New theory could improve the design and operation of wind farms

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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 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 adds.

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.

"This is what we're so excited about, is that it has immediate and direct potential for impact across the value chain of wind power," Howland says.

Modeling the momentum

Known as momentum theory, the previous model of how rotors interact with their fluid environment—air, water, or otherwise—was initially developed late in the 19th 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.

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% 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 direction. In fact, in an earlier 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, for example, that 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."

And the inaccuracy occurs very close to the point of the Betz limit that theoretically predicts the maximum performance of a turbine—and therefore is just the desired operating regime for the turbines. "So, we have Betz's prediction of where we should operate turbines, and within 10 percent of that operational set point that we think maximizes power, the theory completely deteriorates and doesn't work," Howland says.

Through their modeling, the researchers also found a way to compensate for the original formula's reliance on one-dimensional modeling that assumed the rotor was always precisely aligned with the airflow. To do so, they used fundamental equations that were developed to predict the lift of three-dimensional wings for aerospace applications.

The researchers derived their new model, which they call a unified momentum model, based on theoretical analysis, and then validated it

using computational fluid dynamics modeling. In follow-up work not yet published, they are doing further validation using wind tunnel and field tests.

Fundamental understanding

One interesting outcome of the new formula is that it changes the calculation of the Betz limit, showing that it's possible to extract a bit more power than the original formula predicted. Although it's not a significant change—on the order of a few percent—"it's interesting that now we have a new theory, and the Betz limit that's been the rule of thumb for a hundred years is actually modified because of the new theory," Howland says. "And that's immediately useful."

The new model shows how to maximize power from turbines that are misaligned with the airflow, for which the Betz limit cannot account.

The aspects related to controlling both individual turbines and arrays of turbines can be implemented without requiring any modifications to existing hardware in place within wind farms. In fact, this has already happened, based on earlier work from Howland and his collaborators two years ago that dealt with the wake interactions between turbines in a wind farm, and was based on the existing empirically-based formulas.

"This breakthrough is a natural extension of our previous work on optimizing utility-scale wind farms," he says, because in doing that analysis, they saw the shortcomings of the existing methods for analyzing the forces at work and predicting power produced by wind turbines. "Existing modeling using empiricism just wasn't getting the job done," he says.

In a wind farm, individual turbines will sap some of the energy available to neighboring turbines, because of wake effects. Accurate wake

modeling is important both for designing the layout of turbines in a wind farm, and also for the operation of that farm, determining moment to moment how to set the angles and speeds of each turbine in the array.

Until now, Howland says, even the operators of wind farms, the manufacturers, and the designers of the turbine blades had no way to predict how much the power output of a turbine would be affected by a given change such as its angle to the wind without using empirical corrections.

"That's because there was no theory for it. So, that's what we worked on here. Our theory can directly tell you, without any empirical corrections, for the first time, how you should actually operate a wind turbine to maximize its power," he says.

Because the fluid flow regimes are similar, the model also applies to propellers, whether for aircraft or ships, and also for hydrokinetic turbines such as tidal or river turbines. Although they didn't focus on that aspect in this research, "it's in the theoretical modeling naturally," he says.

The new theory exists in the form of a set of mathematical formulas that a user could incorporate in their own software, or as an open-source software package that can be freely downloaded from GitHub.

"It's an engineering model developed for fast-running tools for rapid prototyping and control and optimization," Howland says. "The goal of our modeling is to position the field of wind energy research to move more aggressively in the development of the wind capacity and reliability necessary to respond to climate change."

More information: Unified momentum theory for rotor aerodynamics across operating regimes, *Nature Communications* (2024). On *arXiv*:

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