Project Title: Development of a High-Resolution Virtual Wind Simulator for Optimal Design of Wind Energy Projects

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FINAL REPORT

Executive Summary:
This project aimed at developing a ‘Virtual Wind Simulator’ (VWiS) for the prediction of atmospheric boundary layer flow and its interactions with wind turbines and wind farms. The use of the simulator will assist in the improved design of potential wind energy projects by providing more accurate predictions of local wind turbulence at site and turbine levels. Additionally, the VWiS will help to increase the level of wind energy utilization and reduce the cost of energy production.

Computational Fluid Dynamics (CFD) methods were used in this project to develop a computational framework for conducting high-resolution simulations of wind turbulence at the meso and micro scales. In particular, the Large-Eddy Simulation (LES) technique will allow for accurate simulations of the turbulent flow at spatial resolutions as small as one to ten meters, and temporal resolutions of just a few seconds. Parameterizations for wind turbine forces were also developed in the LES framework. The SAFL computational models were coupled to meso-scale regional models to develop a powerful multi-scale computational tool, the VWiS. The VWiS integrated the latest advancements in computational fluid dynamics research and provided reliable, high-resolution descriptions of wind turbulence across the entire range of scales that are relevant to wind power production. This information provides objective, scientifically based criteria that can be used by wind energy project developers for the site-specific, optimal selection and placement (micro-siting) of wind turbines.
A common and computationally cheap approach for engineering calculations of wind farm performance is the use of theoretical and empirical models. Such models, however, are based on several assumptions that simplify the problem. As a consequence of this, they work fine only in ideal and special cases, such as uniform inflow, flat terrain, stand-alone turbine and etc. The prediction of the mechanisms involved in the interaction between the atmospheric turbulence, wind turbines and wakes, which essentially determine the wind farm power output and dynamic loadings, require the use of sophisticated and efficient computational models. Our developed VWiS is able to directly simulate the main processes involved in the operation of wind farms under realistic situations. As an example, the placement of wind turbines depends on the topography of specific potential site. Our simulations of Prairie Island site showed that the complex terrains significantly affect the wind distribution and turbulence. The effect of complex terrains is very site-specific and cannot be accounted in standard engineering models. The VWiS solver developed herein, on the other hand, which can account for complex topography effects, can serve as a powerful simulation tool for site-specific design of wind farms.

The accuracy of the VWiS was evaluated using both wind tunnel and field measurements. For the comparison with wind tunnel measurements, the discrepancy (defined in terms of the of the wind velocity and turbulent statistics) was found to be less than 10% for locations two rotor diameters further from the turbine. For the field comparison on the wind farm at the Mower County, the discrepancy in terms of the turbine power output resulted less than 10% and 20% for turbines located in the wake of others and under free flow, respectively. It should be noted that the turbulence at the inlet for Mower County case, which was generated using a kinematic method, is not physical. It can be expected that the agreement for the power output from turbines in the other turbines’ wakes can be improved significantly if more realistic turbulence is fed at the inlet, which can be generated using a pre-computed fully developed turbulent flow obtained by applying the VWiS.

This report summarizes all the main findings obtained during the project, which includes wind-tunnel, field and numerical simulations performed towards the Development of a High-Resolution Virtual Wind Simulator.

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**Project Benefits:**
Atmospheric turbulence affects the performance of wind turbines and wind farms significantly in terms of the power output and dynamic loadings. However, turbulence effects are not accurately accounted in engineering models for wind turbines and wind farms due to the inherent complexity of the interaction between the atmospheric turbulence and wind turbines within wind farms. The VWiS provides wind farm developers and operators with a powerful science-based computational tool that can take into account site-specific topography, turbine-atmosphere and turbine-turbine interactions in wind farms. Therefore, the project outcomes can improve micro-siting methods and
thereby improve project economics by reducing the current gap between projected and actual wind farm economic performance.

Extensive validation studies with wind tunnel and utility-scale measurements established the VWiS as a reliable computational model for predicting the power output of and dynamic loading on wind turbines in wind farms. Therefore, the model can become a trusted computational tool for the industry.

The VWiS can be used to improve the reliability of existing wind farms by allowing operators to assess turbulence loads on turbine blades under a wide range of atmospheric conditions in order to:

1. Identify excessively loaded turbine blades that are likely to fatigue; and
2. Develop proactive turbine maintenance and health monitoring strategies.

The VWiS can also serve as a powerful tool for guiding future wind project development by:

1. Providing a scientific approach for arranging and spacing wind turbines;
2. Optimizing wind farm efficiency and enhancing reliability by reducing turbulence loads on blades; and
3. Taking into account complex terrain and enabling the development of wind projects at challenging sites.

Ultimately, the VWiS will enable wind farm developers to arrive at a better match between the turbine design and the site turbulence characteristic. This can improve wind farm economics by reducing turbine down time and decreasing the costs of out-of-warranty turbine repairs and parts replacement.

**Project Lessons Learned:**

Simplifying approximations of the turbine geometry with actuator disks or rotating actuator lines can capture the flow dynamics in the region downstream of the turbine (referred to hereafter as the “turbine wake” or simply “wake”) starting from distances of 1-2 rotor diameter or where the effects of turbine geometry are low. Such models can also predict with good accuracy turbine power output at utility-scale wind farms.

