Volume 92 Number 9 September 2011

BAMS

Bulletin of the American Meteorological Society

AEROSPACE DESIGN CRITERIA

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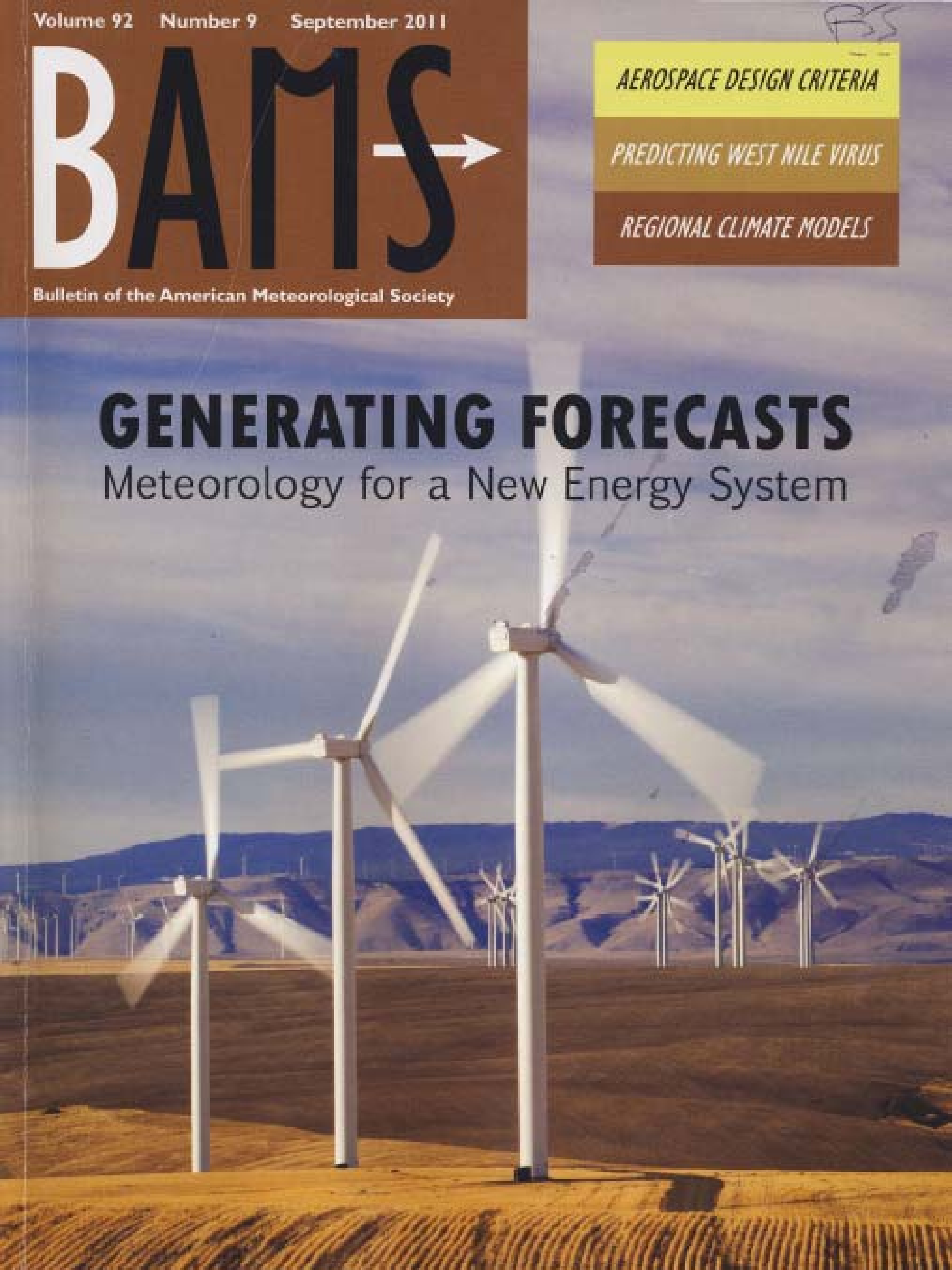

GENERATING FORECASTS

Meteorology for a New Energy System

FORECASTING THE WIND TO REACH SIGNIFICANT PENETRATION LEVELS OF WIND ENERGY

BY MELINDA MARQUIS, JIM WILCZAK, MARK AHLSTROM, JUSTIN SHARP, ANDREW STERN,
J. CHARLES SMITH, AND STAN CALVERT

Improved weather forecasts help system operators know with greater accuracy how much variable renewable energy can be generated and how much other electric power they will need.

The benefits of weather-dependent renewable energy are tremendous and weather-dependent sources are abundant. A recent study shows that land-based wind turbines on nonforested, nonurban, ice-free areas, operating at only 20% of their rated capacity, could supply 40 times the current global demand for electricity (Lu et al. 2009). Unlike fossil fuels and nuclear energy, wind energy and solar photovoltaic (PV) systems require virtually no water (Stillwell et al. 2009). Wind and solar energy are produced domestically and increase the diversity of the nation's electricity sources, which promotes energy independence, national security, and domestic economic growth.

Because of the multiple benefits of renewable energy, its annual growth rate in the United States has been phenomenal in recent years, averaging 39% for wind and 22% for solar electric [PV and concentrating solar power (CSP)] over the past 5 yr [2004–09; see American Wind Energy Association (2010a) and Solar Energy Industries Association (2010)]. A recent National Academy of Sciences report (National Research Council 2009a) finds that "there are no current technological constraints for wind, solar photovoltaics and concentrating solar power . . . to accelerate deployment" (p. 322). According to the U.S. Department of Energy (DOE), reaching 20% of our electricity from wind by 2030 is possible (U.S. DOE 2008b), and many areas are already above 10% today.[1] Figure 1

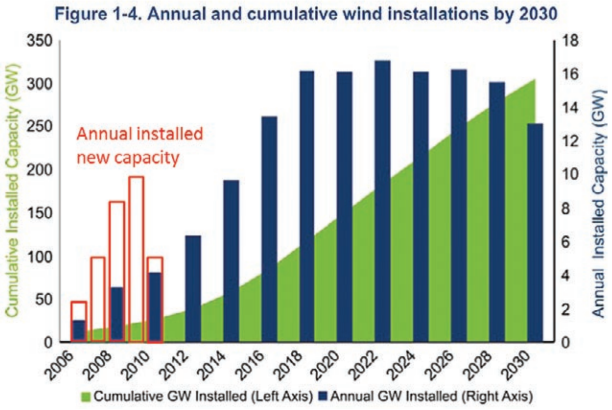

FIG. 1. Annual and cumulative installations of wind energy capacity, anticipated by DOE for one scenario providing 20% wind penetration by 2030. The projected needed annual installations (solid blue bars), and the projected cumulative wind installations needed to reach 20% penetration (green shaded area) are also shown. The actual new capacity that has been added in recent years is indicated by the red outlines, which exceeds the projected needed new capacity, even in the recession-affected year of 2010. [Figure adapted from the U.S. DOE (2008b) and American Wind Energy Association (2010a)].

