%	12.4%	2.4%	-9.6%

Pitch Setting: 5°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-38.4%	-39.6%	-41.1%	-42.9%	-44.1%	-45.4%	-48.6%	-52.6%	-57.1%	-62.0%	-67.3%	-72.8%	-78.3%
0.85	-30.1%	-31.2%	-32.7%	-34.5%	-35.5%	-36.8%	-39.8%	-43.7%	-48.4%	-53.8%	-59.6%	-65.8%	-72.2%
0.90	-21.3%	-22.5%	-23.9%	-25.7%	-26.7%	-27.9%	-30.8%	-34.5%	-39.2%	-44.9%	-51.2%	-58.0%	-65.2%
0.95	-12.0%	-13.3%	-14.8%	-16.5%	-17.6%	-18.8%	-21.5%	-25.1%	-29.7%	-35.5%	-42.2%	-49.6%	-57.6%
1.00	-2.4%	-3.7%	-5.3%	-7.1%	-8.1%	-9.3%	-12.1%	-15.5%	-19.9%	-25.7%	-32.7%	-40.6%	-49.2%
1.05	7.6%	6.2%	4.6%	2.7%	1.6%	0.5%	-2.3%	-5.7%	-10.0%	-15.6%	-22.6%	-31.0%	-40.3%
1.10	17.8%	16.6%	14.9%	12.9%	11.7%	10.5%	7.8%	4.4%	0.2%	-5.3%	-12.3%	-20.9%	-30.8%
1.15	28.4%	27.2%	25.5%	23.4%	22.3%	21.0%	18.1%	14.7%	10.5%	5.3%	-1.7%	-10.3%	-20.7%
1.20	39.2%	38.1%	36.5%	34.4%	33.1%	31.8%	28.8%	25.4%	21.1%	16.0%	9.2%	0.5%	-10.1%

Pitch Setting: 6°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-40.4%	-41.5%	-42.9%	-44.5%	-45.5%	-46.7%	-49.5%	-53.0%	-57.1%	-61.7%	-66.6%	-71.8%	-77.2%
0.85	-32.4%	-33.6%	-34.9%	-36.6%	-37.5%	-38.6%	-41.2%	-44.6%	-48.8%	-53.7%	-59.2%	-65.0%	-71.0%
0.90	-24.2%	-25.4%	-26.7%	-28.4%	-29.4%	-30.4%	-32.9%	-36.1%	-40.2%	-45.3%	-51.1%	-57.5%	-64.2%
0.95	-15.5%	-16.8%	-18.2%	-19.9%	-20.8%	-21.9%	-24.3%	-27.4%	-31.4%	-36.4%	-42.5%	-49.4%	-56.8%
1.00	-6.6%	-7.9%	-9.4%	-11.1%	-12.1%	-13.1%	-15.6%	-18.5%	-22.3%	-27.3%	-33.5%	-40.7%	-48.7%
1.05	2.5%	1.3%	-0.2%	-2.0%	-3.0%	-4.1%	-6.5%	-9.5%	-13.2%	-18.0%	-24.1%	-31.6%	-40.1%
1.10	11.9%	10.7%	9.2%	7.4%	6.3%	5.2%	2.7%	-0.3%	-3.9%	-8.5%	-14.6%	-22.1%	-31.0%
1.15	21.4%	20.3%	18.9%	17.1%	16.0%	14.8%	12.2%	9.2%	5.6%	1.1%	-4.7%	-12.3%	-21.5%
1.20	31.1%	30.1%	28.8%	27.0%	25.9%	24.7%	22.0%	18.9%	15.3%	10.8%	5.2%	-2.3%	-11.6%

Pitch Setting: 7°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-42.7%	-43.8%	-45.0%	-46.5%	-47.3%	-48.3%	-50.7%	-53.8%	-57.4%	-61.6%	-66.2%	-71.2%	-76.2%
0.85	-35.4%	-36.4%	-37.6%	-39.1%	-40.0%	-40.9%	-43.1%	-46.0%	-49.7%	-54.1%	-59.1%	-64.5%	-70.2%
0.90	-27.7%	-28.8%	-30.1%	-31.5%	-32.4%	-33.3%	-35.4%	-38.1%	-41.7%	-46.2%	-51.4%	-57.2%	-63.6%
0.95	-19.9%	-21.0%	-22.2%	-23.7%	-24.6%	-25.5%	-27.6%	-30.2%	-33.5%	-37.9%	-43.3%	-49.5%	-56.4%
1.00	-11.9%	-12.9%	-14.2%	-15.7%	-16.5%	-17.5%	-19.6%	-22.1%	-25.3%	-29.5%	-34.9%	-41.3%	-48.6%
1.05	-3.8%	-4.7%	-5.9%	-7.4%	-8.3%	-9.2%	-11.3%	-13.9%	-17.0%	-20.9%	-26.3%	-32.8%	-40.4%
1.10	4.4%	3.6%	2.5%	1.0%	0.2%	-0.8%	-2.9%	-5.4%	-8.6%	-12.4%	-17.4%	-24.0%	-31.9%
1.15	12.7%	12.0%	11.0%	9.6%	8.8%	7.8%	5.7%	3.1%	0.0%	-3.7%	-8.5%	-15.0%	-23.0%
1.20	21.0%	20.4%	19.6%	18.3%	17.5%	16.6%	14.5%	11.9%	8.8%	5.0%	0.4%	-5.8%	-13.9%

Pitch Setting: 8°

Percentage Difference from Baseline

Radius Scale Factor	RPM 24.00	23.00	22.00	21.00	Baseline 20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
0.80	-45.5%	-46.4%	-47.4%	-48.7%	-49.5%	-50.3%	-52.3%	-54.9%	-58.1%	-61.9%	-66.1%	-70.7%	-75.5%
0.85	-38.8%	-39.7%	-40.7%	-42.0%	-42.7%	-43.5%	-45.3%	-47.8%	-51.0%	-54.8%	-59.3%	-64.3%	-69.7%
0.90	-32.0%	-32.8%	-33.9%	-35.1%	-35.8%	-36.6%	-38.4%	-40.6%	-43.6%	-47.4%	-52.1%	-57.4%	-63.2%
0.95	-25.1%	-25.8%	-26.8%	-28.0%	-28.7%	-29.5%	-31.2%	-33.4%	-36.2%	-39.9%	-44.5%	-50.1%	-56.3%
1.00	-18.1%	-18.8%	-19.7%	-20.9%	-21.5%	-22.3%	-24.0%	-26.1%	-28.8%	-32.2%	-36.8%	-42.4%	-49.0%
1.05	-11.2%	-11.7%	-12.5%	-13.5%	-14.2%	-14.9%	-16.6%	-18.7%	-21.3%	-24.5%	-28.8%	-34.5%	-41.3%
1.10	-4.3%	-4.6%	-5.3%	-6.2%	-6.8%	-7.5%	-9.1%	-11.1%	-13.7%	-16.8%	-20.9%	-26.5%	-33.4%
1.15	2.5%	2.4%	1.9%	1.2%	0.6%	0.0%	-1.5%	-3.5%	-5.9%	-9.1%	-12.9%	-18.2%	-25.2%
1.20	9.0%	9.2%	9.1%	8.5%	8.1%	7.5%	6.1%	4.2%	1.8%	-1.2%	-5.0%	-9.9%	-16.8%

