The Atmospheric Grand Challenges in the Science of Wind Energy

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Introduction

Harvested by advanced technical systems honed over decades of research and development, wind energy has become a mainstream energy resource. However, continued innovation is needed to realize the potential of wind to serve the global demand for clean energy. Here, we outline three interdependent, cross-disciplinary grand challenges underpinning this research endeavor. The first is the need for a deeper understanding of the physics of atmospheric flow in the critical zone of plant operation. The second involves science and engineering of the largest dynamic, rotating machines in the world. The third encompasses optimization and control of fleets of wind plants working synergistically within the electricity grid. Addressing these challenges could enable wind power to provide as much as half of our global electricity needs and perhaps beyond.

Grand challenges in the science of wind energy
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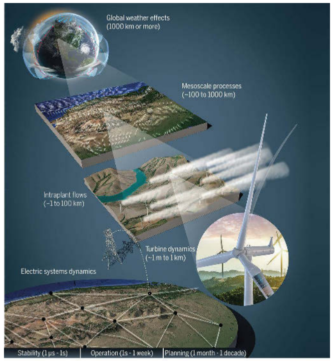

The cascade of scales underlying wind energy scientific grand challenges. Length scales from weather systems at a global level down to the boundary layer of a wind turbine airfoil and timescales from seasonal fluctuations in weather to subsecond dynamic control and balancing of electrical generation and demand must be understood and managed.

ILLUSTRATION: BY JOSH BAUER AND BESIKI KAZAISHVILI, NATIONAL RENEWABLE ENERGY LABORATORY

Three Grand Challenges

1st Improved understanding of atmospheric and wind power plant flow physics
2nd Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines
3rd Systems science for integration of wind power plants into the future electricity grid

Atmospheric Grand Challenges

- Terra incognita
- Meteorological - oceanic (metocean) processes
- Wakes
- Impacts of wind plant on downstream wind plant(s) and local environment
- Longer-term changes of wind resources by climate change

The papers cited in the middle and right columns of this poster are examples of efforts to address these atmospheric grand challenges.

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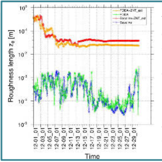
Terra incognita

Models for wind power have historically used idealized physics and assumptions about atmospheric flows and interactions between the atmosphere and turbines. Need to better model processes and phenomena that are on the order of 1.5 km to 0.5 km, which lie in the so-called "terra incognita" in between the mesoscale and microscale, where models have difficulty in simulating such processes because their length scales are similar to the grid spacing. Among others, U.S. Department of Energy's Atmosphere to Electrons Mesocale to Microscale Coupling Project is tackling this grand challenge.

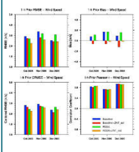
Metocean processes

These processes include waves, atmospheric stability, and tropical storms. A major challenge of offshore wind development is numerical weather prediction's (NWP's) poorer skill at predicting wind speed and turbulence over oceans than over land. For example, Lee, J.A. et al (2017) "Improving Wind Predictions in the Marine ABL through Parameter Estimation in a Single Column Model," MWR, 145, 5-24, examine the impact on hub-height offshore wind 1-h forecasts that result from estimating a key parameter in the marine boundary layer (BL) using ensemble data assimilation (DA) and a single-column model (SCM).

Figures from , Lee, et al. (2017) "Improving Wind Predictions in the Marine ABL through Parameter Estimation in a Single Column Model," MWR, 145, 5-24.



Time series of the ensemble mean sea surface roughness length z0 from four experiments - Baseline (blue), Baseline1ZNT_est (red), FDDA (green), and FDDA1ZNT_est (orange) - for December 2006 simulations.

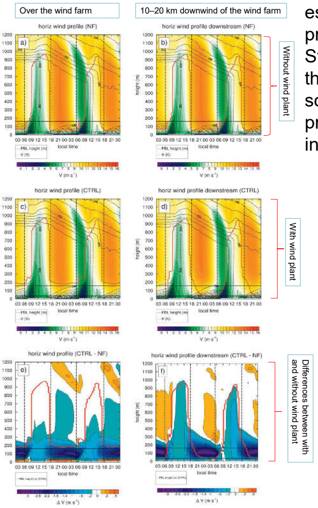


(Top left) RMSE, (top right) bias error, (bottom left) centered RMSE, and (bottom right) correlation of 1-h wind speed predictions for the months of Oct., Nov., and Dec. 2006. Shown are values for the Baseline (blue), Baseline1ZNT_est (red), FDDA (green), and FDDA1ZNT_est (orange) experiments.

Lee et al. improved NWP analyses and forecasts of low-level winds in the marine BL as estimated and predicted with an SCM and ensemble DA system by using the WRF-SCM, state estimation algorithms from Data Assimilation Research Testbed, and observations of at the FINO1 tower in the North Sea.