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[1] In terms of estimated wind energy supply as a proportion of in-state electricity generation, the front-runners include Iowa (19.7%), South Dakota (13.3%), North Dakota (11.9%), and Minnesota (10.7%). Some utilities are seeing higher percentages of wind energy supply than these state totals, with nine utilities estimated to have in excess of 10% wind energy on their systems (U.S. DOE 2010).

(U.S. DOE 2008b) illustrates one scenario of annual and cumulative installations of wind energy capacity for reaching 20% wind penetration by 2030. As of January 2011, the total U.S. wind capacity was 40,180 MW, and for the first time, U.S. capacity fell second to China's, whose capacity grew 62% in the preceding year (American Wind Energy Association 2010b).

Although weather-dependent renewable energy has many advantages over traditional energy generation, its variable nature adds new challenges. Wind, solar, hydropower, biomass, and wave energy all have output that varies with the weather. Wind and solar often vary by large amounts over short time scales, with the energy output from wind and solar energy farms changing from near zero to maximum output in periods of several hours or less. Because of their short-term variability, and the fact that at present there are no economically viable means of large-scale storage for wind, solar, and wave energy (unlike hydropower and biomass), in this paper we refer to these energy sources as variable renewable energy resources (VREs). Further, we focus on the most rapidly growing segment of VRE generation (measured in new capacity installed per year) that has some level of maturity as an industry, with significant potential for growth in the next several decades: wind energy. The pathway to the use of less-developed, weather-dependent renewable energies, such as solar energy and ocean surface waves, will be similar.

Because of the variable nature of the weather, there are some implications for the bulk electric system of using weather-dependent energy sources that need to be addressed as their penetration increases. Electric grid system operators must instantaneously and continuously balance supply and demand to maintain the reliability of the power grid. The grid consists of balancing areas that encompass the generation, transmission, and loads within a defined and metered boundary. Each balancing authority (BA) balances the supply and demand of electric power within a balancing area through many means, such as by controlling the amount of power that is generated within the boundary or exchanged with neighboring areas. Generation resources that can be controlled for the purpose of balancing are known as dispatchable resources. Because of the uncertainty associated with VREs, they are typically not considered as dispatchable.[2]

Fossil fuel plants run at their highest efficiency, producing the most energy and least CO_2 emissions per unit of fuel, when they are run at their optimal capacity level; reducing output results in lower thermal efficiency. This favors turning off some fossil fuel plants when VRE generation is high, rather than keeping an entire fleet of plants operating at a suboptimal output level. However, restarting a fossil fuel plant is often a lengthy process, taking from several hours to 1 day, depending on the plant type and age, while increasing the output of a plant that is running at a reduced capacity is relatively quick. The challenge to grid operators is to decide how to manage the traditional fossil fuel generation plants to maximize plant efficiency and minimize costs. Improved weather forecasts help system operators know with greater accuracy how much VRE can be generated and how much other electric power they will need. If the uncertainty associated with VREs can be reduced and better quantified, then the generation mix can be more effectively optimized with less traditional thermal generation needing to be held ready to balance unexpected variability. In addition, as uncertainty metrics become more reliable, variable generation can be integrated more cost effectively, because it can be scheduled with a higher level of confidence, thus reducing the costs of additional reserves or other mitigation options.

Electric grid stability (reliability) is maintained by keeping system flexibility available in the form of reserves that can move their power level up or down quickly, to respond to forced equipment outages (such as the failure of a major power plant or transmission line) and errors in forecasted load or

AFFILIATIONS: Marquis and Wilczak—NOAA/Earth System Research Laboratory, Boulder, Colorado; Ahlstrom—WindLogics, St. Paul, Minnesota; Sharp—Iberdrola Renewables, Portland, Oregon; Stern—NOAA/National Weather Service, Silver Spring, Maryland; Smith—Utility Wind Integration Group, Reston, Virginia; Calvert—Energy Efficiency and Renewable Energy, Wind and Water Power Program, Department of Energy, Washington, D.C.

CORRESPONDING AUTHOR: Melinda Marquis, NOAA/Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305
E-mail: melinda.marquis@noaa.gov

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/2011BAMS3033.1

In final form 31 March 2011

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[2] Wind energy can be curtailed and therefore it is "dispatchable" in a downward direction when there is an abundance of wind energy in an area; with improved forecasts and flexible market design, wind energy could be considered to have some degree of upward dispatchability.

generation. As the Eastern Wind Integration and Transmission Study (described below) reports, when wind energy reaches sufficiently high penetration levels, increased operating reserves are needed to balance supply and demand. These increased reserves create additional costs, sometimes referred to as *wind integration costs*, although the studies also show that the economic benefits from wind energy may actually lower the overall cost of energy for the system as a whole.

The value of improved wind forecasts for the wind energy industry is well established (National Research Council 2009a; Giebel et al. 2006; Ernst et al. 2007; U.S. DOE 2008; North American Electric Reliability Corporation 2009; Argonne National Laboratory 2009; Delucchi and Jacobson 2011). VRE output needs to be better predicted across a range of time scales from minutes to years. At shorter time horizons (from minutes to a few days), the more accurately the output from VREs can be forecasted and the more reliably forecast uncertainty can be characterized, the more efficiently VREs can be integrated into grid operations, with lower costs. At longer time horizons (from weeks to years), better characterization of VRE output would be very valuable for effective long-term planning of a new energy system that creates electricity from domestic, weather-dependent, climate-dependent energy sources. These characteristics include average energy production; diurnal, seasonal, annual, and decadal VRE resources, trends, and variability; volatility (how quickly and how often a resource ramps); forecastability; and risk of shifting resources resulting from climate variability and change. Additionally, a related area of research is needed to understand how VRE systems may affect the environment, including local weather and climate, even though the expected benefits of VRE dwarf concerns about possible unintended impacts. All of these improvements in forecasting and modeling depend in part on more and better observations.

