A SIMULATED COMPARISON OF LINEAR AND RANS BASED CFD MODELING

IN REGARD TO CRITICAL SLOPE

Dissertation in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE WITH A MAJOR IN WIND POWER
PROJECT MANAGEMENT

UPPSALA
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Uppsala University
Department of Earth Sciences, Campus Gotland

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December 2018
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Approved by:

Supervisor, Assoc. Prof. Karl Nilsson

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December 2018
The aim of this study is to compare the performance of a linear model to a nonlinear model focusing on flow separation based on a critical slope value. Specifically, the WindPRO WAsP model will be compared with the WindSIM CFD model over a simulated terrain to determine the point the two models differ in relation to the inclination of the terrain. The results of this study will verify if the proposed critical slope value of roughly 17 degrees is truly representative of the limitation of the WAsP model in producing accurate results as compared to a CFD model.

Multiple similar studies have been performed using existing sites with actual met mast data as a comparison to the model outputs. Many of these cases have come up with varying results due primarily to the large number of uncontrolled factors influencing the data. This study will be designed in a fully simulated environment where all variables can be controlled, allowing for the manipulation of a single variable to understand its’ specific influence over the model. The primary variable being tested in this study will be the slope of the terrain with all other factors held constant.

Based on the outcome of 7 alternative runs with ridge heights of 100, 120, 140, 160, 180, 200, and 300 meters and respective maximum slope values of 10.31, 12.32, 14.29, 16.23, 18.14, 20, and 28.63 degrees a defined separation point at a hub height of 94 meters could not be found. Each run demonstrated correlation between wind speeds and terrain slope variations but a considerable difference in estimated wind resources was present between the linear and non-linear CFD models where any slope in terrain is present. This, as expected, increases where terrain inclination increases, but a clearly defined difference between the two models is not evident at the previously established critical slope value of approximately 17 degrees (30%).
ACKNOWLEDGEMENTS

I would like to thank my supervisor, Kalle, for his guidance, support, and patience throughout the course of this research and for assisting me even over his vacation periods.

Thanks also go to my friends, colleagues, and the department faculty and staff for a memorable experience during my time in Visby and for the quality relationships we have established and will hopefully maintain for years to come. It has been an honor and a pleasure meeting and working with all of you over the past year.

Finally, thanks to my girlfriend Vanessa for moving with me to Gotland and supporting me over the course of this program.
# NOMENCLATURE

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABL</td>
<td>Atmospheric Boundary Layer</td>
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<tr>
<td>AEP</td>
<td>Annual Energy Production</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>DNS</td>
<td>Direct Numerical Simulation</td>
</tr>
<tr>
<td>k-e</td>
<td>K-epsilon</td>
</tr>
<tr>
<td>LES</td>
<td>Large Eddy Simulation</td>
</tr>
<tr>
<td>NWP</td>
<td>National Weather Prediction</td>
</tr>
<tr>
<td>PDE</td>
<td>Partial Differential Equation</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds’ Averaged Navier Stokes equations</td>
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<tr>
<td>REWS</td>
<td>Rotor Equivalent Wind Speed</td>
</tr>
<tr>
<td>RIX</td>
<td>Ruggedness Index</td>
</tr>
<tr>
<td>STATGEN</td>
<td>Generate Wind Statistics Module</td>
</tr>
<tr>
<td>TI</td>
<td>Turbulence Intensity</td>
</tr>
<tr>
<td>TIN</td>
<td>Triangular Irregular Network</td>
</tr>
<tr>
<td>TKE</td>
<td>Turbulent Kinetic Energy</td>
</tr>
<tr>
<td>WAsP</td>
<td>Wind Atlas Analysis and Application Program</td>
</tr>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
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<tr>
<td>3D</td>
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1 INTRODUCTION

1.1 Expansion of an Industry

During the latter half of the 20th century, due to growing energy needs and environmental concerns, industrial level wind energy began to develop with increasing speed. By the early 2000s large scale wind farms were being erected in numerous locations around the globe and turbine technology was solidifying the industry as a competitive and serious element in the global electrical generation market. To insure wind energy continued to gain market share, software was developed and refined, allowing for optimal site selection and layouts of the wind farms being constructed. One of the first programs used for this purpose was the EMD A/S’s wind atlas tool known as WindPRO. For increased accuracy, WindPRO software relies on a linear solver developed by the Danish Technical University known as the Wind Atlas Analysis and Application Program (WAsP), to produce wind resource maps of locations of interest. This method works sufficiently in the simple, relatively flat terrain early developments took advantage of, but as those spaces begin to run out a need to move to areas of greater terrain complexity demonstrated weaknesses with the linear modeling approach.

1.2 Uncertainty in the Hills

Acknowledging the value of accurate modeling, studies like the famous Askervein Hill study were conducted as a means of depicting the reliability of differing flow models over a relatively smooth hill (Taylor and Teunissen, 1987). This study has highlighted weaknesses in both computational fluid dynamic (CFD) modeling and linear modeling methods regarding speed-up estimations, turbulence intensity (TI), and flow separation due to the adverse pressure gradient (Svenningsen, 2013; Mickle, et al., 1988). Blind testing runs were completed this and other sites like the Bolund hill study where 57
differing models were run and compared to the actual recorded data again illustrating the weaknesses in linear models but proving both Reynolds Averaged Navier Stokes (RANS) and Large Eddie Simulation (LES) models also struggle accurately model flows in complex terrain. (Bechmann, 2011).

1.3 Modeling Progression

With growing understanding of the variety of variables capable of influencing wind resource projections, a multitude of alternative forecasting models began to be developed. As stated previously, the early versions of modeling like WindPRO’s WAsP module and WindFarmer, relied on 2D linear models based on the log law. While this formula was adapted over time to include some representation of turbulence and terrain correction techniques, the need for more accurate methods drove the development of alternative modeling methods. This, coupled with the advancement of computational technology, led to CFD based solvers such as WindSIM’s RANS, ANSYS CFD, Meteodyn CFD and the LES, which can more accurately model flows with the inclusion of turbulence models among other factors (Smagorinsky, 1963). Even with these advancements, the linear models are still broadly used because of the reduced time and computational demands required. Due to availability of access only the WindPRO WAsP based software and WindSIM RANS CFD software are used for this study.

1.4 Objectives

This study will perform a controlled comparison of two separate modeling tools in an entirely simulated environment. While this does not provide actual measured data to use as a reference, the objective of this study is to allow for absolute control over all variables to insure the outcomes of each simulation reflect only the alteration the terrain slope, eliminating unknown/uncontrolled influence. The results produced by this study aim to answer the following questions:
• Is the industry accepted critical slope value of 30\%, roughly 17 degrees, a suitable indication of a difference between WindPRO’s linear modeling estimations and those produced by WindSIM’s CFD RANS modeling software?

