RESEARCH NEEDS FOR WIND RESOURCE CHARACTERIZATION

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As energy demand increases, the need to reach beyond traditional hydrocarbon-based sources of power is becoming ever clearer and is in tandem with a compelling need to reduce emissions of greenhouse gases. Despite significant wind resources, the U.S. currently obtains about 1% of its electric power from wind generation. A recent analysis by the U.S. Department of Energy (DOE), the National Renewable Energy Laboratory (NREL), and the American Wind Energy Association demonstrated the technical feasibility of expanding the U.S. wind industry to meet 20% of U.S. electric power needs by 2030 (U.S. DOE 2008).

Many of the challenges associated with a substantial increase in the use of wind energy reflect fundamental gaps that remain in our knowledge of both atmospheric flow and the interaction of that flow with turbines. To better define these gaps, the DOE's Office of Science and Office of Energy Efficiency and Renewable Energy jointly convened a workshop to assess the current state of the science for wind power production and to define fruitful directions for research (Schreck et al. 2008). More than 120 international participants, representing national laboratories, academia, and the wind energy industry, attended the workshop, which focused on the following four potential research areas: 1) turbine dynamics, 2) micrositing and array effects, 3) mesoscale processes, and 4) climate effects. An overview of each area was followed by a discussion that included all participants. Based on the discussions, the participants generated recommendations for new research. The remainder of this report summarizes the reviews and then details the research recommendations from the workshop. (The full report is available online at www.nrel.gov/docs/fy08osti/43521.pdf.)

DOE WORKSHOP ON RESEARCH NEEDS FOR WIND RESOURCE CHARACTERIZATION

WHAT: Atmospheric scientists and wind industry participants defined priorities for research in wind resource characterization to enable the expansion of wind power.
WHEN: 14–16 January 2008
WHERE: Broomfield, Colorado

KEY WORKSHOP PRESENTATIONS.[1] ***Wind turbine dynamics.*** The design of wind turbines has progressed from extreme load criteria (with minimal testing) in the 1980s to the current substantial effort to incorporate extreme loads, turbulence effects, techniques for load mitigation, site-specific design,

[1] The following keynote addresses were given at the workshop: "Wind turbine dynamics," Sandy Butterfield, National Renewable Energy Laboratory; "Wakes and wind farm performance," Jakob Mann, Risø National Laboratory, Denmark; "Modeling of mesoscale processes," Jerome Fast, Pacific Northwest National Laboratory; and "The climatology of wind," Katherine Klink, University of Minnesota.

and other factors into the turbine design process. As a result, there have been some notable successes in the development of wind turbines. The reported availability of installed turbines for power production at any given time is about 98%. Rotor performance is excellent, yielding approximately 80% of the theoretical limit for energy capture. Improved design techniques are enabling unprecedented growth in machine size, with some planned offshore turbines expected to achieve rated capacities in excess of 5 MW within the next 10 yr as blade diameters approach 140 m. At the same time, however, operating expenditures for wind turbines remain too high because of unscheduled maintenance or repair (especially from premature bearing failures in gearboxes), and the overall capital outlay for turbines remains an impediment to development of this power source in the United States.

Despite the increased sophistication of the turbine design process, a number of areas are ripe for improvement. Some of these involve engineering challenges, such as translating prediction methods for dynamic rotor loads into design codes for turbine components. Fundamental gaps exist in our knowledge of flow on the scale of the turbine blade, including aeroacoustic effects, which become important at blade tips as the turbine diameters and rotation rates increase, and the interaction of realistic turbulence with the blade. Properly accounting for turbulence–blade interactions, including wakes, also requires detailed information on the inflow to the turbine. Thus, improving our knowledge of and ability to forecast both the turbulence structure of the lowest 200 m of the atmosphere and the effects of wakes generated by upwind turbines is essential to improving turbine design and operation.