For the simulations using actuator line parameterization, the inclusion of a turbine nacelle and tower in a simulation requires in principle locally fine grid, which is computationally very expensive rendering wind farm simulations challenging if not impossible. The comparison with wind tunnel measurements has shown, however, that these structures (nacelle and tower) have only significant effects in the near wake region, which are not relevant for wind farm simulations. The best and simple solution was found to be extending the geometry of the blade to the center of wind turbine without directly modeling the effects of nacelle and tower.

Extensive wind tunnel experiments combined with strategically collected field measurements provide a feasible and effective approach for validating computational
models. For the comparisons with wind tunnel measurements, we focused on the comparison between the vertical distribution of mean velocity and turbulence intensities. For the field measurements, the comparisons were focused on mean velocity profiles at specific measurement locations and the power output of selected wind turbines. For the comparison with wind tunnel measurements, the discrepancy (defined in terms of the of the wind velocity and turbulent statistics) was found to be less than 10% for locations two rotor diameters further from the turbine. For the field comparison on the wind farm at the Mower County, the discrepancy in terms of the turbine power output resulted less than 10% and 20% for turbines located in the wake of others and under free flow, respectively.

Taking into account the effects of atmospheric turbulence at a specific wind farm site is extremely important for obtaining accurate wind resource assessment results. Neglecting turbulence leads to artificially long turbine wakes and can underpredict the performance of utility-scale wind turbines in wind farms by as much as 60 percent.

Arranging turbines in staggered fashion, as compared to the more traditional aligned arrangement, can lead to significant gains in wind farm performance (as high as 10 percent).

Turbulence distribution from complex topography can have a profound effect on wind farm performance and needs to be taken into account when deciding turbine placement. For instance, our numerical experiments on placing turbines at Prairie Island site revealed the need of avoiding areas of complex topography. In particular, our results point to the need to deploy potential turbines more than 1km away from the complex topography and to place them carefully considering the impact of site topography on wind patterns if the goal is to maximize the energy extraction and load reduction.

**Usefulness of Project Findings:**

The project will have direct and measurable benefits to the Xcel Energy ratepayers by contributing to:

1. Decrease the cost of energy for new and existing wind farm installations by increasing power production, reducing maintenance costs, and improving turbine designs;
2. Reduce future energy rates and the need for the federal and state governments to subsidize new wind farm development; and
3. Help Minnesota reach its renewable energy goal (25% by 2025) by advancing wind energy as a major renewable electricity resource.

**Technical Progress:**

We have successfully completed all the Tasks (4) of the project. A concise summary including the major achievements of each task is described as follows.

**Task 1. Development of the Virtual Wind Simulator for high-resolution simulations of wind turbulence and their effect on energy production**
In this project, the Virtual Wind Simulator (VWiS) software was developed for simulating turbulent flow over wind turbines and wind farms. The conceptual features of the VWiS are shown in Figure 1.

**Figure 1:** Schematic of the VWiS (Virtual Wind Simulator). The Weather Research and Forecasting (WRF) model is used to carry out mesoscale simulations of atmospheric wind conditions to provide boundary conditions for a fine mesh Large-Eddy Simulation (LES) model. The latter resolves wind-farm scale turbulence, including site-specific topographic features, turbine blades using actuator lines, and multiple turbine wake interactions.

With reference to Figure 1, the major features of the software VWiS are:

1. Mesoscale simulations at hundreds of kilometers were carried out using WRF (Weather research and forecasting model) to obtain boundary conditions (see #3 below) for the inner domain where wind-farm-scale simulations were carried out.

2. Wind farm scale simulations were carried out using LES (Kang et al., 2011; Yang et al. 2012) with input from the WRF mesoscale simulations (see #3 below). The LES resolves unsteady turbulent fluctuations, which are responsible for intermittent fluctuations of power output and dynamic loadings on wind turbines.

3. Inflow (upwind) wind conditions for the LES domain can be generated from WRF with unresolved small scales reconstructed either using a synthetic turbulence generation technique (Mann, 1998), or using the simulation of a fully developed turbulent boundary layer flows, which has the same wind characteristics with field measurements.

4. Arbitrarily complex, site-specific land topography was simulated using the curvilinear immersed boundary method (CURVIB) (Ge and Sotiropoulos, 2007), which can reduce the time for grid generation and take advantage of efficient solver for structured grids. Thus, the VWiS can simulate directly the interactions between turbulence generated by a complex terrain with a wind farm. This capability of the model is illustrated in Figure 2 which shows its application to simulate a hypothetical scenario of wind turbines.

5. Different atmospheric stratification conditions (stable, neutral, unstable) can be taken into account, in which a dynamic subgrid scale model is employed for
subgrid scale temperature fluctuations and a wall model is used for temperature near the wall.

6. Wind turbines were parameterized using either actuator disk or actuator line theory (Yang et al., 2012; Yang and Sotiropoulos 2013). Turbine blades were assumed to be rigid and turbine controls were not taken into account in the simulation.