• What are the prevalent differences between linear and CFD based flow models over ridges of varying slopes with a perpendicular flow?

• Does measuring at a hub height of 94 meters incur noticeable differences in results compared to those produced in similar past studies?
2 LITERATURE REVIEW

2.1 Introduction

This section will cover the linear and nonlinear modeling tools used for wind resource mapping. An overview of the software which applies these methods, WindPRO’s WAsP module and WindSIM’s RANS interface, will be made. As the primary focus of this report is the performance difference between these tools, specifically regarding critical slope in complex terrain, a detailed review of flow separation and model limitations related to this element is provided. The section concludes with current industry trends regarding these models’ adaptation to current projects.

2.2 Wind Resource Modeling

The wind power industry has undergone large levels of expansion over the past two decades due to the global focus on developing renewable energy harvesting methods. This expansion has led to an increasing need for accurate modeling methods to ensure optimal siting and turbine selections are made. The original models developed to aid in wind resource mapping were based on the mathematical representation of fluid flows. The fundamentals behind this mathematical representation were established in the 1800s with the development of the Navier-Stokes equations. These equations represent conservation of mass, conservation of momentum, and conservation of energy using a combination of time dependent equations to describe the relationship of temperature, pressure, velocity, and density of a fluid (Hall, 2015). Due to the complexity of these equations and associated variables, simplifications and assumptions were made to allow for reasonable solutions to be obtained, but the large scale and high-resolution models required for wind farm sites dictated that a modeling method requiring less computational power was still needed. This need resulted in the production of a 2D linear model known as the Wind Atlas Analysis and Application Program (WAsP), the modeling solver used by the WindPRO software.
Recent advancements in technology have resulted in the development of computers with the computational power to solve the complex 3D nonlinear Navier-Stokes equations, although many assumptions and simplifications are still required due to the presence of turbulence within the models. These 3D models, known as computational fluid dynamics (CFD) models, are used in the field to provide improved modeling of fluid flows including effects of turbulence and possible surface separation. The Reynolds Averaged Navier-Stokes Equations (RANS) are the version of this CFD solver used by the WindSIM software and will be covered in greater detail in section 2.7 of this report.

2.3 Flow Separation

When modeling wind resources over complex terrain, there is a point when the flow separates from the surface layer resulting in an alteration to the boundary layer flow. This point of separation is defined as the point where shear stress equals zero due to a reduction in the flow speed at the surface level to zero. The speed reduction can be explained using the Bernoulli’s Principal, which states that the speed of an incompressible fluid flow (air in this case) will increase as pressure decreases and vice versa (Pietro, 2015). Therefore, as air flows up the slope of a hill, at some angular steepness, the pressure at the surface begins increasing. The increase in pressure corresponding to the air’s direction of flow produces an effect known as an adverse pressure gradient. As the pressure continues to increase, the kinetic energy of the air flow will decrease, respectively decreasing the flow’s speed (the wind) until it reaches zero or reverses. The following figure provides an illustration of this process.
Figure 1: Adverse pressure gradient and flow separation

The adverse pressure gradient is an occurrence which has been extensively studied as it has the potential to produce large deviations between modeled outputs and actual flows experienced. This is applicable in wind resource modeling, but more commonly noted in aerodynamic modeling regarding the optimal angle of attack for airfoils and to what levels lift and drag forces can be manipulated without resulting in stall. For the scope of this report, the adverse pressure gradient pertaining to air flow over varying terrain slopes will be the area of focus.

Fluid dynamic research extending back to the 1800s with the advent of the Navier-Stokes equations, covered in greater detail in section 2.8 of this report, has attempted to quantify the relationship of fluid flows interacting with objects. During the mid-1900s research in this subject became more directly focused on air flow interactions with surface terrain primarily for meteorological and pollution dispersion purposes. Scorer (1955) began
examining separation of air flows over mountains and noted the resulting large eddies being created. Studies like those performed by Jackson and Hunt (1975) investigating the relationship between terrain profiles, specifically hills, and wind speeds acknowledge the need for further relevant research. In 1995, Nigel Wood published a paper describing the critical slope, the maximum angular inclination of terrain before flow separation occurs. His study points out possible alternative values to those previously established by producing results depicting an underestimation of the point of separation by the previously accepted values, thus demonstrating the lack of a solidified separation point value. Wood also acknowledges limitations in his study based on the small number of modeling runs completed and the large difference in slopes between each (Wood, 1995). Rathmann et al. (1996) refers to the accepted critical slope value as “a course measure of the extent of flow separation”, further illustrating the lack of a definite critical slope value regarding flow separation.

The present-day value used when assuming flow separation pertaining to slope is approximately 17 degrees or a 30% slope. This value was referenced in the 1993 Wind Atlas Analysis and Application Program’s volume 1 “Getting Started” and throughout other related literature through the 90s (Wood, 1995; Bowen and Mortenson, 1996; Rathmann et al, 1996), leading to its adoption as the present-day standard for the critical slope. It is also important to note that this critical slope value is identified as the point when the model accuracy of linear modeling tools becomes unacceptable as compared to nonlinear modeling tools, a point this study aims to test.

2.4 Ruggedness Index (RIX)

The ruggedness index (RIX) was implemented as a means of measuring and classifying the complexity of terrain. The basis of this classification involves the previously mentioned limitations of linear modeling regarding slope of the terrain and the degree to which these limitations are violated. Defined specifically as “the percentage fraction of
the terrain along the prevailing wind direction, which is over a critical slope of 0.3” (Bowen and Mortensen, 2004). This index provides a rough idea of when the orography of a site exceeds the WAsP performance envelope, indicating the presence of errors in the modeled flow but not the specific magnitude of the error (Bowen and Mortensen, 2004).

2.5 Linear Modeling

Linear modeling, in the case of wind resource modeling, was adapted as a means of simplifying wind resource estimations in place of attempting to use the complex Navier-Stokes equations. The process involves inputting local measurement data which is then generalized to represent a regional wind profile. Firstly, the location and associated dimensions are entered, followed by roughness values and finally the height contours. Once the wind profile is applied to the entire area, the specific turbine locations and heights are entered and, using the log law to adjust for alternative heights, an estimation of annual energy production (AEP) can then be given (Mortensen, 1998).

