Newest wind turbine technology

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The blades of propellers and wind turbines are designed based on aerodynamics principles that were first described mathematically more than a century ago. But engineers have long realized that these formulas don"t work in every situation. To compensate, they have added ad hoc "correction factors" based on empirical observations.

Now, for the first time, engineers at MIT have developed a comprehensive, physics-based model that accurately represents the airflow around rotors even under extreme conditions, such as when the blades are operating at high forces and speeds, or are angled in certain directions. The model could improve the way rotors themselves are designed, but also the way wind farms are laid out and operated. The new findings are described today in the journal Nature Communications, in an open-access paper by MIT postdoc Jaime Liew, doctoral student Kirby Heck, and Michael Howland, the Esther and Harold E. Edgerton Assistant Professor of Civil and Environmental Engineering.

"We"ve developed a new theory for the aerodynamics of rotors," Howland says. This theory can be used to determine the forces, flow velocities, and power of a rotor, whether that rotor is extracting energy from the airflow, as in a wind turbine, or applying energy to the flow, as in a ship or airplane propeller. "The theory works in both directions," he says.

Because the new understanding is a fundamental mathematical model, some of its implications could potentially be applied right away. For example, operators of wind farms must constantly adjust a variety of parameters, including the orientation of each turbine as well as its rotation speed and the angle of its blades, in order to maximize power output while maintaining safety margins. The new model can provide a simple, speedy way of optimizing those factors in real time.

Known as momentum theory, the previous model of how rotors interact with their fluid environment -- air, water, or otherwise -- was initially developed late in the19th century. With this theory, engineers can start with a given rotor design and configuration, and determine the maximum amount of power that can be derived from that rotor -- or, conversely, if it"s a propeller, how much power is needed to generate a given amount of propulsive force.

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Momentum theory equations "are the first thing you would read about in a wind energy textbook, and are the first thing that I talk about in my classes when I teach about wind power," Howland says. From that theory, physicist Albert Betz calculated in 1920 the maximum amount of energy that could theoretically be extracted from wind. Known as the Betz limit, this amount is 59.3 percent of the kinetic energy of the incoming wind.

But just a few years later, others found that the momentum theory broke down "in a pretty dramatic way" at higher forces that correspond to faster blade rotation speeds or different blade angles, Howland says. It fails to predict not only the amount, but even the direction of changes in thrust force at higher rotation speeds or different blade angles: Whereas the theory said the force should start going down above a certain rotation speed or blade angle, experiments show the opposite -- that the force continues to increase. "So, it"s not just quantitatively wrong, it"s qualitatively wrong," Howland says.

The theory also breaks down when there is any misalignment between the rotor and the airflow, which Howland says is "ubiquitous" on wind farms, where turbines are constantly adjusting to changes in wind directions. In fact, in anearlier paper in 2022, Howland and his team found that deliberately misaligning some turbines slightly relative to the incoming airflow within a wind farm significantly improves the overall power output of the wind farm by reducing wake disturbances to the downstream turbines.

In the past, when designing the profile of rotor blades, the layout of wind turbines in a farm, or the day-to-day operation of wind turbines, engineers have relied on ad hoc adjustments added to the original mathematical formulas, based on some wind tunnel tests and experience with operating wind farms, but with no theoretical underpinnings.

Instead, to arrive at the new model, the team analyzed the interaction of airflow and turbines using detailed computational modeling of the aerodynamics. They found that, for example, the original model had assumed that a drop in air pressure immediately behind the rotor would rapidly return to normal ambient pressure just a short way downstream. But it turns out, Howland says, that as the thrust force keeps increasing, "that assumption is increasingly inaccurate."