Pitch Setting:		9°												
				Percentage Difference from Baseline										
	Radius Scale	RPM				Baseline								
	Factor	24.00	23.00	22.00	21.00	20.50	20.00	19.00	18.00	17.00	16.00	15.00	14.00	13.00
	0.80	-48.6%	-49.3%	-50.2%	-51.2%	-51.8%	-52.5%	-54.1%	-56.3%	-59.1%	-62.5%	-66.3%	-70.6%	-75.1%
	0.85	-42.7%	-43.4%	-44.2%	-45.1%	-45.7%	-46.4%	-47.9%	-49.9%	-52.5%	-55.9%	-59.9%	-64.4%	-69.4%
	0.90	-36.8%	-37.3%	-38.1%	-39.0%	-39.5%	-40.1%	-41.6%	-43.5%	-45.8%	-49.1%	-53.1%	-57.9%	-63.2%
	0.95	-30.9%	-31.3%	-31.9%	-32.8%	-33.3%	-33.9%	-35.2%	-37.0%	-39.2%	-42.2%	-46.2%	-51.0%	-56.7%
	1.00	-25.2%	-25.4%	-25.8%	-26.5%	-27.0%	-27.5%	-28.8%	-30.4%	-32.6%	-35.3%	-39.1%	-44.0%	-49.8%
	1.05	-19.6%	-19.6%	-19.8%	-20.3%	-20.7%	-21.2%	-22.3%	-23.9%	-25.9%	-28.5%	-31.9%	-36.7%	-42.7%
	1.10	-14.3%	-13.9%	-13.9%	-14.2%	-14.4%	-14.8%	-15.9%	-17.3%	-19.1%	-21.6%	-24.9%	-29.4%	-35.3%
	1.15	-9.3%	-8.6%	-8.2%	-8.2%	-8.3%	-8.6%	-9.4%	-10.7%	-12.4%	-14.7%	-17.9%	-22.0%	-27.9%
	1.20	-4.6%	-3.5%	-2.7%	-2.3%	-2.3%	-2.4%	-3.0%	-4.1%	-5.7%	-7.8%	-10.8%	-14.7%	-20.2%

Appendix Y

Root Bending Moment Results for NREL 5MW Turbine Radius vs. Pitch Parametric Study at 11.4 m/s

Pitch Setting: -2°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-30.2%	-33.2%	-36.5%	-40.0%	-44.0%	-48.4%	-49.0%	-57.2%	-63.7%	-69.9%	-76.0%	-81.7%	-87.1%
0.85	-14.9%	-18.5%	-22.3%	-26.5%	-31.2%	-36.0%	-36.6%	-44.7%	-54.1%	-61.8%	-69.4%	-76.5%	-83.2%
0.90	2.6%	-1.8%	-6.2%	-11.1%	-16.5%	-22.1%	-22.8%	-30.7%	-42.8%	-52.4%	-61.6%	-70.4%	-78.5%
0.95	22.5%	17.2%	11.9%	6.3%	0.0%	-6.3%	-7.1%	-15.6%	-28.4%	-41.3%	-52.5%	-63.2%	-73.0%
1.00	44.9%	38.6%	32.2%	25.8%	18.6%	11.4%	10.5%	0.9%	-11.5%	-28.6%	-42.0%	-54.8%	-66.7%
1.05	70.0%	62.5%	55.0%	47.4%	39.4%	31.2%	30.2%	19.3%	6.4%	-13.4%	-29.9%	-45.1%	-59.4%
1.10	98.0%	89.2%	80.4%	71.5%	62.4%	53.1%	52.1%	39.8%	25.5%	5.5%	-16.1%	-34.1%	-51.1%
1.15	129.1%	118.8%	108.5%	98.2%	87.7%	77.4%	76.2%	62.6%	46.5%	26.5%	-0.4%	-21.6%	-41.5%
1.20	163.5%	151.5%	139.6%	127.6%	115.5%	104.1%	102.7%	87.6%	69.6%	48.4%	17.7%	-7.6%	-30.6%

Pitch Setting: -1°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-34.5%	-37.0%	-39.6%	-42.7%	-46.3%	-50.2%	-50.7%	-57.3%	-64.3%	-70.2%	-76.1%	-81.7%	-87.0%
0.85	-20.4%	-23.4%	-26.5%	-30.0%	-34.1%	-38.6%	-39.2%	-45.6%	-55.0%	-62.4%	-69.6%	-76.6%	-83.1%
0.90	-4.4%	-8.0%	-11.7%	-15.7%	-20.4%	-25.5%	-26.1%	-32.9%	-43.1%	-53.2%	-62.0%	-70.5%	-78.4%
0.95	13.7%	9.4%	5.0%	0.4%	-4.9%	-10.6%	-11.3%	-19.1%	-29.0%	-42.4%	-53.1%	-63.4%	-73.0%
1.00	34.0%	28.9%	23.7%	18.3%	12.4%	5.9%	5.2%	-3.6%	-14.0%	-29.5%	-42.8%	-55.1%	-66.8%
1.05	56.7%	50.7%	44.6%	38.3%	31.6%	24.4%	23.5%	13.7%	2.2%	-13.5%	-31.1%	-45.6%	-59.6%
1.10	81.8%	74.8%	67.7%	60.4%	52.8%	44.9%	43.9%	33.0%	20.0%	4.0%	-17.6%	-34.9%	-51.3%
1.15	109.5%	101.3%	93.1%	84.8%	76.0%	67.3%	66.2%	54.0%	39.6%	22.6%	-1.8%	-22.7%	-41.8%
1.20	140.0%	130.6%	121.1%	111.5%	101.5%	91.8%	90.6%	77.2%	61.2%	42.5%	17.3%	-9.0%	-31.2%