From the time of Jackson and Hunt’s early investigation of turbulent flow over hills in 1975, modeling complex terrain’s influence on flow patterns has become an area of great interest and ongoing research. Its impacts were not included in the National Weather Prediction (NWP) models until 1986 even though a hill with a slope of 1/3 has the potential to result in a speed up of the wind by a factor of $\frac{1}{2}$ (Bletcher and Hunt, 1998). In 1987 the Wind Atlas Analysis and Application Program (WAsP) was released by the Risø National Laboratory’s Wind Energy and Atmospheric Physics Department, providing a computer software capable of modeling wind flows over simple terrain using linear modeling (Mortenson and Heathfield, 1999).
2.6 Wind Atlas Analysis and Application Program (WAsP)

The Wind Atlas Analysis and Application Program, known as WAsP, is a computer software which uses wind measurements to generate modeled vertical and horizontal wind statistics known as a wind atlas. By incorporating an areas’ terrain profile, the relevant roughness and elevations, the software can then produce wind climate estimations within the area. The software goes one step further by allowing a turbines’ power curve to be entered and calculates an annual energy production (AEP) estimation for the turbine specific to the location chosen (Mortenson and Heathfield, 1999). Since its inception in 1987, the WAsP modeling software has been continuously updated to increase the accuracy of estimations produced by the program.

The underlying basis on which WAsP relies to extrapolate wind profiles to different heights is the logarithmic law.

\[
U_z = \frac{u^*}{k} \left[ \ln \left( \frac{z - d}{z_0} \right) \right]
\]  

(2.1)

Where \( U_z \) represents the mean wind speed, \( z \) is the height, \( k \) is the Von Kármán constant, \( z_0 \) is the roughness length, \( d \) is the displacement height where a wind speed of zero occurs due to an obstacle, and \( u^* \) is friction velocity. This formula is useful in predicting wind speeds within the first 100 meters of the boundary layer, although it still incurs errors below that level (Troen and Petersen, 1989). A limitation of this simplistic formula is its’ lack of inclusion of temperature and its’ relative effect on mixing within the flow. This issue was rectified by including the Monin-Obukhov length \( L \), a figure representative of a length scale associated with dimensionless height of turbulent kinetic energy (TKE).
\[ U_z = \frac{u_*}{k} \left[ \ln \left( \frac{z - d}{z_0} \right) + \psi(z/L) \right] \]  

(2.2)

The other additional term, \( \psi \), is an empirical function (Troen and Petersen, 1989). The result of this updated equation produces an accurate estimation of wind profiles at the specified heights including basic adjustments for the inclusion of turbulence but continue to struggle relative to the increase of the terrain’s complexity. During this study conditions were set to be neutral, therefore stability corrections has not been used.

### 2.7 WindSIM

The second software being used in this study is WindSIM, which is a CFD modeling software developed by VECTOR AS originally used to assist in consulting clients. In 2003 WindSIM 4.2 was released as their first commercially available platform for wind resource modeling. WindSIM is now an established wind resource modeling and micro-siting program used within the wind power industry, recently releasing WindSIM 9.0 in 2018.

The WindSIM software uses an adaptation of the PHOENICS open code CFD solver to simulate the Atmospheric Boundary Layer (ABL). This adaptation uses the Reynolds Averaged Navier Stokes equations (RANS) combined with the k-\( \varepsilon \) turbulence closure model to produce predictions of local wind fields (Gravdahl, 1998). The options within the software have increased to include alternative turbulence closure models but for the scope of this study only the k-\( \varepsilon \) closure model will be discussed. To fully understand this modeling process, we will first break down the mathematical basis on which it is founded, the Navier-Stokes equations.
2.8 Navier-Stokes Equations

The Navier-Stokes equations are a continuation of the Euler Equations, partial differential equations representing inviscid flows, with the addition of viscosity and thermal conductivity. They are, as previously stated, comprised of time dependent equations representative of the conservation of mass, momentum, and energy. The continuity equation for the conservation of mass provides a mathematical representation of a fluid moving through a domain, it’s mass remaining constant, and the relationship between its’ velocity, density, area, and time of the fluid flow (Hall, 2015; Schneiderbauer and Krieger, 2014).

Conservation of momentum, based on Newton’s 2nd Law of motion, states that the sum of all forces is equal to mass times the acceleration (Schneiderbauer and Krieger, 2014). The momentum equations must be individually computed for each of the three spatial coordinates, x, y, and z. The final component, conservation of energy, represents the first law of thermodynamics, stating that energy cannot be created or destroyed, only transformed into different forms (Honig, 2007; Schneiderbauer and Krieger, 2014). The combination of these equations describes the aspects of compressible viscous fluid flows.

The WindSIM CFD software used in this study relies on a RANS based solver to simplify the Navier Stokes equations by assuming an incompressible viscous fluid resulting in a constant density. This eliminates the need for the energy equation when solving for the unknown variables, the pressure and velocity components, thus decoupling the energy equation from others (Leroy et al., 1999). This statement may not clearly highlight what is occurring for those unfamiliar with these complex equations, so the following section will break down each portion of the equations to provide a visualization of the Reynolds averaging process. Firstly, we will look at the equation’s representative of two of the underlying concepts of the Navier-Stokes equations, conservation of mass, and
conservation of momentum. The conservation of energy portion will not be covered in
greater detail as the decoupling allowed by assuming an incompressible flow, and thus
constant density, eliminates the need for the energy equation.

2.8.1 Conservation of Mass

Conservation of mass is generally represented by Equation 2.3:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial t} + \frac{\partial \rho v}{\partial t} + \frac{\partial \rho w}{\partial t} = 0$$ (2.3)

which can be simplified to Equation 2.4

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho u = 0$$ (2.4)

in this case, \( \mathbf{u} \) is representative of the fluid’s velocity in each of the x, y, and z directions. The \( \rho \) represents the fluids density, and the \( t \) represents time. Being that the air flow is considered an incompressible fluid as previously discussed, the equation can be further simplified by removing the density variable to that of Equation 2.5

$$\nabla \cdot \mathbf{u} = 0$$ (2.5)

2.8.2 Conservation of Momentum

The conservation of momentum, represented by Equation 2.6, is derived from Newton’s laws of motion and dictates the total momentum is constant in a closed system regardless of particle interactions.

$$\sum F = ma = \rho V \frac{du}{dt}$$ (2.6)
In this form \( \mathbf{F} \) is representative of force, \( \mathbf{m} \) is mass, and \( \mathbf{a} \) is acceleration. This equation is adjusted when implemented in the Navier-Stokes equations to include multiple vectors of influence on a particle within a flow. This is expressed mathematically by Equation 2.7

\[
\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + v \frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i
\]  

(2.7)

where \( \mathbf{u} \) is velocity, \( t \) is time, \( \rho \) is pressure, \( \mathbf{v} \) is kinematic viscosity (a fluids’ thickness), and \( f_i \), also noted as \( \mathbf{g} \), represents additional external forces such as gravity. The indexes \( i \) and \( j \) symbolize different vectors (DeSena, 2017).

It would appear this is the optimal solution for all wind resource modeling, but due to the presence of turbulence occurring within these flows, exact solutions continue to elude the scientific community. The random, unpredictable nature of turbulence down to molecular levels continues to require the incorporation of assumptions and simplifications for any feasible modeling on a scale equivalent to that of wind farm sites. While there are models such as the Direct Numerical Simulation (DNS) and the Large Eddy Simulation (LES) which can more accurately model the wind flows, they currently require an unfeasible amount of time and computational resources to run and will therefore not be covered in greater detail in this report. As briefly mentioned previously, the WindSIM software uses the RANS method, in combination the \( k-\varepsilon \) turbulence closure model, to address the complex issue of turbulence.

