Exascale Computing and Wind Energy

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White paper submitted to the DOE ASCR *Turbulent Flow Simulation at the Exascale: Opportunities and Challenges Workshop*, Mayflower Autograph Hotel, Washington, D.C., August 4-5, 2015

We describe here the need for, and the challenges facing, exascale computing that enables predictive simulation of large wind plants, and the important outcomes that will be realized through those simulations. The wind energy problem is difficult because the flows are highly turbulent and contain a huge range of spatio-temporal scales. For example, the mesoscale weather patterns that affect the flow at the wind plant are on the order of hundreds of kilometers in length, a typical wind plant can cover an area up to one hundred square kilometers, and at the smallest scale are blade boundary layers, which may be only millimeters thick. These physics span $O(10^5)$ m to $O(10^{-3})$m – an eight-order-of-magnitude range.

The need for exascale computing: With today's state-of-the-art wind simulation capability as a backdrop, we consider the resource requirements for physics-based predictive wind plan simulations. As an example, we focus on the flow within the wind plant, which is considered the micro-scale-flow domain. At the meso-scale are larger-scale weather-related flows. The computational "box" containing the wind plant is about 5 km x 5 km in the horizontal and extending 1 km into the atmosphere, and we consider models where the turbine structures (tower, nacelle, blades) are resolved (as in Sitaraman et al., 2014). The preferred flow model will be hybrid RANS-LES, where blade boundary layers are computed with a RANS turbulences model, and where off-blade flows are computed with LES. Ground-surface boundary layers can be calculated with wall-modeled LES (Moeng, 1984). Before considering a full wind plant, consider the computational "box" domain containing a single turbine. With the flow modeled as described above, we anticipate that a sufficiently resolved simulation will have $O(10^{-6})$ m wall normal resolution on the blade, $O(10^{-2})$ m resolution in the near wake, and O(1) m resolution in the far wake. For the single-turbine "box" extending downstream by one typical turbine spacing distance this resolution corresponds to $O(10^8)$ grid cells. Assuming incompresible flow and a semi-implicit time update algorithm, time steps will be $O(10^{-3})$ s, which necessitate $O(10^6)$ time steps for a simulation of 30 minutes. It is not hard to see that simulating the flow in around a single-turbine and its wake is a petascale-class problem. Combining these boxes (a "weak" scale up) to represent a modern wind plant array of hundreds of turbines clearly will require exascale-class computing, where simulations will have $O(10^{10})$ cells.

Opportunities with exascale computing: While the wind industry has solved the show-stopping problems of designing, deploying, and operating a single wind turbine, large-scale deployment of wind energy will include large many-turbine wind plants. Energy losses within wind plant are typically 20%, and can be much higher in areas of complex terrain. Further, turbines in wind plants experience significantly higher rates of failure than stand-alone turbines, which is taken to be due to the complex wake interactions. In order to make wind energy competitive with fossil fuels without subsidies, the wind plant losses need to be minimized, but more importantly, losses and wind plant performance need to be understood, predicted, and quantified. However, the wind industry and research communities have a poor grasp of the nature of wind plant flow dynamics, and do not have adequate tools for the design and

optimization of wind plants. Some specific opportunities envisioned with exascale computing are as follows:

- Results from high-fidelity simulations will be the foundation on which lower-fidelity engineering/design models are improved. For example, the actuator line approach (see, e.g., Churchfield et al., 2013) will be the "high-fidelity" simulation approach used in siting optimization and analysis for wind plants. Actuator lines show great promise, but the have yet to be systematically validated and analyzed for their predictive capability
- Performing comprehensive field measurement campaigns with highly instrumented turbines and high-accuracy measurement flow measurement tools is costly. To date, no single field measurement campaign of a wind plant stands out as comprehensive. Being able to simulate such a flow and place virtual (and non-invasive) measurement devices in many more locations than is physically possible today is highly attractive. The data set would contain uncertainty from the models used, such as the turbulence models or LES wall models, but it would yield insights into flow phenomena that would otherwise go unnoticed. Such simulations could then guide experimentalists in designing more targeted field campaigns using a more tractable amount of measurement devices.
- Such simulations would allow a better understanding of phenomena like blade boundary layer separation and dynamic stall and a detailed understanding of the turbine structural response to the passage of turbulence structures. For example, the response of the blade structure to the passage of a turbulent eddy from the atmosphere or from an upstream wake is likely not instantaneous, and simulations of this kind would allow that process to be well captured with a reduced-order model.
- Not only would exascale computing allow for wind plant computations of a scale never performed before, but it also would allow for large batches of smaller computations. This would be useful for exploring parameters spaces, such as wind plant response to variation of a large number of atmospheric variables.

In summary, we envision exascale computing to afford huge improvements in understanding of wind plant aerodynamics, which would then allow for better lower-fidelity models that engineers could use to design the next generation of wind turbines and wind plants. These wind plants would be true "systems of systems" utilizing global control systems, more sophisticated sensors (such as lidar scanning the incoming flow field), customized turbines for different locations within the plant, and advanced weather forecasting techniques. With such simulations comes great challenges, such as data reduction, visualization of the time history of the flow, data storage, and parallel-efficient, on-the-fly, interactive data sampling.

References

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