Pitch Setting: 0°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-38.6%	-40.7%	-42.9%	-45.5%	-48.8%	-52.3%	-52.7%	-57.9%	-65.0%	-70.7%	-76.3%	-81.8%	-86.9%
0.85	-25.7%	-28.1%	-30.8%	-33.8%	-37.4%	-41.4%	-41.9%	-47.3%	-55.4%	-63.1%	-69.9%	-76.7%	-83.0%
0.90	-11.1%	-14.0%	-17.1%	-20.5%	-24.6%	-29.1%	-29.7%	-35.8%	-43.8%	-54.1%	-62.5%	-70.7%	-78.4%
0.95	5.3%	1.9%	-1.7%	-5.7%	-10.4%	-15.4%	-16.0%	-22.8%	-31.1%	-43.3%	-53.8%	-63.7%	-73.2%
1.00	23.5%	19.6%	15.4%	10.7%	5.5%	0.0%	-0.7%	-8.3%	-17.5%	-29.9%	-43.9%	-55.6%	-66.9%
1.05	43.8%	39.1%	34.3%	29.0%	23.1%	16.9%	16.2%	7.7%	-2.5%	-15.2%	-32.4%	-46.4%	-59.8%
1.10	66.1%	60.8%	55.2%	49.2%	42.4%	35.5%	34.7%	25.3%	14.1%	0.5%	-18.7%	-35.9%	-51.6%
1.15	90.5%	84.5%	78.1%	71.3%	63.6%	55.9%	55.0%	44.8%	32.3%	17.4%	-2.4%	-24.0%	-42.3%
1.20	117.2%	110.4%	103.2%	95.4%	86.8%	78.1%	77.1%	65.8%	52.1%	35.8%	15.5%	-10.7%	-31.9%

Pitch Setting: 1°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-42.7%	-44.4%	-46.4%	-48.7%	-51.5%	-54.5%	-54.9%	-59.2%	-65.5%	-71.3%	-76.6%	-81.8%	-86.8%
0.85	-30.9%	-33.0%	-35.3%	-37.9%	-41.0%	-44.4%	-44.9%	-49.5%	-56.0%	-63.9%	-70.4%	-76.8%	-83.0%
0.90	-17.8%	-20.1%	-22.8%	-25.8%	-29.4%	-33.1%	-33.6%	-38.8%	-45.4%	-54.9%	-63.1%	-70.9%	-78.5%
0.95	-3.1%	-5.8%	-8.9%	-12.4%	-16.3%	-20.6%	-21.1%	-26.9%	-34.0%	-43.8%	-54.8%	-64.1%	-73.3%
1.00	13.2%	10.0%	6.5%	2.6%	-2.0%	-6.7%	-7.2%	-13.6%	-21.4%	-31.5%	-45.1%	-56.3%	-67.1%
1.05	31.0%	27.5%	23.5%	19.0%	13.9%	8.7%	8.0%	1.1%	-7.5%	-18.2%	-33.3%	-47.3%	-60.1%
1.10	50.5%	46.6%	42.1%	37.1%	31.3%	25.4%	24.7%	17.0%	7.6%	-3.9%	-19.6%	-37.2%	-52.1%
1.15	71.8%	67.4%	62.4%	56.7%	50.3%	43.6%	42.9%	34.4%	24.2%	11.6%	-4.5%	-25.7%	-43.0%
1.20	94.7%	89.9%	84.5%	78.2%	70.9%	63.5%	62.7%	53.3%	42.3%	28.6%	11.6%	-12.3%	-32.9%

Pitch Setting: 2°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-47.0%	-48.5%	-50.2%	-52.1%	-54.4%	-56.9%	-57.2%	-60.8%	-66.0%	-71.9%	-76.9%	-81.9%	-86.8%
0.85	-36.5%	-38.2%	-40.2%	-42.4%	-45.0%	-47.7%	-48.1%	-52.0%	-57.2%	-64.6%	-70.9%	-77.0%	-83.0%
0.90	-24.9%	-26.8%	-29.0%	-31.5%	-34.4%	-37.6%	-37.9%	-42.2%	-47.7%	-55.5%	-64.0%	-71.3%	-78.6%
0.95	-12.0%	-14.2%	-16.7%	-19.5%	-22.8%	-26.2%	-26.6%	-31.3%	-37.2%	-45.2%	-55.8%	-64.7%	-73.4%
1.00	2.0%	-0.3%	-3.1%	-6.3%	-10.0%	-13.8%	-14.2%	-19.4%	-25.7%	-34.0%	-45.9%	-57.1%	-67.4%
1.05	17.3%	14.8%	11.8%	8.2%	4.1%	-0.2%	-0.7%	-6.3%	-13.1%	-22.0%	-34.3%	-48.4%	-60.5%
1.10	33.9%	31.2%	27.9%	23.9%	19.4%	14.7%	14.1%	8.0%	0.5%	-8.9%	-21.7%	-38.6%	-52.7%
1.15	51.7%	48.9%	45.3%	41.0%	35.9%	30.8%	30.1%	23.4%	15.3%	5.2%	-8.0%	-27.0%	-44.0%
1.20	70.8%	67.8%	64.0%	59.4%	53.9%	48.2%	47.5%	40.1%	31.4%	20.6%	6.4%	-13.4%	-34.2%

Pitch Setting: 3°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-51.8%	-52.9%	-54.2%	-55.7%	-57.6%	-59.6%	-59.9%	-62.8%	-66.9%	-72.5%	-77.3%	-82.1%	-86.8%
0.85	-42.7%	-43.9%	-45.4%	-47.1%	-49.1%	-51.4%	-51.6%	-54.7%	-58.9%	-65.1%	-71.6%	-77.3%	-83.1%
0.90	-32.8%	-34.1%	-35.7%	-37.5%	-39.8%	-42.2%	-42.5%	-45.9%	-50.3%	-56.6%	-64.8%	-71.7%	-78.7%
0.95	-21.9%	-23.3%	-25.0%	-27.1%	-29.5%	-32.2%	-32.5%	-36.2%	-40.8%	-47.2%	-56.6%	-65.3%	-73.6%
1.00	-10.3%	-11.7%	-13.4%	-15.7%	-18.3%	-21.2%	-21.6%	-25.5%	-30.5%	-37.2%	-46.9%	-58.1%	-67.8%
1.05	2.2%	0.9%	-1.0%	-3.3%	-6.2%	-9.3%	-9.7%	-13.9%	-19.3%	-26.2%	-36.3%	-49.7%	-61.1%
1.10	15.5%	14.2%	12.4%	10.0%	6.9%	3.5%	3.1%	-1.4%	-7.2%	-14.5%	-24.7%	-39.7%	-53.6%
1.15	29.5%	28.4%	26.6%	24.2%	21.0%	17.4%	16.9%	12.0%	6.0%	-1.8%	-12.5%	-28.2%	-45.1%
1.20	44.2%	43.3%	41.7%	39.3%	35.9%	32.1%	31.7%	26.4%	20.0%	11.7%	0.6%	-15.6%	-35.8%

