Enhanced Short-Term Wind Power Forecasting and Value to Grid Operations

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Enhanced Short-Term Wind Power Forecasting and Value to Grid Operations

The Wind Forecasting Improvement Project

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Abstract—**The current state-of-the-art wind power forecasting in the 0- to 6-h timeframe has levels of uncertainty that are adding increased costs and risks to the U.S. electrical grid. It is widely recognized within the electrical grid community that improvements to these forecasts could greatly reduce the costs and risks associated with integrating higher penetrations of wind energy. The U.S. Department of Energy has sponsored a research campaign in partnership with the National Oceanic and Atmospheric Administration (NOAA) and private industry to foster improvements in wind power forecasting. The research campaign involves a three-pronged approach: (1) a one-year field measurement campaign within two regions; (2) enhancement of NOAA's experimental 3-km High-Resolution Rapid Refresh (HRRR) model by assimilating the data from the field campaign; and (3) evaluation of the economic and reliability benefits of improved forecasts to grid operators. This paper and presentation provide an overview of the regions selected, instrumentation deployed, data quality and control, assimilation of data into HRRR, and preliminary results of HRRR performance analysis.**

Keywords-forecast; numerical weather prediction; economic value; measurements; grid operations; wind variability

I. INTRODUCTION

A number of wind energy integration and other studies [1–3] have shown that wind power forecasting can provide significant economic and reliability benefits for grid operators; however, these studies have focused only on day-ahead forecasts. The potential value of shorter term forecasts has not been explored.

The uncertainty of wind power forecasts also has an impact on the potential value to the user. Errors in the forecast could pose substantial economic and reliability risks, particularly for grid operators and market participants. Current state-of-the-art (SOA) wind power forecasting has uncertainties that range from 10% to 15% mean absolute error MAE (e.g., [4]). Uncertainties in the forecast can stem from poor spatial resolution, inadequate boundary layer physics, model drift, data assimilation technique, wind speed to power conversion, etc.

Many meteorologists in and outside of the energy industry believe that better and more widespread measurements could significantly reduce the uncertainty of current SOA forecasts. This argument stems from the recognition that most near-surface meteorological measurements assimilated into numerical weather prediction (NWP) models are from below the wind turbine hub height and that few observations resolve the full depth of the boundary layer and the lower troposphere up to ~3km depth.

Therefore, the DOE sponsored a partnership with the National Oceanic and Atmospheric Administration (NOAA), private industry, and academia to answer the following questions:

1. Do additional measurements lead to better forecasts?
2. Do modified NWP models improve power forecasts?
3. What value do grid operators get from better short-term (0- to 6-h) power forecasts?

The U.S. Department of Energy Wind and Water Power Program, in partnership with the National Oceanic and Atmospheric Administration, sponsored the work presented here.

This research campaign, called the Wind Forecasting Improvement Project (WFIP), began in October 2010 and consists of two project teams (Tables 1 and 2). Both projects are being conducted in three overlapping phases. The first phase is a one-year field campaign; the second phase examines the value of additional measurements in the NWP and power forecasts; and the third phase assesses the operational and economic benefits of the improvements. The DOE, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, and Argonne National Laboratory provided supplemental instrumentation, technical support, and analyses. This paper discusses the three phases for each project in detail, with focus on the field campaign and NWP enhancements. Additional details from the southern study region can be found in two accompanying papers: (1) "The Wind Forecasting Improvement Project: Description and Results from the Southern Study Region" by J. Freedman et al. [5] and (2) "Economic Evaluation of Short-Term Wind Power Forecasts in ERCOT: Preliminary Results" by K. Orwig et al. [6].

TABLE I. SOUTHERN STUDY REGION LED BY AWST

Team Members	Field Campaign	Forecasts	Power System Analysis
NOAA	X	X	
AWS Truepower	X	X	
MESO		X	
NC State University	X	X	
OK University	X	X	
TX Tech University	X	X	
ICF International			X
NREL			X
ERCOT			X

TABLE II. NORTHERN STUDY REGION LED BY WINDLOGICS

Team Members	Field Campaign	Forecasts	Power System Analysis
NOAA	X	X	
WindLogics	X	X	
NextEra	X		
SD State University	X		
NREL			X
MISO			X

II. FIELD CAMPAIGN

The field campaign began in August 2011 and concludes in September 2012. During this period, NOAA has been assimilating the data collected into their NWP models, discussed in Section III.

