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DOE/SNL-TTU Scaled Wind Farm Technology Facility: Research Opportunities for Study of Turbine-Turbine Interaction

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Abstract

The proposed DOE/Sandia Scaled Wind Farm Technology Facility (SWiFT) hosted by Texas Tech University at Reese Technology Center in Lubbock, TX, will provide a facility for experimental study of turbine-turbine interaction and complex wind farm aerodynamics. This document surveys the current status of wind turbine wake and turbine-turbine interaction research, identifying knowledge and data gaps that the proposed test site can potentially fill. A number of turbine layouts is proposed, allowing for up to ten turbines at the site.

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1 Introduction

In August 2011, the U.S. Department of Energy (DOE), Sandia National Laboratories (SNL), Texas Tech University (TTU), and National Institute for Renewable Energy (NIRE) announced plans for a new wind energy test facility. The facility will be located at the Reese Technology Center near Lubbock, TX. The primary roles of the new test site will be to develop and evaluate innovative wind turbine rotor technology, develop and test new measurement techniques, and study turbine-turbine interactions and complex wind farm aerodynamics. Field testing of new rotor technology and wind turbine diagnostic techniques represents a continuation of SNL's innovative turbine test program, which has been active for over thirty years. This mission will continue and be enhanced by the new test site's upgraded turbines, infrastructure, instrumentation, and opportunities for collaboration with TTU's wind engineering program. Areas of rotor-oriented research that will benefit from the test site include advanced rotor designs, active load control, rotor aerodynamics, and rotor aeroacoustics.

The study of wind turbine wakes and turbine-turbine interaction (T-TI) is a newly chartered research area, for which the new test site will be specifically configured. The initial plan for the site includes installation of two mid-size wind turbines, such as the 225 kW Vestas V-27 or similar machine. The V-27 has a rotor diameter of 27 meters, operates in two-speed mode as-purchased, and has collective blade pitch control. SNL will be converting the machines to variable speed. As part of the turbine purchase agreement, SNL will have access to detailed design specifications and drawings of the turbines. This is important, as it will allow researchers to construct detailed models of the control system, aerodynamics and structural dynamics of the machines.

The new test facility presents a unique opportunity to construct a test site that can be specifically used to study T-TI. While initially the site will have only two turbines, the available land area is large enough to accomodate additional turbines in the future. The objective of this report is to recommend a turbine siting layout for the test site, including the possibility of additional turbines. First, the T-TI problem and its relevance to the field of wind energy is described. Next, a survey of previous wind turbine wake and T-TI field measurements is presented, highlighting the research progress that has been made to date and documenting previous and existing field test efforts (mostly overseas) for studying T-TI. As part of this survey, fundamental research questions and model validation data needs are identified. Given this background information, a series of turbine layouts is presented that offers opportunities to address important research needs within the constraints of the site.

2 Wind Turbine Wakes and Turbine-Turbine Interaction

In the process of extracting kinetic energy from the wind, wind turbine rotors also remove momentum from the wind. This results in a region of relatively low wind velocity downwind of the turbine, known as the wake. Operation of a turbine within the wake of another turbine can lead to power losses, due to the lower wind velocity encountered by the downwind turbine. These power losses can be very large for individual turbines (exceeding 40%) and also very significant for wind farms (up to 20%), leading to obvious economic consequences. The losses are particularly important for offshore installations, where the relatively high electrical infrastructure costs of offshore wind farms leads to an economic benefit if turbines are sited close to one another. Also, wind turbulence is usually lower at offshore sites than for terrestrial sites, which causes wind turbine wakes to persist over longer distances offshore.

A turbine operating within one or more wakes can also experience higher loads, for two main reasons. First, turbulence within the wake adds to the already existing atmospheric boundary layer turbulence, resulting in more intense turbulence within the wake than in the undisturbed wind. Second, turbulent wind fluctuations within the atmospheric boundary layer buffet the wake in the lateral and vertical directions, causing so-called wake meandering. A meandering wake that encounters a downwind rotor can cause an additional “apparent turbulence” due to the intermittent nature of the wake/rotor interaction. This apparent turbulence can significantly increase loads on the downwind rotor. Wake-induced loading is currently addressed in the IEC design standards for wind turbines [2], in the form of a wake turbulence intensity that is added to the atmospheric turbulence intensity. This is a somewhat crude approximation, however, and does not account for the change in turbulent structure and length scale due to the wake, or the effect of wake meandering.

Power losses due to wind turbine wakes lead to decrease in energy capture, with direct loss of revenue and increase in cost of energy. Uncertainty in wake-induced fatigue loads decrease wind turbine reliability and potentially increase operations and maintenance costs, which also increases cost of energy. There is, therefore, a large incentive to improve our ability to predict wake effects such that their effects can be mitigated. As discussed in this report, predictive models have seen continued improvement and now leverage unprecedented amounts of available computing power. However, there is a critical need for detailed data sets to properly validate these models.

3 Wind Turbine Wake Field Experiments: Previous Research

A number of field experiments on wind turbine wakes have been conducted at a variety of sites. Many small scale wind tunnel experiments on wind turbine wakes and wind farms have also been performed, although these are not discussed here. This section catalogues many of the field experiments that have been conducted over the past twenty-five years that have focused particularly on wakes and turbine-turbine interactions. These experiments can be placed in one of two broad categories: wind farm performance experiments and turbine-turbine interaction experiments.