Pitch Setting: 4°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-56.9%	-57.6%	-58.5%	-59.6%	-60.9%	-62.5%	-62.7%	-64.9%	-68.2%	-73.0%	-77.9%	-82.3%	-86.9%
0.85	-49.4%	-50.0%	-50.9%	-52.0%	-53.5%	-55.1%	-55.3%	-57.8%	-61.0%	-66.0%	-72.3%	-77.7%	-83.2%
0.90	-41.3%	-41.8%	-42.7%	-43.8%	-45.3%	-47.1%	-47.3%	-49.9%	-53.2%	-58.2%	-65.5%	-72.3%	-78.9%
0.95	-32.7%	-33.1%	-33.8%	-34.9%	-36.5%	-38.3%	-38.6%	-41.2%	-44.8%	-49.8%	-57.5%	-66.2%	-73.9%
1.00	-23.6%	-23.8%	-24.4%	-25.4%	-27.0%	-28.9%	-29.1%	-31.9%	-35.7%	-40.8%	-48.5%	-59.1%	-68.3%
1.05	-14.2%	-14.1%	-14.4%	-15.3%	-16.8%	-18.7%	-19.0%	-21.9%	-25.7%	-31.0%	-38.8%	-50.7%	-61.8%
1.10	-4.6%	-4.0%	-4.0%	-4.6%	-6.0%	-7.9%	-8.2%	-11.1%	-15.1%	-20.7%	-28.6%	-40.9%	-54.6%
1.15	5.3%	6.4%	6.9%	6.5%	5.4%	3.6%	3.3%	0.3%	-3.8%	-9.6%	-17.6%	-30.2%	-46.5%
1.20	15.1%	17.0%	18.1%	18.2%	17.3%	15.7%	15.5%	12.5%	8.2%	2.4%	-5.9%	-18.7%	-37.3%

Pitch Setting: 5°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-62.4%	-62.5%	-62.9%	-63.5%	-64.4%	-65.4%	-65.6%	-67.3%	-69.8%	-73.7%	-78.5%	-82.6%	-86.9%
0.85	-56.4%	-56.4%	-56.6%	-57.1%	-58.0%	-59.0%	-59.2%	-60.9%	-63.4%	-67.3%	-72.9%	-78.2%	-83.3%
0.90	-50.3%	-49.9%	-49.9%	-50.3%	-51.1%	-52.1%	-52.2%	-54.0%	-56.5%	-60.2%	-66.3%	-73.0%	-79.2%
0.95	-44.0%	-43.3%	-43.0%	-43.1%	-43.7%	-44.7%	-44.8%	-46.5%	-49.1%	-52.8%	-58.8%	-67.1%	-74.4%
1.00	-37.7%	-36.5%	-35.8%	-35.5%	-35.9%	-36.7%	-36.9%	-38.5%	-41.0%	-44.8%	-50.7%	-60.0%	-68.9%
1.05	-31.6%	-29.7%	-28.4%	-27.7%	-27.7%	-28.4%	-28.5%	-30.0%	-32.5%	-36.3%	-42.1%	-51.8%	-62.7%
1.10	-25.8%	-23.0%	-21.0%	-19.8%	-19.3%	-19.6%	-19.7%	-21.0%	-23.4%	-27.2%	-33.0%	-42.8%	-55.8%
1.15	-20.3%	-16.6%	-13.7%	-11.7%	-10.6%	-10.5%	-10.6%	-11.6%	-13.8%	-17.5%	-23.4%	-33.0%	-47.9%
1.20	-15.6%	-10.5%	-6.6%	-3.6%	-1.8%	-1.2%	-1.1%	-1.8%	-3.7%	-7.3%	-13.3%	-22.7%	-38.6%

Pitch Setting: 6°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-68.0%	-67.6%	-67.4%	-67.5%	-67.9%	-68.5%	-68.6%	-69.8%	-71.6%	-74.7%	-79.0%	-83.0%	-87.0%
0.85	-63.7%	-63.0%	-62.5%	-62.3%	-62.5%	-63.0%	-63.1%	-64.2%	-66.0%	-68.8%	-73.6%	-78.7%	-83.5%
0.90	-59.6%	-58.3%	-57.4%	-56.9%	-56.9%	-57.2%	-57.3%	-58.2%	-60.0%	-62.7%	-67.4%	-73.8%	-79.5%
0.95	-55.8%	-53.9%	-52.4%	-51.4%	-51.0%	-51.1%	-51.1%	-51.9%	-53.4%	-56.1%	-60.6%	-67.9%	-74.9%
1.00	-52.4%	-49.7%	-47.5%	-45.9%	-45.0%	-44.7%	-44.7%	-45.2%	-46.6%	-49.2%	-53.4%	-61.0%	-69.7%
1.05	-49.7%	-45.9%	-42.9%	-40.5%	-38.9%	-38.2%	-38.2%	-38.3%	-39.4%	-41.7%	-45.9%	-53.4%	-63.8%
1.10	-48.0%	-42.8%	-38.6%	-35.3%	-32.9%	-31.6%	-31.5%	-31.1%	-31.8%	-33.9%	-38.0%	-45.2%	-57.0%
1.15	-47.3%	-40.6%	-34.9%	-30.4%	-27.0%	-24.9%	-24.7%	-23.7%	-24.0%	-25.7%	-29.6%	-36.5%	-49.1%
1.20	-48.1%	-39.4%	-32.0%	-26.1%	-21.4%	-18.4%	-18.1%	-16.2%	-15.9%	-17.2%	-20.8%	-27.6%	-40.3%

Pitch Setting: 7°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-73.8%	-72.8%	-72.1%	-71.6%	-71.5%	-71.7%	-71.7%	-72.4%	-73.7%	-75.8%	-79.5%	-83.4%	-87.2%
0.85	-71.3%	-69.7%	-68.5%	-67.7%	-67.2%	-67.1%	-67.2%	-67.6%	-68.7%	-70.7%	-74.4%	-79.4%	-83.8%
0.90	-69.3%	-67.0%	-65.1%	-63.7%	-62.8%	-62.4%	-62.4%	-62.6%	-63.5%	-65.4%	-68.8%	-74.5%	-79.9%
0.95	-68.1%	-64.8%	-62.1%	-60.0%	-58.5%	-57.7%	-57.6%	-57.4%	-58.0%	-59.7%	-62.8%	-68.7%	-75.5%
1.00	-67.8%	-63.3%	-59.6%	-56.5%	-54.3%	-52.9%	-52.7%	-52.1%	-52.3%	-53.6%	-56.6%	-62.4%	-70.6%
1.05	-68.9%	-62.8%	-57.7%	-53.6%	-50.3%	-48.2%	-48.0%	-46.6%	-46.4%	-47.3%	-50.1%	-55.5%	-64.8%
1.10	-71.4%	-63.5%	-56.8%	-51.2%	-46.7%	-43.7%	-43.4%	-41.2%	-40.3%	-40.8%	-43.2%	-48.3%	-58.1%
1.15	-75.6%	-65.8%	-57.0%	-49.6%	-43.7%	-39.5%	-39.1%	-36.0%	-34.2%	-34.1%	-36.0%	-40.8%	-50.6%
1.20	-81.8%	-69.7%	-58.7%	-49.2%	-41.4%	-35.9%	-35.3%	-30.9%	-28.1%	-27.3%	-28.6%	-33.1%	-42.5%

