Development and Testing of A Wind Energy Forecasting System

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1. Introduction

In recent years, there is growing interest in developing wind energy resources. Wind energy is intermittent and hence poses considerable difficulties to utilities and system operators in scheduling the wind power generation. To alleviate these difficulties, a forecasting system is needed to accurately forecast next-day wind speed and power. AMI Environmental (AMI) has developed a state of the art forecasting system based on the most advanced numerical weather prediction models and wind modeling technologies. Under the sponsorship of Electric Power Research Institute, AMI has adapted and tested the system at a 75 Mw wind plant in southwest Texas (EPRI, 2004). The forecasting system and results of its application to the Texas wind plant are described below.

2. System Development

As shown in Figure 1, the AMI Wind Energy Forecasting System (WEFS) consists of the following modules: (1) a mesoscale model; (2) a diagnostic wind model; (3) an adaptive statistical model; and (4) the forecast access by users. The following sections describe the development and operation of the WEFS modules.

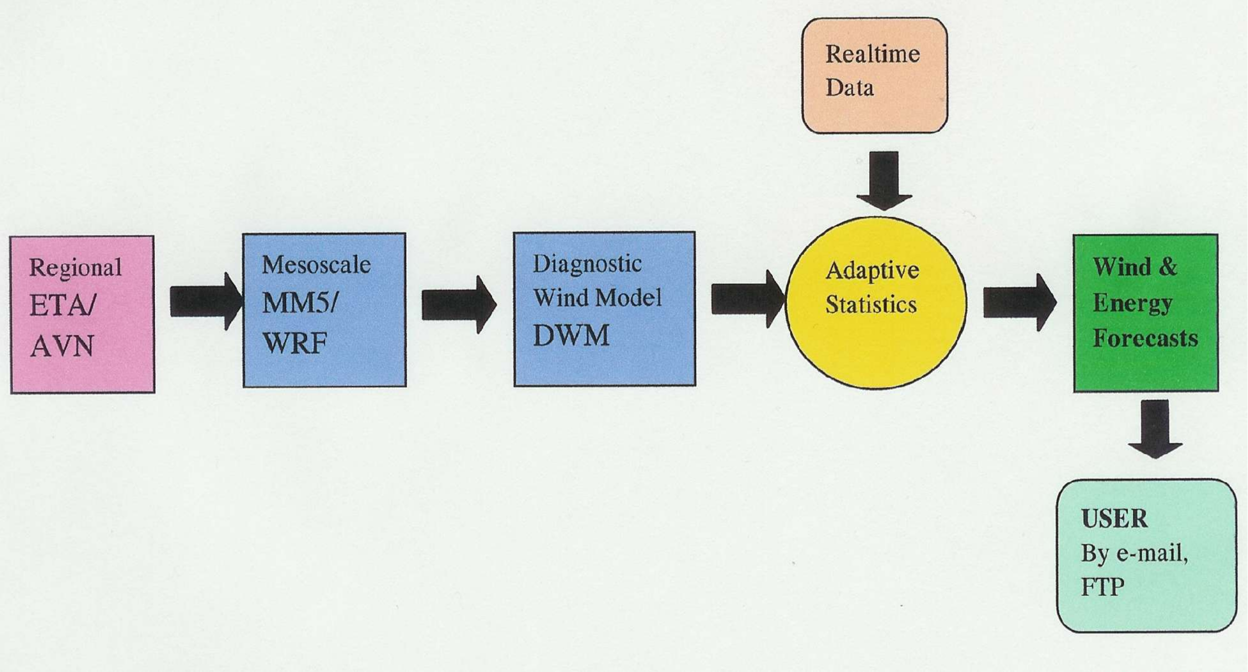


Figure 1 Schematic of AMI Wind Energy Forecasting System (WEFS)

