Wind Power

ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling

A key challenge to wide-scale deployment of wind energy in the utility grid without subsidies is predicting and minimizing plant-level energy losses, which are currently estimated to be 20% in relatively flat areas and much higher in regions of complex terrain. Current methods for modeling wind plant performance fall far short due to insufficient model fidelity and inadequate treatment of key phenomena, combined with a lack of computational power necessary to address the wide range of relevant length scales associated with wind plants. Thus, the ExaWind challenge problem is a predictive simulation of a wind farm with tens of megawatt-scale wind turbines dispersed over an area of 50 km^2, with complex terrain, involving simulations with O(100) billion grid points. These predictive, physics-based, high-fidelity computational models, validated with targeted experiments, will drive innovation in the blade, turbine, and wind plant design processes by providing a validated "ground truth" foundation for new turbine design models, wind plant siting, operational controls, and reliably integrating wind energy into the grid.

The scientific goal of the ExaWind project is to advance our fundamental understanding of the flow physics governing whole wind plant performance, including wake formation, complex terrain impacts, and turbine–turbine interaction effects. Greater use of the nation's abundant wind resources for electric power generation—reaching 30% of US electrical supply—will have profound societal and economic impacts: strengthening US energy security through greater diversity in its energy supply, providing cost-competitive electricity to key regions across the country, reducing greenhouse gas emissions, and reducing water used in thermoelectric power generation.

This multidisciplinary project embodies a systematic development of the modeling capability and computational performance and scalability required for effective exascale simulations. The project plan builds progressively from predictive petascale simulations of a single turbine, for which the detailed blade geometry is resolved, meshes rotate and deform with blade and tower motions, and atmospheric turbulence is realistically modeled, to a multi-turbine array in complex terrain.
This new modeling and simulation capability will establish a virtual wind plant test bed that will revolutionize the design and control of wind farms and result in a significant advance in the scientific community's ability to predict the response of wind farms to a wide range of atmospheric conditions.

The ExaWind challenge problem is a predictive simulation of a wind farm with tens of megawatt-scale wind turbines dispersed over an area of 50 km^2. The project goal is to capture crucial phenomena that are under-resolved in today's models, including wake formation, complex-terrain impacts, wake–atmosphere interaction, turbine–turbine interaction, and blade boundary layer dynamics. This target requires a modeling and simulation capability that resolves turbine geometry and utilizes adequate grid resolution (down to micron scales within the blade boundary layers). The resolution must capture the upstream chord-scale atmospheric turbulent eddies, generation of near-blade vorticity, and propagation and breakdown of this vorticity within the turbine wake to a distance of many rotor diameters downstream. This application uses the Nalu-Wind computional fluid dynamics (CFD) code and the OpenFAST turbine simulation code, both of which have been specifically designed for wind turbine and wind farm simulations. The simulation will require a hybrid Reynolds-averaged-Navier-Stokes/large-eddy-simulation (RANS/LES) turbulence model, fluid–structure interaction, and atmospheric turbulent flow.

The simulation will contain at least nine megawatt-scale turbines (e.g., NREL 5 MW reference turbines) organized in a 3×3 array and residing in a 4 km×4 km domain with a height of at least 1 km. A hybrid-RANS/LES model will be employed for which an unsteady RANS model will be used near turbine surfaces and an LES model will be used in the wake region. The simulation will have a mean wind speed at the turbines' rated speed (e.g., 11.4 m/s for the NREL 5 MW reference turbine). The model will require at least 30B grid points (and 150B degrees of freedom) to resolve the system, and near-blade grid spacing will be such that the viscous sublayer (within the RANS region) is resolved. A successful simulation will require an optimized solver stack that minimizes time per time step. A scientifically meaningful simulation duration will be for at least one domain transit time (~500 s for the 4 km×4 km domain at 11.4 m/s). The project will demonstrate that such a simulation is feasible within 4 weeks of system time. The simulation described here will require at least 150,000 time steps, which requires that the average time per time step must be no greater than 16 seconds per time step.

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Progress to date

- Completed transition of key low-Mach-number-CFD computational physics kernels to a highly portable, high-performance Kokkos-based design paradigm.
- Reduced cost of the pressure system solve to 17% of the total simulation time with algorithmic optimizations. In early ExaWind wind turbine simulations with the Nalu-Wind CFD solver stack, about 80% of the wall-clock simulation time was dedicated to the setup and solve of the momentum and pressure linear systems.
- In collaboration with the DOE Wind Energy Technologies Office High-Fidelity Modeling project, implemented and tested a full set of baseline physics models in the Nalu-Wind/OpenFAST modeling and simulation environment, including hybrid-RANS/LES models and fluid–structure interaction coupling. A demonstration calculation of a single NREL 5 MW turbine was performed for which inflow conditions were derived from an atmospheric boundary layer precursor simulation and overset meshes were used for individual blades, nacelle, and tower. The full set of turbine motions from OpenFAST were coupled to the Nalu-Wind fluid mesh, including blade pitch, variable rotation rate, blade deformation, and tower bending.

Exascale computing will help drive innovation in the design of wind farms resulting in increased efficiency and reduced cost per MW-hour of energy production.