7. An improved roughness height model was developed for engineering calculations of wind farm performance.

8. The VWiS was efficiently parallelized using Message Passing Interface (MPI) (Kang et al., 2011) and can take full advantage of HPC resources.

a. The flow solver
For the flow solver of VWiS, the governing equations for the incompressible turbulent flows are the 3D, unsteady, filtered continuity and Navier-Stokes equations in non-orthogonal, generalized, curvilinear coordinate. Second-order central differencing was employed for spatial discretization. A second-order accurate fractional step method was used for advancing the continuity and momentum equations. An algebraic multigrid acceleration along with GMRES solver was used to solve the pressure Poisson equation and matrix-free Newton-Krylov method was used for the filtered momentum equation. The subgrid scale stress tensors for both velocity and temperature fields were modeled by the dynamic eddy-viscosity subgrid scale model. At the bottom boundary, the shear stress boundary condition and no-flux boundary condition were used for the wall-parallel and wall-normal velocity components, respectively. The wall shear stress was calculated from the logarithmic law for rough wall. For a smooth wall, the wall shear stress was calculated from a simplified boundary layer equation. A wall model for the temperature was also employed. Arbitrarily complex geometries were represented by the CURVIB method. In CURVIB method, the grid nodes near the immersed boundaries provide boundary conditions for the flow simulation, where the velocities are interpolated from the surrounding fluid nodes and boundary values.

b. Inflow generation technique
Inflow conditions are essential for wind farm simulations using LES. As mentioned in last paragraph, two inflow generation techniques were employed in the VWiS. For the first one, the turbulent flow field at the inlet was generated from a separate fully developed turbulent flow as shown in Figure 2. Using this method, the domain size, the mesh as the a-b plane and time step usually should be the same as those of the wind farm simulation. If they are different, interpolation over space and time are needed. For the second one, the flow filed (the velocity and temperature) at the inlet of wind farm region was interpolated spatially and temporally from the WRF solution. Because of the coarse grid using in WRF (hundreds of meters, which are usually ten or twenty times larger than that used in LES), the turbulence scales explicitly resolved by WRF are much larger that in LES.
Figure 2: Schematic of inflow generation from a separate fully developed turbulent flow. The inflow generation domain is shown in the left figure. Periodic boundary conditions are applied in the streamwise (x) direction. Time series of velocities at a y-z plane (e.g. a-b plane) are saved, which are then applied to the inlet of wind farm domain.

Figure 3: Inflow field from mesoscale simulation of WRF (left) and the added synthetic turbulence (right).

To reconstruct the small unresolved turbulence scales for inflow velocities of the LES, a synthetic turbulence generation technique developed by Mann (Prob. Engng. Mech., Vol. 13, No. 4, pp. 269-282, 1998) was used. In Figure 3, we show the synthetic turbulent flow field generated from this technique. In the right figure of Figure 3, from top to below, we show the contours of the streamwise, spanwise and wall-normal velocity fluctuations at an x-z plane (where x and z represent the streamwise and wall-normal directions, respectively).

c. Parameterization of wind turbines

To avoid an excessive computational cost to solve the boundary layer flow around the blade, actuator disk and actuator line models were employed for parameterization of the effects of wind turbine on the flow. For the actuator disk model, the wind turbine rotor is represented by a permeable disk as shown in left plot of Figure 4. The forces are uniformly distributed on the disk for actuator disk model, in which the thrust force coefficient is from the one-dimensional momentum theory, which is shown as follows:

\[ C_T = 4\alpha (1 - \alpha) \]

where \( \alpha \) is the induction factor. For the actuator line model, the rotor blade is represented by a single line as shown in Figure 4. The drag and lift coefficients were obtained from a look-up table. The mesh for the actuator disk/line model generally does
not coincide with the background mesh for the fluid. A regularized delta function was used to transfer the quantities between the two meshes.

**Figure 4:** Schematic of the meshes used for actuator disk model (left) and actuator line model (right).

d. Improved roughness height model

A useful and very efficient approach for engineering calculations of wind farm performance is the use of theoretical approaches. One of the commonly used models is the effective roughness height model [S. Frandsen, *J. Wind Engng. Ind. Aerodyn.* 39, 251-265, 1992]. Conventionally used effective roughness models take the turbine spacing effects into account through the turbine density. Available models, however, do not take into account the effects of varying the streamwise ($S_x$) and spanwise ($S_y$) turbine spacing. To address this shortcoming, we carried out a series of Large-Eddy Simulations (LES) for infinite aligned wind farms and systematically varied the streamwise and spanwise turbine spacings. The results of these simulations were used to develop a new effective roughness height model that takes into account turbine spacing effects. The details of the model are described in a journal paper, which has been submitted for publication (Yang et al. 2012). Figure 5 shows sample results illustrating the performance of the new model by comparing quantities predicted by the model with those calculated directly from the LES. The figure also shows results obtained with the previously developed model by Frandsen to gauge the performance of our new model relative to available models in the literature. As seen in this figure, the present model can capture the different effects of the streamwise and spanwise spacing effects with good accuracy. Such effects are entirely missed by Frandsen’s model, which, as discussed above, is not sensitized to turbine spacing effects. The new model developed herein provides a powerful engineering approach for evaluating the performance of aligned wind farm and can be used to estimate the effects turbine spacing on wind farm power output and efficiency.
Figure 5: Comparison of the model predictions with those predicted by LES. Left figure: \( S_x \) equals 5D, 7D, 9D, 11D, 13D, 15D, 17D, 20D with a fixed \( S_y = 4D \). Right figure: \( S_y \) equals 2D, 4D, 6D and 8D with a fixed \( S_x = 7D \).

e. Weather model for large-scale wind patterns

A simulation was conducted with the Weather Research and Forecast (WRF) model to assess the ability of the model to characterize the wind in an operating wind farm when the turbines are operating. For the simulation, we chose a time period of several days during the field measurement period when the wind direction was relatively steady from the south and the atmospheric boundary layer conditions varied from convective (daytime) stable (nocturnal). During this time period, the sodars were able to measure several instances of waking in the southernmost row of turbines during periods of both convective and stable boundary layer conditions. Thus, this time period provides the best opportunity for comparisons between models and the sodar and the turbine data.