### 2.9 Reynolds Averaged Navier Stokes Equations

The Reynolds Averaged Navier Stokes (RANS) equation simplifies the Navier Stokes equations by separating the flow variables into both a time averaged and fluctuating component, referred to as Reynolds decomposition. The application of the Reynolds decomposition originated from Osborn Reynolds recognition of the relationship between
fluid viscosity and inertia during his studies of fluid dynamics, thus resulting in the creation of the Reynolds number (Reynolds, 1895).

By applying this time-averaged methodology using mean values of the velocity and pressure variables, the RANS equations produce estimated solutions which, through studies such as “Turbulent flows over mountainous terrain modelled by the Reynolds equations” and "The Bolund Experiment, Part II: Blind Comparison of Microscale Flow Models", have proven to be acceptably reliable (Utnes and Eidsvik, 1996; Bechmann, 2011). However, simplifying the RANS equations using the Reynolds decomposition does not, in itself, produce accurate flow models due to the addition of the Reynolds stress component. This component represents the turbulent fluctuations of the fluid momentum, referred to as the chaotic changes in a fluids pressure and velocity (Bernard and Handler, 1990). This represents one of the most difficult modeling components of fluid dynamics due to the occurrence of turbulence down to a molecular level and requires a turbulence closure model to provide an estimated solution for the Reynolds stress component. Although a variety of turbulence closure models have been created, as previously mentioned, the k-ε closure model will suffice for the scope of this study.

2.9.1 RANS
The approach used by the WindSIM software, Reynolds averaging, splits the variables into a mean part and fluctuating part, as seen graphically in figure 2 below.
The base equation representative of this division is shown by Equation 2.8

\[ U(x,t) = \langle U(x) \rangle + u(x,t) \]  

(2.8)

where \( \langle U \rangle \) is the mean value and \( u(t) \) is the fluctuation one.

The decomposed Reynolds averaged version of the conservation of mass equation, with the assumption of an incompressible flow, results in Equation 2.9, while the Reynolds averaged conservation of momentum equation produces Equation 2.10.

\[ \frac{\partial U_i}{\partial x_i} = 0 \]  

(2.9)
\[
\rho \frac{\partial U_i}{\partial t} + \rho U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} (2\mu S_{ij} - \rho \overline{u'_i u'_j})
\] (2.10)

As in Equation 2.8, the uppercase letters indicate mean values, while the prime notation signifies a fluctuation variable, and the overbars denote time-averaging. \(S_{ij}\) signifies the strain rate tensor, a variable representative of the “relative change in the position of points within a body that has undergone deformation” (Burnley, 2018). The \(-\rho \overline{u'_i u'_j}\) term is the Reynolds stress, a representation of turbulence and the highly complex portion of the RANS equations.

### 2.9.2 Reynolds Stress

This is a multi-dimensional array of values which describes the physical state of a particle within the observed flow. Specifically focused on 9 different components of force influencing the particle which denote the state of stress experienced by the particle (Burnley, 2018). This is illustrated by figure 3 below.

![Stress tensor illustration](Source: Burnley, 2018)
To solve for the Reynolds stress tensor, a turbulence closure model must be employed. In WindSIM the basic model used for this is the coupled turbulent energy and turbulent dissipation transport equations model known as the k-ε turbulence closure model.

### 2.10 k-ε Closure Model

The k-ε turbulence closure model is a two-equation model and one of the most widely used turbulence closure model in CFD. It was first developed by Harlow and Nakayama, but later modified by Lauder and Spalding during the 1970’s as a means of solving two partial differential equations (PDEs) for turbulent kinetic energy (TKE) and the dissipation rate of the TKE in a universally applicable form (Launder and Spalding, 1974).

The TKE, represented by $k$, is defined specifically as “the kinetic energy per unit mass of the fluctuating turbulent velocity” (Wilcox, 2010; DeSena, 2017). It represents the measure of turbulence intensity related to the transfer of momentum, heat, and moisture within the boundary layer (Stull, 1988). The dissipation rate, $\varepsilon$, is defined as “the rate at which TKE is converted into thermal internal energy” (CFD Online, 2015). While it is known that the k-ε closure model cannot predict all elements of a flow perfectly, it has been proven to produce acceptably good results even when adverse pressure gradients are present (Leroy et al., 1999). The equations which make up this model are seen below.

\[
V_T = C_\mu \frac{k^2}{\varepsilon} \tag{2.11}
\]

\[
\frac{\partial}{\partial x_i} (U_i k) = \frac{\partial}{\partial x_i} \left( \frac{V_T}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + P_k - \varepsilon \tag{2.12}
\]

\[
\frac{\partial}{\partial x_i} (U_i \varepsilon) = \frac{\partial}{\partial x_i} \left( \frac{V_T}{\sigma_k} \frac{\partial \varepsilon}{\partial x_i} \right) + c_{\varepsilon 1} \frac{\varepsilon}{k} P_k - c_{\varepsilon 2} \frac{\varepsilon^2}{k} \tag{2.13}
\]
Through their research, Lauder and Spalding also established the series of closure coefficients for use in the \( k-\varepsilon \) equations, which can be seen in table 1, to be used as constants when using the \( k-\varepsilon \) closure model and have been proven to produce quality results in mixing layers and when used regarding atmospheric flows. (Lauder and Spalding, 1974; DeSena, 2017).

Table 1: \( k-\varepsilon \) closure coefficients (Source: Leroy et al., 1999)

<table>
<thead>
<tr>
<th>( C_\mu )</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( \sigma_K )</th>
<th>( \sigma_\varepsilon )</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>1.0</td>
<td>1.3</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Once solved, the \( k-\varepsilon \) equation is used to close the RANS equations.

### 2.11 Industry Adaptation/Trends

WindPRO, along with comparable linear modeling software like WindFarmer, currently stand as dominate wind resource estimation tools commonly used throughout the industry. Continued advancement in available computational power and software refinement has allowed CFD modeling software to continue to grow its presence, resulting in a continued expansion of its market share. WindPRO has recently added a CFD module, run through a 3rd party, which performs calculations remotely for customers and returns the CFD modeled results. While the trend of changing to the more versatile CFD software continues, the much faster and relatively reliable linear modeling tools will continue to be used at least as the initial siting tool.
3 METHODOLOGY

3.1 Introduction

The following section introduces the modeling parameters selected for this study and the reason for their selection. The techniques used for establishing the simulations and the reasoning behind the chosen approach is then discussed, followed by a detailed account of how the simulations were run.

