1.2 **A TURBINE HUB HEIGHT WIND SPEED CONSENSUS FORECASTING SYSTEM**

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1. INTRODUCTION

The contribution of wind power to the nation's energy production continues to grow. Due to the variable and uncertain nature of this energy source and the need to balance output with fossil-based generators, accurate forecasts of the power generated by wind farms are becoming increasingly important. This is a difficult forecast because the atmosphere at the hub height of modern turbines is not well represented in numerical weather prediction (NWP) models.

This paper describes the application of the Dynamic Integrated ForeCast system (DICast®) to turbine hub height wind speed forecasting. DICast® is a weather prediction system that was designed to emulate the human forecast process. It has been developed and refined at the National Center for Atmospheric Research (NCAR) for more than 10 years. It first post-processes output of several individual NWP models separately, and then generates an intelligent consensus forecast from these optimized modules. A strength of DICast is that it continually learns how to make a better forecast based on comparisons of recent forecasts and observations.

Some unique components that go into the overall system that is currently being run at NCAR's Research Applications Laboratory (NCAR/RAL) are a deterministic Weather Research and Forecasting (WRF) model, WRF and Mesoscale Model (version-5) (MM5) ensembles, and an advanced wind speed-to-power conversion system. Additional inputs include the National Centers for Environmental Prediction (NCEP) and Environment Canada NWP models and observations from turbines, farms, and connection nodes.

This research and development has been funded by Xcel Energy who has service areas in three distinct regions of the US, which are roughly described as Minnesota, Colorado, and North Texas/East New Mexico. In these 3 regions, there is roughly 3.75 GW of installed wind power capacity from 2934 wind turbines. Decisions involving this magnitude of power production are critical to the company's success and the economy of the regions.

2. OBSERVATIONAL DATA AND PREDICTANDS

Forecasts that are tuned using statistical and artificial intelligence methods require observations as targets. The most relevant observational data sets for this project are hub height wind speed and power. Xcel provides NCAR with high temporal resolution observations of both hub height wind speed and power from roughly 90% of the turbines from which it obtains wind energy. NCAR has chosen a two step approach to the forecast process. First, DICast® predicts the wind speed at hub height. Then the advanced power conversion system converts those wind speeds to power forecasts that can be summed to provide farm or connection node power forecasts.

The wind speed instrumentation on the turbines is the nacelle anemometer. They are located at hub height, atop the hub, just behind the turbine blades. It can be argued that the measurements taken by these instruments do not reflect the free atmosphere wind speeds due to their positioning and the effects of the upwind, rotating turbine blades. However, there is an extensive empirical relationship between the nacelle wind speed and the power produced by the turbine. Therefore DICast® was configured to predict the nacelle wind speeds rather than the free atmosphere wind speeds (as might be measured at an 80m meteorological tower).

3. DYNAMIC MODEL OUTPUT STATISTICS (DMOS)

DMOS is the first forecast optimization step in DICast®. It is a statistical post-processing step that attempts to optimize the raw forecast from each NWP model. This process is similar to what NCEP does in its Model Output Statistics (MOS) product generation. A key difference is that DMOS has been designed to work on

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relatively short forecast/observational histories. By carefully choosing the inputs from the NWP model that are used in the generation of the statistical relationships to come up with a forecast, reasonable DMOS equations can be generated with only 30 days of history. These relationships get stronger as the history goes to 90 days, but beyond that point we (at NCAR) have observed diminishing marginal returns in forecast skill. The effect of DMOS is that within a fairly short time, tuned forecasts can be made for new turbines that have been recently added to the system.

DMOS empirical relationships are generated for each turbine based on the predictors derived from each NWP model and the nacelle observations. For each turbine, different empirical relationships are determined for each forecast lead time. Also, since the important inputs to a 3-hour lead time forecast made at noon will differ significantly from the inputs important to a 3-hour forecast made at midnight, different DMOS equations are generated for each lead time and <u>each model forecast generation time</u> (2-8 times per day, e.g. for the NAM, 00Z, 06Z, 12Z, and 18Z). These equations are recalculated weekly using the latest model and observational data, and thus, the system learns how to make a better forecast. Since DMOS is applied independently, these equations will differ for each NWP model. When the current NWP model data arrive, the appropriate DMOS equations are applied to produce an optimized forecast from that model.

The success of the DMOS step lies in the derivation of predictors from the NWP models. Each model provides a different set of predictors. The most relevant model variables to the prediction of hub height wind speeds, i.e. at 50-120 meters, are the pressure level (or sigma level) wind speeds and the 10m wind speed. Different combinations of these variables can be used to generate an estimate of the wind speed at hub height. These independent estimates of hub height wind speed are used as separate inputs to DMOS. The predictors that are chosen for use in the optimal DMOS equation will vary by turbine, time of day, forecast generation time, lead time, and season.

