quick study

Emergent aerodynamics in wind farms

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New designs for inexpensively harvesting wind energy were inspired by the fluid mechanics of fish schools.

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The defining element of modern wind farms is the propeller-like structure known as a horizontal-axis wind turbine. A marvel of engineering, the HAWT typically comprises more than 8000 parts, and its blades reach more than 200 m above the ground.

The HAWT is also impressive in the efficiency with which it converts wind energy into electricity. In 1920 Albert Betz derived a theoretical limit on that efficiency by considering the kinetic energy flux conveyed by the wind upstream and downstream of a wind turbine. The difference in those energy fluxes, P —the result of energy extraction by the wind turbine—is related to the wind speeds in the vicinity of the turbine by $P = ½\cdot(\rho U_1)\cdot(U_0^2 - U_2^2)$. Here U_1 is the wind speed at the turbine rotor, and U_0 and U_2 are the speeds upstream and downstream of the rotor, respectively. The first term in parentheses quantifies the mass flux of air with density ρ through the area swept out by the wind turbine's rotor blades. The second term (with the leading factor of ½ included) is the difference, per unit mass, of wind kinetic energy upstream and downstream from the wind turbine.

With the help of Bernoulli's equation, one can show that $U_1 = ½\cdot(U_0 + U_2)$. Hence the efficiency of power extraction from the wind C_p (also called the power coefficient) depends on the ratio of U_2/U_0 as

$$C_p = P/(½\cdot\rho U_0^3) = ½\cdot[1 + U_2/U_0 - (U_2/U_0)^2 - (U_2/U_0)^3].$$

The efficiency is maximized for $U_2/U_0 = ⅓$, which gives the Betz efficiency limit $C_p = 16/27 = 59.3\%$.

Remarkably, the peak performance of modern wind turbines exceeds 50% efficiency, which leaves relatively little room for further improvement. Unfortunately, because of turbulence created by the wind turbines situated farthest upstream, the downwind turbines perform less well than they would if they operated in isolation. Increasingly sophisticated numerical models can quantify the farm-scale aerodynamics; still, wind-farm designers have generally limited their strategies to mitigating the deleterious effects of wake turbulence.

A new school of thought

Observations of fish schooling in the ocean inspired my colleagues and me to pursue physical principles that could enable wind-farm design to go beyond the usual strategies and achieve synergies in farm-scale aerodynamics. Like the wind turbines, individual swimming fish generate turbulent wakes that could negatively affect their neighbors. Yet, rather than take the prevailing approach in wind-farm design and simply spread out as far as possible to avoid hydrodynamic interactions, the fish instead coordinate their swimming in relatively close proximity. To be sure, if an optimization strategy underlies the behavior exhibited by fish schools, the objective is not energy harvesting per se. However, the same theoretical optimization tools that successfully predict the observed drag-minimizing configurations of fish schools can be applied to the design of wind farms. In our case, we are interested in farms with vertical-axis wind turbines (VAWTs), whose airfoil blades rotate about a vertical axis.

In schooling fish and wind-farm turbines alike, the flow conditions around each member of the group depend on the flow induced by neighboring members. The induced fluid velocity can, in principle, degrade or enhance the flow conditions for each group member. Furthermore, the degree of alteration can vary with location.

For conventional HAWT farms, the induced velocity appears to be uniformly detrimental. In contrast, field measurements at Caltech of full-scale (10-m-tall) VAWTs in close proximity have demonstrated the potential for augmented wind-turbine performance due to enhanced wind speeds generated by neighboring VAWTs. The effects seem to be most beneficial if neighboring VAWTs are counterrotating, staggered, or both.