3.2 Model Parameters

To insure the continuation of a controlled study, the flow parameters have been established separately. The flow used throughout this study has an 8m/s speed running perpendicular to the theoretical ridge at a height of 94 meters to represent the potential hub height of a turbine. A constant density is maintained throughout with a boundary layer extending 500 meters above the surface.

Table 2: Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed</td>
<td>8 m/s</td>
<td>Roughness Length</td>
<td>0.004 (grass)</td>
</tr>
<tr>
<td>Measurement Height</td>
<td>94 meters</td>
<td>Ridge Width</td>
<td>2000 meters</td>
</tr>
<tr>
<td>Air Density</td>
<td>1.225</td>
<td>Boundary Layer Height</td>
<td>500 meters</td>
</tr>
</tbody>
</table>

3.2.1 Simulated Terrain

The terrain used throughout this study was developed using a MATLAB code to produce an artificial ridge with a constant width of 2000 meters and a height adjusted for each of the 7 cases to alter the slope of the ridge. Specifically, 7 ridges with heights of 100, 120, 140, 160, 180, 200, and 300 meters have been created along with a control case using flat
terrain. The simulated ridge used throughout this study is produced using a gaussian function where $a$ represents the height of the curve’s (or ridge’s) peak, $b$ is the position of the center of the peak, and $c$ is the standard deviation (the width of the ridge). This allows for the creation of a symmetrical bell curve shaped ridge whose height can easily be manipulated, while maintaining the width, to produce alterations in the degree of the slope. The mathematical representation of the ridge can be seen below.

$$f(x) = ae^{-\frac{(x-b)^2}{2c^2}}$$ (3.1)

The measurement points used in this study are 94 meters above the surface running perpendicular to the ridge with a spacing of 25 meters. This can be seen in figure 4, with each measurement point being visually represented by a theoretical turbine. It is important to note that the measurements produced do not assume the presence of a turbine structure, they are simply a monitoring point used for measuring the flow velocity at differing points over the ridge. The 94-meter height is used because it is the height of the Vestas V112 3.3-megawatt turbine, a commonly used turbine model whose power curve and relevant production information were available for use in this study and are provided in Appendix A.

Figure 4: Visual representation of the model layout and flow perpendicular to the ridge
3.2.2 Roughness

The surface roughness, represented by the $z_0$ variable in the logarithmic law formula, must be specified for the entire area being used for the simulation. To do this, the line data object in WindPRO is again used but its’ purpose is allocated as roughness lines. To insure the roughness does not distort the simulation results one value is used for the entire area. The roughness length of 0.004 meters was used for this study as it is representative of a grassy landscape. After allocating the value, the area is defined by manually outlining the roughness area using the draw function. The file can then be converted to a WAsP .map file using the WindPRO software.

3.2.3 Meteorological Data

The meteorological data is needed for both software to produce wind resource and energy estimations, the performance comparisons used in this study. Multiple methods can be used to insert the meteorological data but for the scope of this study a frequency distribution method was used. This method entailed creating a simulated two year excel file using the time stamp, wind speed, and direction with fixed values of 8m/s wind speeds occurring from a westerly (270 degree) direction at 100 percent frequency at a height of 94 meters. This file was then imported into a meteo data object in the WindPRO program which converted the data into a usable form for the program, producing a flow running perpendicular to the artificial ridge. Once this method has been used a frequency table of the wind speed and direction can be exported as a .tab file.

3.2.4 STATGEN, WAsP, and PARK modules

Once all elements are in place a STATGEN site data object is implemented to produce a wind statistics file combining the meteo and terrain data (EMD International A/S, 2018). This must be completed for each individual case where the ridge elevation is altered. Once
completed and run, a WAsP site data object can be added using the wind statistics file and the WAsP module can be run. The PARK calculation then uses the WAsP site data to produce an estimate wind speed and AEP value for each turbine, the two outputs being used being compared in this study. Each of these steps must be completed for each alternative model case.

3.3 WindSIM Implementation

Upon the completion of setting up the WindPRO simulation, all relevant files then must be transferred and implemented in the WindSIM software. The files required to create models with all variables constant between both programs are the terrain roughness, height contours, meteorological data, theoretical wind turbine locations (measurement points), and turbine model production values. With these values all held constant the only variation between the two programs will be those produced due to the use of a linear verse a CFD based solver.

3.3.1 Terrain Conversion

To import the roughness and height contours the .map files for both must be exported from the WindPRO software as a combined file. This can be achieved when entering a WAsP site data object by selecting the “export combined map file” option under the terrain tab as seen in figure 5.
The terrain conversion option provided within the WindSIM software is then used to convert the .map file into a .gws file usable by WindSIM. When performing this conversion WindSIM establishes a computational domain defining the range of the model. For this study a rectangular area of roughly 14 kilometers long (latitudinal) by 7 kilometers wide (longitudinal) was used in both software to insure consistency. This was based on recommendations by the WindPRO software for orography values extending 7 kilometers from the point of interest as seen in figure 6. The areas’ fulfilment of this value in a latitudinal basis and not a longitudinal one is due to the direction of flow being constant from west to east. The boundary layer height was set to 500 meters, the default value used by WindSIM. While this could vary significantly outside of an artificially modeled environment, especially in complex terrain, maintaining the constant 500 meter value throughout this study at least insures a controlled influence of this variable throughout all modeling cases.

Figure 5: Combined map file export option in WindPRO
After completion of the terrain module, a 3D grid is generated for the site by specifying a quantity of coordinates in the x, y, and z directions. A maximum number of cells is allocated based on computational power, time, and convergence of results. The standard practice for establishing this limit is to begin with a minimal number of cells and continuously increase the limit until little to no variation is evident in the model’s results. Alternatively, the y plus concept can also be applied to insure proper mesh distribution. In this case, an initial cell limit of 100,000, WindSIM’s default value, was used. The value was then increased to 300,000, then 500,000 maximum cells. Once attempting to surpass 500,000 an error occurs due to the large value of x coordinates required because of the elongated model layout running from east to west. While this could be overcome using available techniques such as nesting and refinement to achieve higher resolution, the resolution achieved at 500,000 cells was determined to be sufficient for this study. During this step other terrain file options and limitations can also be adjusted such as the number of cells in the vertical (Z) direction. For this study the 20-cell default value was used. This is discussed in greater detail in section 3.3.5.

Figure 6: WindPRO orography and roughness suggested parameters
3.3.2 Wind Fields

Following the establishment of a 3D terrain replication of the site, the previously discussed RANS equations, coupled with the k-ε turbulence closure model, can be applied to acquire the flow properties over the terrain. At this point the boundary layer height and geostrophic wind speed and air density are set, which for this study all default values of 500 meters, 10m/s, and 1.225 were used respectively. The software then iteratively solves for the variables P1, U1, W1, V1, KE, and EP (defined below in table 3) for each coordinate point until an acceptable convergence value is achieved (WindSIM AS, 2014). An illustration of the convergence process can be seen in figure 7 as well.