A. *Northern Study Region*

The northern study is led by WindLogics and covers a large portion of the Midwest Independent System Operator (MISO) service area (Fig. 1). There is extensive wind energy development within this region, and the meteorological conditions are representative of the broader Great Plains, where the majority of wind energy development is taking place. Seven 915-Mhz Radio Acoustic Sounding System (RASS) profilers (new); 2 449-Mhz RASS profilers (new); 5 sodars (new); 39 tall towers (existing); 3 surface flux (new); and approximately 400 nacelle anemometers were utilized for assimilation into NOAA's NWP models.

B. *Southern Study Region*

The southern study is led by AWS Truepower (AWST) and covers most of the Electricity and Reliability Council of Texas (ERCOT) service area (Fig. 2). As of March 2012, ERCOT had 9,838 MW of wind capacity installed and is seeing instantaneous presentations up to 24% of the load [7].

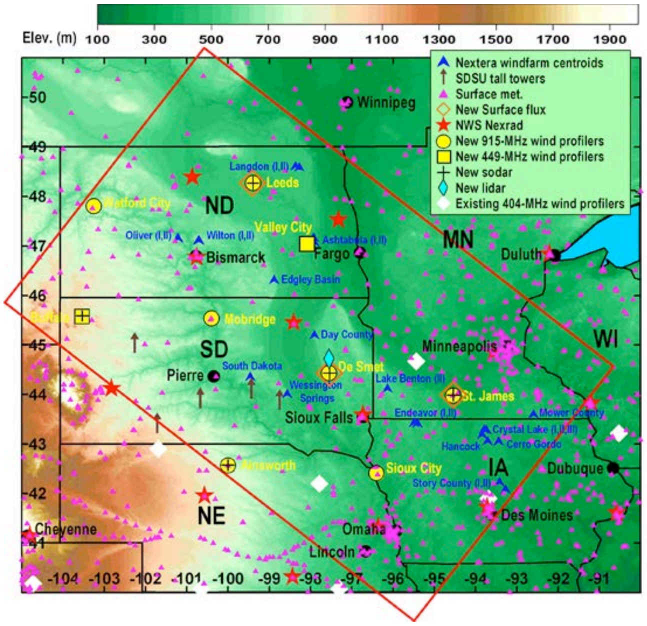

Figure 1. Northern study region and instrumentation.

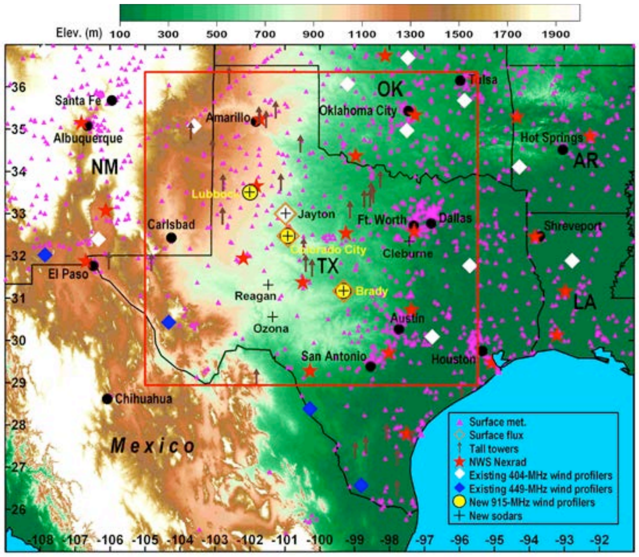

Figure 2. Southern study region and instrumentation.

For WFIP, new measurement systems were utilized, including 2 915-Mhz RASS profilers (new); 7 sodars (new); 3 surface flux stations (new); a 200-m instrumented tower and 915-Mhz RASS profiler at Texas Tech University's Reese Technology Center near Lubbock, Texas (existing); and 34 wind plant tall towers within the ERCOT domain (only 15 of which ended up providing reliable data).

