by Wayne Miller and Arnie Heller

BREATH OF AIR

Predicting wind power with greater accuracy

Researchers at Lawrence Livermore National Laboratory in the USA are combining fieldwork, advanced simulations and statistical analysis to help wind farm and electric grid operators maximize power production

The wind is a variable and uncertain power source that is dependent on a number of complex atmospheric forces. Reducing the uncertainty of wind power forecasts, upon which wind farm operators and power grid operators depend, is the goal of a team of researchers at Lawrence Livermore National Laboratory in California.

Many wind farms generate less energy than expected because of uncertainties in forecasting winds and simulating the complex flows within wind farms. Greater understanding of the wind is needed to optimize power production from wind farms and to develop higher-fidelity forecasting models relating atmospheric conditions to power output. A major goal is to better understand how power production is related to windspeed variability and other atmospheric variables, such as turbulence, across a broad range of spatial and temporal scales, and in wildly varying geographic areas.

Turbulence and simulations

Livermore field researchers are characterizing winds in numerous locations, but especially in complex terrain. They have made significant discoveries studying the dynamics of atmospheric stability and turbulence in the lower atmosphere and their effects on wind farm power output. A particularly important variable is turbulence, which can be thought of as a fluctuation of background wind flow, as it affects the power extracted from wind turbines, as well as the reliability and lifespans of turbine components.

Atmospheric scientist Sonia Wharton explains, "Our measurements help us better understand the atmospheric physics of the atmospheric boundary layer. Increased understanding can help optimize power generation from wind farms and validate our numerical models." She uses wind profile data to investigate stability factors including turbulence, veer, vertical intensity, horizontal turbulence intensity, and shear. She compares the data to supervisory control and data acquisition (SCADA) data remotely transmitted by the turbines.

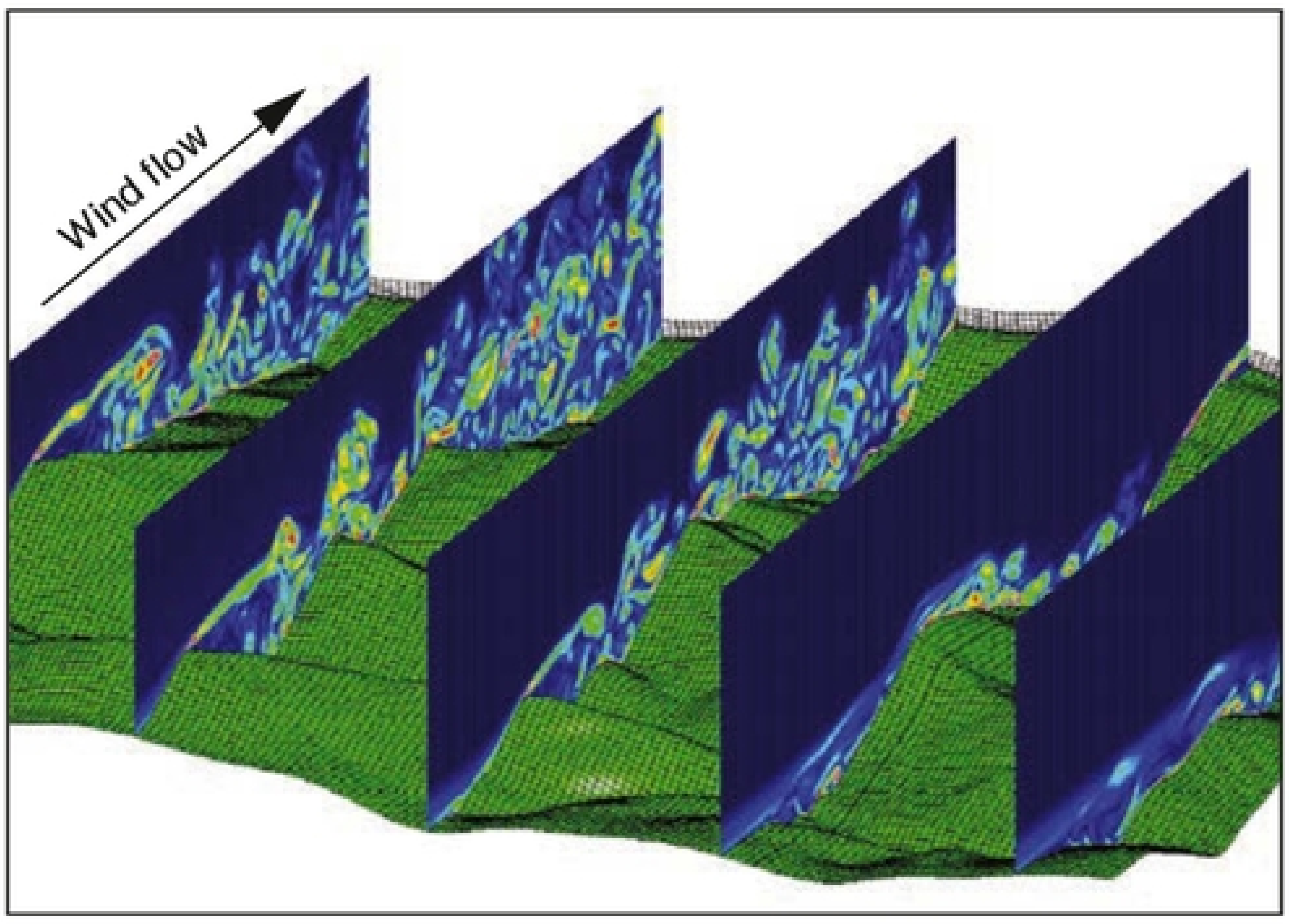
Wharton notes that wind turbine manufacturers typically provide operators with a simple IEC power curve that frequently err by ±50% of actual power output. "We're trying to add refinements to power curve models so that they reflect our improved understanding of the aerodynamic environment. While the average windspeed in a turbine rotor disk largely determines the amount of power that is generated, wind shear and turbulence intensity also influence power output." The result, she says, is that "the more you understand atmospheric processes, the more accurate your power predictions."