Table 3: Flow variables solved for by WindSIM’s RANS software

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Velocity Components</th>
<th>Turbulent Kinetic Energy</th>
<th>Turbulence Dissipation Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>U1, W1, V1</td>
<td>KE</td>
<td>EP</td>
</tr>
</tbody>
</table>

Figure 7: WindSIM RANS convergence example per variable (Source: WindSIM AS, 2014)

The default maximum number of iterations is set to 300 but is dependent on the complexity of the variables in each directional sector and can be adjusted to allow a higher likelihood
of achieving convergence (Hines, 2012). Once convergence has been reached a wind fields model is established allowing for the integration of objects.

### 3.3.3 Objects

The object section allows for the placement of turbines and meteorological masts throughout the established terrain. In this study the meteorological data, exported as a .tab file from the WindPRO software, was converted using the WindSIM convert meteo data option to produce a .wws file and establishes a meteo object with a fixed location within the WindSIM simulation. This allowed for the flow parameters established using an independent software to be applied within the WindSIM model. The measurement points, marked by theoretical turbine locations, were entered manually due to a lack of interchangeable layout file formats between the software. The turbine’s production values, i.e. the power curve, also had to be entered manually to create a .pws file which could then be applied to each of the turbines added to the simulation. The turbine production values were obtained from the WindPRO software to insure consistency and are provided in appendix A of this report. Once all these variables have been successfully entered a .ows file could be created, saving the object locations and associated information for easy application in alternative modeling runs.

### 3.3.4 Energy Module

The primary area of focus for this portion of this study is the annual energy production (AEP) values produced in the energy module of WindSIM. In this module meteo object data is applied to the wind fields, producing a simulated flow surrounding the meteo object. The simulated flow can then be applied to the individual measurement points to produce estimated AEP values for each individual turbine. This can be done with or without the inclusion of a wake model. For this study turbine wake influence was not a point of interest and has no influence as there are no actual turbines present, only
monitoring points at hub heights therefore no model has been selected. The AEP values are produced in two formats, a frequency table and a Weibull distribution of the frequencies (Hines, 2012). The frequency table output was used being that the meteo file used in WindPRO was also designed based on a frequency distribution.

3.3.5 Grid Resolution and Validation

The initial WindSIM run was done using a maximum cell amount of 100,000 which resulted in a grid spacing of 80 meters. Two additional cases were run using a 300,000 and 500,000 maximum cell limit, producing a respective grid spacing of 60 and 40 meters respectively. Attempts to refine beyond the 500,000 cell limit produced an error due to the length and relevant quantity of cells along the x axis. This issue could be resolved through nesting or refinement techniques, but the 500,000 cell limit was deemed sufficient for this study. The results of the grid refinement process used can be seen in figure 8 which illustrates the attempted convergence of the model runs based on the resolution of the grid.

Figure 8: Comparison of WindSIM model outputs using different grid resolutions.
The finalized 500,000 cell limit produced an actual grid layout consisting of 295,000 cells and can be seen in figure 9.

Figure 9: A 3D image of the 500,000 cell limit output for a 200 meter ridge.

As stated previously, the default z value of 20 cells was used, as was the default arithmetic sequence to determine the distribution of those 20 cells through the height of the domain. The resulting z grid distribution can be seen in figure 10.

If the default vertical cell distribution values provided by WindSIM were not used, the y plus concept could be incorporated to provides an accurate method of determining the mesh spacing. This method insures the proper mesh or grid distribution is used to appropriately model the viscous sublayer and turbulence layer found within the boundary layer. Y plus is a nondimensional distance from the wall measured in terms of viscous lengths (Mali, 2016). Obtaining the correct y+ value helps to insures the model correctly predicts the flow and the appropriate turbulence model is used.
3.4 CONCLUSIONS

This section has introduced the parameters used throughout this study along with the reasoning for their respective selection. This was followed with a detailed overview of the methodology used to address the underlying questions of this report concerning the critical slope value where the WAsP linear model results diverge from those produced by the WindSIM RANS CFD model. A breakdown of each model’s construction accompanied by the methods used to integrate the data between the two has also been presented.
4 RESULTS AND DISCUSSION

4.1 Introduction

The following sections provided an overview of each case which has been run. The data is presented using a comparison of both wind speed and AEP to the slope of terrain for both WindPRO and WindSIM. The data produced by each modeling program is then used to illustrate the areas where the terrain’s slope results in a difference in wind resource estimations between the two modeling techniques.

4.1.1 Control Case Flat Terrain

To provide a referenceable control case, both models were run with a flat terrain profile. By eliminating the ridge induced effects, the production estimation and wind fields for both can be viewed, influenced only by roughness values and associated turbulence. Figures 11 and 12 shows the initial wind speed values being perfectly correlated but differing consistently as the flow travels over the terrain. Figures 13 and 14 reflect this difference but display a preexisting presence of a difference in AEP estimations with WindPRO over estimating WindSIM by 6.85 percent at the first turbine location. The WindSIM model predicts a gradual weakening of the wind speed, presumably due to the influence of terrain roughness and turbulence, while WindPRO estimates a continuous, undisturbed flow throughout the area.
Figure 11: Mean wind speed comparison over flat terrain

Figure 12: Wind speed percentage difference of WindPRO over WindSIM (flat)
Figure 13: AEP comparison over flat terrain

Figure 14: AEP percentage difference of WindPRO over WindSIM (flat)
4.1.2 100 Meter Ridge Case

Once the previously discussed issues concerning meteo data were addressed, an initial run of both software was made beginning with the 100-meter ridge height. The outcome can be seen in figure 15 and 17, showing what appears to be a mirror image of the terrain in both wind speed and AEP estimation with WindPRO predicting wind speeds of around 3.4 percent above WindSIM on both slopes of the ridge, demonstrated by figure 16. This over prediction is reflected in the AEP percentage differences approaching and even exceeding 15 percent in the same regions as seen in figure 18.

Figure 15: Mean wind speed comparison over the 100 meter ridge
Figure 16: Wind speed percentage difference of WindPRO over WindSIM (100m)

Figure 17: AEP comparison over a 100 meter ridge
Figure 18: AEP percentage difference of WindPRO over WindSIM (100m)

The roughly 3.4 percent overprediction by WindPRO, while reduced, continues within the measured range in the lee of the ridge. This is a weakness noted throughout previous studies regarding the linear model.