III. FORECAST ENHANCEMENT

A. Numerical Weather Prediction Models

NOAA's NWP models are the foundation for the wind power forecasts generated by private industry providers such as WindLogics and AWST, the industry team leads for the two WFIP projects. When WFIP began, the SOA in operational meteorological forecasts produced by NOAA was the 13-km resolution Rapid Update Cycle (RUC) model (which is no longer operational). The domain covers the area in black in Fig. 3. The RUC generated new forecasts every hour for 0- to 18-h horizons [8].

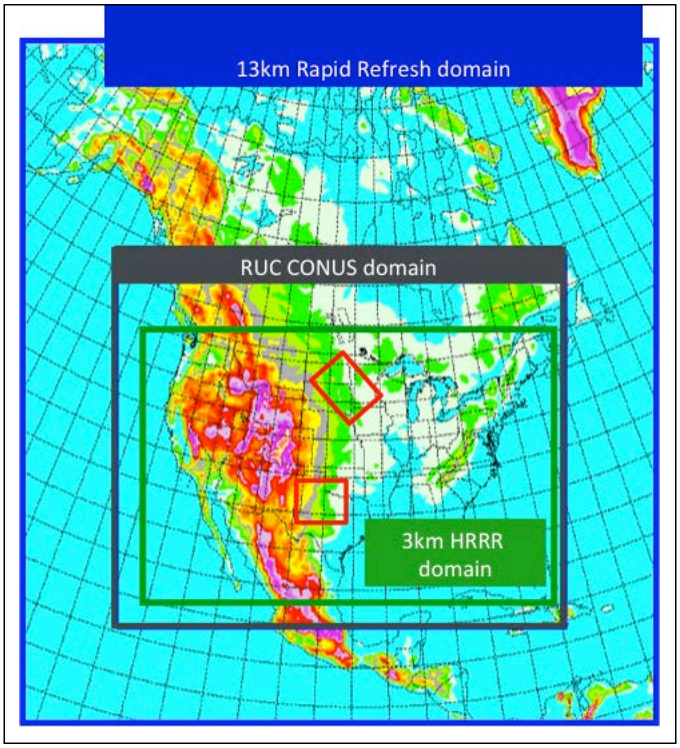

Figure 3. NOAA NWP domains: 13-km RAP in blue, retired RUC domain in black, 3-km HRRR in green, and study regions in red [9].

1) The Rapid Refresh Model

The National Centers for Environmental Prediction (NCEP) Rapid Refresh (RAP) model went operational on May 1, 2012, replacing the RUC model. The NCEP RAP, like the RUC, has a 13-km resolution, but it covers a larger domain and has several significant differences [10]. These differences include:

- The Weather Research and Forecasting (WRF) model v3.2.1+ with rapid refresh capabilities as the model core, replacing the RUC forecast model;
- A terrain-following vertical coordinate system (referred to as the sigma vertical coordinate system);
- A rotated latitude-longitude projection grid; and
- A rapid refresh version of the Gridpoint Statistical Interpolation (GSI) analysis system for updating model initial fields with recent observations.

A second version of the RAP, which is currently experimental, is the NOAA Earth Systems Research Laboratory (ESRL) version of the model [10]. The ESRL RAP has some additional modifications. These modifications include:

- WRF v3.3.1+ as the model core;
- Improved physics;
- MODIS land-surface data including fractional coverage;
- A newer version of the GSI system;
- Improved assimilation techniques, especially in the near-surface layer; and
- The assimilation of new data collected within the two study areas, as well as other data.

Additionally, the ESRL RAP is used to initialize the High-Resolution Rapid Refresh (HRRR) model, discussed in more detail in the next section.

2) High Resolution Rapid Refresh

The HRRR model is an experimental, 3-km resolution, hourly updated NWP model [11]. It is based on the WRF v3.3.1, and its configuration is similar to that of the ESRL RAP, but it does not include a convective parameterization. Improvement in HRRR performance is strongly dependent on the enhancements made to the ESRL RAP and the data assimilation process.

B. Data Denial Study

To evaluate how new measurements impact the HRRR and ESRL RAP performance, retrospective simulations will be run with and without the new data for the same time periods. Each of the study areas will be examined, and a detailed meteorological analysis of ramp events will be conducted. This analysis will be performed in fall 2012.