The improved performance is primarily attributable to the acceleration of the wind as it passes around the main structure of each turbine. Figure 1 shows that velocity increase, obtained with a "potential flow" model for a single cylinder. When extended to an array of bodies, the model assumes that the effects of all neighbors are linearly superposed. Thus it only approx-

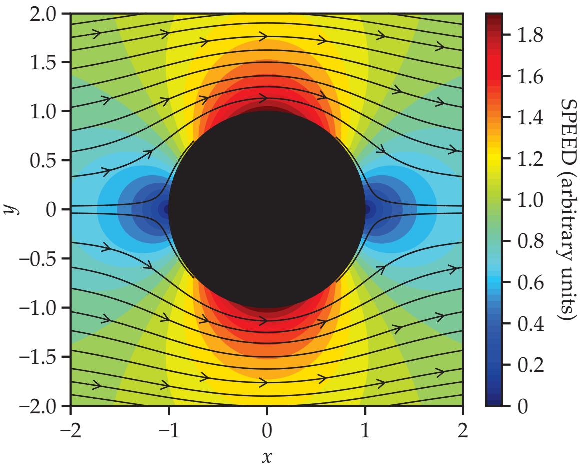

Figure 1. Wind accelerates as it flows around the elements of a vertical-axis wind turbine array. The detailed results here are derived from a simplified model of flow past a circular cylinder. Streamlines indicate flow direction. Contours of flow speeds indicate deceleration (blue) in front of and behind the cylinder coupled with acceleration (red) at the sides. Axes indicate position coordinates in units of the cylinder radius.

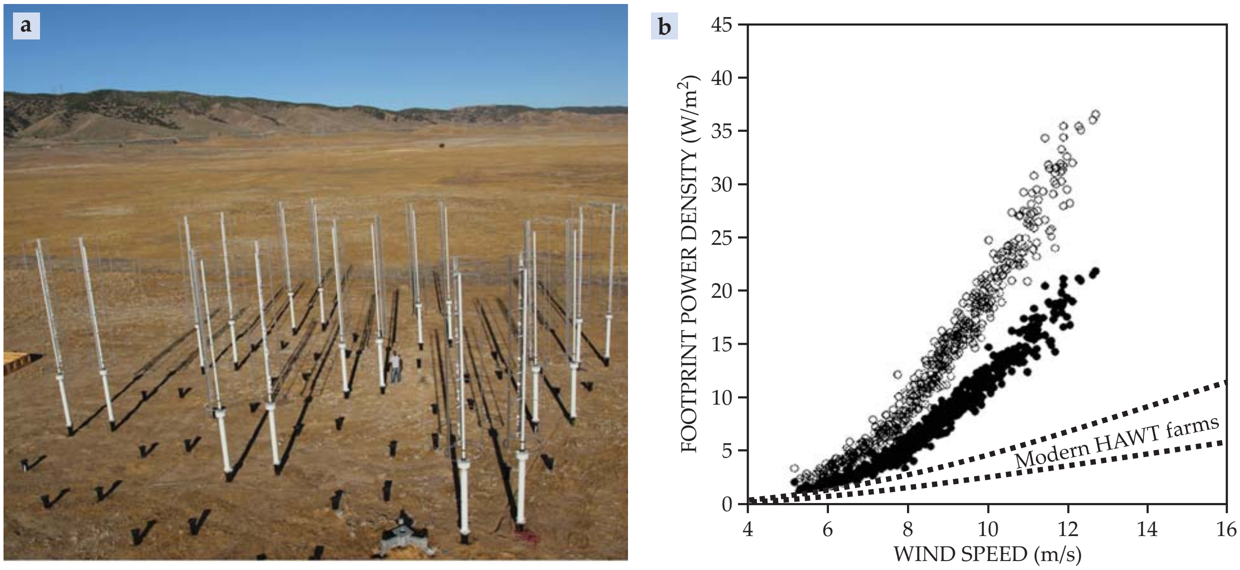

Figure 2. This bioinspired vertical-axis wind turbine (VAWT) farm (a) is located at Caltech's Field Laboratory for Optimized Wind Energy (FLOWE). There, arrays of up to 24 commercially available VAWTs are being tested in various configurations to study aerodynamic interactions and power generation. Scale is indicated by the author, who is standing in the center of the array. Video showing the turbines in operation is available at http://www.youtube.com/watch?v=cZu-4Plk_5A. **(b)** Shown here are measurements of footprint power density for 18-VAWT arrays at FLOWE. Open circles indicate direct measurements; filled circles show an extrapolation to an infinite VAWT array. The dashed range indicates performance with modern horizontal-axis wind turbines (HAWTs).