Advanced simulation challenges

Livermore simulation and modeling efforts use massive parallel computation to study atmospheric flows relevant to wind farm operations. The task is enormous because the length scales involved span eight orders of magnitude from the mesoscale (about 100-1,000km) to wind farm scales (1 to several kilometers) to turbine blade aerodynamic features (meters to millimeters).

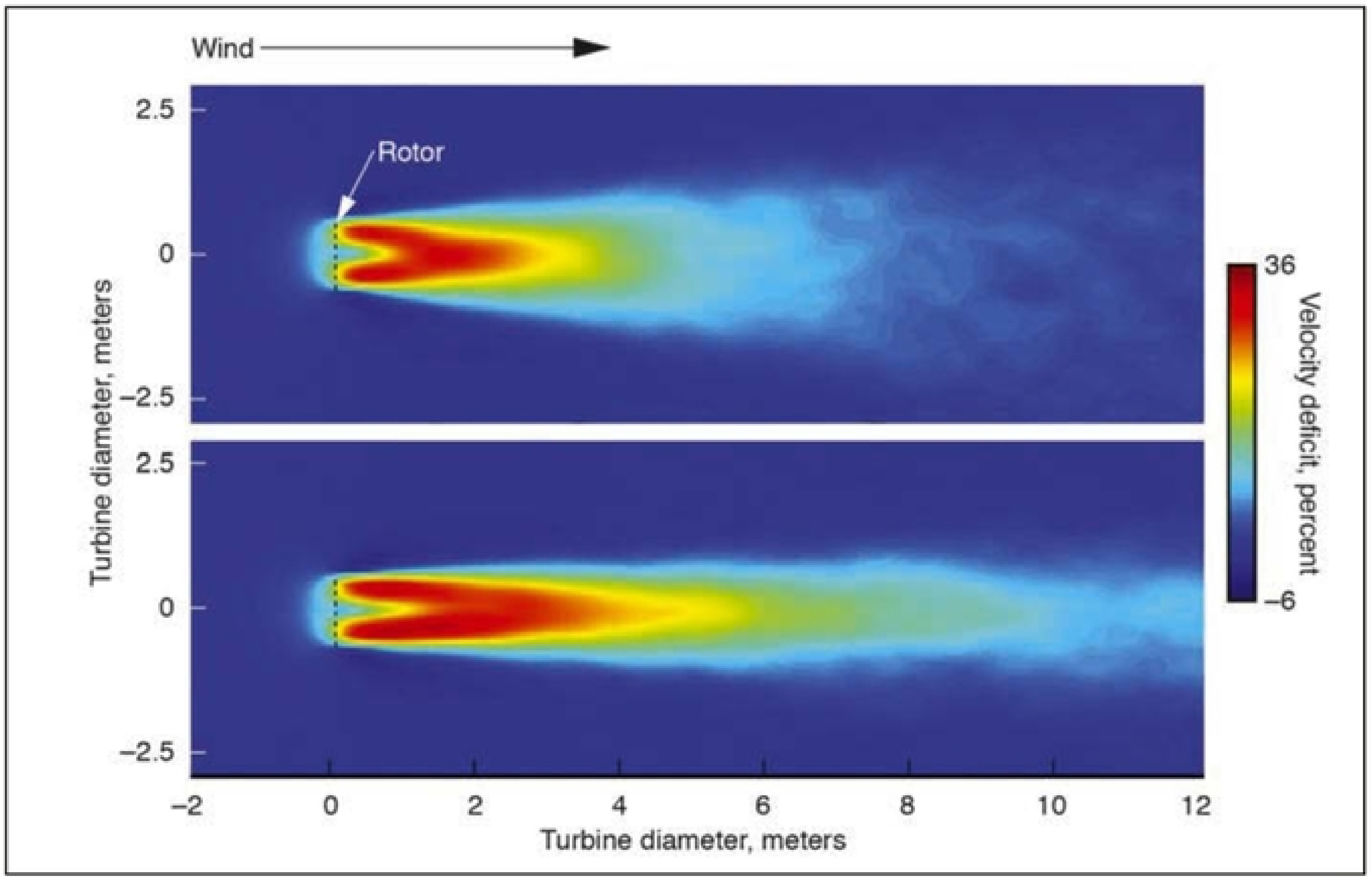
The job is vastly compounded when attempting to model a wind farm consisting of 100 or more turbines. What's more, simulations must account for varying terrain that can affect power output from one wind turbine to the next, and turbulent wakes from the front rank of spinning turbine blades that can rob power from turbines downstream. Fortunately, Lawrence Livermore has the required computational horsepower and also simulation expertise.

Atmospheric scientist Jeff Mirocha and others are engaged in efforts to advance the state-of-the-art weather research and



A wind simulation shows the evolution of large turbulent eddies as they propagate over complex terrain at Livermore's Site 300 experimental research facility. The wind flows in the direction of the simulated slices, from lower left to upper right. The colors denote the strength of the turbulence, with red representing the strongest

A researcher checks a solar-powered lidar station at a wind farm near Lawrence Livermore. Lidar stations provide vertical profiles of windspeed, direction and turbulence in the lower layer of the atmosphere



Left: Two simulations of a generalized actuator disk wind turbine model within the Weather Research and Forecasting (WRF) code depict the wake downstream from a wind turbine rotor plane (dashed line). The simulations, viewed from above looking down at the turbines, show how the strength of background atmospheric turbulence (convective instability) influences turbine wakes. Stronger turbulence (top) attenuates the wake more rapidly than weaker turbulence (bottom)

forecasting (WRF) model. This atmospheric simulation code, used and maintained collectively by more than 10,000 users and contributors worldwide, was developed primarily for larger-scale weather applications. Livermore researchers are extending the applicability of this popular model to the wind farm scale to address knowledge gaps and research challenges associated with the simulation of flows at those scales.