The period of modeling started July 1, 2010 at 0000 UTC and ended July 5, 2010 at 0000 UTC. The WRF outermost domain had a grid interval of 13.5 km, and its initial and lateral boundary conditions were provided from global forecast system (GFS) model analyses (for 0000, 0600, 1200, and 1800 UTC) and 3-hour forecasts (for 0300, 0900, 1500, and 2100 UTC). Two-way nesting was used for the inner domains, which had grid intervals of 4.5 km, 1.5 km, and 500 meters. The innermost grid encompassed the Mower County wind farm and neighboring wind farms to the south and north.

The latest version of WRF has a wind turbine parameterization that can be utilized to predict the effects of wind power generation on the atmospheric flow. For this particular run, we modified the wind turbine parameterization to employ the turbine thrust coefficients specific to the Siemens 2.3 MW turbines operating at the Mower County wind farm. The turbines were assumed to be operating during the entire model run period. For the neighboring wind farms, there was no data available regarding the specific turbines or their thrust coefficients, but the locations of individual turbines within these wind farms could be determined using Google Earth™. To provide at least a rough estimate of the operation of these surrounding farms, the farms were assumed to have General Electric SLE 1.5 MW turbines.

Figure 6 shows a snapshot of the WRF output wind speeds and direction. The turbine wakes are evident in the reduced wind speeds to the north of the operating turbines in the farm with a particularly sharp contrast in the southernmost half of the farm. Due to the available grid interval in WRF, the gradients of wind speed are not nearly as sharp as are
observed in the wind farm, and the turbine wakes are artificially wide compared to the individual turbine wakes, particularly in the near field region (less than 10 rotor diameters downstream).

Figure 6: RF model wind speed at 80 meters AGL (colored shading), wind speed measured by the wind turbine SCADA system (colored shapes), streamlines on the 80 meter AGL surface, and SCADA wind vectors (arrows) at 1440 UTC July 3, 2010.

Task 2. Validation of Virtual Wind Simulator using wind tunnel measurements

a. Wind tunnel experiments
Several experiments were performed to get a fundamental understanding of the turbulent processes around a single wind turbine and wind farms. The information was used to test and validate the Virtual Wind Simulator as well as to develop new parameterizations to address the problem of wind farm siting.

i. Single wind turbine. Wind-tunnel experiments on a single turbine focused on describing the mean characteristics on the wake (Figure 7) and the Reynolds number dependence of turbulence statistics in the wake (Figure 8). For the latter, the miniature wind turbine was placed in a boundary layer flow developed over a smooth surface under various Reynolds numbers, based on the turbine rotor diameter and the velocity at hub height, ranging from $\text{Re} = 1.66 \times 10^4$ to $1.73 \times 10^5$. Results suggest that main flow statistics (mean velocity, turbulence intensity, kinematic shear stress and velocity skewness) become independent of Reynolds number starting from $\text{Re} \approx 9.3 \times 10^4$. Figures 9 and 10 show the mean velocity and turbulence intensity distributions for various Reynolds numbers. In general, stronger Reynolds number dependence was observed in the near wake region where the flow is strongly affected by the aerodynamics of the wind turbine blades. In contrast, in the far wake region, where the boundary layer flow starts to modulate the dynamics of the wake, main statistics showed weak Reynolds dependence.

These results allowed us to extrapolate wind tunnel and CFD simulations, which often are conducted at lower Reynolds numbers, to full scale conditions. In particular, these findings motivated us to improve existing parameterizations for wind turbine wakes (e.g.,
velocity deficit, wake expansion, turbulence intensity) under neutral conditions and the predictive capabilities of atmospheric LES models.

Figure 7: Schematic of the miniature wind turbine and experimental set-up (left). Mean velocity distribution in the central plane of the wake (a) and relative velocity deficit in the wake (b).

Figure 8: Experimental set-up. Top: front and lateral views of the miniature wind turbine, bottom: measurement locations of Figures 9 and 10.

Figure 9: Left: normalized velocity distribution at x/d=4; right: Normalized velocity at hub height for different Reynolds numbers.
ii. Aligned wind farms. Main flow properties of the turbulent flow within and above aligned wind farms (Figure 11) were obtained and compared with staggered wind turbine arrays to infer the effect of the layout on the overall wind-farm efficiency. High-resolution spatial and temporal fields of velocity and turbulence statistics, using a hotwire anemometer, were obtained at different locations to characterize the wake flows in two aligned wind-farm scenarios (e.g., Figure 12).

Figure 10: Left: Turbulence intensity distribution at x/d=4; right: Turbulence intensity at hub height for different Reynolds numbers.

