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

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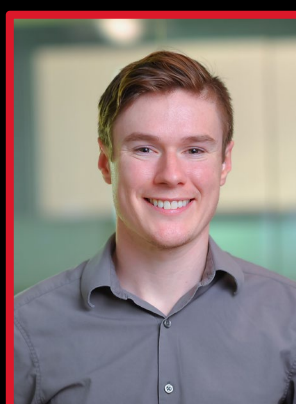
Abstract: To meet net-zero carbon emissions targets by mid-century, up to a ~30-fold increase in wind power capacity is required. Acceleration to this rate requires urgent improvements to efficiency and reliability of installed wind farms, as well as cost reductions for future offshore farms. To expand 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 engineering 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. Going from the scale of a turbine to a farm, wake losses can reduce farm energy 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. The wind farm model is leveraged for applications including collective control and for control co-design, applied in both simulations and utility-scale field experiments. Collective control can increase the energy generation of wind farms through software modifications, without additional turbines or hardware.



Bio: 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 and his M.S. from Stanford University. He received his Ph.D. from Stanford 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, lab 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 recipient of the Robert George Gerstmyer Award, the Creel Family Teaching Award, and the James F. Bell Award from Johns Hopkins. At MIT, he has received the Maseeh Excellence in Teaching Award and the Office of Naval Research Young Investigator Program award.