Extracting More Power from the Wind

WIND power use in the U.S.—and worldwide—is expanding rapidly. In 2008, more than 40 percent of our nation's newly installed electricity-producing plants involved wind power. Currently, wind energy plants produce enough electricity on a typical day to power nearly 7 million American homes. The Department of Energy (DOE), which is supporting research at Lawrence Livermore and other facilities to improve the performance and efficiency of wind turbines, calculates that wind power could provide 20 percent of U.S. electricity needs by 2030, up from about just 1 percent in 2009.

To help DOE meet this ambitious goal, Livermore researchers are working to achieve a better understanding of how wind speed variability—in particular with relation to height—and atmospheric turbulence can affect power production. The researchers are also building advanced numerical models to aid in designing wind turbines, siting wind farms, and integrating wind power into the electrical grid. The Livermore effort is supported by DOE's Energy Efficiency and Renewable Energy Program, the Laboratory Directed Research and Development (LDRD) Program, and a cooperative research and development agreement (CRADA) with Siemens Energy, Inc.

Wind power offers significant advantages over other energy technologies. For example, wind farms can be developed and linked to the electrical grid more rapidly and cheaply than other energy technologies. Also, wind power generates almost no carbon emissions. However, according to Livermore's Jeff Mirocha, significant expansion of wind power production cannot be met by installing a massive number of new wind turbines alone. A host of technological and scientific challenges that must also be overcome involve extracting power from the wind and integrating it into the electrical grid. "At the core of these challenges is improved understanding and prediction of winds across a broad range of spatial and temporal scales," Mirocha says.

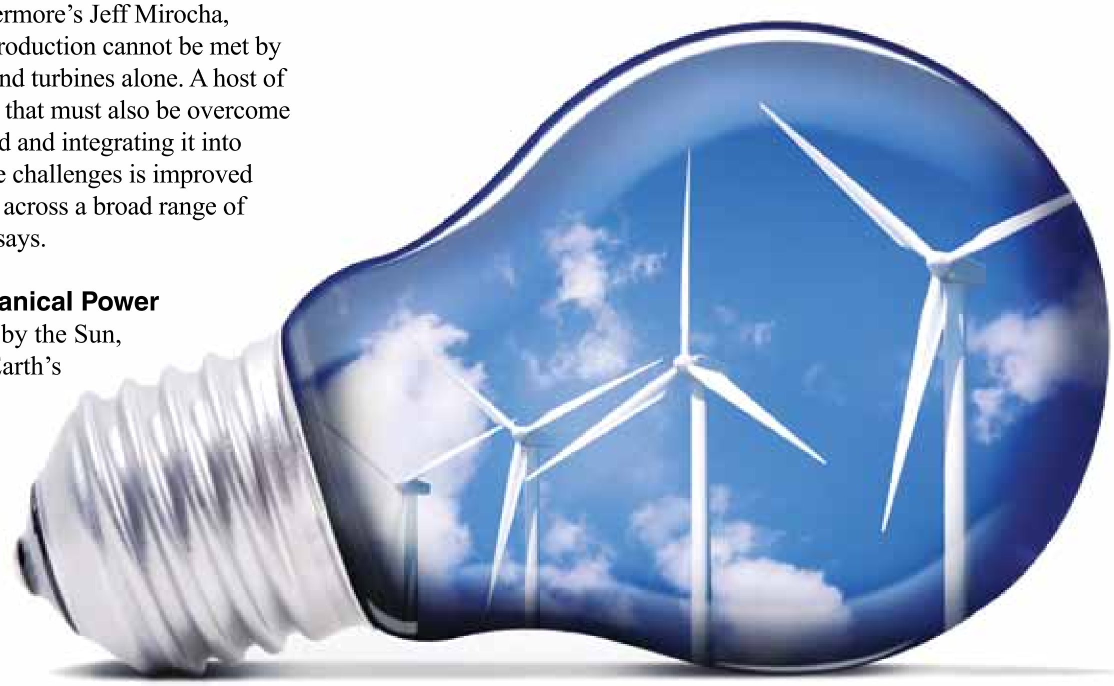
Converting Wind Flows to Mechanical Power

Uneven heating of the atmosphere by the Sun, irregularities of Earth's surface, and Earth's rotation all contribute to wind flows. Wind turbines are used to convert the kinetic energy from the wind into mechanical power. Most turbines have either two or three blades, and the wind blowing over these blades causes them to lift and rotate. As the blades rotate, they spin a shaft, which connects to an electrical generator.

Wind turbines are complicated devices that include a sophisticated gearbox for increasing a spinning shaft's speed from about 30 to 60 revolutions per minute (rpm) to the 1,000 to 1,800 rpm required by most generators to produce electricity. Utility-scale turbines can produce from 100 kilowatts to several megawatts of power each and are grouped together into wind farms to provide power to the electrical grid.