Figure 11: Measurements locations in the aligned wind farm.
iii. Staggered wind farm. Fundamental properties of the turbulent flow around a perfectly staggered wind farm placed in a boundary layer flow were also investigated. Main results reveal that turbulent flow around a staggered and aligned wind farm are quite different. In particular, it was found that vertical transport in the staggered wind farm appears to be higher, which leads to an enhanced power. Figures 13 and 14 illustrate the experimental set-up, the mean velocity and turbulence intensity distribution in the central plane of measurements. Figure 15 shows the comparison of the angular velocity of staggered and aligned wind farms.

Figure 12: Non-dimensional velocity distribution in the central plane of the wind farm in the case with streamwise separation of 5 rotor diameters (top); and the turbulence intensity distribution (bottom).

Figure 13: Left: Miniature wind farm in a staggered configuration placed in a turbulent boundary layer flow at the SAFL wind tunnel. Right: Schematic of wind turbine array and measurement locations. More details are given in Chamorro, Arndt and Sotiropoulos (2011).
iv. Fully developed wind farms. Wind tunnel experiments were performed to quantify the turbulent processes occurring in large wind farms with different layouts (turbine spacing of 6, 8, 10 and 12 rotor diameters). Experiments were performed in the Reynolds numbers independence regime (Chamorro, Arndt and Sotiropoulos, 2011). Figure 16 shows the general set-up of the fully developed wind farm in the wind tunnel. Flow statistics are illustrated in Figures 17, 18 and 19.
Figure 16: Wind tunnel set-up for the fully-developed wind farm study.

Figure 17: Example of measurements (mean velocity and turbulence levels) in a fully developed wind farm with turbine spacing of 6 and 3 rotor diameters in the streamwise and spanwise directions, respectively.
Figure 18: Example of measurements (mean velocity, turbulence levels and shear stress) in a fully developed wind farm with turbine spacing of 12 and 3 rotor diameters in the streamwise and spanwise directions, respectively.

Figure 19: Example of parameterization for wind farms (from wind tunnel experiments).
b. Validation of VWiS

i. Single turbine. The actuator disk/line model was first validated with wind tunnel experiments on a single turbine case. The comparison of inflow velocity and turbulence statistics at the inlet are shown in first column of Figure 20. As seen, the inflow conditions used in the present LES show good agreement with that in experiment. The comparison of mean velocity profiles are shown in the first row of Figure 20. In the second row and third row of Figure 20, we compare the turbulence intensities and primary Reynolds shear stress at different downstream locations, respectively. As seen in Figure 20, the predictions from actuator line model and actuator disk model agree very well (less than 10 percent maximum error) with the experimental measurements for downstream locations larger than two rotor diameters (D) in terms of both mean streamwise velocity and turbulence intensity. In the near wake locations (less than 2D), both models show discrepancies with the wind tunnel measurements, although the predictions from actuator line model are somewhat better that from actuator disk model. The contours of the time-averaged flow field are shown in Figure 21.

Figure 20: Comparison of mean velocity profiles (first row), streamwise turbulence intensities (second row) and Reynolds shear stresses (third row) at different downstream locations. From left to right: Inflow, 2D, 5D and 10D. Symbols: experiment; solid line: actuator line model; dashed line: actuator disk model.
Figure 21: The time-averaged flow (streamwise velocity (top), streamwise turbulence intensity (middle), Reynolds shear stress (bottom)) for flow past a stand-alone wind turbine.

**ii. Aligned wind farm.** The present Virtual Wind Simulator, which employs large-eddy simulation (LES) for the wind field and actuator disk/line model for parameterizing the wind turbine rotors, was further validated for finite-size wind farms using measurements from wind tunnel experiment. The size of the computational domain is 30D, 12D and 5D in the streamwise (x), spanwise (y) and vertical (z) directions, respectively, where D is the diameter of the wind turbine rotor. The grid employs 600, 240 and 100 grid cells in x, y and z directions, respectively, which are uniformly distributed in all three directions. There are six rows in the streamwise direction. Each row has four turbines. The streamwise turbine spacing and spanwise turbine is 5D and 4D, respectively. The velocity field at the inflow boundary is generated from a separate simulation of a fully developed turbulent channel flow. The Reynolds number based on the height of boundary layer and
the inflow bulk velocity is 140000. For the actuator disk model, the induction factor is fixed at 0.25 for all the turbines.

The right column of Figure 22 shows the time-averaged streamwise velocity at different vertical locations. As seen, the predictions from the actuator disk model are lower than that from the experiment at the bottom of wind turbines. At the other vertical locations, the mean velocity profiles from actuator disk model and actuator line model are nearly the same and agree well with that from wind tunnel measurements.

**Figure 22:** Comparison of the mean streamwise velocity (left column) and streamwise turbulence intensity (right column) from actuator disk model and actuator line model with wind tunnel measurements at different vertical locations (bottom tip (top), hub height (middle) and top tip (bottom)).

The left column of Figure 22 shows the streamwise turbulence intensities at the bottom, hub and top of wind turbines. As seen, the predictions from actuator disk model and actuator line model are somewhat higher than that from the experiment for the region between the 1st and 2nd rows at the bottom of wind turbines. For all the other locations, good agreements are obtained for both actuator disk model and actuator line model.