Mirocha says, "We have modified WRF extensively to make it applicable to the smaller scales relevant to wind turbines. The reason for these modifications is that many different scales of motion, from weather systems to turbulence, all interact and combine to determine the flow conditions at the wind farm scale, and therefore the power that can be produced. Accurate wind power forecasts therefore require a multiscale simulation approach to account for all these important scales."

As an example of multiscale methodology, one can start with a simulation of Europe to capture the evolution of large-scale weather patterns. Thereafter, a combination of smaller grid spacing and Livermore-developed submodels can accurately resolve the additional smaller-scale features important at wind farms.

In addition, once smaller scales of flow are resolved, engineering wind turbine models can be implemented to investigate processes important to engineering applications, such as wakes, power production and turbine component fatigue. "Wind power simulation lies at the boundary of engineering and atmospheric sciences," says Mirocha, who is attempting to seamlessly blend WRF atmospheric simulation with scales of motion traditionally handled by computational fluid dynamics (CFD) codes.

To capture the interactions between wind turbines and complex atmospheric flows, Mirocha has implemented a generalized actuator disk (GAD) wind turbine model into WRF. This approach depicts a 2D disk containing the rotating turbine, with the lift and drag forces of a turbine in response to atmospheric flow. The GAD calculates both the power output of a turbine, as well as the wakes that emanate downstream. These wakes, which feature both reduced windspeeds and increased turbulence, are of key concern because they are associated with significant power losses (up to 40%) as well as shortened operational lifespans.

Immersed boundary method

Because the standard WRF model was designed primarily for larger scales, it was restricted to simple terrain with shallow slopes. However, an additional Livermore development effort, the immersed boundary method (IBM), eliminates this restriction.

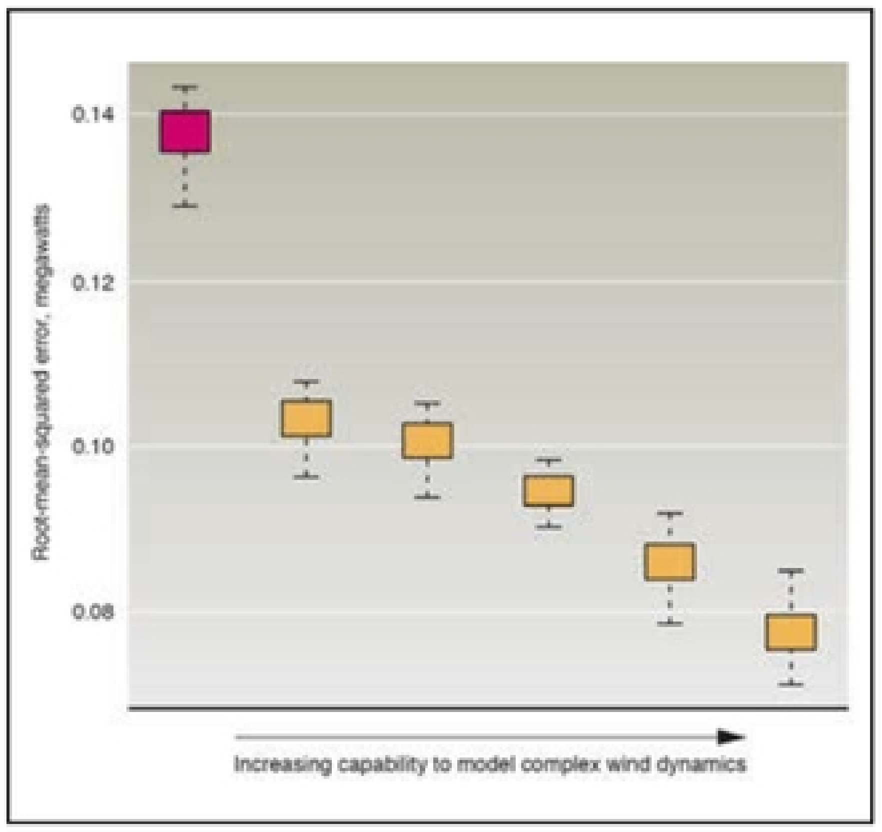
Using the IBM approach, WRF can simulate highly complex terrain. Mechanical engineer Katie Lundquist developed the code for her dissertation, and is currently refining it so that it communicates well with WRF. "IBM allows us to use a Cartesian grid," says Lundquist. For the first time, she says, simulations of flow in highly complex mountainous terrain with near vertical slopes can be accommodated without compromising accuracy and with grids as small as 1m.