imates the real, nonlinear dynamics of a wind farm. However, comparisons with field measurements of VAWTs suggest that such linear models can accurately capture important features—including, for example, the mean flow field in the wind farm—from which one can estimate power generation.

Figure 2 shows a specific array of 18 VAWTs that we studied and compares the footprint power density (power extracted per area of footprint) with the corresponding figure for HAWT arrays. Analysis of the 18 VAWT data suggests that with optimal turbine spacing, a large VAWT farm can potentially outperform a HAWT farm by an order of magnitude. That unexpected, even provocative conclusion awaits confirmation either experimentally in larger-scale field studies or numerically in large-scale simulations that account for how the atmospheric boundary layer adjusts to the presence of the VAWT farm.

Note that the individual VAWTs in the farm are less efficient than HAWTs of similar capacity. But improved efficiency for single wind turbines may come at the expense of the performance of neighboring turbines in a wind farm—for example, if the wake becomes more turbulent as the Betz limit is approached. At present, the possible tradeoff between individual turbine efficiency and performance of a wind farm as a whole is unexplored territory.

Headwinds

The significant increase in footprint power density that might be afforded by VAWT farms could enable energy production using smaller and simpler (though more numerous) wind turbines that can be manufactured, operated, and maintained at lower costs than conventional HAWTs. However, the aerodynamics of VAWTs is more complex than for HAWTs, and more research is needed to develop tools capable of predicting and designing for the unique fatigue loads that VAWTs need to deal with. Recent advances across the disciplines required to achieve a reliable VAWT system—including computational mechanics, materials science, and electrical engineering—make that problem ripe for a solution.

No alternative scheme for wind-energy harvesting can claim a record of success similar to that of the standard HAWT. In particular, VAWTs have thus far proven to be a less efficient, less reliable, and more expensive alternative. However, many researchers attribute that state of affairs primarily to the divergent records of investment in HAWT and VAWT R&D. During the past three decades, researchers have focused on individual turbine efficiency, and in that regard, HAWTs systematically outperform VAWTs. As a result, relatively little effort has gone into improving VAWTs.

Wind energy promises to be a meaningful component of the future global energy portfolio. But realizing that potential will require significant advances to lower the cost of extracting the energy. Many of the promising avenues of exploration under way emphasize individual HAWT design, manufacturing, operations, and maintenance. A greater opportunity for fundamental improvement in wind-energy technology may exist in the emergent aerodynamics of wind farms. The bioinspired VAWT concept is one promising approach.

Additional resources

▶ R. Kwartin et al., *An Analysis of the Technical and Economic Potential for Mid-Scale Distributed Wind*, subcontract report NREL/SR-500-44280, National Renewable Energy Laboratory (December 2008).

▶ R. J. Barthelmie et al., "Quantifying the impact of wind turbine wakes on power output at offshore wind farms," *J. Atmos. Ocean. Technol.* **27**, 1302 (2010).

▶ R. W. Whittlesey, S. Liska, J. O. Dabiri, "Fish schooling as a basis for vertical axis wind turbine farm design," *Bioinspir. Biomim.* **5**, 035005 (2010).

▶ J. O. Dabiri, "Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays," *J. Renew. Sustain. Energy* **3**, 043104 (2011).

▶ J. Meyers, C. Meneveau, "Optimal turbine spacing in fully developed wind farm boundary layers," *Wind Energy* **15**, 305 (2012). ■