The power available in wind is proportional to the cube of the wind speed. That is, doubling the wind speed provides eight times the power. For example, a 20-kilometer-per-hour wind has eight times the energy of a 10-kilometer-per-hour wind. However, wind is rarely constant; its speed and variability depend on many factors such as time of day, topography, and changes in temperature with height. Turbulence variability with height is more complicated. In general, wind increases with altitude and becomes more turbulent at higher altitudes.

Modern land-based wind turbines are typically 60 to 100 meters tall (measured from the ground to the centerline of the turbine rotor) but can be as tall as 135 meters. Rotor blade diameters can exceed 120 meters. (See the figure on p. 13.) Because of a turbine's operating altitude and rotor diameter, wind speeds can vary significantly at opposite ends of the blades. This difference may cause the blades to twist and deform, resulting in reduced power output and often in blade and gear failures.



Mirocha, the technical lead of Livermore's growing number of wind energy projects, says the effects of turbulence have been underestimated by both wind turbine manufacturers and wind farm operators. Livermore's research aims to help the industry improve power-generation efficiency and reliability as well as turbine longevity by better understanding winds and building a forecasting mechanism.

Livermore postdoctoral researcher Sonia Wharton recently analyzed an unusually extensive data set from a West Coast wind farm with modern wind turbines. The data were generated over 12 months by meteorological instruments not typically used at wind farms. The instruments collected information every 10 meters up to 200 meters, well above the wind turbines, yielding a high-resolution vertical profile of wind speed, direction, and turbulence.

The data were invaluable because most wind farms record only intermittent measurements of wind speed and direction at a small number of locations about 10 meters aboveground and sometimes isolated measurements at turbine hub height. As a result, manufacturers must make assumptions about the conditions turbine blades experience as they slice through the air at much higher altitudes.

Wharton analyzed the yearlong data set to determine the effect of atmospheric stability on power production of tall turbines. She calculated detailed power curves, which show the relation between wind speed (in meters per second) and power (in kilowatts). The data showed that in unstable atmospheric conditions (high turbulence) turbines generated less power than expected, while in stable conditions (low turbulence) they generated more power than expected. This finding is important because it allows wind farm operators to better predict the amount of power they will supply to the grid over a wide range of meteorological conditions.

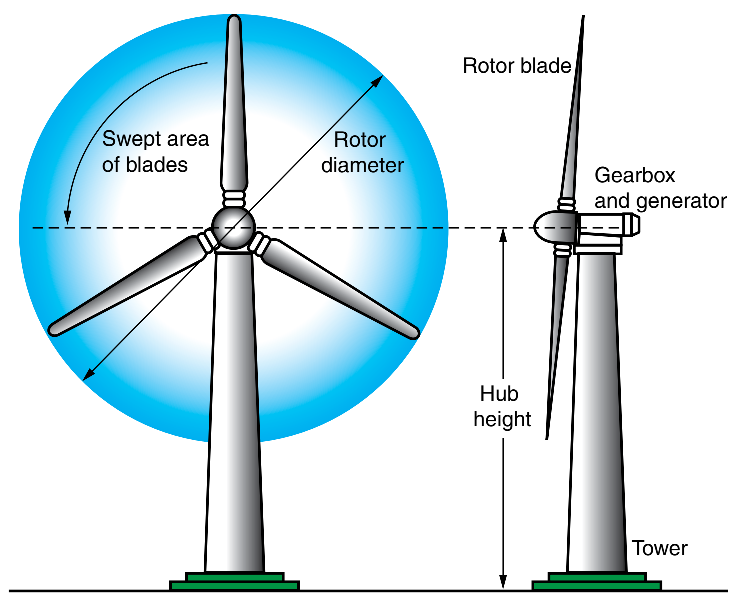
Building a Wind Forecast Capability

The project's second phase builds on this wind farm data set. Using Livermore supercomputers, researchers will simulate wind flow through the same West Coast wind farm during different weather patterns, seasons, and times of day. The project has a special focus on "ramping events," which are sudden changes in wind speed that can either significantly decrease or increase the generative capacity of the wind farm. Wharton says ramping events are of particular interest to the wind power industry because they challenge the ability of the grid to absorb unexpectedly large amounts of wind power or, in the opposite case, generate power from other sources when winds rapidly drop.