Right: As statistical models account for increasingly complex information about wind dynamics, the root mean squared error associated with predicted power output from a wind turbine decreases considerably. Livermore researchers used lidar data as input to five power curve models (gold squares) and compared their results with a manufacturer's power curve (pink square) for a number of data sets. The power curve models incorporating successively more information about wind dynamics tended to have a much lower prediction error

Minimizing uncertainties

A group of Livermore researchers is studying how to reduce uncertainties both in the errors associated with data they gather, as well as the assumptions, inputs and approximations inherent in the physics of the WRF code, its constituent modules, and the nested CFD codes. The work takes advantage of the laboratory's strength in statistical modeling and uncertainty quantification. Livermore researchers are applying uncertainty quantification to collected field data as well as to groups of forecasts.

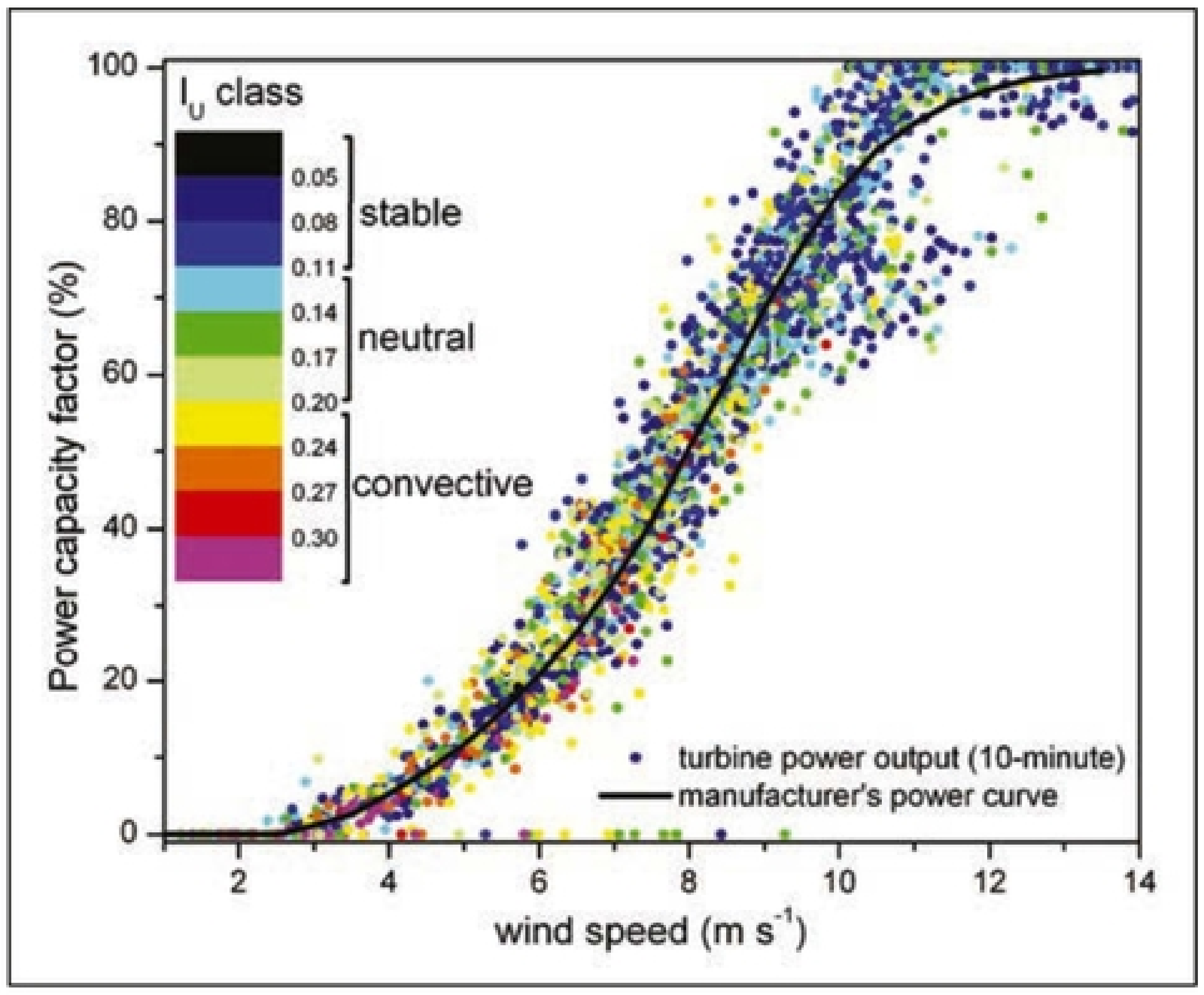
"Wind power forecasting involves converting atmospheric forecasts into a forecast of power output from an individual turbine or many turbines in a wind farm," says statistician Vera Bulaevskaya. Traditional manufacturer-supplied power curves model power as a function of the windspeed at the hub height of the turbine. In reality, however, power output is a function of many additional variables. For