Impacts of wind plant on downstream wind plant(s) and local environment

Fitch, et al. (2013) "Mesoscale Influences of Wind Farms throughout a Diurnal Cycle," MWR, 2173 – 2198, quantified the impact of a 10 km × 10 km wind plant on a BL through the diurnal cycle. Daytime convective conditions led to a small effect of the wind plant on wind speeds. At night, the stable layer in the layer of the turbine rotor inhibits mixing, which led to a shallower wake and a greater reduction in wind speed in the wake. The low level jet is eliminated in the wind plant. At night, a maximum warming of 1 K results at the lowest part of the turbine rotor layer. Reduced warming (0.5 K) at the surface. Surface temp modification downwind is small, e.g., a cooling of up to 0.3 K. A mean temperature perturbation at 2 m over the region of the wind plant is a very slight warming (0.2 K).



Evolution of mean wind and potential temp profiles and PBL height **over the wind farm area: (a)** without the wind farm, **(c)** with the wind farm, **(e)** the difference in wind speed.
Evolution of mean wind and potential temp profiles and PBL height **10–20 km downwind** of the wind farm: **(b)** without the wind farm, **(d)** with the wind farm, and **(f)** the difference in wind speed. Vertical dashed lines indicate sunrise and sunset times; horizontal lines indicate the extent of the rotor area.

Wakes

Wakes are reduced wind speed areas behind turbines, which also cause increased load and therefore operational and capital expenses.

Nygaard and Newcombe (2018), "**Wake behind an offshore wind farm observed with dual- Doppler radars"** IOP Conf. Series: Journal of Physics: Conf. Ser. **1037** 072008. doi:10.1088/1742-6596/1037/7/072008 present dual-Doppler measurements of the wake behind an offshore wind farm. The measured wind speed in the wake is compared with TWO wake models, one resolved single wakes from individual turbines; the other treated the wind farm as increased roughness. The radar measurements track the evolution of the wakes through the wind farm and further downstream. The wake region extends at least 17 km downstream of the wind farm. Both models are in good agreement with observations if one considers the coastal gradient.

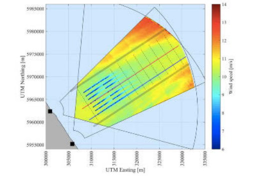


Figure 1. One-hour averaged dual-Doppler wind speed at hub height. The black dots represent the wind turbines. The radars are indicated by the black squares and their azimuthal scan sectors are shown by the thin black lines. The blue and red lines mark the transects along which the wind speed is plotted in Figure 3. They are aligned with turbine rows 1 and 4, respectively. The dashed lines show the locations of the cross-sections in Figure 4 and the upstream plane. The shaded areas are freestream bands (see the text).

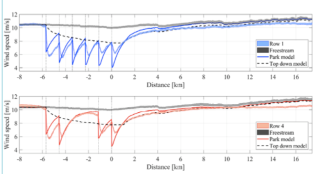


Figure 3. One-hour averaged wind speed at hub height along the blue and red lines in Figure 1 aligned with rows 1 and 4 in the layout, respectively, and the estimated free stream wind speed. The shaded bands represent the uncertainty of the one-hour mean wind speed. Also plotted are the predictions of the two models. The vertical dashed lines indicate the turbine positions. Note that there is a two-turbine gap in the middle of row 4. Distance is relative to the last turbine in the rows.

Figures from Nygaard and Newcombe (2018) IOP Conf. Series: Journal of Physics: Conf. Ser. **1037** 072008.

Changes of wind resources by climate change

Climate change is expected to modify wind resources throughout the globe. Among others, Karnauskus, K. et al. (2018) "Southward shift of the global wind energy resource under high carbon dioxide emissions," Nature Geoscience, vol. 11, 38–43, have studied this. Authors applied an industry wind turbine power curve to simulations of high and low future greenhouse gas concentration scenarios. They used 10 fully coupled global climate models to estimate changes in wind power. Wind resources/power modifications are predicted to differ based on the region of the world. In the central United States, wind power is projected to decline by 8% (14%) by 2050 (2100) under the RCP4.5 scenario or by 10% (18%) by 2050 (2100) under the RCP8.5 scenario. However, for eastern Brazil a large increase in wind power is projected under the RCP8.5 scenario: 21% (42%) by 2050 (2100). These increases are only a quarter as large under the RCP4.5 scenario.

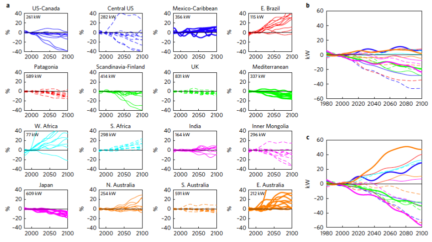


Fig. 4 | Evolution of regional wind power over the twenty-first century. a, Time series of changes in wind power (per cent of baseline) averaged across each regional domain (Figs. 2 and 3e, and Supplementary Table 2) and from each model over the course of the twenty-first century in the RCP8.5 forcing scenario. For clarity, the seasonal-to-interannual variability is removed from each time series prior to plotting, using a multidecadal low-pass filter (30-year period). The multi-model median, baseline averaged (1980–2005) power (kW) averaged across each domain is given in the upper-left corner of each panel. **b**, As in **a** but for the RCP4.5 forcing scenario, with each region collapsed to its multi-model mean, and changes relative to baseline expressed in kW. **c**, As in **b** but for the RCP8.5 forcing scenario.

Figures from Karnauskus et al. (2018) Southward shift of the global wind energy resource under high carbon dioxide emissions, Nature Geoscience, vol. 11, 38–43

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