The contours of the time-averaged flow field are shown in Figure 23.
Figure 23: The time-averaged flow (streamwise velocity (top), streamwise turbulence intensity (middle), Reynolds shear stress (bottom)) for flow past an aligned wind-turbine array.

**iii. Fully developed wind farm.** After validating the actuator disk/line model for one turbine case, the actuator disk model was further validated for infinite wind farm simulations. We employ the same layout of wind turbines with the reference (Calaf et al., Phys. Fluids, 22, 015110, 2010). There are 4 turbines and 6 turbines in the streamwise (x) and spanwise directions (y). At the top, free slip boundary condition and non-penetration boundary conditions are used for parallel and normal velocity components, respectively. At the bottom wall, wall model is used. Periodic boundary condition is used in horizontal directions. It should be noted, however, that there are some differences between our solver with that used in reference. First, Calaf et al. employed a pseudospectral discretization in the horizontal directions and finite differencing in the vertical direction in order to solve the filtered Navier-Stokes equations, while we employed second-order accurate finite-differencing in all three directions. Second, the actuator disk model is implemented slightly differently in the two models. While Calaf et al. obtained the averaged velocity on the disk by using spatial and temporal averaging; we only used the spatial averaging. Finally, the subgrid scale models employed by Calaf et al. are the Lagrangian dynamic Smagorinsky model and the standard Smagorinsky model, while we employed the dynamic Smagorinsky model.
In Figure 24, we show the comparison the results from the present simulation with the reference. As seen, both the mean velocity profile and Reynolds and dispersive shear stresses show good agreements with the reference despite of the differences of the two solvers.

![Comparison of the predictions from the present LES with actuator model with the reference.](image)

**Figure 24**: Comparison of the predictions from the present LES with actuator model with the reference. Symbols: reference; solid lines: present. Left: mean velocity profile; right: Reynolds and dispersive shear stresses.

Computed results of fully developed aligned wind-turbine arrays with different streamwise spacing $S_x$ and spanwise spacings $S_y$ are presented in this part. Some cases have the same spanwise spacing $S_y = 4D$, and the other cases are with the same streamwise spacing $S_x = 7D$. For all the cases, the Reynolds number based on the bulk velocity and the height of the boundary layer is $1 \times 10^6$. The axial induction factor $\alpha$ equals 0.25. Figure 25 shows the mean velocity profiles with different streamwise spacing and spanwise spacing. We can see that the double log laws exist beneath the wind turbine region and beyond the wind turbine region for all the cases. The left figure of Figure 11 shows the normalized extracted power density for different spacing. The extracted power density is defined as $P_d = \frac{1}{N_t} \sum_{t=1}^{N_t} \frac{P_t}{S_x S_y}$, where $P_t$ is the extracted power of the $t^{th}$ turbine. From this figure, it can be seen that the maximum extracted power density is larger when we increase the streamwise spacing or the spanwise spacing. And it can be seen that it is more efficient when we increase the streamwise spacing. The right figure of Figure 26 shows the disk-averaged root-mean-square (RMS) velocity fluctuations on the disk which are non-dimensionalized by the averaged streamwise velocity on the disk $U_d$. This figure shows that the RMS of velocity fluctuations decreases quickly when we increase the streamwise spacings. The RMS of velocity fluctuations decreases when we increase $S_y$ from $2D$ to $4D$ but it doesn't change very much if we further increase the spanwise spacing.

In all, we find that the extracted power can be increased by increasing both of the streamwise spacing and spanwise spacing, but it is more efficient to increase the streamwise spacing. The extracted power densities are larger for the layouts which have the larger streamwise spacing at the same occupied area. For the turbulence intensities on the disc, the increases in the streamwise spacing can reduce them effectively and the effects are minor when we increase the spanwise spacing.
Figure 25. Mean velocity profiles for different spacing. Left: different streamwise spacing with fixed spanwise spacing $S_y = 4D$; Right: different spanwise spacing with fixed streamwise spacing $S_x = 7D$.

Figure 26. Extracted power density (left) and Averaged root-mean-square velocity fluctuations on the disc normalized by the disc-averaging streamwise velocity $\bar{U}_d$ (right) for different streamwise and spanwise spacing.

The spacing effects in staggered wind farms were studied and compared with the corresponding aligned wind farms. Different from aligned wind farms, the wake from one turbine has complex interactions with its downstream wind turbine wakes. Figure 1 shows the contours of the mean streamwise velocity at hub height. Figures 27 (a) to 27 (b) show the contours for staggered wind farms. Figures 27 (e) to 27 (f) show the contours for the aligned wind farms, which has the same turbine occupied area with case shown in figure 27 (c).
Figure 27: Contours of mean streamwise velocity at hub height for staggered wind farms with comparisons with aligned wind farms.