ACCURATE PREDICTIONS BENEFIT EVERYONE

Taken together, the field observations, simulations and statistical modeling are combining to greatly improve wind power predictions. Lawrence Livermore National Laboratory is sharing this work with the wind industry and governing bodies to help them refine their power curves and incorporate findings about which specific atmospheric processes are important in wind power forecasting.

With improved models, wind farm operators will know how to better maximize their sizable investments, more skillfully bid into the energy market, site turbines more optimally, and minimize effects of the turbulent wakes from upstream turbines. The biggest winner, however, may well be the energy consumer, who will enjoy abundant supplies of energy from a clean and inexhaustible source.



Left: Wind turbine manufacturers typically provide operators with a simple 'power curve', which shows power from the turbine as primarily the cube of hub-height windspeed. However, Livermore researchers are showing that power curves frequently err by ±50% of actual power output, as seen in this plot of observed power versus windspeed at a northern California wind farm. The color map relates atmospheric stability conditions to reported power-output observations

example, windspeed at heights below and above the hub, as well as air density, wind shear and turbulence, are also strong predictors of power production, so taking them into account provides a more complete power curve model, she says.

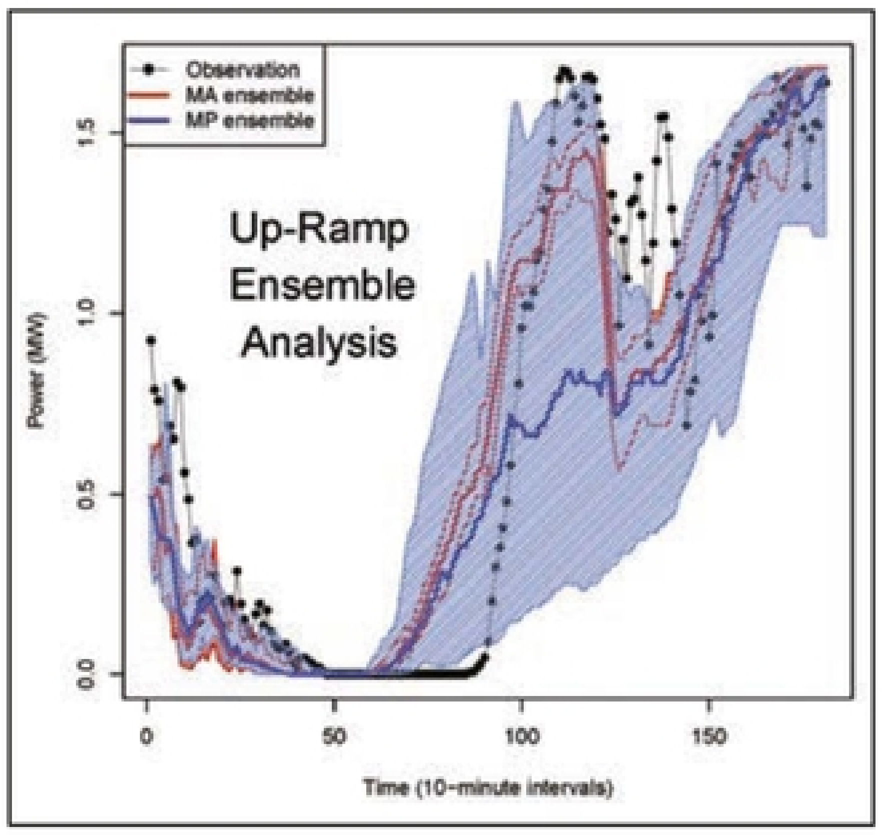
Moreover, to be valuable, a forecasting tool must not only produce accurate forecasts of power, but also correctly quantify the uncertainty, or confidence level, associated with these predictions. Such confidence levels are particularly of value to electricity grid operators, who use predictions of output (with their associated confidence) to determine which sources of power to turn on and off, and when. Quantifying uncertainty in output is also critical for selecting sites for wind farms.

Bulaevskaya has investigated various statistical approaches for modeling power as a function of changes in atmospheric conditions. She discovered that their performance in terms of prediction accuracy is significantly better than that of manufacturers' power curves. One statistical technique, known as a Gaussian process model, has an additional advantage: unlike the other approaches, it easily provides the uncertainty estimates associated with predictions.

Ensemble modeling