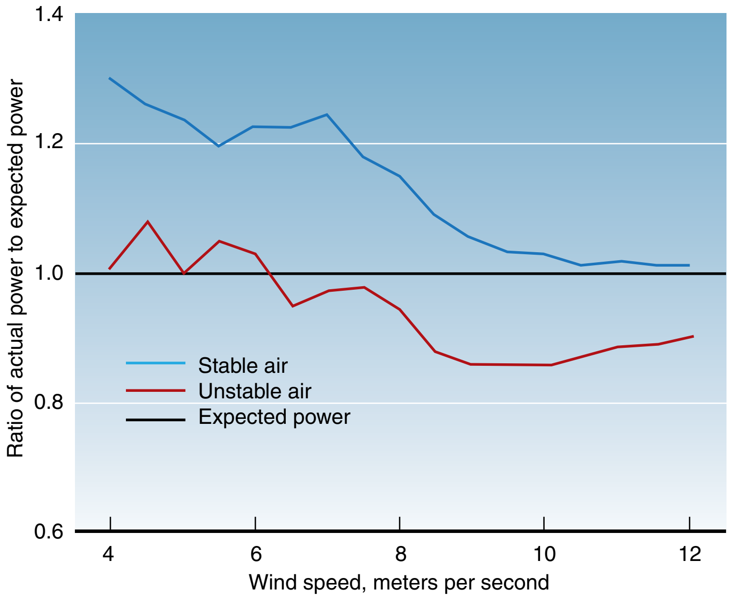
Wharton, along with university collaborators, is using the yearlong data set together with different versions of the Weather Research and Forecasting Model (a supercomputer code collectively maintained and refined by atmospheric researchers worldwide) to determine how to better predict wind patterns and therefore improve the extraction process. The scales of interest vary from the mesoscale (1 to 4 kilometers) for weather fronts to the turbulence scale (10 meters) for much smaller areas of swirling, chaotic winds.

Mirocha notes that energy experts have traditionally used simplified numerical models based on a sparse number of atmospheric measurements. As a result, these models have not fully taken into account turbulence and rapid changes in wind speed and direction. With the wind farm data, the Livermore researchers are confident they can build a better numerical model of wind turbulence that will improve short-term wind forecasting and therefore short-term power forecasting for wind farms. Because atmospheric stability plays such an important role in power production, power predictions may be improved with accurate weather forecasting models.

The forecasting effort partners Livermore scientists with colleagues at University of Colorado at Boulder, Colorado School of Mines, and University of California at Berkeley. Former Livermore scientist Julie Lundquist is leading the University of Colorado's participation in the project. While at Livermore, Lundquist worked on advanced atmospheric turbulence simulations with LDRD and DOE support. Livermore scientists have been incorporating turbulence more accurately in atmospheric forecasting models for the National Atmospheric Release Advisory Center. Lundquist focused on how topography affects winds and realized how the research could be useful for advancing wind energy.



As wind turbine blades rotate, they spin a shaft, which is connected to an electrical generator. Wind turbines include a gearbox to increase the spinning shaft's speed from about 30 to 60 revolutions per minute (rpm) to the 1,000 to 1,800 rpm required by most generators to produce electricity. The hub height of most land-based turbines ranges from 60 to 100 meters. Rotor diameters can exceed 120 meters.



Results from the Livermore wind study show that more power is produced than expected during stable atmospheric conditions (low turbulence) and less power is produced than expected during unstable atmospheric conditions (high turbulence) over a wind speed range of 4 to 12 meters per second.

The importance of wind forecasting was underscored last year, when Lawrence Livermore signed a $2.3 million, two-year CRADA with Siemens Energy, Inc., to provide high-resolution atmospheric modeling capabilities for improving the efficiency of turbine design and wind farm siting and operations. This agreement with a major wind turbine manufacturer is an outgrowth of informal conversations beginning in early 2007 about how winds affect turbines and why wind farms generate more power than expected on some days and less power on other days. The LDRD research on high-resolution atmospheric modeling led directly to Livermore's ability to propose the CRADA to Siemens.

Under the CRADA, the Livermore team, led by Lee Glascoe, is combining its atmospheric turbulence modeling capabilities with complex databases of topography and atmospheric conditions supplied by Siemens for its wind farms in Europe and the U.S. The goal is to merge real-time meteorological data streams with a high-resolution numerical weather prediction model to develop a tool for wind forecasting.

Mirocha is confident that improved models will help wind farms operate more efficiently and thereby provide more power to electrical grids. Many U.S. wind farms are generating up to 20 percent less energy than predicted because of uncertain wind forecasts. More accurate predictions would help farm operators know hours or even days ahead of time how wind conditions will likely affect power generation.

The Livermore research should also ensure more reliable integration of large amounts of renewable energy into power grids, which are not designed for large fluctuations of power input. For example, if electrical utility operators are aware that an impending ramping event is likely to significantly decrease power production at a wind farm, they can prepare to fill the gap with power from other sources such as nuclear, natural gas, or coal plants. Improved model accuracy could also reduce the investment risks in large wind power projects and eventually improve the design of wind turbines to better withstand high-turbulence conditions. A more complete understanding of wind patterns for a specific area should also provide better siting of wind farms and individual turbines to take advantage of maximal wind speeds and minimal turbulence. Finally, understanding how to optimize turbine performance could help the nation more quickly reduce its dependence on foreign oil.

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