The first category of experiments focuses on the power production efficiency and, to a lesser extent, wake-induced fatigue loads, of large wind farms. These experiments are carried out at full scale on production machines, and the resulting data often consist of turbine SCADA data (power, yaw angle, nacelle wind speed, turbine state, etc.), along with wind measurements from nearby meteorological masts. The primary advantages of full-scale testing are:

- the direct relevance of the atmospheric conditions and turbine hardware; and,
- no special effort is required to scale the results.

The disadvantages include:

- the difficulty of access by researchers to details of the turbine, which are operating as production machines; and,
- the relatively sparse data that can be collected due to the large scale and associated expense.

The second category of experiments focuses on details of the interaction between a relatively small number of turbines. The goals of these experiments vary, and include characterization of single turbine wakes, study of energy losses due to wakes, study of the wake-induced loads on downwind turbines, and development of new turbine and wake measurement technology. Some of these experiments are performed at full-scale, while others are performed at sub-scale. In this context, "sub-scale" means at a machine size that is smaller than modern, MW-scale wind turbines. The advantages of sub-scale experiments are:

- lower testing cost, allowing for more detailed measurements and a greater variety of testing conditions;
- the use of research turbines, which may be fully characterized and the details of which are usually not constrained by a manufacturer's proprietary limitations; and
- greater accessibility of the turbine, allowing for easier and more frequent access to turbine (and especially rotor) instrumentation.

Disadvantages of sub-scale experiments include:

- the need to scale the aerodynamic loads and structural response to full-scale;
- differences in available drive train configurations between mid-size and utility scale wind turbines; and
- differences in control scheme between mid-size and utility scale wind turbines.

The sub-scale turbines to be installed at the DOE/SNL test site are small enough to allow relatively easy and inexpensive access to all turbine components. At the same time, they are large enough such that the test results can be extrapolated to full-scale. Blade chord Reynolds numbers are large enough such that the aerodynamic and noise characteristics are similar to those of MW-scale wind turbines. The scub-scale turbines will likely be two-speed machines with collective blade pitch control. SNL is investigating the possibility of upgrading the machines to full variable speed operation, while it is feasible that the turbines could be modified for individual blade pitch control in the future.

A survey of previous and planned wind turbine wake and T-TI field experiments is given in Table 1. The experiments are divided into T-TI experiments and wind farm experiments. Most of the test sites are in northern Europe, with all of the wind farm experiments taking place in offshore or coastal farms. A wide variety of inter-turbine spacings have been considered, although for any given test site the available spacings are limited. An exception to this within the T-TI experiments was the Alsvik test site in Sweden, where the turbines were arranged such that several different spacings could be studied. The Tjæreborg site also allows for different spacings, although a T-TI study including the effects of spacing has not been published to our knowledge. These previous experiments are now divided into several categories according to their goals, and summarized in the following sections.

3.1 Wake-Induced Turbine Loads

Several experimental studies have been conducted to investigate the increased fatigue loading of a wind turbine operating within the wake of an upwind turbine. The two-turbine experiments of [6] and [7] found that the standard deviation of blade flapwise bending moment increases by approximately a factor of two for operation in the near wake ($2D$ to $2.5D$ spacing, where D is the rotor diameter). Dahlberg *et al.* [5] found significant wake-induced fatigue loads in a four-turbine configuration for turbine spacings up to $9.5D$, with a factor of three increase in standard deviation of blade flapwise moment for $5D$ spacing.

Increased fatigue loads have been measured in wind farms, see *e.g.*, [15, 16]. Measurements in the Vindeby offshore wind farm [15] ($8.6D$ spacing) indicated that only the wakes from the nearest turbines contribute to increased fatigue loading. In other words, while energy production of a large wind farm needs to consider all wake interactions, fatigue loading may only need to consider local wake interactions. Verifying this hypothesis in a systematic way could be an important contribution for future T-TI test efforts.

Location	# Turbines	Turbine Type	Turbine Spacing	Instrumentation	Reference(s)
Turbine-Turbine Interaction Experiments					
Nibe, Denmark	2	630 kW	5*D*	4 met masts, blade bending moments	[3, 4]
Alsvik, Sweden	4	180 kW Danwin	5*D*, 7*D*, and 9.5*D*	2 met masts, blade and tower loads	[5]
Risø Test Station, Denmark	2	250 kW Nordex and 225 kW Vestas V27	2*D*	blade loads	[6]
Kegnæs Ende, Denmark	2	450 kW Bonus	2.5*D*	blade, nacelle, tower loads	[7]
Tjæreborg wind farm, Denmark	5	2 MW Nordtec-Micon NM80	3.3*D* [a]	blade loads, 5-hole pitot tube	[8]
ECN WT Test Site Wieringermeer, The Netherlands	5	2.5 MW Nordex N80	3.8*D*	met mast, turbine data, blade and tower loads	[9, 10]
ECN Scale Wind Farm, The Netherlands	10	10 kW Aircon	?	14 met masts, turbine data	[11]
Full Scale Wind Farm Experiments					
Nørrekær Enge II wind farm, Denmark	42	300 kW Nordtank	6*D*-8*D*	2 met masts, blade loads	[12, 13]
Vindeby offshore wind farm, Denmark	11	450 kW Bonus	8.6*D*	blade and tower loads, 3 met masts, sodar	[14, 15, 16, 17]
Bockstigen offshore wind farm, Sweden	5	550 kW Wind World	8.8*D*-20.9*D*	one met mast	[18]
Middlegrunden offshore wind farm, Denmark	20	2 MW Bonus	2.4*D*	one met mast, SCADA data	[19]
Horns Rev offshore wind farm, Denmark	80	2 MW Vestas V80	7*D*	three met masts, SCADA data	[20, 21]
Nysted offshore wind farm, Denmark	72	2.3 MW Bonus	10.5*D*, 5.8*D*	four met masts, SCADA data	[22]
Purdue/GE wind energy park, Indiana, U.S.A.	60	1.5 MW GE	–	–	[23]

Table 1. Survey of previous field test sites and campaigns to study turbine-turbine interactions.