To reduce uncertainties in wind forecasts, atmospheric scientist Matthew Simpson processes 'ensemble modeling', which means running a forecast dozens or even hundreds of times using slightly different starting conditions. "Ensemble modeling shows us competing models of reality," says Simpson.

He explains that WRF constitutes many individual packages, each representing a particular atmospheric physics such as turbulence, aerosols, solar radiation, precipitation, surface roughness, clouds, boundary layer mixing (turbulence), heat rising from the ground, aerosols, wind shear, etc. One way to capture uncertainty in forecasts is by running ensembles with different values of parameters in a given package. Also, Simpson can substitute different physics packages that attempt to describe the same phenomena. For example, there exist several different models of cloud simulation in WRF, and each offers the developer's best description of physical processes.



Above: Ensemble forecasts provide a statistically relevant range of possible outcomes for future wind conditions. In this example, an ensemble is used to predict an observed up-ramp (black line). The up-ramp is bracketed by the range of ensemble outcomes (blue shaded area). Different methods of creating the ensembles such as multi-analysis (red line) and multiphysics (blue line) produce different outcomes. Selecting the best approach is site-specific

One of the chief advantages of ensembles is the ability to spot outliers such as a wind ramp. Because power is proportional to the cube of the windspeed, it is important to be aware of outliers. "If you get a sudden increase in power, it is not a big problem because you can always shut down wind turbines," says Simpson. "However, if electricity demand increases and the wind suddenly drops, grid operators must start up a natural gas plant or import power, and that can be costly."

Atmospheric scientist Don Lucas has worked extensively with climate and atmospheric model uncertainties and has run thousands of ensemble simulations during his career. "Uncertainty quantification is at the interface of simulation and statistical analysis," he says.

"Sometimes changing parameters or their relative strengths doesn't affect the output or exerts only a small influence," says Lucas. "We can also look for which factors greatly influence forecast, and then focus computational resources on that."

Lucas also notes that relevant field data helps keep models "honest". "We want to improve uncertainty quantification calculations with observations to see how well we know the model and how well the model performs." ∎

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