Task 3. Testing of Virtual Wind Simulator using wind and turbulence measurements collected at an operational farm

a. Numerical simulations of Mower County wind farm
Using the multi-scale modeling for our VWiS, we simulated a Mower County wind farm and performed comparison studies with field measurements for the time period ranging from 6 am to 8 am on July 2, 2010. In Figure 28, we show the computational domains for this case. The left image shows the computational domain for WRF with the size of approximate 50 kilometers. The right one shows the computational domain for LES with the size of approximate 2 kilometers. The WRF simulation was carried out by Robert J Conzemius at WindLogics Inc. The grid spacings for WRF simulations are approximately 170 and 20 meters in the horizontal and wall-normal directions, respectively. The grid spacings employed in LES are 20 and 9 meters in the horizontal and wall-normal directions, respectively. There are five turbines within this area as shown in the LES-
domain of Figure 28. The field measurements were taken at two locations s1 and s2. Actuator disk parameterizations are used for the wind turbine modeling. The atmospheric boundary layer was stably stratified during the period of analysis. Those stratification effects are considered in the simulations. A wall model for temperature (Phys. Fluids, 23, 126603 (2011)) was also used.

Figure 28: Computational domains for multi-scale simulation.

Figure 29 illustrates contours of the mean streamwise velocity at hub height, where the left and right figures show the computed results with and without adding synthetic turbulence, respectively. It is seen that inflow synthetic turbulence significantly accelerates the recovery of the turbine wakes. Figure 30 shows the comparison of the computed mean streamwise velocity profiles with the field measurements. Very good agreements are obtained for the measurements at location S1, which is not located within the wind turbines wakes. For location S2 which is located within the wake of turbine T41, some deviations are observed.

Figure 29: Comparison of time-averaged streamwise velocity at hub height at Mower County Wind farm. Left: Unsteady inflow with synthetic turbulence superimposed on the mean velocity field obtained by WRF. Right: Steady flow at the inlet, i.e. without taking into account turbulence effects, prescribed from
the results of the WRF calculation; Notice how the turbulent inflow (right) greatly impacts the recovery of the turbine wakes.

Figure 30: Comparison of the computed mean streamwise velocity profiles with field measurements.

Table 1 shows the comparisons of the power output with the field measurements. It is seen that overall good agreements are obtained for turbines T39, T40, T41 and T43 for both cases, that is, for the simulation with and without synthetic turbulence at the inlet. For the T42 turbine, however, which is in the wake of T41, the simulation with synthetic turbulence significantly improves the predictions of power output compared with the one without inflow synthetic turbulence. These results underscore the ability of the VWiS to simulate with good accuracy the power output of real-life wind farms and underscore the need to account in the simulation for the effects of atmospheric turbulence.

Table 1: Comparison of the mean power output

<table>
<thead>
<tr>
<th></th>
<th>T39 (MW)</th>
<th>T40(MW)</th>
<th>T41(MW)</th>
<th>T42(MW)</th>
<th>T43(MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements</td>
<td>2.15</td>
<td>2.14</td>
<td>1.86</td>
<td>1.85</td>
<td></td>
</tr>
<tr>
<td>Inflow: without synthetic turbulence</td>
<td>2.38</td>
<td>2.25</td>
<td>2.07</td>
<td>0.79</td>
<td>1.94</td>
</tr>
<tr>
<td>Inflow: with synthetic turbulence</td>
<td>2.38</td>
<td>2.13</td>
<td>2.75</td>
<td>1.51</td>
<td>2.14</td>
</tr>
</tbody>
</table>

b. Field experiments at Mower County wind farm

In collaboration with our partners from WindLogics, Inc. and Barr Engineering, we performed flow measurements in a wind farm located in Mower County. Two Sodars provided by WindLogics collected several months of data. A LiDAR was also used to
support the work. Field campaign (WindLogics activities) included data analysis of the SODAR and SCADA data collected from the Mower County wind farm and refinements of quality control and quality assurance procedures for the SCADA data. The sodar data was composited to form turbine wake cross sections. Prior analyses formed the composite cross-sections for all data in the sampling period, but latest analyses categorized the cross sections according to atmospheric stability. An example is illustrated in Figure 31. It shows a cross section of the ratio of the waked sodar wind speed to the free stream (upstream from the turbine wake) wind speed and vertical velocity for stable conditions during a field campaign. All three sodars were able to measure the rotation of the turbine wake flow. Specifically, Figure 31 shows that the vertical velocity is upward to the left of the wake centerline (Y=0) and downward to the right of the centerline. These results are qualitatively consistent with large eddy simulations that have been conducted.

![Figure 31: Y-Z cross section of turbine wake measured by the Triton sodars for stable atmospheric conditions during summer 2010. Shading indicates the ratio of wind speeds of the waked to unwaked sodar (the waked sodar is downstream from Turbine 41), and the contour lines show vertical velocity (contour interval of 0.05 m/s, dashed lines are negative, zero line is bold).](image)