[a] The Tjæreborg site consists of a row of four turbines Southwest of the instrumented turbine. The closest turbine is spaced 3.3*D* from the instrumented turbine.

More recent work on wake-induced loads in Denmark has focused on the phenomenon of wake meandering. Wake meandering occurs when large-scale turbulent eddies in the atmospheric boundary layer cause unsteady motion of the wake in the two cross-wind directions. The dynamic nature of the position of a meandering wake means that a downwind turbine can experience an intermittant wake load, rather than a constant wake forcing. This has implications for both energy capture and loads. The average velocity deficit experienced by a downwind turbine is effectively smoothed out, causing lower power losses than for the steady wake case. The meandering motion also creates an additional apparent turbulence effect due to the intermittancy of the velocity deficit, leading to increased fatigue loading. Wake meandering has been studied experimentally for the case of a stable atmospheric boundary layer with low turbulence intensity, characteristic of many coastal European sites [8]. More detailed field studies of wake meandering, employing extensive measurements of turbine inflow, wake velocity field, and turbine response are needed under a variety of atmospheric conditions common to sites in the U.S. Further, the fundamental physics of the interaction of multiple meandering wakes have not been studied, and have implications for correct modeling of wind farm power and loads.

3.2 Wind Farm Wake Losses

Power losses due to wind turbine wake effects can reach up to 20% in large wind farms [24]. Power losses due to turbine-wake interactions in wind farms have been studied in a number of field experiments, mostly conducted in Europe. Many of the largest European wind farms of the future will be placed offshore. There is also an economic incentive to place offshore turbines close to one another, due to the relatively large electrical infrastructure costs. These considerations have led to a focus in these European studies on gathering data at offshore, rather than onshore, wind farms.

Initially these measurement campaigns were conducted in wind farms of modest size, comprised of twenty or fewer turbines. Vindeby wind farm [14] consists of eleven turbines arranged in two parallel rows. Bockstigen wind farm [18] consists of five turbines arranged in an arrowhead formation, while Middlegrunden wind farm [19] has twenty turbines arranged in along a single, slightly curving arc. More recently, data have been collected at the Horns Rev wind farm [21] and Nysted wind farm [22] off the Danish coast. Horns Rev consists of 80 turbines, arranged in a 8×10 grid while Nysted wind farm consists of 72 turbines in a 8×9 grid.

These data campaigns have resulted in a large amount of data that has been useful for evaluating model predictions of wake losses. The physical scale of the experiments leads to numerous challenges [25], including establishing a unique free stream flow for a large wind farm. The data collection is also usually limited to met mast and turbine SCADA data, such that insight into the details of the wind farm flowfield is not possible. Nonetheless, these experiments at full scale will continue to play an important role in quantifying the full-scale impacts of wakes and providing realistic data for validating wind farm models. The DOE/SNL test site is seen as complementary to these full scale experiments, in that details of wakes and turbine interactions can be investigated at subscale, while the integrated effects on wind farm efficiency continue to be measured at full scale.

3.3 Wake Measurement Techniques

Methods for measuring the operating environment, and structural and aerodynamic responses of wind turbines have made great strides in recent years. The development of remote wind measurement techniques such as SODAR and LIDAR, as well as detailed rotor flowfield diagnostics, have created tremendous opportunities for increasing our understanding of wind turbine systems. Current and future R&D field tests will utilize these measurement systems; however, these systems are not mature, and require further development to realize their potential. While application of these measurement techniques to multi-MW scale turbines is an ultimate goal, development activities are much more efficient at a smaller scale. The proposed test site offers the ability to apply these techniques at large enough scale where most of the turbine behavior and responses are relevant to larger scale, but at small enough scale that the expense and complexity of deploying the systems are greatly reduced.

An example of recent research on wind turbine wake measurement techniques is the development of fast-scanning LIDAR systems for measurement of wind turbine wakes. In [26] and [27], a new nacelle-mounted LIDAR system is described that is able to perform fast velocity measurements at rates of up to 136 points per second. This system allows for unprecedented spatial and temporal resolution for wake measurements, creating detailed data sets that are very useful for model validation. Notably, this system was tested on a 95 kW test turbine in Denmark to enable proof-of-concept, and the resulting data have proved very useful for wake model validation. Subsequent studies of the wake of a 2MW turbine using this system [28] have provided new insights into wind turbine wake turbulence.

Yet more detailed wind turbine flow field mapping will become possible in the very near future. Developments in field-deployable Particle Image Velocimetry (PIV) techniques with large fields of view will allow for very detailed velocity field measurements near wind turbine blades and within wind turbine wakes [29]. Before deployment to multi-MW machines, these measurement techniques will require extensive testing and development at sub-scale.