The U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE) and the U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA) in January 2011 signed a memorandum of understanding (MOU; www.noaanews.noaa.gov/stories2011/20110124_doedoc_mou.html) to collaborate to enhance the accuracy, precision, and completeness of renewable energy resource information to support weather-dependent and oceanic renewable energy, including wind (onshore and offshore), solar, biofuel and biopower, hydropower, hydrokinetic (wave, tides, and currents), and new innovations that may develop in the future. The MOU calls for improvements in relevant atmospheric and oceanic observations, modeling, numerical weather prediction, and climate research.

Well-coordinated public–private collaboration is required to obtain the relevant observations and model improvements to yield improved operational weather forecasts. Though the atmospheric science community cannot change the variability of weather-dependent renewable energy, through a well-designed public–private partnership it can improve the accuracy and uncertainty of forecasts of renewable energy production.

WIND INTEGRATION CHARGES AND CURTAILMENT

Under current operating practices, and with the present-day accuracy of wind forecasting, some regions are assessing significant additional costs to wind plant operators. For example, in the Bonneville Power Administration (BPA) BA, a wind integration charge of \$1.29 $(\text{kW month})^{-1}$ was applied to all of the wind facility capacity for the 2010–11 rate period. Because it is a capacity charge, wind facilities pay this rate regardless of whether energy is produced. At a typical capacity factor of 33% the cost equates to about \$5.85 MWh^{-1}, or 15%–25% of the typical real-time wholesale value of energy within the BPA BA. Wind integration tariffs or qualifying facility[3] deductions equivalent to \$5–\$13 MWh^{-1} have been applied by several BAs, including BPA, PacifiCorp, Westar, Avista, and the Idaho Power Company. Puget Sound Energy recently filed with Federal Energy Regulatory Commission (FERC) for a wind integration tariff of \$2.70 $(\text{kW month})^{-1}$, equivalent to about \$12 MWh^{-1}.

Curtailment of wind energy production, which occurs when there is more wind energy produced than can be instantaneously integrated onto the electrical grid or handled by available transmission lines, is also becoming common. During curtailment episodes (accomplished by feathering of the turbine blades), a wind energy facility is not generating revenue or displacing fossil generation when it could be. Improved forecasting has the potential to minimize wind integration charges and to reduce wind energy curtailments.

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[3] A qualifying facility is a wind energy provider from which a utility must accept power under a negotiated Power Purchase Agreement (PPA) at a rate that covers the utility's avoided costs, that is, the utility's savings in fuel costs avoided by using wind energy. Recently, utilities have begun to deduct a wind integration charge from their negotiated PPA rate to cover their perceived integration costs.

THREE VARIABLE RENEWABLE ENERGY HIGH-PENETRATION STUDIES. The results of three recent VRE feasibility studies provide additional information about the need for improved weather forecasts as a means to realize the benefits of weather-dependent VRE.

20% wind by 2030 (December 2008). A U.S. DOE (2008b) report looked at the costs, challenges, impacts, and benefits of generating 20% of the nation's electricity from wind by the year 2030. For the 20% wind scenario, installed U.S. wind power capacity would be 305 GW by 2030 with the majority (251 GW) of it being produced on land and the remainder (54 GW) offshore. New transmission lines, larger BAs, and better regional planning would be required. Benefits include reduced emissions (825 million metric tons of avoided CO_2 emissions per year) and an 8% reduction in water use by the electric sector (4 trillion gallons). The 20% wind scenario could also displace natural gas consumption by 11% and substantially reduce the use of coal plants, thereby reducing emissions of mercury and acidification of lakes and streams from acid rain and mining. Wind energy that displaces fossil fuel generation also can reduce emissions of criteria pollutants, such as sulfur dioxide and nitrogen oxides. This study determined that the cost of the 20% wind scenario could be $43 billion more than the base-case scenario, which assumes no new wind power generation. This would amount to less than 0.06 cents per kilowatt hour of total generation by 2030, or about 50 cents per month per household. Importantly, this report emphasizes the necessity of accurate wind and wind power forecasts: "Improved short-term wind production forecasts let operators make better day-ahead market operation and unit commitment decisions, help real-time operations in the hour ahead, and warn operators about severe weather events. Advanced forecasting systems can also help warn the system operator if extreme wind events are likely so that the operator can implement a defensive system posture if needed" (U.S. DOE 2008b, p. 86).

Eastern Wind Integration and Transmission Study (EWITS, January 2010). An EnerNex Corporation (2010) report considered similar costs, challenges,