Barr monitored an ASC Sodar unit deployed at Mower County, post data on project website, and coordinated analysis with WindLogics. Final monitoring adjustments for Mower County site, including Natural Power Lidar and ASC Sodar relocations to new sites within the wind farm were performed. Barr coordinated final high-resolution data burst from ASC SoDAR at Mower County site, retrieved ASC SoDAR for review and redeployment at Prairie Island complex terrain site. They installed a meteorological tower and associated equipment near the Prairie Island Indian Community Treasure Island Casino for monitoring at complex terrain site.
Task 4. Application of Virtual Wind Simulator for assessment of wind resources at an undeveloped site with complex terrain

a. Numerical simulations of Prairie Island case
In this task, we applied the VWiS to assess wind resources at Prairie Island Indian Community which has effects of a complex topography. The topography in the area of Prairie Island is shown in Figure 33. The incoming velocity at one measurement point (M1) of the complex terrains in the upstream of Prairie Island is 9.4 m/s. The wind is from southwest, in which direction complex terrains are located. The size of the computational domain, the contours of the land surface elevation and the 8 suppositional wind turbines are shown in Figure 33. The elevation of a southwest hill is about 100 meters above Prairie Island. The complex topography is modeled using CURVIB method. Actuator line model is employed for the wind turbine parameterization. Two cases are performed: one without wind turbines; the other with 8 simulated wind turbines. The Siemens SWT-2.3-93 wind turbine is simulated, which is the same as that used in Mower County wind farm. The rotor diameter of the turbine is 93 meters. The Hub height of the turbine is 80 meters.

Figure 33: Topography and 8 suppositional wind turbines (T1-T8) at Prairie Island. The two points (M1 and M2) in the figure show the locations of the Sodars. The wind is from left to right.
The comparisons of the time-averaged mean streamwise velocity with the field measurements are shown in Figure 34. As seen, good agreements are obtained for both upstream (M1 in Figure 33) and downstream locations (M2 in Figure 33). The time-averaged contours of the streamwise velocity and turbulence kinetic energy at horizontal plane located at hub height for the case without wind turbines are shown in Figure 35. It is seen that the mean flow field is composed of high speed and low speed streaks caused by the upstream complex terrains. One significant lower speed streak is located behind the trench of the upstream complex terrains. The TKE is very significant behind the complex terrains and lasts about 1000 meters from the upstream complex terrains. The TKE behind the trench is much weaker than that in the other locations behind the terrains. However, the wind speed behind the trench is also smaller than that from the other locations.

Figure 34: Comparison of the computed time-averaged streamwise velocity with measurements for Prairie Island case, in which the comparison at M1 (at the upstream complex terrains) and M2 (at the downstream Prairie Island) are shown in the left and right figures, respectively.

The time averaged streamwise velocity and turbulence kinetic energy with 8 suppositional wind turbines are shown in Figure 36. The power outputs are illustrated in Table 2. It is seen that turbine T2 and T7, which are located in the low speed streak, produce less power than the other turbines.
**Figure 35:** Time-averaged flow field (mean streamwise velocity (top) and turbulence kinetic energy (bottom)) at hub height (80 meters from the Prairie Island) for Prairie Island case.

**Figure 36:** Time-averaged flow field (mean streamwise velocity (top) and turbulence kinetic energy (bottom)) at hub height (80 meters from the Prairie Island) for Prairie Island case with 8 suppositional wind turbines.

**Table 2:** Power output from the 8 suppositional wind turbines

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>0.4</td>
<td>0.17</td>
<td>0.45</td>
<td>0.65</td>
<td>0.55</td>
<td>0.55</td>
<td>0.25</td>
<td>0.45</td>
</tr>
</tbody>
</table>
In summary, the VWiS are successfully applied to simulate the wind field at Prairie Island with a hypothetical wind farm that contains eight turbines. The effects of the complex terrains on the wind at Prairies Island were investigated. What we learn from this simulation is that it is better to place turbines away from complex terrains that create ground turbulence to extract more power and lower the dynamic loading at the same time.

b. Field experiments at Prairie Island
Measurements were performed in collaboration with our partners from WindLogics, Inc. and Barr Engineering. WindLogics collected measurements from the sodar atop the bluff near Prairie Island. A Triton SODAR, owned by WindLogics Inc., was deployed at the Prairie Island bluff location just east of County Road 18 on the Minnesota side of the Mississippi River. Mariah Resources was contracted for the deployment and worked with the Prairie Island Indian Community in preparing the site prior to the SODAR deployments. An example of the data collected so far is included in Figures 37 and 38.

![Figure 37: Wind profile analysis for the SODAR data collected from the Prairie Island bluff site.](image)

![Figure 38: Wind rose at 40 meters above ground level for the SODAR data collected from the Prairie Island bluff site.](image)

Barr monitored data from equipment deployed at this “complex terrain” site at Prairie Island, near Red Wing, Minnesota. The equipment was deployed on property owned by
the Prairie Island Indian Community, at sites selected in cooperation with the Prairie Island Indian Community.

The following data were collected at the Prairie Island “complex terrain” site:

- Conventional anemometry data from a 50-meter meteorological tower at the Prairie Island Casino Site;
- Three-dimensional data from two CSAT3 sonic anemometers installed on the same 50-meter tower as the conventional anemometry;
- High resolution “moments” data and standard 10-minute increment data from the ASC sodar unit at the Prairie Island Casino Site;
- 10-minute increment data from a Triton Sodar unit at the Prairie Island “Bluff Site.”

Figure 39 is a photograph of the CSAT3 and conventional anemometry installed on the meteorological tower at the Prairie Island Casino Site. Having collected over six months of Sodar data at the Prairie Island site, Barr and WindLogics both removed their Sodar units from site.

![Figure 39: Conventional and sonic anemometry installed on 50-meter tower at Prairie Island “Casino Site”](image)

**Project Status:**

The project tasks have been fully completed and the goals have been achieved.

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Appendix:

List publications

Papers in Refereed Journals


Conference Presentations