3.4 Model Validation Data

Development of accurate models of wind turbine wakes and wind farm array performance and loads is important for further reductions in cost of electricity for wind energy projects. Various data campaigns in Europe have been conducted in the past with the specific intent of generating data for model validation. These have included the ENDOW project [18] and the more recent UpWind [24] and TOPFARM [30] projects. Code development has continued over the past decades at many universities, government laboratories, and within the wind turbine industry. Reviews covering wind turbine wake modeling include [31, 32, 33]. A comprehensive review is not attempted here, but some recent developments are highlighted.

Early wind farm models were based on relatively simple analytical descriptions for wind turbine wakes and superposition of multiple wakes. This approach is still used in many applications where computational expediency is important. This is a critical consideration for many applications including siting optimization and loads analysis. Recent work at Risø-DTU [34, 35, 36] has focused on models for the wake meandering process, with emphasis on coupling these models to aero-elastic turbine models for loads analysis. Continued improvement of analytical and "engineering" models is critical, since these models will be used in the wind turbine and wind farm design process for many more years. As part of the recently completed TOPFARM project in the EU, a range of models of varying fidelity have been applied in a complementary way to address optimal wind farm layouts [30, 37].

Modeling approaches based on Computational Fluid Dynamics (CFD) have become the new state-of-the-art. CFD approaches can be classified according to the method for modeling atmospheric boundary layer and wake turbulence. Reynolds-averaged Navier-Stokes (RANS) methods apply a turbulence model across all scales of turbulent fluid motions, resulting in a set of equations that is solved for the time-averaged flow through the wind farm (see, *e.g.*, [38, 39]. The presence of wind turbines is typically modeled through an actuator disc approach, where wind turbine thrust loads are applied as distributed forces on the surrounding air.

Increasing computing power has made Large Eddy Simulation (LES) a viable technique for computing wind turbine wakes. In LES, only the smallest turbulent motions are modeled and the larger turbulent eddies are calculated directly. The blade forces are now applied instantaneously as the blades rotate via an actuator line method. This approach leads to an unsteady simulation for the three-dimensional velocity field that is much more computationally intensive than RANS. However, much greater physical insight is gained into the development of the wake and its interaction with boundary layer turbulence and other wakes. This approach is currently being examined at national labs [40, 41] and universities [42], but there is a lack of sufficiently detailed data for validation of these models. Note that validation data are especially needed for the case of simple site topography, so that the modeling of the atmospheric boundary layer and wake interactions can be isolated from modeling the effects of complex terrain, which is itself a difficult problem.

Progress is also being made in systematic validation of wind turbine wake models against experimental data. The International Energy Agency's Task 31 "WAKEBENCH" effort [43] is an international collaboration aimed at constructing a set of benchmark models for validation of atmospheric boundary layer and wake models. The National Renewable Energy Centre of Spain (CENER) has constructed a web interface to manage the various validation databases, define best practices, and facilitate access to the data.

4 T-TI Research Roles for the DOE/SNL Test Site

Much work has been done on characterizing wind turbine wakes and T-TI, but much remains to be accomplished. New modeling techniques with unprecedented fidelity require more detailed measurements to assess their accuracy and predictive capability. Further, there is an important gap in measurements performed at land-based sites and in wind conditions characteristic of U.S sites. The following is a brief list of possible contributions the new DOE/SNL test site can make to T-TI research.

- Determine wake-induced fatigue loads for a flat U.S. Great Plains site, including varation of the loads with atmospheric stability, inter-turbine spacing, and turbine operating parameters.
- Determine the dependence of wake-induced fatigue loads on the number of wakes encountered by a turbine within a wind-aligned row.
- Characterize the merging behavior of multiple meandering wakes, with the aim of developing improved models for wake merging within wind farms.
- Characterize wake-induced performance losses with concurrent measurements detailing turbine inflow, wake characteristics, and rotor aerodynamics, to improve understanding of wake-induced losses for different turbine-wake configurations.
- Develop and test novel methods for high-resolution measurement of wind turbine inflow, near-blade flow, and wakes.
- Develop robust, synchronized measurement systems with concurrent rotor loads, power performance, turbine inflow, and turbine wake measurements.
- Provide a test-bed for development of structural health monitoring and other measurement techniques for offshore applications.
- Provide high quality validation data for T-TI models with well-characterized and relatively simple terrain conditions.
- Provide a layout that allows for some variation in inter-turbine spacing depending on wind direction, and, for larger numbers of test turbines, variation in the number of wakes encountered by a downwind turbine.
- Contribute validation test cases for T-TI model development to the international research community.