Through this DMOS process, optimized forecasts specific to each input model are generated. They are optimized in the sense that they reduce the Root Mean Squared Error (RMSE) of the forecast when compared with any of the individual hub height wind speed predictors generated from the model data. The reduction in error varies by month and by region. Also, the best individual predictor varies by time of day and season. DMOS forecasts usually outperform the best predictor by 5-10% in any given month. This can be seen in figure 1 which shows RMSE for individual predictors from NCEP's North American Mesoscale (NAM) model compared to the tuned NAM DMOS forecast for 1976 turbines. The plot shows that the predictor labeled 2304, the 10m wind speed, is by far the worst predictor of hub height wind speed. Yet, because it is generated by a somewhat independent process and thus less correlated with other predictors, it is often used in DMOS equations.

Verification results seen month after month demonstrate the value of DMOS. It makes a strong case for model post-processing to improve hub height wind speed forecasts. If a forecast was generated by any of the individual aforementioned techniques only, it would end up being statistically inferior to a DMOS optimized forecast.

4. FORECAST INTEGRATOR

The second optimization step in DICast® is the integration of the DMOS forecasts into a single consensus forecast. This forecast generation step is analogous to the job done by a human who, once having removed biases from individual models' forecasts, must combine them into a single final forecast. Typically, the human does this based on subjective experience of which models have performed the best at a particular site and lead time. The DICast® forecast integrator does this by objectively determining the optimal combination of DMOS model forecasts. Again, the optimal combination varies depending on location, time of day, forecast generation time, lead time, and season.

The forecast integrator performs a bias-corrected weighted average of the input DMOS forecasts. Each day, the weights are nudged based on the models' performance compared to the observations. The weight change is based on the gradient in weight space. In this way the system learns and adapts to seasonal variations in forecast skill on a site-by-site basis. The integrator's adaptation is relatively rapid. Even if the best individual DMOS forecast changes radically over the course of a month, the integrated forecast adapts to the "best model of the month".

Figure 2 shows the errors of the DMOS-optimized forecasts compared to the DICast® integrated forecast for 1976 sites over the last 4 months. While the relative performance of the NWP models varies from month to month, the DICast® integrated forecast significantly outperforms all the individual models' forecasts. The reduction in error is usually around 10%-15% over the best forecast model.