Pitch Setting: 8°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-79.8%	-78.2%	-76.8%	-75.8%	-75.2%	-74.9%	-74.9%	-75.0%	-75.8%	-77.3%	-80.2%	-83.9%	-87.4%
0.85	-79.1%	-76.7%	-74.7%	-73.1%	-71.9%	-71.3%	-71.2%	-71.1%	-71.5%	-72.9%	-75.5%	-79.9%	-84.2%
0.90	-79.4%	-75.9%	-73.0%	-70.7%	-68.9%	-67.7%	-67.6%	-67.0%	-67.1%	-68.2%	-70.5%	-75.2%	-80.5%
0.95	-81.0%	-76.1%	-72.0%	-68.7%	-66.1%	-64.3%	-64.1%	-63.0%	-62.6%	-63.3%	-65.4%	-69.9%	-76.3%
1.00	-83.9%	-77.6%	-72.0%	-67.4%	-63.7%	-61.1%	-60.9%	-59.0%	-58.0%	-58.2%	-60.0%	-64.1%	-71.4%
1.05	-88.4%	-80.4%	-73.2%	-66.9%	-61.9%	-58.3%	-58.0%	-55.1%	-53.4%	-53.0%	-54.4%	-58.1%	-65.7%
1.10	-94.8%	-84.9%	-75.8%	-67.7%	-60.9%	-56.0%	-55.6%	-51.5%	-48.9%	-47.8%	-48.5%	-51.9%	-59.4%
1.15	-103.5%	-91.1%	-79.9%	-69.7%	-60.9%	-54.4%	-53.8%	-48.4%	-44.6%	-42.6%	-42.6%	-45.5%	-52.6%
1.20	-115.1%	-99.6%	-85.8%	-73.3%	-62.1%	-53.7%	-52.8%	-45.7%	-40.5%	-37.4%	-36.6%	-38.8%	-45.4%

Pitch Setting:		9°												
				Percentage Difference from Baseline										
	Radius Scale	RPM					Baseline							
	Factor	17.00	16.00	15.00	14.00	13.00	12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
	0.80	-86.1%	-83.7%	-81.7%	-80.1%	-78.9%	-78.1%	-78.1%	-77.7%	-77.9%	-78.9%	-81.0%	-84.4%	-87.6%
	0.85	-87.4%	-83.9%	-81.0%	-78.6%	-76.7%	-75.5%	-75.4%	-74.6%	-74.4%	-75.1%	-76.9%	-80.5%	-84.6%
	0.90	-89.8%	-85.3%	-81.2%	-77.7%	-75.0%	-73.1%	-72.9%	-71.5%	-70.8%	-71.1%	-72.6%	-76.1%	-81.1%
	0.95	-93.7%	-87.9%	-82.4%	-77.7%	-73.8%	-71.0%	-70.8%	-68.6%	-67.3%	-67.0%	-68.2%	-71.3%	-77.0%
	1.00	-99.4%	-91.8%	-85.0%	-78.7%	-73.3%	-69.5%	-69.1%	-65.9%	-63.8%	-62.9%	-63.5%	-66.2%	-72.2%
	1.05	-107.5%	-97.6%	-88.9%	-81.0%	-73.9%	-68.6%	-68.1%	-63.7%	-60.6%	-58.9%	-58.8%	-61.1%	-66.9%
	1.10	-118.5%	-105.6%	-94.4%	-84.6%	-75.6%	-68.6%	-67.9%	-62.0%	-57.6%	-54.9%	-54.0%	-55.8%	-61.1%
	1.15	-132.7%	-116.4%	-102.1%	-89.7%	-78.7%	-69.8%	-68.9%	-60.9%	-55.1%	-51.1%	-49.3%	-50.3%	-55.1%
	1.20	-150.6%	-130.4%	-112.4%	-96.7%	-83.2%	-72.3%	-71.1%	-60.8%	-53.1%	-47.6%	-44.7%	-44.6%	-48.9%

Appendix Z

Power Results for NREL 5MW Turbine Radius vs. Pitch Parametric Study at 11.4 m/s

Pitch Setting: -2°

					Percentage Difference from Baseline							
Radius Scale	RPM					Baseline						
Factor	17.00	16.00	15.00	14.00	13.00	12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-40.3%	-39.0%	-38.1%	-37.9%	-37.9%	-39.6%	-40.3%	-50.5%	-61.1%	-70.3%	-78.7%	-86.1%	-92.4%
0.85	-33.0%	-31.2%	-29.8%	-29.2%	-29.1%	-30.1%	-30.3%	-38.1%	-51.6%	-62.9%	-72.9%	-81.9%	-89.6%
0.90	-25.5%	-23.2%	-21.4%	-20.1%	-19.9%	-20.6%	-20.7%	-25.3%	-39.9%	-54.3%	-66.3%	-77.2%	-86.3%
0.95	-17.8%	-15.0%	-12.6%	-10.8%	-10.2%	-10.6%	-10.7%	-13.7%	-26.6%	-44.5%	-58.8%	-71.6%	-82.5%
1.00	-10.0%	-6.5%	-3.6%	-1.2%	0.1%	-0.1%	-0.2%	-2.8%	-11.8%	-32.4%	-50.4%	-65.3%	-78.2%
1.05	-2.3%	2.0%	5.6%	8.6%	10.7%	10.8%	10.7%	8.5%	2.0%	-18.8%	-40.8%	-58.2%	-73.3%
1.10	5.4%	10.6%	15.0%	18.7%	21.5%	22.3%	22.3%	20.2%	14.7%	-3.2%	-29.9%	-50.2%	-67.8%
1.15	13.1%	19.2%	24.5%	28.9%	32.4%	34.2%	34.2%	32.5%	27.2%	13.2%	-16.7%	-41.4%	-61.6%
1.20	20.5%	27.8%	34.1%	39.4%	43.6%	46.3%	46.4%	45.2%	40.1%	28.5%	-1.7%	-31.6%	-54.7%

