Aerodynamic Modeling of Wind Power Across Rotor Operational and Atmospheric Conditions for Optimization

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To meet net-zero carbon emissions targets by mid-century, up to a ~30-fold increase in wind power capacity is required. Acceleration to this rate requires urgent improvements to efficiency and reliability of installed wind farms, as well as cost reductions for future offshore farms. To expand energy production, wind turbines are rapidly increasing in size, wind farms are proliferating to new locations and are increasing in size and siting density, and novel wind farm design and control methods are increasingly deployed. But current flow physics models driving wind power design and control rely on idealized theory that neglects key aspects of the rotor aerodynamics and the atmospheric boundary layer, which are increasingly important for larger turbines and farms. We revisit the first-principles of mass, momentum, and energy conservation to develop a Unified Momentum theory for rotors across operating regimes, accounting for arbitrary misalignments between rotor and inflow and thrust coefficients. The model is validated against large eddy simulations and generalizes and replaces both classical momentum theory and the Betz limit. In the atmospheric boundary layer, the sheared wind speed and direction can change significantly over the rotor area, resulting in a relative inflow wind to the blade airfoil which depends on the radial and azimuthal positions. In order to predict the power and thrust based on the incident boundary layer velocities, we develop a blade element model which accounts for wind speed and direction changes over the rotor area, and the model is validated using experimental data from a utility-scale wind farm. Going from the scale of a turbine to a farm, wake losses can reduce energy production for large, modern wind farms by 30%, a significant loss that negatively impacts economics and is increasing given wind power expansion. Using large eddy simulations of wind turbines operating in a range of atmospheric conditions, we systematically uncover the significant roles of Coriolis effects and stability on wake recovery, trajectory, and morphology. A new fast-running wind farm model that accounts for the coupled rotor operational and atmospheric effects on wakes is developed. We leverage the wind farm model for applications including collective flow control and for control co-design, applied in both simulations and utility-scale field experiments. Collective flow control can increase the energy generation of wind farms through software modifications, without additional turbines or hardware.

Michael F. Howland is the Esther and Harold E. Edgerton Assistant Professor of Civil and Environmental Engineering at MIT. He was a Postdoctoral Scholar at Caltech in the Department of Aerospace Engineering. He received his B.S. from Johns Hopkins University and his M.S. from Stanford University. He received his Ph.D. from Stanford University in the Department of Mechanical Engineering. His work is focused at the intersection of fluid mechanics, weather and climate modeling, uncertainty quantification, and optimization and control with an emphasis on renewable energy systems. He uses synergistic approaches including simulations, laboratory and field experiments, and modeling to understand the operation of renewable energy systems, with the goal of improving the efficiency, predictability, and reliability of low-carbon energy generation. He was the