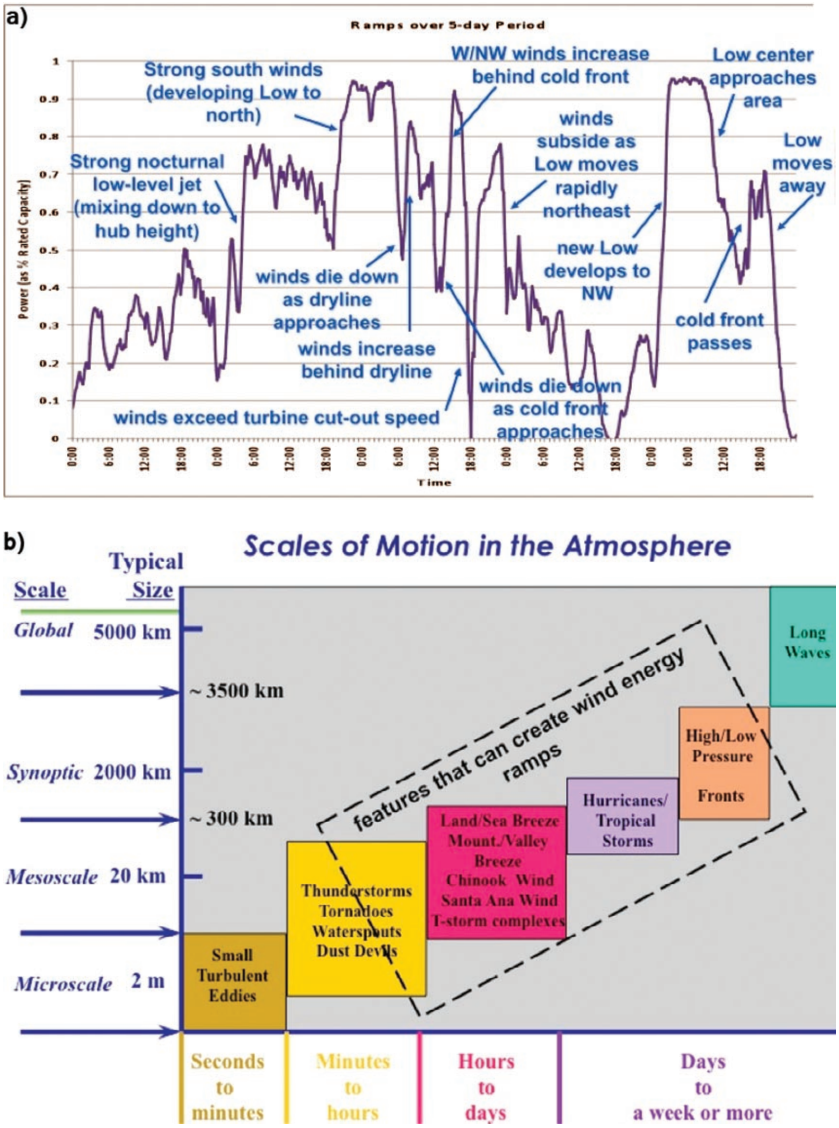

FIG. 2. (a) Examples of the wide variety of meteorological events that produced wind power ramps over a 5-day period. Wind power production is on the *y* axis. Time is on the *x* axis. [Figure courtesy of C. Finley of WindLogics.] (b) Graphical representation of various meteorological events across a range of spatial and temporal ranges. Spatial scale is on the *y* axis. Time is on the *x* axis. [Figure courtesy of C. Finley of WindLogics.]

impacts, and benefits, as does the national 20% by 2030 report, but focuses on operating implications for 20% wind energy in the Eastern Interconnect only for a target date of 2024. The report finds that enhancements to the nation's transmission lines are necessary and that increasing the size of BAs decreases the cost and increases the reliability of systems with wind energy. Benefits are similar to those noted above, including reduced emissions. This study also stressed the value of accurate wind forecasts: "With significant wind generation, forecasting will play a key role in keeping energy markets efficient and reducing the amount of reserves carried while maintaining system security" (EnerNex Corporation 2010, p. 225).

Western Wind and Solar Integration Study (WWSIS, May 2010). The WWSIS investigated the operational impact of up to 30% penetration of wind and 5% solar on the power system operated by the WestConnect group of utilities in Arizona, Colorado, Nevada, New Mexico, and Wyoming along with 20% wind and 3% solar in the remainder of the western interconnection, called the Western Electricity Coordinating Council (WECC). Like the two analyses above, the WWSIS found that it is operationally feasible to accommodate these levels of VRE, assuming substantial increases in the balancing area cooperation or coordination; increased subhourly scheduling for generation and interchanges; and increased utilization of transmission and limited transmission additions. Use of state-of-the-art (SOA) forecasts was assumed. In order to accommodate the increased uncertainty resulting from wind/solar forecast error, options such as increased flexibility in the dispatchable generation portfolio, commitment of additional operating reserves, and/or demand response were identified. The WWSIS found that, depending on the price of natural gas, the 30% wind plus 5% solar scenario yields a reduction of CO_2 emissions of 25% (~120 million tons yr^{-1}) to 45% (200 million tons yr^{-1}) compared to projected emissions for the year 2017 if no new wind and solar energy were used. A high gas price means that wind and solar energy displace gas, whereas a low gas price means that wind and solar energy displace coal instead, leading to greater carbon emission reductions.

The WWSIS reports that weather forecast error is the most challenging impact on the electrical system. "Integrating day-ahead wind and solar forecasts into the unit commitment process is essential to help mitigate the uncertainty of wind and solar generation. Even though SOA wind and solar forecasts are imperfect and sometimes result in reserve shortfalls due to missed forecasts, it is still beneficial to incorporate them into the day-ahead schedule process, because this will reduce the amount of shortfalls" (GE Energy 2010, p. ES-18).

The three recent U.S. DOE reports described above make clear that advances in weather forecast skill are necessary, together with other improvements in power system operational practices, to address all the challenges of integrating wind and solar energy and fully reaping the rewards. Efforts to improve forecasts should occur in tandem with other actions and will be similarly important. For example, the spatial diversity of weather patterns should be exploited by increasing the size of BAs. Larger BAs smooth the overall variability of the weather (and therefore of the VRE generation) while also providing a larger pool of traditional generation for balancing supply and demand. Furthermore, average forecasting error is reduced when aggregating across a larger geographical area. In addition, changes in the energy market structure, such as shortening the schedules on which power is committed and traded, will also facilitate wind integration (Smith et al. 2007).

THE REQUIRED IMPROVEMENTS IN ATMOSPHERIC SCIENCES AND A PATHWAY TO ACHIEVE THEM. Improved short-term weather forecasts and innovative climate studies, both of which depend on new measurements and research, are needed for large-scale, weather-dependent VRE (U.S. DOE 2008a). Improved forecasting of ramp events for wind and solar energy, which are large changes in energy generation over short time periods, is particularly pressing. Balancing authorities need to maintain contingency reserves to respond to these large changes. Ramp events are generally caused by changes in wind speeds (for wind energy) or the movement of clouds (for solar energy). The timing, duration, and amplitude of ramp events are important for accurate forecasts.

Wind ramp events are inherently difficult to forecast accurately and can be caused by many meteorological phenomena at all scales, including development or movement of large-scale weather systems; thunderstorms; boundary layer processes, including vertical mixing and diurnal heating; complex terrain effects; and thermally forced flows, including sea breezes and drainage flows. Cloud ramp events are also difficult to predict because of our relative lack of understanding of fundamental cloud processes. Figures 2a,b illustrate the meteorological phenomena across a range of temporal and spatial scales that cause wind ramp events.

Improvements in short-term weather forecasts are needed. The renewable energy sector uses the forecasts of the National Weather Service (NWS) to initialize models that make tailored forecasts (of wind speed and wind power) for individual wind power plants and/or balancing areas. The NWS forecasts are produced by NWP models that have not been optimized to address the needs of the VRE community, and the VRE industry considers the nation's core operational forecast output to be inadequate to meet the needs of wind power forecasting. Wind forecasting errors are magnified by the fact that wind power increases as the cube of the wind speed. The WWSIS (section 5.6) provided an analysis of day-ahead-simulated wind power forecast error, and determined, among other things, that the size and number of large errors in wind power forecasts increases as wind energy penetration increases. Figure 3 (top panel), from the WWSIS, shows a plot of the wind power forecast errors as a function of the amount of installed wind energy capacity for all hours of the study year within the study footprint for a 30% penetration scenario. The largest forecast error was 11,771 MW, during an hour when the wind power was actually ~ 7,000 MW. Thus, the day-ahead forecast value was ~ 18,771 MW, but the actual wind power produced the next day was only ~ 7,000 MW, resulting in an error of ~ 11,771 MW. (See the sidebar about the monetary value of improved wind forecasts for details about the WWSIS.)