Wakes and wind farm performance. Much of the research European scientists have done on wakes from turbines and their effects on wind farm performance has been carried out at the Horns Rev wind farm. This power generation facility, approximately 14 km offshore west of Denmark, has 80 turbines in a rectangular array, separated by 560 m. It generates 160 MW of power at full production. Observations indicate that the downstream velocity deficit is commonly 10%–20% in the first 10 km downwind of the turbine array.

To better understand the effects of wakes on wind farm performance, four types of wake models have been developed to characterize turbine wake flows. In order of increasing complexity, these are tip vortex models, actuator disk models, actuator line models, and blade geometry–resolving models. Vortex models shed line vortices from blade tips and calculate resulting vortex trajectories. Actuator disk models and actuator line models provide reduced-order representations of the blade flow field, which then are used to develop large-eddy simulations of the turbulent wake. Blade geometry–resolving models fully resolve the details of the flow across turbine blades, but at great computational cost. Very recently, researchers at Risø National Laboratory have developed a dynamic wake meandering (DWM) model, which treats turbine wakes as passive features transported to downstream turbines by large turbulent eddies in the atmospheric boundary layer.

Modeling of mesoscale processes. Current mesoscale models have a number of strengths that are useful to wind energy applications, such as wind forecasting, mapping wind resources, identifying optimal sites for turbines, and evaluating the impact of turbines on local meteorology. They capture qualitative aspects of diurnal phenomena, such as low-level jets, thermally driven circulations in complex terrain and coastal areas, and the overall structure of the boundary layer, including clouds. In many cases, complex flows compare well with measurements. These models, however, also continue to exhibit weaknesses that are particularly troublesome for wind energy applications. The timing and magnitude of mesoscale phenomena are frequently incorrect. The strength and structure of turbulent mixing, particularly under stable stratification, remain generally poorly represented.

Many of these challenges arise from gaps that remain in our fundamental knowledge of the boundary layer. These gaps are reflected in inadequate parameterizations of both the surface layer and the boundary layer as a whole, especially in nonsteady, spatially heterogeneous environments. Parameterizations for turbulence in the boundary layer pose difficulties, particularly in the "*terra incognita*" of 100-m–1-km scales between large-eddy simulation models and more conventional mesoscale models. Ultimately, the

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scale gap may be bridged by a multiscale modeling approach integrating mesoscale and LES models.

The knowledge gaps reflected in failures of parameterizations are caused in part by inadequate measurements of the boundary layer. Observations, particularly of turbulence, remain quite localized and relatively rare above the surface layer. Longer-term observations, beyond episodic field campaigns, are needed to test the effectiveness of parameterizations over the climatological range of conditions. One potentially fruitful approach to address the measurement needs would be to develop infrastructure to support long-term measurements at sites that are representative of environments with high potential for power production from wind.

Climatology of wind. Several decades of data from four wind towers in Minnesota were used to illustrate a distinct pattern of variability in wind speeds both diurnally and annually. The data, collected approximately 75 m AGL (near hub height for larger wind turbines), showed a significant horizontal variability in the wind resource over the region. Data from a 6-yr period, 1996–2001, also demonstrated substantial horizontal and vertical variability in the wind shear exponent (commonly used in the wind energy industry to scale winds from an observation height to a height of interest) over the annual cycle.

For longer-term variations in the wind, a comparison of two 15-yr periods, 1973–87 and 1991–2005, showed that numerous locations in the United States exhibit changes of more than 30% in the energy density of the mean wind; the upper Midwest and Northeast generally show decreases. The trends varied across the wind speed distribution, with the median wind showing a sharper decrease than the 90th percentile wind, where the trend was downward. It may thus be important to examine trends across the wind speed distribution to assess the effect of climate change on the wind resource. Similarly, wind speed anomalies in at least some locations were found to be correlated with both El Niño–Southern Oscillation and the Arctic Oscillation, although the lack of suitable long-term datasets makes it difficult to clearly identify relationships.