C. Wind Power Forecasts

1) Northern Study Region

WindLogics is taking a three-pronged approach by (1) utilizing the raw forecast, (2) generating a trained forecast using Support Vector Machine methods, and (3) generating a trained ensemble forecast. Power forecasts are then generated using each of these approaches for each of three models, the NCEP RAP, ESRL RAP, and the HRRR. The raw forecasts are generated by using a bias corrected model wind speed and a derived plant power curve to create a power forecast. The trained ensemble forecast is a combination of the output of each of the trained models individually with the operational North American Mesoscale model.

2) *Southern Study Region*

AWST currently supplies ERCOT with a Short-Term Wind Power Forecast (STWPF). This forecast is used as a baseline for this study. The new experimental forecast consists of an ensemble of high-resolution rapid update NWP models. Each of these ensemble members incorporates a variety of model configurations, physics parameterizations, and data assimilation techniques. The purpose of integrating all of these ensemble members into one product is to construct an optimized composite forecast to be able to predict forecast uncertainty and assess the relative performance of different modeling approaches. The ensemble members include (Fig. 4):

- NOAA's 3-km HRRR updated hourly;
- Nine NWP models updated every 2 h on a 5-km grid run by MESO:
    - Three configurations of Advanced Regional Prediction System (ARPS);
    - Three configurations of WRF;
    - Three configurations of Mesoscale Atmospheric Simulations System; and
- Oklahoma University's version of ARPS updated every 6 h on a 2-km grid

The data from additional sensors deployed for this project as well as the data from a set of participating wind farms within Texas were assimilated into most of the ensemble members; however, the data from the project sensors were withheld from some ensemble members to gauge their impact on the forecasts.

A Model Output Statistics (MOS) procedure was applied to the forecasts from each NWP system. The MOS is designed to correct systematic errors of relevant NWP meteorological variables (e.g., wind speed and direction) at forecast sites (i.e., the wind farms). Several MOS strategies based on variations of sample selection strategies and statistical prediction tools were used to generate an ensemble of statistical predictions from each NWP system. The MOS output for the individual NWP systems was then used as input to an Optimized Ensemble Model (OEM), which created a composite deterministic or probabilistic forecast from the set of MOS-adjusted NWP forecasts. In addition to the NWP forecasts, statistical predictions based purely on recent observational data were also included in the ensemble. Two OEM training strategies were tested: one was based on a rolling sample of the last 30 days; a second approach was based on a customized "analog" training sample that was constructed by matching key weather parameters for the current forecast period with those for cases in a historical archive. The objective of the regime-based approach was to weight the individual members of the ensemble according to their performance in weather patterns that were similar to the one expected during the forecast period.

The resultant ensemble forecast was then converted to a power generation forecast at 15-min intervals out to 6 h. More details of AWST's forecasting system can be found in [5].

IV. FORECAST PERFORMANCE EVALUATION

A. *Metrics Development*

A key part of WFIP is evaluating the performance of the atmospheric and wind power forecasts. Generally, the industry has used MAE or Root Mean Square Error (RSME)