The minimum requirements needed to support improved wind energy forecasts, which include observations, data assimilation systems, and NWP configurations, are not precisely known at present. Research studies are needed to help define these requirements. The following estimates of horizontal and vertical resolution, data assimilation cycles, and parameters are targets to help guide research efforts. The short-term (next 6 h) time frame is particularly important to real-time operators of the power systems, and a national scale High-Resolution Rapid Refresh (HRRR) model, updated at least hourly and running at a horizontal resolution of at least 3 km, could make a large, beneficial impact. Enhanced forecasts of boundary layer parameters are particularly important for wind energy, with modern turbine hub heights now at 80–120 m above ground level (AGL) and blade diameters spanning 75–120 m. Thus, turbine blades are cutting a swath of atmosphere from 30 to 180 m AGL. A model vertical resolution of ~20 m in the lowest 300 m is therefore desirable to characterize turbulence, shear, and effects of the low-level jet for wind energy. Wind speed, wind direction, and the timing, amplitude, and duration of ramp events are a high priority. In addition, improved forecasts of high and low temperatures at turbine blade levels, air density, and icing conditions will support more efficient operations of wind plants.

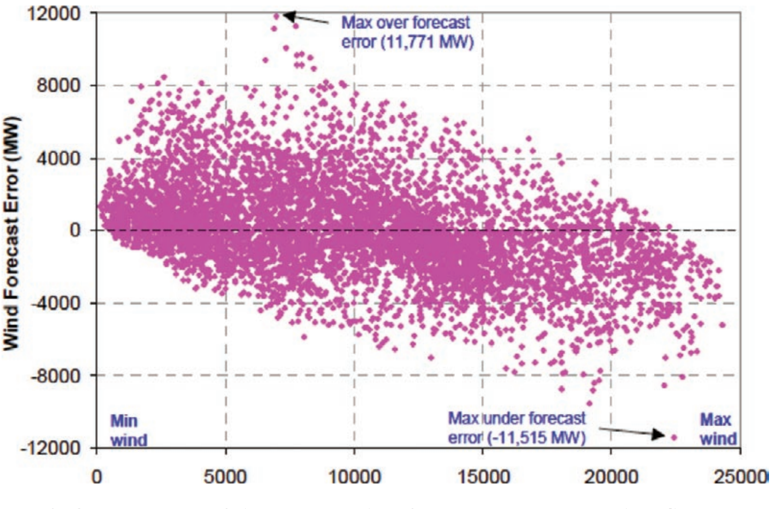

Fig. 3. Scatterplot of simulated wind forecast errors vs wind (installed capacity) for study footprint 30% scenario. [Reprinted from the WWSIS (GE Energy 2010).]

Figure 4 provides an example of typical wind energy forecast skill for a very short range (i.e., aggregate power expected in the next 60–120 min) lead time. Figure 4 shows a concatenation of sequential 1-h forecasts periods that fall between 60 and 120 min ahead of the time the forecast is made. When considering several days (Fig. 4a), the forecast appears to track but when actual error is overlaid, it becomes clear that though periods of little change (i.e., those that are persistent) exhibit low errors [<10% mean absolute error (MAE)], the record is punctuated by large errors that correspond to rapid energy ramps. The inset in Fig. 4a shows that these errors can be more than 80% of the plant maximum capacity. By looking at the forecast errors as a function of coincident energy output change (Fig. 4b) across a 1-yr record, it is found that the period portrayed in Fig. 4a is representative of the general picture; that is, forecast error is a strong function of output change. Unfortunately, these are the hours when accuracy is most important to the end user. Forecast error also increases with the length of the forecast period. Because Fig. 4 shows very short-term (next hour) forecasts, it represents a best-case scenario compared to those found for 6 h, 12 h, or longer-term forecasts.

An additional issue is that, because most hours exhibit few ramps, the bulk verification metrics, such as root-mean-square error (RMSE) and MAE, that are typically used by the industry for performance evaluation are insufficient. Other metrics, such as the critical success index (Ortech Power 2008; E. Grimit 2007, personal communication), have been proposed to better reflect the skill in identifying ramp events. However, as forecasts start to be used in operational settings, the value and performance of such forecasts may be best judged by their impact on operational costs. This suggests that there is still much to be done not just on the forecast but on how the information is presented to end users in actionable ways.