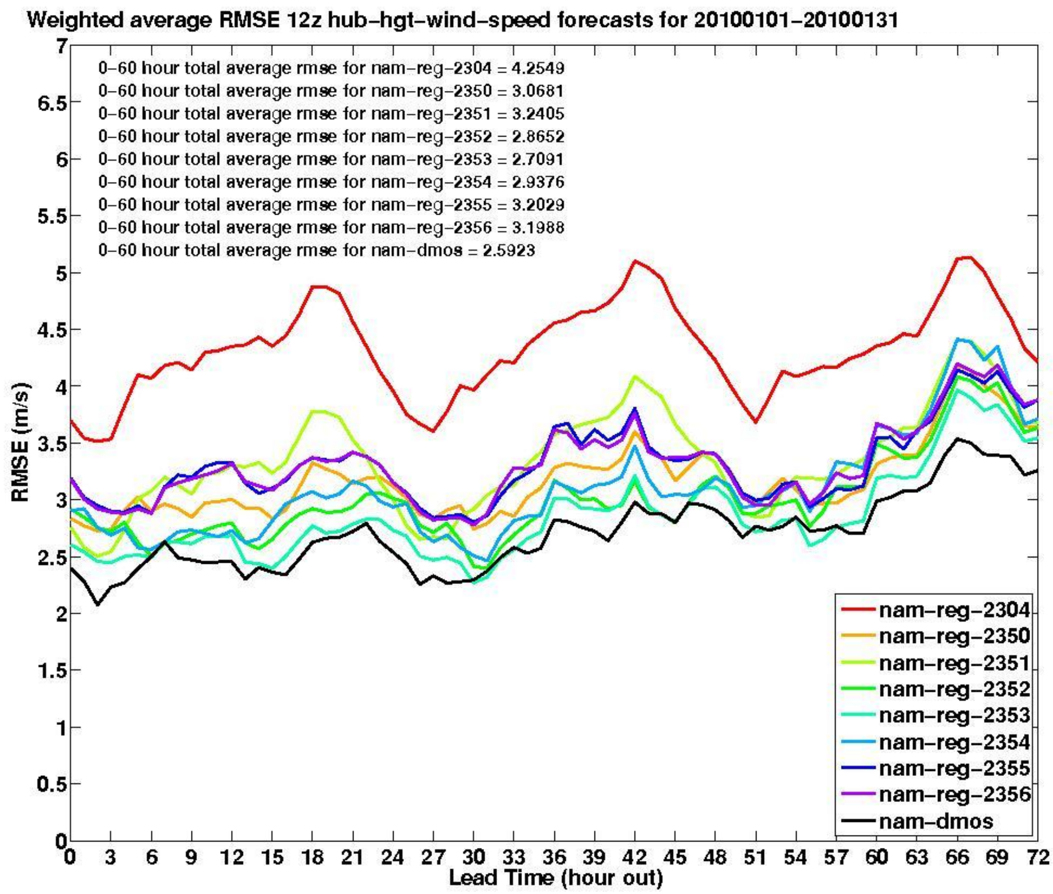

Figure 1: Comparison of errors from hub height wind speed forecasts for NAM regressors compared to the NAM DMOS forecast. Each regressor is a forecast generated by a single technique of deriving a forecast from model output.

Verification of system performance continues to demonstrate the merit of the consensus forecast approach. By design, the DICast® integrator will outperform any ingredient forecast made from one particular model. The result is a robust system that consistently outperforms a single model-based forecast system. Accurate power forecasts are becoming increasingly important to the wind power industry. A variety of methodologies exist to produce hub height wind speed forecasts and future power production at a farm. DICast®, an existing robust consensus forecast technology developed at NCAR/RAL, was applied to this problem. Verification results show that DICast® produces a better hub height wind speed forecast than any one individual model.

5. CONCLUSIONS

For Xcel Energy, DICast® has provided a robust core to an overall power forecast system. The DICast® system optimizes the forecast in two phases, each significantly reducing the forecast error. Other studies show that the reduction in hub height wind speed error translates into similar reductions in power forecast errors. Due to the size of Xcel's wind power operations, these reductions have resulted in major benefits to both the operational and trading groups.

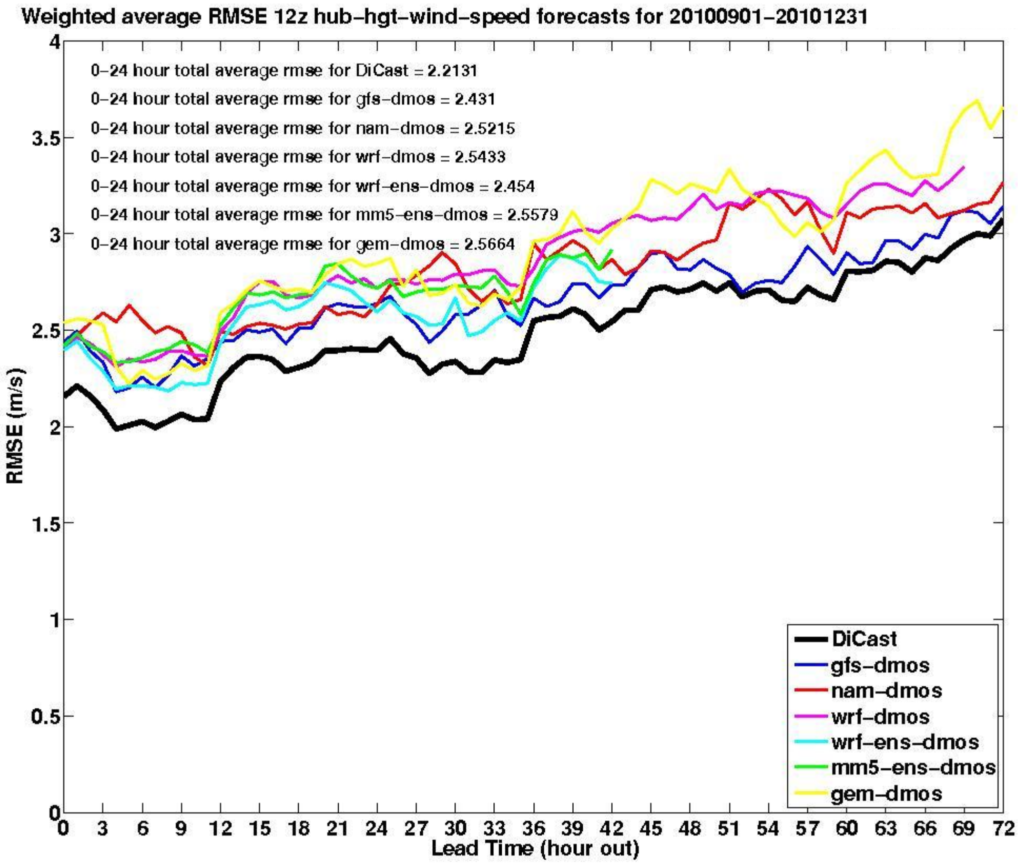

Figure 2: Errors for DMOS forecasts compared to the DICast® integrated forecast made from September though December 2010. The model forecasts are from the runs available at 12Z.

6. ACKNOWLEDGEMENTS

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