Pitch Setting: -1°

					Percentage Difference from Baseline							
Radius Scale	RPM					Baseline						
Factor	17.00	16.00	15.00	14.00	13.00	12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-38.3%	-37.3%	-36.5%	-36.5%	-37.5%	-39.4%	-39.8%	-48.2%	-58.9%	-68.4%	-77.0%	-84.7%	-91.3%
0.85	-30.6%	-29.2%	-28.1%	-27.6%	-28.5%	-30.3%	-30.5%	-36.1%	-48.8%	-60.7%	-71.0%	-80.4%	-88.3%
0.90	-22.6%	-20.8%	-19.4%	-18.4%	-18.8%	-20.6%	-20.9%	-24.9%	-37.1%	-51.7%	-64.1%	-75.3%	-84.8%
0.95	-14.5%	-12.2%	-10.4%	-9.0%	-8.7%	-10.5%	-10.7%	-14.4%	-23.6%	-40.9%	-56.4%	-69.5%	-80.9%
1.00	-6.3%	-3.4%	-1.1%	0.8%	1.7%	0.3%	0.1%	-3.7%	-10.8%	-29.1%	-47.4%	-62.9%	-76.4%
1.05	2.0%	5.5%	8.5%	10.8%	12.3%	11.7%	11.4%	7.5%	1.1%	-14.9%	-37.2%	-55.4%	-71.2%
1.10	10.3%	14.5%	18.2%	21.1%	23.1%	23.3%	23.1%	19.3%	12.9%	-0.1%	-25.1%	-47.2%	-65.3%
1.15	18.5%	23.6%	28.0%	31.6%	34.3%	35.0%	35.0%	31.7%	25.1%	13.9%	-12.1%	-38.0%	-58.8%
1.20	26.5%	32.6%	37.9%	42.3%	45.7%	47.0%	47.0%	44.6%	37.8%	27.2%	2.9%	-27.6%	-51.6%

Pitch Setting: 0°

					Percentage Difference from Baseline							
Radius Scale	RPM					Baseline						
Factor	17.00	16.00	15.00	14.00	13.00	12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-36.6%	-35.8%	-35.4%	-35.7%	-37.4%	-39.7%	-40.1%	-46.2%	-57.0%	-66.6%	-75.5%	-83.5%	-90.2%
0.85	-28.6%	-27.5%	-26.9%	-26.9%	-28.2%	-30.6%	-31.0%	-35.5%	-46.8%	-58.6%	-69.2%	-78.9%	-87.1%
0.90	-20.4%	-19.0%	-18.0%	-17.7%	-18.5%	-21.0%	-21.3%	-25.5%	-34.6%	-49.1%	-62.1%	-73.5%	-83.5%
0.95	-12.1%	-10.2%	-8.8%	-8.2%	-8.7%	-10.7%	-11.1%	-15.4%	-22.7%	-38.6%	-53.9%	-67.4%	-79.3%
1.00	-3.6%	-1.2%	0.7%	1.7%	1.5%	0.0%	-0.3%	-4.9%	-11.5%	-26.0%	-44.5%	-60.6%	-74.5%
1.05	4.9%	7.9%	10.3%	11.8%	12.0%	10.8%	10.6%	6.3%	-0.4%	-12.6%	-33.9%	-52.9%	-69.0%
1.10	13.4%	17.1%	20.1%	22.2%	22.8%	22.0%	21.7%	17.9%	10.9%	0.2%	-22.2%	-44.2%	-62.9%
1.15	21.7%	26.3%	30.0%	32.7%	33.9%	33.4%	33.2%	30.0%	22.8%	12.5%	-8.4%	-34.5%	-56.1%
1.20	29.8%	35.4%	39.9%	43.4%	45.2%	45.1%	45.0%	42.1%	35.2%	24.8%	6.1%	-23.3%	-48.6%

Pitch Setting: 1°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-35.6%	-35.2%	-35.4%	-36.1%	-37.8%	-40.4%	-40.7%	-45.5%	-55.6%	-65.1%	-74.1%	-82.3%	-89.3%
0.85	-27.6%	-27.0%	-26.9%	-27.4%	-28.9%	-31.4%	-31.8%	-36.0%	-44.9%	-56.9%	-67.6%	-77.4%	-86.0%
0.90	-19.4%	-18.5%	-18.1%	-18.5%	-19.7%	-21.9%	-22.3%	-26.7%	-33.8%	-47.6%	-60.2%	-71.9%	-82.2%
0.95	-11.1%	-9.8%	-9.1%	-9.2%	-10.2%	-12.2%	-12.5%	-16.9%	-23.3%	-36.4%	-51.8%	-65.6%	-77.8%
1.00	-2.7%	-0.9%	0.2%	0.3%	-0.5%	-2.3%	-2.6%	-6.6%	-13.1%	-24.4%	-42.5%	-58.5%	-72.7%
1.05	5.6%	8.0%	9.5%	10.1%	9.6%	8.0%	7.7%	4.1%	-2.6%	-12.5%	-31.9%	-50.5%	-67.0%
1.10	13.8%	16.9%	19.1%	20.1%	19.9%	18.4%	18.2%	14.8%	8.4%	-1.3%	-19.5%	-41.5%	-60.7%
1.15	21.8%	25.8%	28.6%	30.2%	30.4%	29.2%	29.0%	25.8%	19.8%	10.1%	-6.5%	-31.6%	-53.7%
1.20	29.3%	34.4%	38.2%	40.4%	41.1%	40.1%	40.0%	37.1%	31.5%	21.6%	6.4%	-20.9%	-46.0%

Pitch Setting: 2°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-36.1%	-36.1%	-36.5%	-37.4%	-39.0%	-41.4%	-41.7%	-45.8%	-54.3%	-63.9%	-72.8%	-81.1%	-88.3%
0.85	-28.4%	-28.2%	-28.4%	-29.2%	-30.6%	-32.8%	-33.1%	-37.2%	-44.1%	-55.9%	-66.2%	-76.1%	-84.9%
0.90	-20.6%	-20.1%	-20.1%	-20.8%	-22.0%	-24.1%	-24.4%	-28.3%	-34.4%	-46.1%	-58.8%	-70.4%	-80.9%
0.95	-12.8%	-11.9%	-11.7%	-12.1%	-13.2%	-15.1%	-15.4%	-18.9%	-24.8%	-35.3%	-50.6%	-64.0%	-76.3%
1.00	-5.1%	-3.7%	-3.1%	-3.2%	-4.2%	-5.9%	-6.1%	-9.5%	-15.2%	-24.4%	-41.0%	-56.7%	-71.1%
1.05	2.4%	4.5%	5.6%	5.8%	5.0%	3.5%	3.3%	0.1%	-5.2%	-14.0%	-30.0%	-48.6%	-65.3%
1.10	9.6%	12.5%	14.2%	14.8%	14.4%	13.1%	12.9%	10.0%	4.9%	-3.6%	-18.3%	-39.9%	-58.8%
1.15	16.3%	20.2%	22.7%	23.9%	23.9%	22.8%	22.6%	19.9%	15.1%	6.9%	-6.6%	-30.1%	-51.5%
1.20	22.6%	27.5%	31.0%	33.0%	33.4%	32.7%	32.5%	30.0%	25.5%	17.7%	4.5%	-18.7%	-43.5%