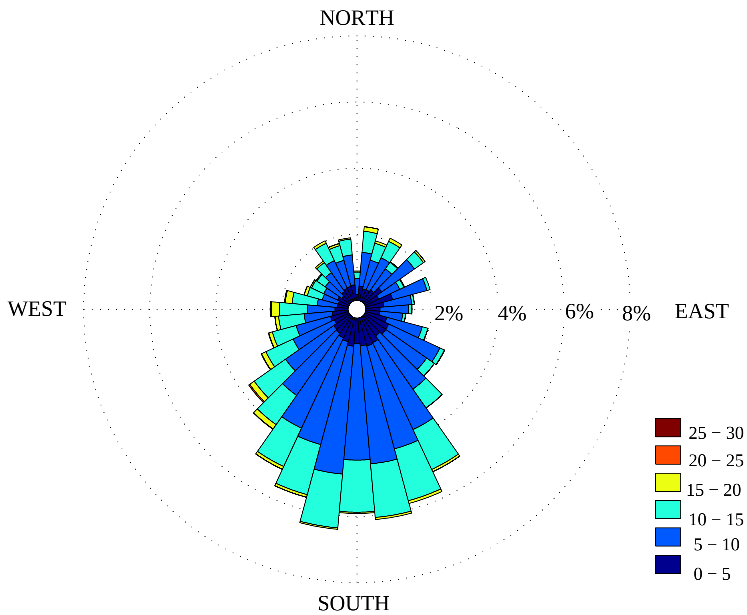


Figure 1. Wind rose at Reese Technology Center, measured at 77 meter height.

5 Recommended Test Site Configuration

Figure 1 shows the wind rose for Reese Technology Center. The dominant direction lies in the southern sector from approximately 150 degrees to 210 degrees, with a minor secondary westerly wind exhibiting strong wind speeds. Atmospheric stability conditions are variable at the site. A characteristic diurnal cycle is typical, with unstable conditions and low shear during the day followed by stable conditions with high shear at night [1]. This leads to a bi-modal probability distribution of the wind shear, as shown in Figure 2. The terrain is very flat with open exposure in all directions with the exception of a collection of low buildings approximately 1.5 km to the southeast. It is anticipated that much of the data collected at the site for turbine-turbine interaction will be collected with winds from the southerly sector from 120 degrees to 270 degrees. The flat, relatively smooth, terrain makes the site ideal for generation of model validation data for T-TI problems. Further, the variety of atmospheric boundary layer conditions allow for several situations to be studied, including stable boundary layers with low turbulence intensity similar to conditions observed offshore.

In the following, several wind turbine layouts are proposed with the goal of maximizing the utility of the sight in performing wake research and generating validation data sets. To estimate the extent of turbine-wake interactions, a simple model for wake development is applied [44, 45]. This model assumes that the diameter of the wake grows linearly with downwind distance from an

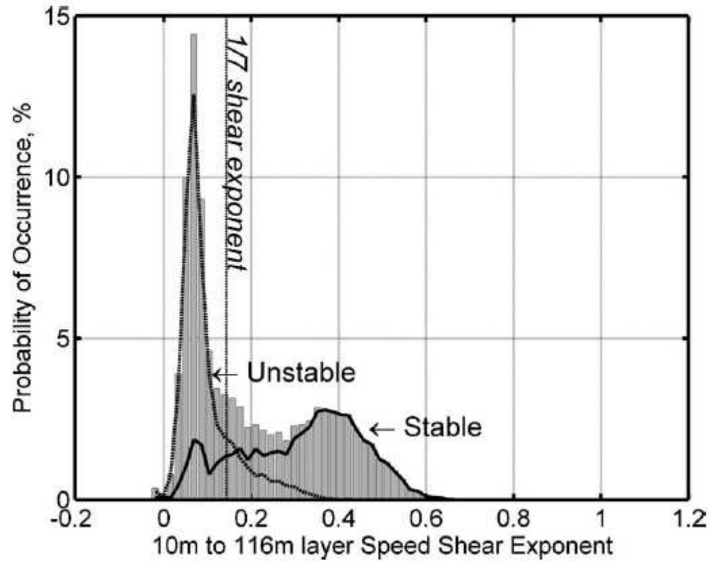


Figure 2. Probability distribution of wind shear exponent at the Reese Technology Center test site. The solid line is the distribution for stable boundary layer conditions, while the dashed line is the distribution for unstable conditions. From [1].

initial diameter D_0, taken as the turbine rotor diameter.

$$D = (1 + 2k)D_0 \tag{1}$$

The wake decay constant, k, is taken as 0.075, the recommended value for onshore cases [45].

We envision development of the site in several phases, with Phase I consisting of the initial pair of DOE turbines in addition to a turbine supplied by an industry partner. Phase II would expand the test site to six turbines, such that multiple wake interactions and turbine array effects could be studied. Phase III would increase the number of turbines to ten, further increasing the complexity of the wake interactions.

Phase I

During Phase I, three turbines would be installed at the test site. Selection of a layout for these turbines requires the balance of the following competing objectives and constraints:

- Available space is constrained by the test site boundaries and the desire to maintain a suitable distance from the TTU 200 meter meteorological tower.
- At least one inter-turbine spacing should be close to a representative “industry standard” spacing of seven rotor diameters.

- Inter-turbine spacings should be close enough to allow for clearly measurable TTI effects, and to allow for clear demonstration of technologies aimed at mitigating wake effects.

- A rich variety of TTI and wake merging cases is desired.

The proposed arrangement shown in Figure 3 places the turbines in a 3*D*-5*D*-6*D* triangle, with the southernmost turbines aligned along the east-west direction. The western-most turbine would be owned by an industry partner, and would encounter mostly undisturbed inflow. This turbine can function as a control turbine for TTI studies. As shown in Figures 3 and 4, the other two turbines would encounter wakes from an upstream turbine spaced at 3*D*, 5*D*, or 6*D*, depending on the wind direction. With winds from 184 degrees (Figure 3), the northern turbine operates within the wake of the southeastern turbine at a distance of 5*D*. With winds from the southwest (Figure 4(a)), the northern turbine would operate within the wake of the western turbine at a distance of 6*D*, while for westerly winds (Figure 4(b)) the southeastern turbine would operate in the wake of the western turbine at a distance of 3*D*. For wind from approximately the 200 degree direction, the northern turbine would operate partially within the wake of the two other turbines (Figure 5(a)). For wind from the southeast, the three turbine wakes would be more or less parallel, allowing for a study of lateral wake merging (Figure 5(b)).