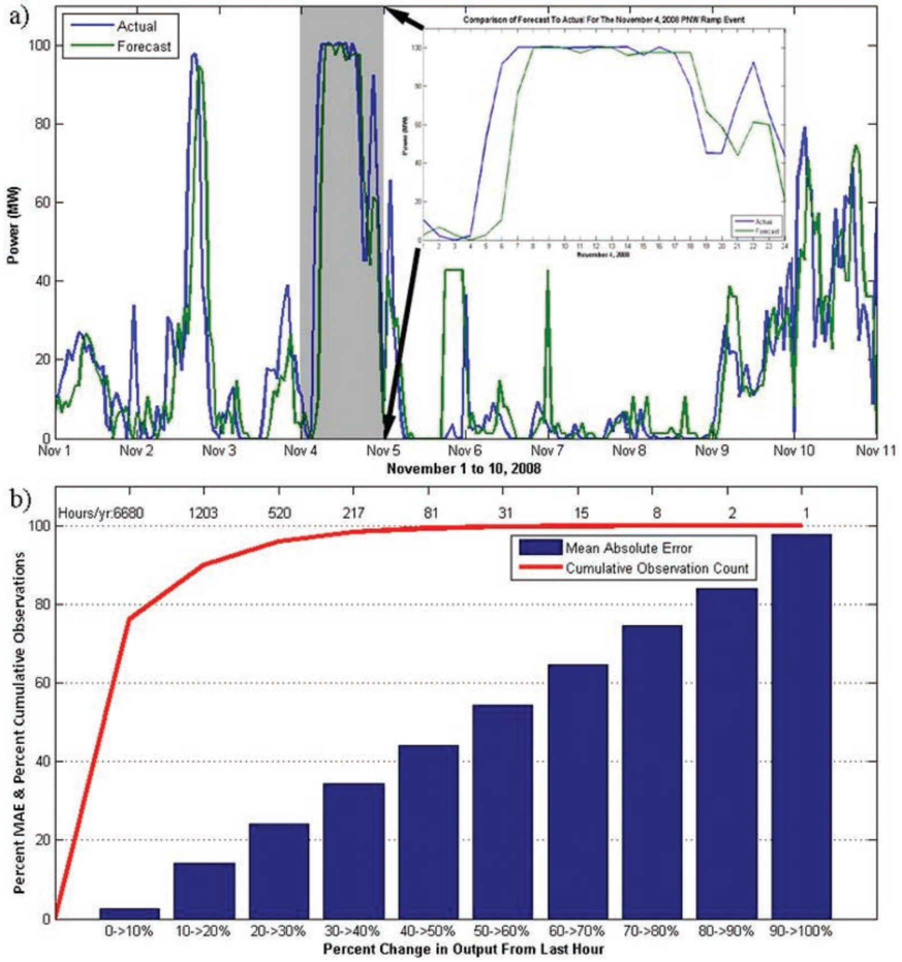

Fig. 4. (a) A typical comparison over a 10-day period of an hour ahead (60–120-min lead time) wind power forecast for a single project. At first glance the forecast looks good, but the inset, which zooms to a 1-day period, illustrates how very large errors occur concurrent with large wind ramps. Large errors like these are a significant factor in reserve allocation irrespective of how accurate the forecast is on average. (b) Chart indicating the relationship between forecast error and hour-to-hour change in wind plant output using 1-yr of hourly data from a wind facility in the Pacific Northwest. The horizontal axis consists of bins of energy change relative to maximum output ranging from less than 10% change in the hour to >90% change in the hour. MAE for each bin is plotted (bars), and the line plot shows the cumulative number of observations. The number of observations for each bin is printed at the top of each category.

Approaches to improving short-term forecasts for VRE. Improving forecasts of winds and solar radiation in the time frame of several hours to several days is feasible. It will require new observations, especially vertical profiles through the boundary layer and above, for winds, and improved moisture information through a deep layer of the atmosphere for solar energy. The addition of new observing instrumentation in the vicinity of wind power plants can improve the very short-term ability to predict the approach of weather disturbances through simple extrapolation in time, but this impact will be limited to short time horizons because ramp-producing meteorological phenomena evolve with time. At all but the shortest time horizons, useful forecasts will almost certainly require assimilation of meteorological observations into NWP models.

The future weather at a wind power plant will be influenced not only by upstream meteorological conditions at turbine heights but also by conditions through the entire depth of the atmosphere. This fact has been demonstrated by weather modeling studies that have investigated the impact of individual observing systems (Benjamin et al. 2010). Therefore, to have the greatest impact on weather forecast model predictions of turbine-height winds, observations should measure through as deep of a layer of the atmosphere as possible at high temporal frequency. This can be accomplished by remote sensing instrumentation. The design of a future observation network should, of course, utilize the most cost-effective means to meet the observational requirements.

Although the assimilation of upstream meteorological measurements into a weather forecast model will almost certainly improve the skill of wind forecasts produced, what is not known is the degree to which the forecast will improve, the extent that this improvement may vary from region to region and season to season, or the optimal sensor type, number, or placement of the instrumentation. For this reason, multiple wind energy test beds should be deployed in regions that have distinct boundary layer meteorology and large renewable energy resources. These wind test beds would collect observations of the boundary layer for studies of phenomena that affect wind resources, provide datasets for NWP model development, determine the most effective sensors for assimilation in NWP models, and identify optimal sensors for a national observational network supporting wind energy. Similarly, solar energy test beds should be deployed, with a focus on the Southwest, which has particularly good resources for concentrating solar energy. Measurements of total irradiance and the direct beam, along with aerosol optical depth and water vapor, are required.

In addition to new observations from test beds, ensemble-based forecasting holds promise for improving forecasts of wind and solar energy, and for providing probabilistic information on the amount of wind or solar energy that will be generated within a given balancing area. Reliable uncertainty information would have profound benefits for reserve allocation and unit commitment (Botterud et al. 2010; Ortega-Vazquez and Kirschen 2009; Matos and Bessa 2010). New techniques (e.g., ensemble Kalman filter, 4D variational data assimilation) have shown promise for improving large-scale weather and forecasts (Buehner et al. 2010), but application of these techniques to mesoscale wind and cloud forecasting is an area that requires further exploration. The NOAA–National Center for Atmospheric Research (NCAR) Developmental Testbed Center could be useful for transitioning NWP models with improved process relevant to wind energy from a research environment to an operational environment.

In addition to improvements in short-term forecasts, improvements in long-term forecasts and studies on possible impacts of VRE systems on the environment are also needed.

Approaches to improving long-term climate predictions of resources and studies of unwanted impacts. To obtain very high levels of renewable energy penetration, long-term predictions of wind and other renewable energy sources are needed. "Climate change has the potential for significant financial consequences within the lifetime of a wind plant" (U.S. DOE 2008a, p. 13). The nation needs a backbone network of high-quality sensors for providing the climatologies of turbine-height winds and turbulence for wind energy. Assessments of the spatial and temporal covariability climatologies of wind, solar, and water resources together with energy demand, using observations and reanalysis products, including analysis of extreme events, are needed. Research into the dependence of variable renewable energy resources on climate drivers, including ENSO, the Pacific decadal oscillation (PDO), etc., and the predictability of renewable energy resources from intraseasonal to multiyear time scales based on these drivers is needed. Much of this work will require an evaluation of boundary layer and cloud parameterization schemes in climate models that strongly impact renewable energy resource estimation, development of new parameterizations, and model improvements. Configuration of a regional climate modeling system for the prediction of turbine-height winds and solar energy, estimation of future renewable energy resources under likely climate change scenarios, development of statistical techniques for estimating uncertainties in renewable energy resources in each scenario, and formulation of guidance for decision support will help inform the nation's energy system. Participation by the academic, public, and private sectors is required to meet these challenges.