Pitch Setting: 3°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-38.2%	-38.3%	-38.7%	-39.5%	-40.9%	-42.9%	-43.2%	-46.8%	-53.6%	-63.4%	-71.8%	-80.1%	-87.5%
0.85	-31.2%	-31.1%	-31.3%	-32.0%	-33.3%	-35.1%	-35.4%	-38.8%	-44.4%	-54.8%	-65.2%	-75.0%	-83.9%
0.90	-24.4%	-23.8%	-23.8%	-24.3%	-25.4%	-27.1%	-27.3%	-30.5%	-35.6%	-45.2%	-58.0%	-69.1%	-79.8%
0.95	-17.7%	-16.7%	-16.3%	-16.6%	-17.5%	-19.0%	-19.2%	-22.1%	-26.9%	-35.3%	-49.6%	-62.6%	-75.0%
1.00	-11.4%	-9.7%	-8.8%	-8.7%	-9.4%	-10.7%	-10.9%	-13.5%	-18.0%	-25.8%	-39.8%	-55.4%	-69.7%
1.05	-5.5%	-3.0%	-1.5%	-0.9%	-1.3%	-2.3%	-2.5%	-4.9%	-9.1%	-16.2%	-29.3%	-47.7%	-63.7%
1.10	-0.1%	3.2%	5.6%	6.8%	6.9%	6.1%	6.0%	3.8%	-0.1%	-6.7%	-18.7%	-38.8%	-57.0%
1.15	4.5%	9.0%	12.3%	14.3%	15.0%	14.5%	14.4%	12.6%	9.1%	2.8%	-8.5%	-28.5%	-49.8%
1.20	8.4%	14.2%	18.6%	21.5%	23.0%	23.0%	22.9%	21.4%	18.2%	12.3%	1.8%	-17.5%	-41.9%

Pitch Setting: 4°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-41.8%	-41.6%	-41.9%	-42.5%	-43.5%	-45.2%	-45.4%	-48.3%	-53.6%	-62.6%	-71.0%	-79.2%	-86.7%
0.85	-36.0%	-35.5%	-35.4%	-35.8%	-36.7%	-38.1%	-38.3%	-41.0%	-45.5%	-54.2%	-64.7%	-74.0%	-83.0%
0.90	-30.6%	-29.5%	-29.0%	-29.1%	-29.7%	-30.9%	-31.1%	-33.5%	-37.6%	-45.2%	-57.3%	-68.1%	-78.7%
0.95	-25.6%	-23.8%	-22.8%	-22.4%	-22.8%	-23.7%	-23.9%	-26.0%	-29.8%	-36.4%	-48.7%	-61.8%	-73.9%
1.00	-21.2%	-18.6%	-16.8%	-15.9%	-15.9%	-16.5%	-16.7%	-18.5%	-21.9%	-27.8%	-39.3%	-54.9%	-68.4%
1.05	-17.6%	-14.0%	-11.3%	-9.7%	-9.1%	-9.4%	-9.5%	-11.0%	-13.9%	-19.3%	-29.7%	-46.9%	-62.4%
1.10	-14.9%	-10.0%	-6.3%	-3.8%	-2.4%	-2.3%	-2.3%	-3.4%	-6.0%	-11.1%	-20.4%	-37.7%	-55.8%
1.15	-13.2%	-6.8%	-1.9%	1.7%	3.9%	4.6%	4.7%	4.0%	1.9%	-2.7%	-11.2%	-27.9%	-48.8%
1.20	-12.9%	-4.7%	1.8%	6.6%	9.9%	11.4%	11.5%	11.4%	9.7%	5.7%	-2.1%	-17.7%	-41.3%

Pitch Setting: 5°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-46.8%	-46.1%	-45.9%	-46.1%	-46.7%	-47.8%	-48.0%	-50.3%	-54.4%	-62.2%	-70.7%	-78.4%	-85.9%
0.85	-42.5%	-41.3%	-40.5%	-40.4%	-40.7%	-41.6%	-41.8%	-43.8%	-47.2%	-54.1%	-64.3%	-73.2%	-82.1%
0.90	-38.9%	-36.9%	-35.5%	-34.8%	-34.8%	-35.4%	-35.5%	-37.1%	-40.3%	-46.0%	-56.7%	-67.6%	-77.8%
0.95	-36.0%	-33.1%	-30.9%	-29.6%	-29.1%	-29.3%	-29.4%	-30.6%	-33.3%	-38.3%	-48.4%	-61.4%	-72.8%
1.00	-34.1%	-30.0%	-26.9%	-24.7%	-23.5%	-23.3%	-23.3%	-24.2%	-26.4%	-30.8%	-39.7%	-54.3%	-67.4%
1.05	-33.3%	-27.8%	-23.5%	-20.3%	-18.3%	-17.5%	-17.5%	-17.8%	-19.5%	-23.5%	-31.3%	-46.2%	-61.6%
1.10	-34.0%	-26.7%	-20.9%	-16.5%	-13.5%	-11.9%	-11.8%	-11.6%	-12.8%	-16.1%	-23.2%	-37.4%	-55.3%
1.15	-36.2%	-26.9%	-19.3%	-13.5%	-9.2%	-6.8%	-6.6%	-5.6%	-6.2%	-8.9%	-15.1%	-28.2%	-48.4%
1.20	-40.4%	-28.5%	-18.8%	-11.3%	-5.6%	-2.0%	-1.7%	0.2%	0.2%	-1.8%	-7.4%	-19.1%	-40.5%

Pitch Setting: 6°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-53.0%	-51.6%	-50.7%	-50.3%	-50.4%	-51.0%	-51.1%	-52.8%	-55.8%	-62.1%	-70.5%	-77.8%	-85.2%
0.85	-50.5%	-48.3%	-46.7%	-45.7%	-45.4%	-45.7%	-45.8%	-47.0%	-49.6%	-54.7%	-63.9%	-72.8%	-81.4%
0.90	-49.0%	-45.7%	-43.2%	-41.5%	-40.6%	-40.5%	-40.5%	-41.3%	-43.4%	-47.8%	-56.6%	-67.4%	-77.0%
0.95	-48.6%	-44.1%	-40.5%	-37.9%	-36.2%	-35.5%	-35.5%	-35.8%	-37.4%	-41.0%	-48.8%	-61.1%	-72.1%
1.00	-49.7%	-43.5%	-38.6%	-34.9%	-32.2%	-30.9%	-30.8%	-30.5%	-31.5%	-34.6%	-41.1%	-53.9%	-66.9%
1.05	-52.4%	-44.3%	-37.7%	-32.6%	-28.8%	-26.6%	-26.4%	-25.4%	-25.8%	-28.1%	-34.0%	-46.0%	-61.2%
1.10	-57.3%	-46.6%	-38.1%	-31.3%	-26.1%	-22.8%	-22.5%	-20.6%	-20.3%	-21.9%	-26.9%	-37.8%	-55.1%
1.15	-64.4%	-50.8%	-39.8%	-31.0%	-24.2%	-19.6%	-19.2%	-16.2%	-15.0%	-15.9%	-20.0%	-29.7%	-47.9%
1.20	-74.3%	-57.2%	-43.1%	-31.9%	-23.1%	-17.2%	-16.6%	-12.2%	-10.0%	-10.2%	-13.3%	-22.0%	-40.1%