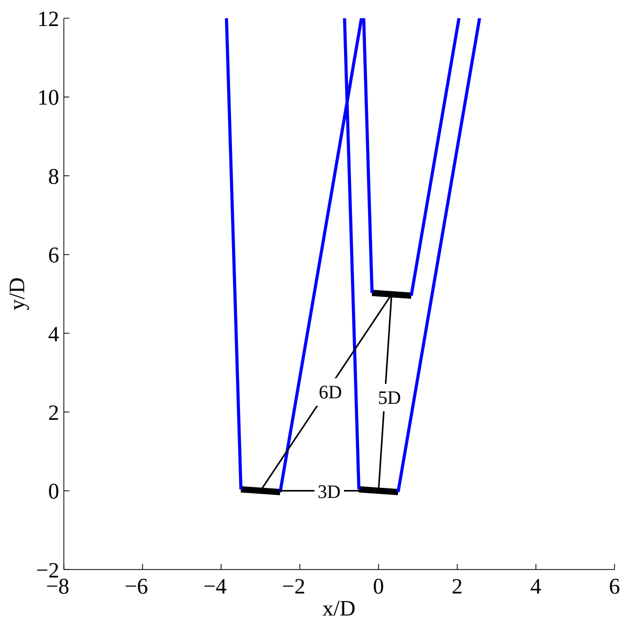
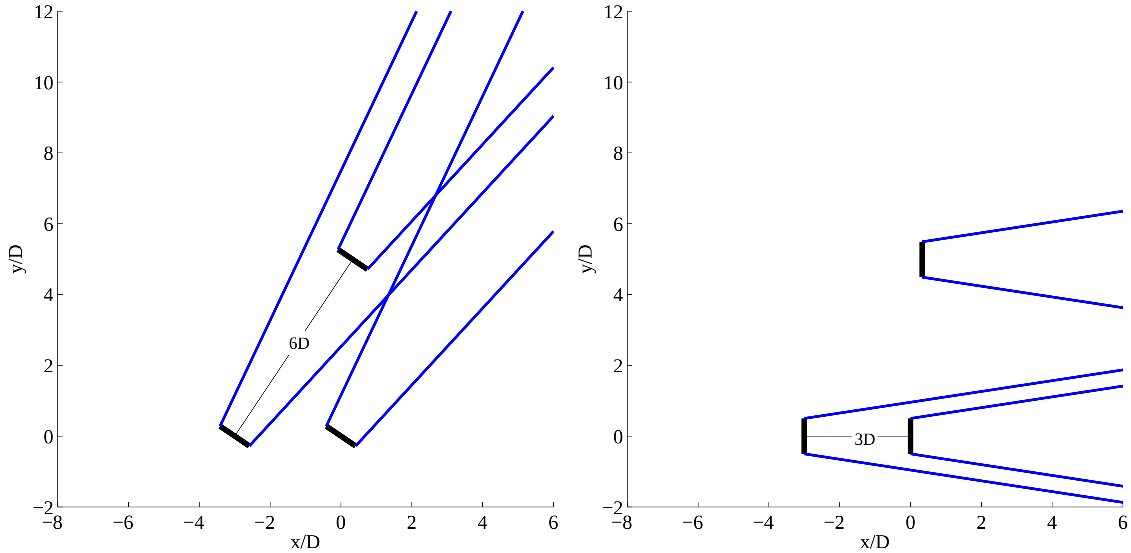
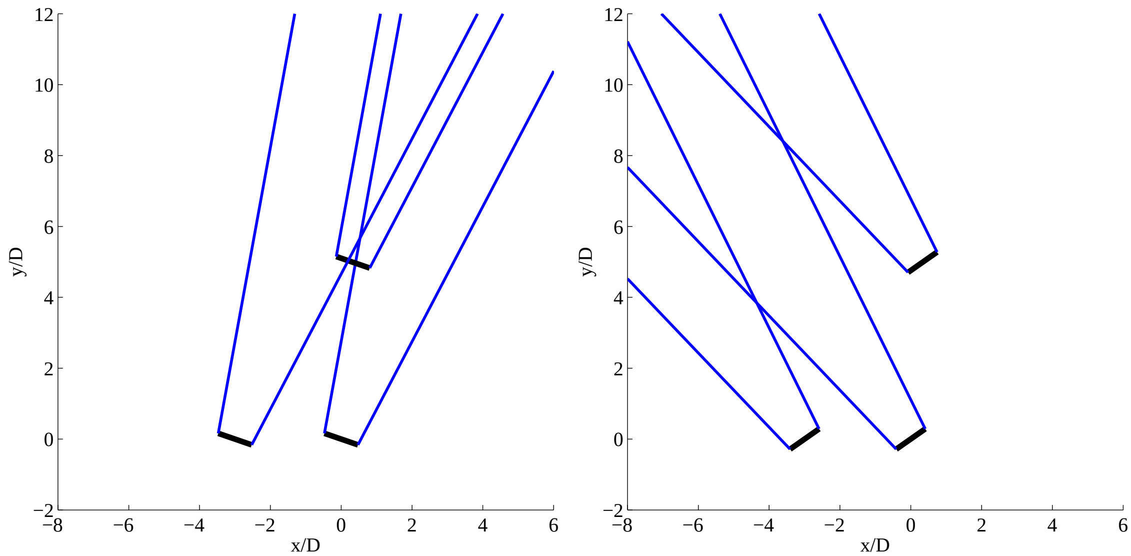


Figure 3. Proposed turbine siting for Phase I, wind from 184 deg..