Very little is known about the potential inadvertent environmental impacts of renewable energy systems, especially if much larger numbers of systems are deployed either nationally or globally. As shown in U.S. DOE (2008b), even these high levels of wind energy would impact only a small percentage of the onshore land mass. Any impacts must also be viewed in light of other options, such as the global trade-offs of generating electricity from coal rather than wind and solar radiation.

Even so, local effects resulting from changes in turbulence and other factors should be understood. Field programs to identify the potential for microclimate impacts of wind power plants (including changes in soil moisture and number of frost-free days, and whether these changes are either detrimental or beneficial) should be conducted. A dense network of sensors up- and downwind of renewable energy power plants, and if possible, before and after the power plants are constructed, should be employed to study possible inadvertent effects.

A PATHWAY AND FRAMEWORK FOR MOVING FORWARD: PUBLIC–PRIVATE PARTNERSHIP. A collaboration of the public and private sectors is required to achieve the advances in atmospheric science needed to support growth of VRE. This community should leverage existing groups and efforts, such as the national "network of networks" that was proposed in a recent National Research Council (NRC) report (National Research Council 2009b). Both public and private funding are needed to obtain the required observations and model

MONETARY VALUE OF FORECASTS

Although it is intuitively apparent that better meteorological information will allow an energy system with VRE resources to run more efficiently, quantifying the monetary value of this information is complicated. Several studies have addressed this issue in some form, including the recent regional studies that were discussed earlier.

Usually these studies model the effect of wind energy on their system operations, including forecasting, plant operations, transmission, and market responses. This approach allows for either the simulation of a future energy system that can be assumed to operate differently than the present-day system or the "redispatch" of the current system with a modified input (such as with a perfect wind forecast in place of the actual wind forecast).

The Eastern Wind and Transmission Study (EnerNex Corporation 2010) used wind speed output from a high-resolution mesoscale NWP model run of three historical years to create a baseline dataset of wind plant output that was assumed to be reasonably representative of actual output. The data from the simulations were then degraded using the Markov chain statistical approach to approximate the errors that were present in current wind power forecasts. The wind integration cost attributed to the synthesized forecast error averaged $2.57 for each megawatt hour of wind energy produced (in 2024 dollars) for the three different 20% wind scenarios modeled. Extrapolating this integration cost to a nationwide basis using a 20% wind scenario with the 2008 national annual electricity production of 4.1 TWh gives a national potential annual savings of $2.1 billion from improving a current SOA wind power forecast to a "perfect" wind power forecast.

The Western Wind and Solar Integration Study (GE Energy 2010) used output from the Weather Research and Forecasting (WRF) mesoscale NWP model run at 2-km resolution to simulate 3 yr of meteorological data, which was then used to create a baseline dataset wind plant output. The model was initialized at regular intervals from the National Centers for Environmental Prediction(NCEP)–NCAR reanalysis dataset. An estimate of the current SOA forecast was then produced by repeating the simulation at a courser 6-km resolution using the Global Forecast System (GFS) grids for initial and boundary conditions. This study found an annual reduction in the system operating costs between the SOA and perfect wind power forecast of up to $2.0 MWh^{-1} of wind and solar energy (in 2017 dollars). Extrapolating to a nationwide basis (as we did earlier for EWITS) implies a value of $1.6 billion yr^{-1} from improving a current SOA wind power forecast to a "perfect" wind power forecast. Additional analysis (Lew et al. 2011) of the WWSIS data by General Electric (GE) and the National Renewable Energy Laboratory (NREL) found that the greatest cost savings are realized with the earlier forecast improvements. The first 10% or 20% improvements in wind forecasts provide the greatest relative benefits. Further improvement will provide diminishing marginal benefits, approaching the perfect forecast.

A third study for the Electric Reliability Council of Texas (ERCOT) Interconnect, which covers most of Texas, was done by GE with methods similar to those used in the WWSIS study (G. Jordan 2008, personal communication; www.uwig.org/Denver/jordan.pdf). Three scenarios were run at different wind penetration levels, with the largest level corresponding to 17% wind-derived energy. In this case, the potential increase in wind generation revenue between SOA and "perfect" forecasts was approximately $4.00 MWh^{-1} of wind energy, which, when extrapolated to a nationwide basis as above, implies a potential value of up to $3.3 billion yr^{-1}.

A somewhat simpler and more direct analysis was performed by Xcel Energy, using operational NOAA forecasts to create wind power forecasts for the existing wind production on their Colorado Public Service system for 2008 (K. Parks 2009, personal communication). Energy production costs were then compared to recalculated production costs that would have occurred had the forecasts performed with perfect skill. The potential savings from the perfect forecast averaged $5.06 MWh^{-1} over the year. Extrapolating this value nationwide for a 20% wind scenario, and again using the 2008 U.S. annual electricity production level, implies a potential savings of up to $4.1 billion yr^{-1} at 20% wind penetration.

As these studies show, the value associated with improved wind forecast skill is significant. While the value implied by smaller systems, such as Xcel and ERCOT, may be somewhat higher than actual national levels, and given that perfect forecasts are not achievable, all of the studies clearly show a potential for billions of dollars in annual value from incremental forecast improvement. And while difficult to quantify given current system operating tools and assumptions, it is also likely that improved understanding of forecast confidence levels can also contribute to significant costs savings and improved grid reliability.

improvements it needs. An upcoming collaborative field program, funded by the U.S. DOE, is a first step in realizing these advancements. This is described below.

Public–private partnership. VRE leaders have publically stated that the observations, data assimilation, and fundamental research required to improve short-term forecasts are beyond what the private sector can accomplish alone (American Wind Energy Association 2011, personal communication). This AWEA report (2011, personal communication; M. Goggin 2010, personal communication; www.ametsoc.org/boardpges/cwce/docs/profiles/GogginMichael/2010-08-AMS-SCM-Slides.pdf) states that, "Members of the wind industry have worked together to identify four priority areas for improving predictive modeling of the boundary layer. These four areas are: expanded data collection (more observations to fill national and regional data gaps, particularly in the boundary layer of the atmosphere), deployment of high-resolution rapid refresh models (more resolution in models, faster refresh of models), creation of a data repository (equitable and secure ways for additional private-sector data to contribute to the expanded data collection and assimilation), and further research (better understanding of boundary layer phenomena)." Defining and clarifying the respective roles of the public, private, and academic sectors in the area of renewable energy will require continuous dialog among the sectors working in the fields of weather and climate. The precise boundaries of a given role may change as progress accrues and the industry matures. Ongoing communication will facilitate the most efficient pathway to overcoming the meteorological challenges in this field. In response to an NRC report (National Research Council 2003), the American Meteorological Society (AMS) Commission on the Weather and Climate Enterprise was created, and provides a helpful venue for promoting a sense of community and better communication among the public, private, and academic sectors.