WORKSHOP RESEARCH RECOMMENDATIONS.

Turbine dynamics. Turbine engineering is currently limited by inadequate characterization of the inflow conditions, which will require the development of models that integrate a hierarchy of scales of flow. Similarly, vortical wakes are not currently well enough understood or represented to account for the effects of one turbine on those downwind. Extreme wind events also pose a significant design and operational challenge for turbines. Advances in our physical understanding that would allow us to characterize these events for design or forecast them for operation could significantly assist the widespread development of wind power.

Micrositing and array effects. Power losses resulting from reduced flow behind individual turbines as well as integrated turbulent wakes from groups of

COLLECTIVE RESEARCH NEEDS

The Research Needs for Wind Resource Characterization workshop contained the following two themes shared by the four focus areas of turbine dynamics, array effects, mesoscale processes, and climate effects.

Appropriate observations for model validation and improvement: There is an outstanding need for integrated datasets that offer information for developing and validating models in their respective domains. These datasets must characterize atmospheric dynamics and thermodynamics in detail, including turbulence and stratification, in the lowest 200 m of the atmosphere. The measurements need to be of a long enough duration to characterize a site at least through the seasonal cycle, and longer still to understand climate change effects on wind resources. Datasets from several such sites (test bed sites) representative of wind farm environments are needed to rigorously exercise proposed new parameterizations and models. Although extensive observations may be available from existing wind farms, significant hurdles pertaining to competitive advantages and intellectual property must be surmounted to enable the atmospheric science community to apply these potentially useful datasets.

Integrated modeling: Many of the modeling research thrusts identified in the workshop span a range of temporal and spatial scales that are not routinely treated by a single type of model (e.g., computational fluid dynamics and mesoscale models). Productive scientific efforts to address these needs must integrate expertise across these spatiotemporal scales rather than promoting isolated development within each scale separately. Further, successfully integrated models should lead to appropriate tools that are practically useful in the wind industry, complete with assessments of model uncertainty.

turbines lead to challenges in optimizing the siting of wind farms. For wind farms with five or more rows of turbines, existing models do not represent these losses because they do not capture the integrated physics of turbine–atmosphere interaction for the overall flow field, whether offshore or in complex terrain. Successfully addressing this issue will not only require advance knowledge of the interaction of turbine fields with turbulent flow, but also the fundamental turbulent structure of the atmospheric surface layer over a wide variety of terrestrial surfaces.

Mesoscale processes. Although the skill of mesoscale forecast models has advanced dramatically in the last several decades, variables relevant to wind energy applications, such as near-surface wind speed, vertical wind shear on the scale of turbine rotor diameter, and low-level turbulence remain subject to significant error. Part of the problem stems from a still-incomplete general understanding of the energy exchange between the Earth's surface and the atmosphere. New knowledge needs to be tested, particularly in complex flows, such as with low-level jets, in stable boundary layers, and in complex terrain. Development also is needed for wind forecasting technology, including data assimilation with rapid update cycles, integration of models of complementary scales, and the quantification of forecast uncertainty. Successful forecasting integrated with turbine array models could provide the opportunity for adaptive operation of wind farms. Observations needed to develop hypotheses and test new parameterizations and modeling capability on this scale will require the development of new instrumentation to reveal the structure of the atmosphere in necessary detail.

Climate effects. Climatic variability plays a significant role in wind power production. The magnitude and causes of historic changes in the wind resource are neither well defined nor well understood. Progress in this area will require both theoretical and numerical advances as well as the development of new techniques to analyze existing records, especially for winds at turbine level. Because global climate change may have significant implications for the economic potential of wind farms, new techniques must be developed to forecast local changes in the wind based on predictions of global climate change (the downscaling problem). Finally, the local, regional, and global effects of widespread extraction of wind energy from the atmosphere should be explored.

REFERENCES

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