(a) Three turbines, wind from 214 deg. **(b)** Three turbines, wind from 270 deg.

Figure 4. Proposed turbine siting for Phase I (continued).

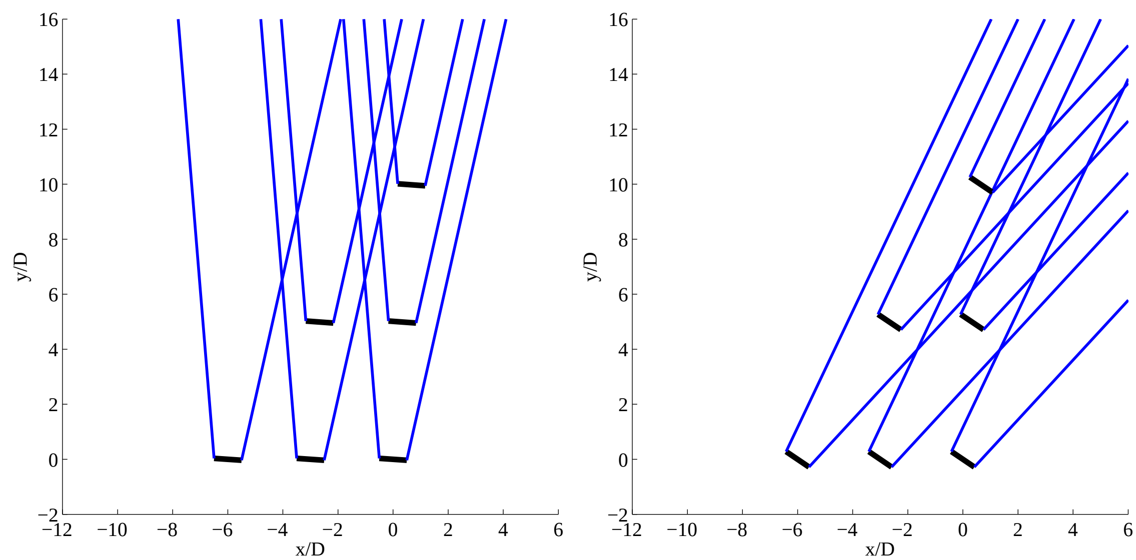


(a) Three turbines, wind from 199 deg. **(b)** Three turbines, wind from 145 deg.

Figure 5. Proposed turbine siting for Phase I (continued).

Phase II

While a small number of turbines allows for very meaningful data to be collected, adding more turbines would make the site more suitable for study of the interaction of many wakes, which is relevant to large wind farms. The size and research scope of this site do not allow for study of “deep array” effects in large wind farms. However, enough turbines can be accomodated to generate data for multiple-wake interactions with downwind turbines and with the atmospheric boundary layer. Figure 6 shows the proposed layout for a six-turbine array. Southerly winds allow for simultaneous study of two- and three-turbine rows at a spacing of 5D, while south-westerly winds allow for a similar study at a spacing of 6D. This configuration also allows for study of multiple wake interaction at the relatively close spacing of 3D with winds from the west.



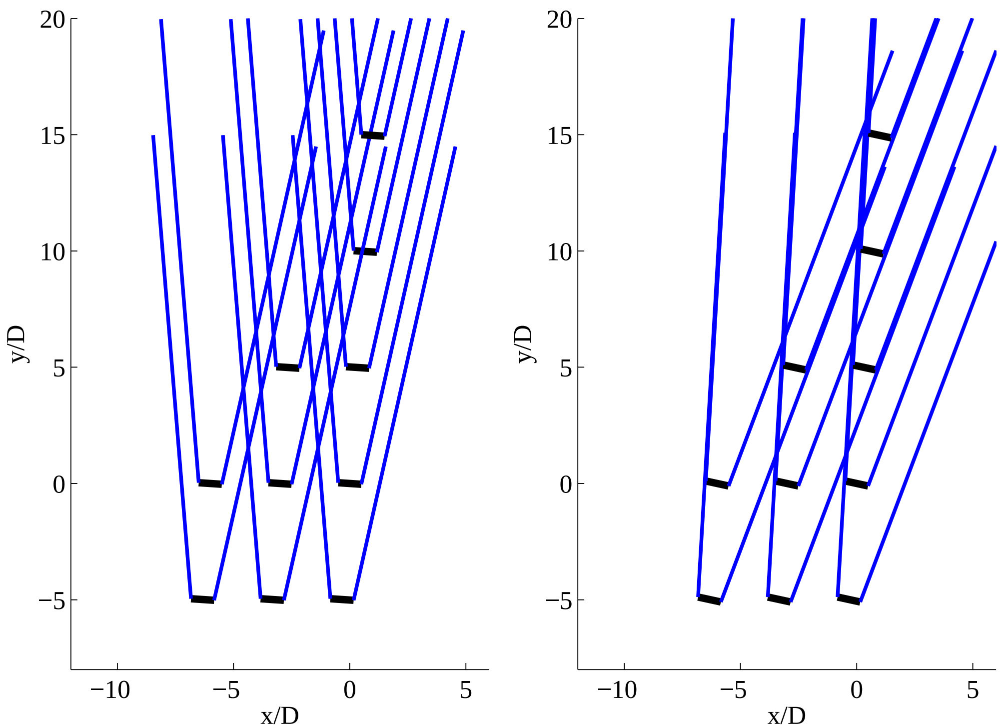
(a) Six turbines, wind from 184 deg.