One strategy that is used to obtain the atmospheric research and operational services needed for increased use of VRE is to build a coalition of government agencies and private companies that will collaborate to meet the challenges of managing high-penetration levels of weather-dependent renewable energy. The public sector should reduce errors in relevant meteorological parameters, such as wind speed and direction in the turbine layer, and clouds and aerosols, thereby allowing for improved foundational weather forecasts to be provided to the public. The private sector will be responsible for providing value-added products, tailored forecasts of VRE power output for use in operations, and scheduling and trading functions. Both the public and private sectors should participate in the design and deployment of a national observation backbone network to support VRE development. The public sector has the demonstrated ability to implement a uniform and wide-scale data collection system.

Another role for a public sector agent could be to act as an "honest broker" to ingest relevant, proprietary, meteorological data, such as those collected at wind power plants, assimilate them into weather forecast models, and maintain confidentiality of these data. The airline industry set a precedent for this type of sharing of proprietary data when Delta, United, and Northwest Airlines began to provide observational data to NOAA for data assimilation into its weather prediction models 18–20 yr ago. Other airlines followed suit, and these data now make an important contribution to the significantly improved model forecasts that NOAA provides to all users, including the aviation community (Benjamin et al. 2010). These improved forecasts also benefit many other NOAA programs that depend on better predictions. Given the tight federal fiscal environment, leveraging all private sector observations and resources for the goal of public support of renewable energy is necessary.

A 12-month field demonstration project to improve forecasts of wind and ramp events by DOE, NOAA, and the private sector. A significant operational forecasting gap that exists is a national short-range forecasting capability with high spatial (<5 km) resolution and rapid updating (~1 h or less). Such a capability would have large societal and economic value in numerous sectors, including surface and air transportation, air quality, homeland security, public safety, fire weather, and, of course, energy management, including renewable energy. Such a capability requires a dense network of observations through as much of the atmospheric volume as possible.

By employing partnerships like those described above, a public–private collaboration is underway that is aimed at piloting such a short-range forecast capability using wind energy prediction skill and especially ramp event prediction skill as the input to metrics for assessing the value proposition of such a system. This program is a collaborative effort among federal agencies and the private sector, which will be conducted in 2011–12. It aims at demonstrating that forecasts of turbine-level wind speeds and wind ramp events can be improved with additional observations from tactically placed vertically profiling instruments and industry-provided wind speed measurements obtained from anemometers on tall towers and wind turbines. The private sector will then use these improved wind forecasts to create more accurate wind power predictions. This planned regional field demonstration comprises the following four main components: 1) collection of new public and private sector meteorological observations to characterize the boundary layer and improve model initialization; 2) assimilation of these observations into NOAA's High Resolution Rapid Refresh (HRRR) model, and the use of this model for wind forecasts; 3) analysis of the impact of assimilating the new observations into the HRRR model on the skill of wind forecasts, particularly ramp events; and 4) analysis of the impact of improving model forecasts on the efficiency and economics of wind power generation. Additionally, we hope to document the relative strengths and weaknesses of various observing platforms, to identify how best to site and operate instrumentation for wind energy applications, and to improve our understanding of wind ramp events.

Wind profiling radars, sodars, and a lidar will provide atmospheric observations through a deep layer of the atmosphere, and over a sufficiently broad area, to influence forecasts out to 6 h of lead time. In addition, the wind energy community will provide data to NOAA under the honest broker role described above. Large amounts of real-time boundary layer data at heights between the surface and turbine hub height could potentially be available for assimilation in this way. Instrumentation will be deployed for the duration of the 12-month field campaign, and all of the observational data (from government-deployed sensors) will be made available in near-real time to the public.

The HRRR model will be the core public sector forecast model for the demonstration project. This model is being run at 3-km horizontal resolution over the conterminous United States (CONUS) in a research mode by NOAA/Earth System Research Laboratory (ESRL)/Global Systems Division (GSD). At some future time, this model could become operational at NOAA/NWS. The private sector participants will play an important role in interfacing with NOAA model output, creating forecast products for the wind energy industry, and evaluating the impacts of improved wind forecasts on energy production.

CONCLUSIONS.

Increasing the accuracy of meteorological forecasts affecting VRE output prediction is one of the necessary steps to reduce the cost of accommodating VREs on the grid. VRE integration charges and curtailment both make VREs less economically viable and ultimately will reduce their rate of adoption unless solutions are found. Combined with market structures and grid operating practices that are appropriate for a mix of VREs and other renewable and traditional generation, this approach will decrease overall generation costs, reduce the reserve needed for reliability, and maximize the output from VREs, thereby reducing CO_2 emissions. The need to do this is especially pressing for continued momentum in wind energy penetration where significant financial penalties are already manifest.

Further, as a key strategy to mitigate climate change and for sound planning of VRE developments, long-term projections of VRE resources are needed. More understanding is needed about the historical variability and covariability of VRE resources (wind, solar, and precipitation), particularly on how these resources may vary and covary in the future under various climate scenarios. Understanding VRE resources and energy demand on regional and national scales, and planning to take advantage of the spatial patterns of weather systems and changing climate could prove to be valuable.

Obtaining the necessary meteorological and climatological observations and making the required improvements to weather forecasts and climate models are key to creating a new energy system—one that is economically viable and environmentally sustainable. Atmospheric scientists have been called upon before to help understand and remediate grave, global environmental problems, such as acid rain and ozone depletion. Providing the scientific information needed for the renewable energy community will require at least as great an effort.

The need for improved predictions from minutes to decades will require new partnerships, observations, and significant high-performance computing resources to assimilate the new data. Studies of VRE resources in the long term, as well as studies of potential inadvertent environmental impacts, are all needed for sound, long-term planning. Robust collaboration among the public, private, and academic sectors is necessary to achieve the advances in measurements and predictions needed for a national VRE system. Fortunately, we appear to be well poised to collaboratively meet this challenge.

ACKNOWLEDGMENTS. The authors wish to thank John Schneider, NOAA ESRL; Debbie Lew, National Renewable Energy Laboratory; and Ken Dragoon, Renewable Northwest Project for their thoughtful comments and helpful suggestions.

The views expressed are those are those of the author(s) and do not necessarily represent those of the National Weather Service.

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