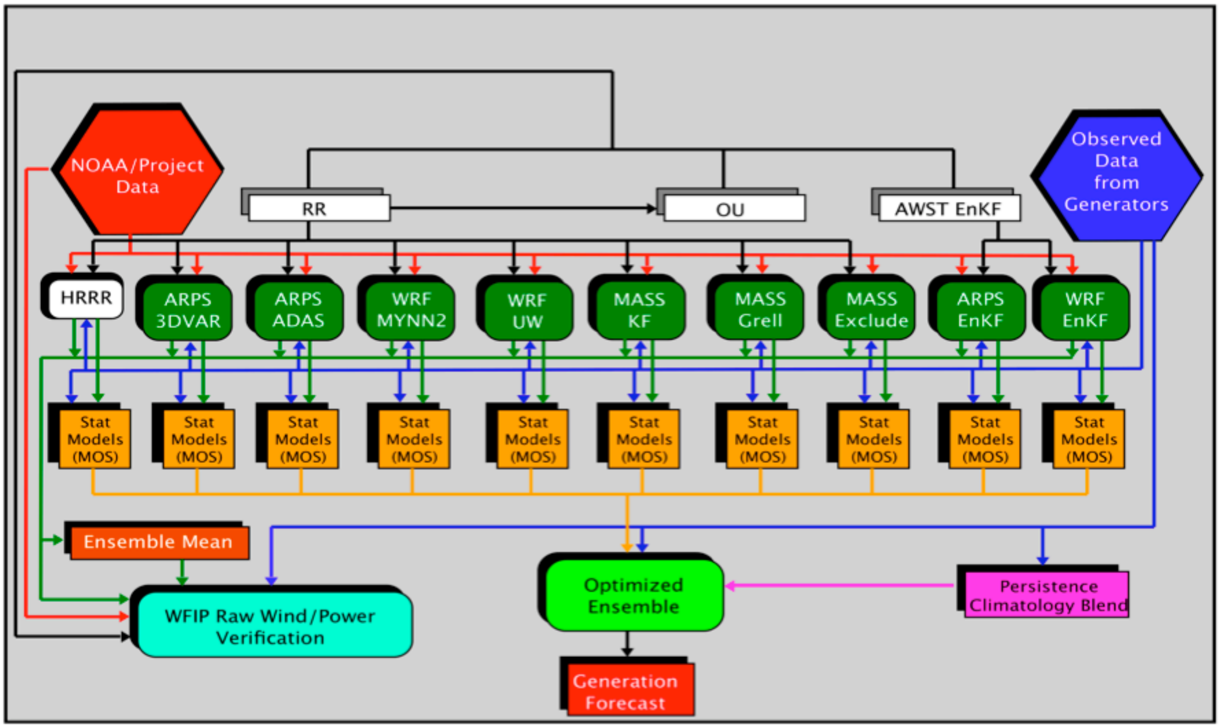

Figure 4. Schematic of AWST wind power forecasting system.

as standard metrics for forecast performance. One major drawback of these metrics, though, is that they assume the errors have a normal or Gaussian distribution. Researchers at the National Renewable Energy Laboratory (NREL) have been investigating nonparametric methods to characterize the errors, such as information entropy and hyperbolic-based methods [12]. The development and utilization of these new metrics for performance evaluation is still underway. Preliminary evaluations using the current standard metrics and qualitative comparisons of the forecasts will be discussed further here.

B. Wind Speed Forecast Performance Verification

1) Northern Study

The evaluation of the wind speed forecast performance for the northern study is still underway. The evaluation will be conducted using current standard metrics, such as MAE and RSME, but will also be evaluated using the new metrics being developed.

2) Southern Study

Forecast performance is being extensively analyzed. This includes an evaluation of each physics-based and statistical component of the forecast system as well as the performance of “final” ensemble composite forecasts. It also includes an evaluation of the variations in forecast performance by time of year, time of day, weather regime, and other factors. Preliminary results from December 2011 (Fig. 6) show the comparative MAEs among the ensemble members, persistence, and the new ensemble forecast. The ensemble forecast performs the best, with ~10% lower MAE than most of the ensemble members individually. More details can be found in [5].

C. Wind Power Forecast Performance Verification

1) Northern Study

The evaluation of the wind power forecast is ongoing; however, preliminary results are showing some improvement in MAE between the NCEP RAP, ESLR RAP, and HRRR. Fig. 7 shows an example of this improvement with the percent of the normalized difference in MAE between the RUC and HRRR (red) and the NCEP RAP and HRRR (blue) for all forecast horizons out to 12 h. For all sites, HRRR performs better than the RUC; and for most sites, HRRR performs better than the NCEP RAP.

2) Southern Study

The evaluation of the wind power forecast performance for the southern study is also ongoing. Similar to the northern study, though, preliminary results show that the new ensemble-based power forecast outperformed the power forecasts generated by single members of the ensemble or the current operational ERCOT STWPF forecast (Fig. 8). More details are included in [6].

V. ECONOMIC EVALUATION

The final phase of WFIP is to evaluate the benefits of improved wind power forecasts for MISO and ERCOT. This evaluation involves determining the impact on what was delivered versus scheduled, imbalance costs and penalties, market participation, ancillary service costs, and potential emissions implications.