(b) Six turbines, wind from 214 deg.

Figure 6. Proposed turbine siting for Phase II.

Phase III

Space constraints at the site, in addition to practical cost considerations, limits the number of sub-scale turbines at the site to approximately ten. The proposed ten-turbine configurations is shown in Figure 7. In this configuration, there is one row of three turbines parallel to another row of five turbines. For southerly winds, there is interaction and merging of five wakes along the main row of turbines. For winds from 192 degrees, this arrangement leads to interaction of a large number of the turbine wakes with the northernmost turbine.



(a) Ten turbines, wind from 184 deg.   **(b)** Ten turbines, wind from 192 deg.

Figure 7. Proposed turbine siting for Phase III.

Proposed Layout at Reese Technology Center

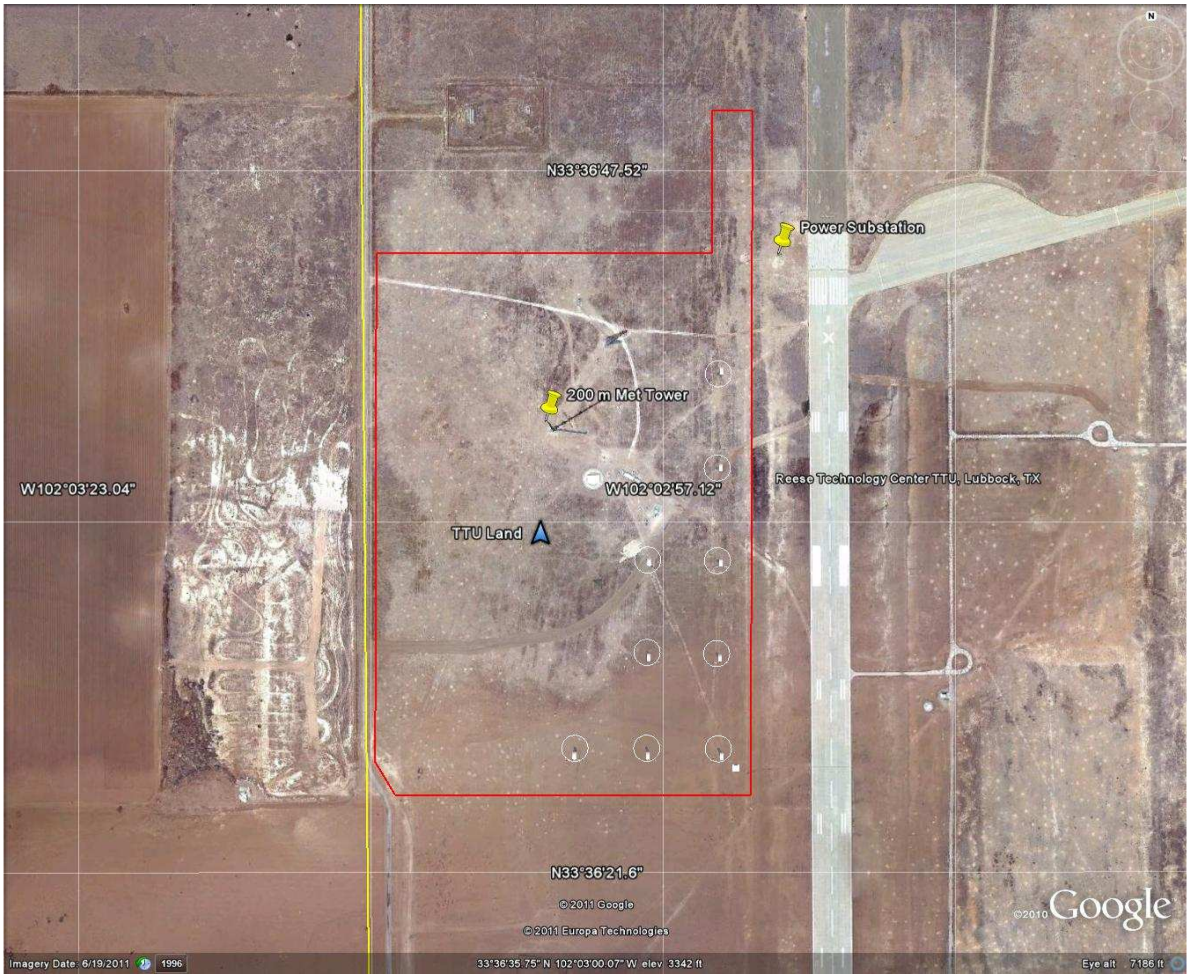


Figure 8. Map of the northwestern portion of Reese Technology Center. The yellow line is the technology center's western border. The red boundary encloses land leased by Texas Tech. The white circles are proposed turbine locations.

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