This demonstrates a notable difference occurring in values far below the proposed threshold around 17 degrees but does not provide a clear moment of separation. The areas around the crest of the ridge where turbine construction is most likely due to a reduced gradient and higher level of wind resources, shows the models coming back into alignment.
4.1.3 120 Meter Ridge Case

In a similar case to the 100 meter ridge, the 120 meter ridge also clearly shows both model outputs mirroring the ridge. The mean windspeed can also be seen following a similar style with WindPRO over estimating in comparison to WindSIM on both the forward and lee slopes, with a continued difference on the leeward side as far as the model extends. There is also the near alignment present near the crest of the ridge. This is illustrated by figures 19 and 20.

Figure 19: Mean wind speed comparison over the 120 meter ridge
Figure 20: Wind speed percentage difference of WindPRO over WindSIM (120m)

Figure 21: Zoomed in view of the AEP comparison between WindPRO and WindSIM
Figure 22: AEP percentage difference of WindPRO over WindSIM (120m)

The difference in this case can be seen in terms of AEP production comparisons. Even with higher mean winds continuously estimated by the WindPRO model, WindSIM’s AEP estimations nearly align with WindPRO’s on the ridge crest. This may be due to WindSIM accounting for the variations over the entire swept area where WindPRO is only incorporating flow velocity at hub height.

4.1.4 140 Meter Ridge Case

With a continued increase in ridge height, resulting in a relative increase in the slope of the terrain, a similar pattern emerges on the slopes, crest, and leeward side of the ridge. The oddities continue to appear in the differences between expected and actual output of the models between mean wind speeds and AEP estimations as illustrated by figures 23, 24, 25, and 26 below.
Figure 23: Mean wind speed comparison over the 140 meter ridge

Figure 24: Wind speed percentage difference of WindPRO over WindSIM (140m)
Figure 25: AEP comparison over a 140 meter ridge

Figure 26: AEP percentage difference of WindPRO over WindSIM (140m)
4.1.5 160 Meter Ridge Case

The 160 meter ridge is the first case of the terrain profile approaching the established critical slope value of roughly 17 degrees. A continued increase in differences between the two software estimations is seen on both forward and leeward slopes of the ridge but an underestimation by WindPRO in respect to AEP is experienced over the crest of the ridge. The leeward slope shows an increase to values nearing a 4.5 percent difference between the WindPRO and WindSIM mean wind speed results, with WindPRO overpredicting the wind speed and relevant AEP as shown in figures 27, 28, 29, and 30 below.

Figure 27: Mean wind speed comparison over the 160 meter ridge
Figure 28: Wind speed percentage difference of WindPRO over WindSIM (160m)

Figure 29: AEP comparison over a 160 meter ridge
4.1.6 180 Meter Ridge Case

The 180 meter ridge represents the first case where the proposed critical slope value of 17 degrees is surpassed. As expected, a distinguishable separation is observed on both the forward and leeward slopes, the latter of which reducing slightly but extending to the extent of the modeled range. The interesting outcome is the noticeable increase in the difference of the two results on the crest of the ridge with WindPRO largely underpredicting AEP over the top of the ridge.

Figure 30: AEP percentage difference of WindPRO over WindSIM (160m)
Figure 31: Mean wind speed comparison over the 180 meter ridge

Figure 32: Wind speed percentage difference of WindPRO over WindSIM (180m)
Figure 33: AEP comparison over a 180 meter ridge

Figure 34: AEP percentage difference of WindPRO over WindSIM (180m)
4.1.7 200 Meter Ridge Case

The 200 meter ridge reaches a maximum slope of approximately 20 degrees, well above the critical slope point for separation. Both slopes and the leeward area of the ridge produce large differences between the models caused by adverse pressure gradients resulting from flow separation due to the inclination of the terrain. The CFD model is known to incorporate the flow separation reasonably well in its wind resource estimation output, while a recognized limitation of the linear model is its inability to accurately do so. Interestingly, at the hub height of 94 meters, the mean wind values produced by both modeling techniques continue to correlate relatively well over the top of the ridge, the area of interest for wind turbine construction. This is apparent in both figures 35 and 36. While this appears promising for the continued acceptance of linear models in these conditions, it should be noted that separation and speed-up effects may still be occurring at lower heights which still fall within the swept area of a turbine’s blades. This could mean much higher levels of turbulence intensity (TI) and altered flow angles, variables that have large impacts on wind turbines power output, capacity, and structural integrity. These additional influences are reflected through the AEP estimates produced by the two modeling programs. Here, WindPRO can be seen vastly over estimating values on the slopes and underestimating AEP values over the ridge top by up to 6.5 percent.
Figure 35: Mean wind speed comparison over the 200 meter ridge

Figure 36: Wind speed percentage difference of WindPRO over WindSIM (200m)
Figure 37: AEP comparison over a 200 meter ridge

Figure 38: AEP percentage difference of WindPRO over WindSIM (200m)
4.1.8 300 Meter Ridge Case

The 300 meter ridge case was run as a means of demonstrating the influence of terrain inclination far surpassing the proposed limitation of roughly 17 degrees. The maximum slope of the terrain in this case reaches approximately 28.6 degrees. Figures 39, 40, 41, and 42 provide a clear illustration of the difference between the two software with a slope of this magnitude occurring.

![300 Meter Ridge Mean Wind Speed](image)

Figure 39: Mean wind speed comparison over the 300 meter ridge
Figure 40: Wind speed percentage difference of WindPRO over WindSIM (300m)

Figure 41: AEP comparison over a 300 meter ridge
This further demonstrates WindPRO’s overestimation of mean wind speeds over all parts of the ridge in respect to the WindSIM estimations, a weakness noted throughout relevant literature regarding the linear modeling software (Bowen and Mortensen, 2004). At this point the two models have become highly separated in their results, at some points even surpassing a 50 percent difference in estimated AEP.

4.2 Discussion

When viewing the results of this study, the data illustrates a difference in linear verses nonlinear model performance far before the proposed 16.7 degree critical slope indication suggested by Wood (1995). This coincides with the study produced by Yamaguchi et. al., where a comparison of a linear and nonlinear model regarding terrain slope yielded results indicating division in performance at slope values beginning at 5 degrees. They suggest linear models consistently underpredict when slope angles ranging from 5 to 15 degrees are present, and over predict when slopes exceed 15 degrees (Yamaguchi et al., 2002).
This study’s results support differences of the model outputs occurring as early as slopes of 10 degrees however, our linear model wind estimations are consistently overestimated in all cases. The AEP produced regarding the ridge top in each case illustrates the inverse of the Yamaguchi et. al. study, with the linear output overpredicting until the slope surpasses roughly 14 degrees, then underpredicting afterwards. This may be due to the difference in the height above the surface where the flow is being observed, 94 meters in this study as opposed to 10 meters in the Yamaguchi et. al. study. An interesting point is the mean wind speeds not fully correlating to the AEP differences produced by the models.