A. Midwest Independent System Operator

To determine the potential benefits for MISO, NREL researchers are using PLEXOS [14], a sub-hourly production cost model. Coal, nuclear, and large oil and gas generating units are committed on 15-h-ahead wind generation forecasts.

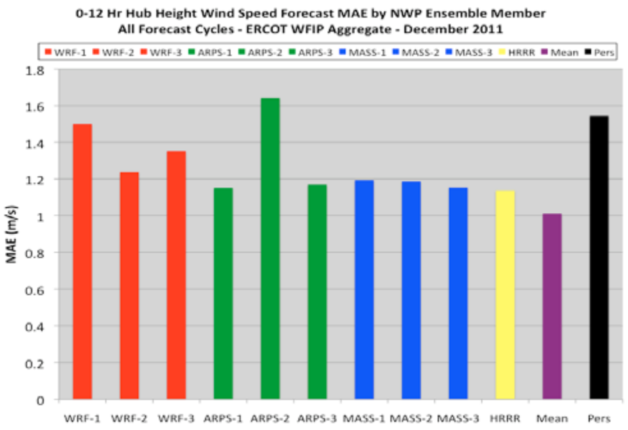

Figure 5. Hub height wind speed forecast MAE for December 2011 for the southern study [13].

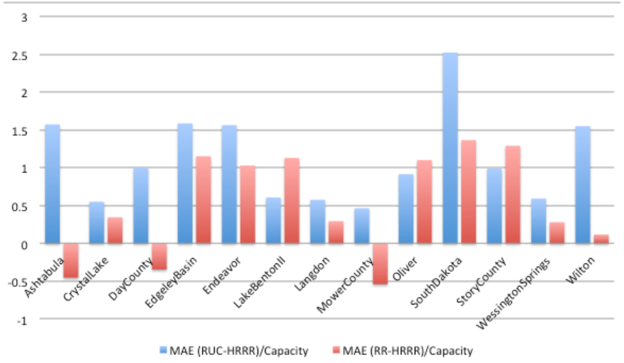

Figure 6. Percent difference of normalized MAE for wind power forecasts at various sites in northern study.

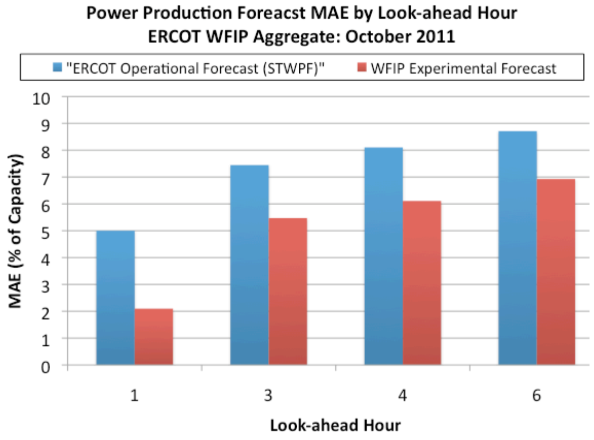

Figure 7. Percent MAE for the current SOA versus the new experimental forecast. [13]

Combined cycle and combustion turbines are committed based on short-term wind power forecasts. Additionally, MISO has a Dispatchable Intermittent Resource (DIR) program in place, which is a mechanism for variable generators, such as wind generators, to participate in the market. The benefits of the forecasts will be evaluated both with and without the DIR system.

B. Electric Reliability Council of Texas

The wind power forecasts generated by the AWST team will be used to evaluate the benefits of any forecast improvements to ERCOT. The production cost model used was GE-MAPS (MAPS) [15], which simulated the power market on an hourly resolution, committing and dispatching generators to meet load by optimizing the production cost. A base case was run simulating the current ERCOT system. A gas sensitivity case was also run to evaluate how the results would change for various gas price scenarios. Preliminary results are available for the first six months of forecasts and are presented in [6]. Alternative reserve scenarios will also be evaluated.

VI. CONCLUSION

The goal of the DOE/NOAA/industry partnership is to advance wind power forecasting by demonstrating the benefit of measurement networks and enhanced NOAA foundational NWP products, and ultimately show the potential value of those improvements to end users—in this case, the energy industry. Preliminary results are promising and show that significant reductions in wind power forecast errors are possible and can provide substantial value to the grid.

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