The Atmosphere to Electrons (A2e) Initiative, Wind Plant Simulations, and Exascale Computing

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Atmosphere to electrons (A2e) is a new initiative supported by the US Department of Energy, Wind and Water Program. At the heart of A2e is the goal to reduce the cost of energy produced by large wind plants composed of tens to hundreds of wind turbines by using high-fidelity computational modeling in conjunction with a validation-focused experimental campaign. Through the modeling effort, we will increase our understanding of the fundamental wind plant flow physics governing whole plant performance, including wake formation, complex-terrain impacts, and turbine-turbine-interaction effects. Predictive, physics-based high-fidelity computational models, validated with targeted experiments, will directly influence the blade, turbine, and wind plant design process by providing a validated "ground truth" foundation for new reduced-order models in computer-aided engineering, wind plant siting, operational controls, and reliably integrating wind energy into the grid. Simulations will need to capture and predict physics spanning from the atmospheric boundary layer (ABL) down to the near-blade turbulent flow and structural dynamics of blades undergoing large deflections.

Wide-scale deployment (high penetration) of wind without subsidies requires the reduction of plant-level energy losses, which are currently estimated to be 20%, and much higher in areas of complex terrain, and better quantification of the uncertainty in plant performance. Greater use of the nation's abundant wind resources for electric power generation, reaching 30% of U.S. electrical supply, will have profound societal and economic impact: strengthening U.S. 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 thermo-electric power generation. While significant technological advances in blades, gearboxes, and individual turbines have enabled the wind industry to reach its current level of electrical supply, significant challenges still remain to allow increased electricity generated by wind.

Wind Plant Simulation Today: Simulations of the flow within wind plants, where individual turbines are resolved in some fashion, are in the early stages of development. While the majority of simulations either represent individual turbines as actuator discs (e.g., [3]) or actuator lines (e.g., [4]), there are a few simulations where the fluid mesh conforms to blade geometry [5]. Whereas actuator-disc and -line methods work in a fixed grid mesh, geometry conforming simulations require overset and/or sliding-interface capabilities. With direct numerical simulation of atmospheric and turbine flow being inconceivable, and with Reynolds-averaged Navier-Stokes (RANS) computations filtering out important eddy dynamics that affect wind plant performance, large-eddy simulation (LES) or hybrid LES/RANS seems to be the best approach to improving model fidelity within the expected available computing. The standard approach is to model the wind plant within a "box" of fluid, for which specification of boundary conditions representing the surrounding atmosphere is an active research problem (the so-called meso-scale micro-scale coupling; see e.g., [6]). Boundary conditions are either (1) periodic (thereby representing an "infinite" wind plant), (2) taken from a separate ABL simulation in a box with periodic boundary conditions, or (3) taken from a separate simulation in a numerical weather prediction code (e.g., WRF). Due to inadequate resolution, unknown uncertainties, and inadequate validation, today's highest fidelity models are limited to providing high-level qualitative insight.

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Vision for Predictive Wind Plant Simulation: To maximize the impact of exascale-class computing for wind, the DOE A2e program plans to invest in a multi-lab, high-fidelity modeling effort to develop a community-based, open-source modeling and simulation environment utilizing leading-edge high-performance computing (HPC) systems to understand and accurately predict the fundamental flow physics of the whole wind plant, from the atmospheric boundary layer, its interaction with the wind plant, down to and including turbine-turbine interactions, the response of individual turbines, and the impact of complex terrain. This research will enable *predictive* wind plant simulations at unprecedented fidelity, and provide understanding and insights into the fundamental flow physics of whole wind plants. The new simulation tools will require extensive leveraging of software supported by DOE Office of Science and NNSA programs, and access to existing and next-generation DOE leadership-class computing facilities. Simulations will require extensive storage (models with $O(10^9)$ to $O(10^{11})$ grid points will be common), *in situ* data-analysis capabilities, and tools for uncertainty quantification.

As articulated at the recent DOE A2e ModSim Environment Planning Meeting [1] and Wind Plant Physics Planning Meeting [2], we envision that a wind plant simulation capability that is truly predictive will have the following features:

- Blade structural dynamics model that includes complicated composite structure and large, nonlinear deflections that can address, e.g., bend-twist coupling,
- Blade/nacelle/tower conforming fluid meshes that deform with large blade deflection,
- Overset/sliding fluid mesh capabilities that accommodate the rotor rotation, and nacelle yaw,
- Fluid meshes and models that accommodate complex terrain,
- Hybrid LES/RANS turbulence modeling, where LES captures the dynamics of wakes and RANS captures sufficiently the boundary layer at the blade surface, and
- Coupling of mean flow and turbulence from the meso-scale via numerical weather prediction.

A simulation for a *single wind turbine* that encompasses the above features and is sufficiently resolved in space and time is a petascale-class computing problem. As such, scaling up a single-turbine model to a wind plant composed of hundreds of turbines is a *weak scaling* of the single-turbine model, which makes a wind plant well suited for exascale computing. We need exascale computing to accommodate larger models, and not to provide more resolution.

To effectively utilize extreme-scale systems, the end-to-end modeling and simulation system will have to be reworked. The scale of future architectures and challenges associated with I/O, fault-tolerance, etc., will make the current sequential workflow paradigm of create-run-output-analyze impossible. We plan to focus on *in situ* analysis in particular and an integrated approach starting with problem setup (meshing) through analytics. Known challenges include mesh generation at scale, in situ visualization, and uncertainty quantification algorithms that efficiently exploit future machine architectures. In-situ data analytics with the explicit goals of enabling scientific discovery and improving plant-scale design and controls will also be incorporated into the end-to-end workflow.

References

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