The desired outcome of this study, a defined value indicating the point of flow separation and at resulting differentiation between the two modeling methods regarding critical slope, was not produced. Large differences of AEP, nearing 7.5 percent, appear even in the 100 meter ridge case before any terrain inclination is experienced. When viewing the control case using a flat terrain profile, a difference of nearly 7 percent in AEP is constant in flows between the two models before any terrain influence is incorporated. Although the separation point was not clearly defined, the different flow profiles produced clearly show a difference between the two modeling techniques in the lee of the ridge. While this does not have a major impact on turbine siting regarding the singular ridge, it could be assumed there would be major impacts on additional sites in the lee direction, especially as the terrain complexity increased.

An interesting and unexpected outcome produced through this study is the constant difference in wind speeds of around 2 percent maintained by the models regarding the top of the ridge as the slope of the ridge increases to levels as high as 20 degrees (the maximum slope reached in the 200 meter ridge case). The most plausible reasoning for this is the fixed 94 meter hub height used for all flow results being compared. This may extend above the zone influenced by the speed up and flow separation occurring due to the surrounding terrain inclination. In past years, a turbines’ proposed hub height was deemed acceptable for use in producing AEP estimations but, experience has shown the entire swept area of
the blades is of equal importance and must also be included in production estimations. WindSIMs’ 9.0 software now offers the rotor equivalent wind speed (REWS) tool, a means of viewing the entire vertical swept area, providing a visual representation of the large potential variations in wind speed over the area and producing higher quality results (WindSIM, 2018).
5 CONCLUSIONS

5.1 Summary

This study has produced a controlled means of evaluating the performance of WindPRO’s linear modeling software against WindSIM’s RANS based CFD modeling software at a height of 94 meters above the surface. By establishing 8 comparable cases with all variables held constant excluding the inclination of the terrain, fluid flow estimations were produced and compared. The outcome of those comparisons was used to attempt to obtain a value representative of a critical slope angle indicative of flow separation. This value would also represent the differing point in model output validity between the two previously mentioned modeling techniques. Unfortunately, a specific value was not obtained, however other interesting outcomes were produced.

5.2 Objectives and Conclusions

- Is the industry accepted critical slope value of 30%, roughly 17 degrees, a suitable indication of a difference between WindPRO’s linear modeling estimations and those produced by WindSIM’s CFD RANS modeling software?

Evidence of a difference in performance appeared in cases where the slope angle exceeded just over 10 degrees, far below the accepted 17 degree range presently applied by the wind power industry (Wood, 1995; Bowen and Mortenson, 1996; Rathmann et al., 1996). Table 4 provides an average percentage of the over prediction in AEP and wind speed produced by WindPRO compared to WindSIM at specific slope values. This illustrates a relatively linear increase in the difference between the two models as the degree of inclination increases, not a defined point as previously stated.
Table 4: Average percentage difference of WindPro over WindSIM estimations vs slope

<table>
<thead>
<tr>
<th>Degree of Slope</th>
<th>AEP Percentage Difference</th>
<th>Wind Speed Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>13%</td>
<td>2%</td>
</tr>
<tr>
<td>10</td>
<td>17%</td>
<td>4%</td>
</tr>
<tr>
<td>15</td>
<td>22%</td>
<td>5%</td>
</tr>
<tr>
<td>20</td>
<td>36%</td>
<td>9%</td>
</tr>
</tbody>
</table>

A point of interest was a minimal difference of the two models’ mean wind speed results appearing over the crest of the ridge, hovering around a 2 percent over estimation by WindPRO. This trend continued until the slope surpassed roughly 20 degrees. This is of interest particularly because the ridge top is commonly the desired location for turbine siting due to, among other things, the higher quality wind resource available. It should be noted that TI and inflow angle are not covered in this study, nor is the wind profile over the entire swept area of the rotor, only the specific 94 meter height. These factors can vary greatly in areas of complex terrain where speed up and flow separation are known to occur.

- What are the prevalent differences between linear and CFD based flow models over ridges of varying slopes with a perpendicular flow?

The dominant variations occurred on both the windward and leeward slopes of the ridge with notable differences occurring even with the 100 meter ridge case with a maximum slope of 10 degrees. The indication of a difference in AEP estimations nearing 7 percent, even in the controlled case using a flat terrain profile, demonstrates an underlying difference between the models’ estimations. The oddity is the lack of a correlation in mean wind speed and AEP estimations. Once slopes surpassed 14 degrees an inverse divergence could be observed with WindPRO beginning to underestimate AEP over the crest of the ridge while continuing to overestimate on the slopes. The leeward side of the ridge also illustrated the disagreement between the two software programs as the linear model flow
profile produces a mirror image to the forward side of the hill, dictating an attached flow even in the 300m ridge case.

- Does measuring at a hub height of 94 meters incur noticeable differences in results compared to those produced in similar past studies?

Although past studies have produced an array of results representative of fluid flows over inclinations, those using the same modeling techniques compared in this study have produced similar outcomes. As noted previously, one of the most similar studies produced by Yamaguchi et. al, obtained results indicative of model divergence occurring at a much lower degree of slope than previously thought, like the results of this study (2002). The difference here occurs between the 5 and 15 degrees of slope where Yamaguchi et. al. linear model produces underestimations in wind speed and our results maintain an overestimation. The 94 meter measurement height on a singular ridge reduces the influence of flow separation when it initially occurs, only demonstrating an influence once a relatively large inverse pressure gradient is present.

5.3 Limitations

The results of this study provide minimal additional insight into the recognition and establishment of the critical slope value concerning linear model performance. Having a higher resolution of data points at multiple heights over the terrain would produce a more precise moment of flow separation. The establishment of a minimal height at which this separation influences the linear model outputs is also hard to solidify as turbine hub heights and rotor diameters continue to grow and ratios between the two are constantly altered. Testing alternative turbulence models such as SST k-w and realizable k-e for possible better recognition of flow separation would could also increase the accuracy of the data. Finally, it would be very useful to have data from a physical model of equal dimensions with which to compare the output of the two simulated models being tested.
While this has been done in some degree with sites like the Bolund and Askervein hills, the presence of potential of alternative variable influence does not allow for a fully controlled result.
REFERENCES


T. UTNES and K.J. EIDSVIK (1996) "Turbulent flow over mountainous terrain modelled by the Reynolds equations" NTNU, Trondheim, Norway


APPENDIX A.

Vestas V112 3.3-megawatt Turbine Power Curve

<table>
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<tr>
<th>Turbine type</th>
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<tr>
<td>Rated wind speed (m/s)</td>
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<tr>
<td>Cut-in wind speed (m/s)</td>
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<tr>
<td>Cut-off wind speed (m/s)</td>
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<td>Diameter (m)</td>
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<td>air density (kg/m³)</td>
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<table>
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Table 4.2 Turbine characteristics with power and thrust coefficient

Additional Figures
120 Meter Ridge AEP vs Elevation

140 Meter Ridge AEP vs Elevation

WindPRO over WindSIM
WTG Elevation