Pitch Setting: 7°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-60.3%	-57.9%	-56.2%	-55.1%	-54.5%	-54.6%	-54.6%	-55.6%	-57.8%	-62.5%	-70.2%	-77.5%	-84.6%
0.85	-59.9%	-56.4%	-53.7%	-51.8%	-50.6%	-50.2%	-50.2%	-50.6%	-52.3%	-56.1%	-63.8%	-72.7%	-80.7%
0.90	-60.8%	-56.0%	-52.1%	-49.2%	-47.2%	-46.1%	-46.1%	-46.0%	-47.0%	-50.1%	-56.9%	-67.2%	-76.4%
0.95	-63.5%	-56.8%	-51.5%	-47.3%	-44.2%	-42.5%	-42.3%	-41.5%	-42.0%	-44.3%	-50.0%	-60.8%	-71.7%
1.00	-68.2%	-59.3%	-52.1%	-46.3%	-42.0%	-39.3%	-39.0%	-37.4%	-37.2%	-38.7%	-43.6%	-53.9%	-66.7%
1.05	-75.4%	-63.6%	-54.1%	-46.5%	-40.6%	-36.7%	-36.3%	-33.7%	-32.6%	-33.4%	-37.3%	-46.6%	-61.2%
1.10	-85.2%	-70.2%	-57.8%	-47.9%	-40.2%	-34.8%	-34.4%	-30.4%	-28.4%	-28.4%	-31.3%	-39.3%	-54.8%
1.15	-97.9%	-79.4%	-63.6%	-50.8%	-40.8%	-33.8%	-33.2%	-27.8%	-24.5%	-23.6%	-25.5%	-32.5%	-47.7%
1.20	-113.7%	-91.1%	-71.6%	-55.5%	-42.7%	-33.8%	-33.0%	-25.8%	-21.1%	-19.1%	-20.0%	-26.0%	-40.3%

Pitch Setting: 8°

Percentage Difference from Baseline

Radius Scale Factor	RPM 17.00	16.00	15.00	14.00	13.00	Baseline 12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-68.6%	-65.2%	-62.4%	-60.4%	-59.1%	-58.5%	-58.5%	-58.7%	-60.1%	-63.5%	-70.2%	-77.4%	-84.1%
0.85	-70.6%	-65.6%	-61.7%	-58.6%	-56.4%	-55.2%	-55.1%	-54.7%	-55.4%	-58.1%	-64.1%	-72.7%	-80.3%
0.90	-74.7%	-67.6%	-62.0%	-57.6%	-54.3%	-52.3%	-52.1%	-51.0%	-51.0%	-52.9%	-57.9%	-67.1%	-76.1%
0.95	-81.0%	-71.6%	-63.8%	-57.8%	-53.1%	-50.0%	-49.7%	-47.7%	-47.0%	-48.0%	-52.1%	-60.9%	-71.6%
1.00	-89.8%	-77.6%	-67.4%	-59.1%	-52.8%	-48.4%	-48.0%	-44.8%	-43.2%	-43.4%	-46.5%	-54.4%	-66.7%
1.05	-101.3%	-86.1%	-72.9%	-62.0%	-53.6%	-47.7%	-47.1%	-42.6%	-39.9%	-39.2%	-41.2%	-48.0%	-61.0%
1.10	-115.9%	-97.0%	-80.7%	-66.8%	-55.7%	-48.0%	-47.2%	-41.0%	-37.0%	-35.3%	-36.2%	-41.9%	-54.7%
1.15	-134.1%	-110.8%	-90.8%	-73.6%	-59.4%	-49.4%	-48.4%	-40.3%	-34.7%	-31.7%	-31.5%	-36.1%	-48.1%
1.20	-156.6%	-127.9%	-103.5%	-82.6%	-64.9%	-52.1%	-50.9%	-40.5%	-33.0%	-28.6%	-27.2%	-30.4%	-41.2%

Pitch Setting:	9°												
			Percentage Difference from Baseline										
Radius Scale	RPM					Baseline							
Factor	17.00	16.00	15.00	14.00	13.00	12.10	12.00	11.00	10.00	9.00	8.00	7.00	6.00
0.80	-78.3%	-73.3%	-69.3%	-66.3%	-64.1%	-62.8%	-62.7%	-62.1%	-62.7%	-65.1%	-70.4%	-77.4%	-83.7%
0.85	-83.2%	-76.2%	-70.4%	-66.0%	-62.7%	-60.5%	-60.3%	-59.0%	-58.8%	-60.4%	-64.8%	-72.6%	-80.0%
0.90	-90.3%	-81.1%	-73.3%	-66.9%	-62.2%	-58.9%	-58.6%	-56.4%	-55.4%	-56.0%	-59.6%	-67.2%	-76.0%
0.95	-99.9%	-88.2%	-77.9%	-69.4%	-62.7%	-58.2%	-57.7%	-54.3%	-52.3%	-52.1%	-54.7%	-61.5%	-71.7%
1.00	-112.6%	-97.6%	-84.7%	-73.6%	-64.5%	-58.4%	-57.8%	-52.8%	-49.7%	-48.5%	-49.9%	-55.7%	-66.7%
1.05	-129.0%	-109.8%	-93.6%	-79.7%	-68.0%	-59.6%	-58.9%	-52.2%	-47.7%	-45.3%	-45.5%	-50.3%	-61.1%
1.10	-149.7%	-125.4%	-105.0%	-87.8%	-73.2%	-62.3%	-61.3%	-52.5%	-46.2%	-42.6%	-41.6%	-45.1%	-55.2%
1.15	-174.9%	-144.9%	-119.3%	-98.1%	-80.3%	-66.6%	-65.3%	-53.7%	-45.5%	-40.3%	-38.1%	-40.2%	-49.1%
1.20	-204.9%	-168.7%	-137.3%	-110.9%	-89.2%	-72.7%	-71.0%	-56.3%	-45.7%	-38.6%	-35.0%	-35.5%	-43.2%