Mesoscale Model MM5

The first WEFS module is a PC-based version of the advanced, three-dimensional mesoscale model MM5 (Version 3), developed by AMI. The Fifth Generation Mesoscale Model (MM5) is a limited-area, nonhydrostatic, terrain-following, sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation. It was originally developed as a community mesoscale model at Penn State University and National Center of Atmospheric Research (NCAR) during the 1970s. It is continuously being improved by contributions from several universities and government laboratories as well as private consulting firms around the world. As a result, the MM5 model offers several advanced parameterizations for turbulence, cloud and precipitation. It also incorporates detailed topographical and land use databases, both for the U.S. and elsewhere. The MM5 model is the most widely-used and verified mesoscale model today. It is used in diverse applications, from air pollution modeling studies to forecasting storms and tornadoes. AMI is currently using the MM5 model to forecast tropical storms in Southeast Asia and delivers four forecasts daily via the Internet.

Mesoscale models such as MM5 are traditionally run on large computer systems, such as supercomputers or Unix workstations. Recently, AMI developed a PC-based MM5 version running with the Linux operating system. Realistic tests conducted by AMI indicate that a PC equipped with two or more CPU (i.e. multiprocessor) is as fast as the best Unix workstations. Yet the Linux PC only costs a small fraction of these expensive computers.

The MM5 forecasts use the outputs of a regional or global model for initial and boundary conditions. In its current configuration, the MM5 model can use the outputs from either the regional-scale ETA model or the global-scale AVN model. All ETA/AVN outputs are downloaded from the FTP server of the NOAA National Center of Environmental Prediction (NCEP) in Maryland. To enhance the accuracy of the forecasts, the MM5 model is generally configured to use a modeling domain with several nested grids with varying spatial resolutions. For sites located in complex terrain, it is necessary to deploy modeling grids with the lowest possible resolution (a few kilometers or less). AMI has a global topographical and land use data base with a one-km resolution for use with MM5. AMI has also recently implemented the Weather Research and Forecasting model (WRF) as a replacement for the MM5 model. The WRF model is the most advanced mesoscale model available today with updated physics, flexible initialization and data assimilation, and efficient computer operations.

Diagnostic Wind Model

To further resolve the local topography and microscale flow effects, the MM5 predictions are coupled with a diagnostic wind model (DWM) developed by AMI. The DWM model can derive mass-consistent, three-dimensional wind fields that includes treatment for localized flow phenomena such as terrain channeling, thermal drainage and overland/overwater transition. A refined resolution of 100 m or less is frequently used in the DWM simulations. The same number of vertical layers is used in both MM5 and DWM simulations, including those at the wind anemometer and turbine hub heights. Hourly-averaged predictions from the MM5 model serve as inputs to the DWM model. To enhance the accuracy of short-term (e.g., next-hour) forecasts, the DWM model can also accept onsite real-time wind measurements as inputs.

Adaptive Statistical Model

Even with the best available models such as MM5 and DWM, forecast errors are still present and can be caused by both systematic and non-systematic factors. Non-systematic or inherent errors include those due to random atmospheric turbulence. While there is little that can be done about these inherent errors, systematic biases in the forecasts can be characterized and at least partially addressed. AMI devised an adaptive and efficient statistical scheme to minimize biases towards either overpredictions or underpredictions. For each forecast, the statistical model computes simple linear regression equations using recent actual measurements at the facility. Monitoring data (wind, power and temperature) from the last 10 days or less are used to derive the regression equations. Separate equations can be easily generated for different intervals of wind speed and direction for wind and power predictions or time of day for temperature predictions.

The AMI scheme is fully dynamic and adaptive since new regression equations are derived for each new forecast and take into consideration the most recent model biases. Unlike the traditional MOS (Model Output Statistics) approach, the AMI statistical scheme does not require long sampling time and extensive monitoring data. Furthermore, it is much simpler to implement than MOS, which requires extensive recalculations due to changes in the forecast models, weather conditions or wind plant configurations.

Forecast Access by Users

Upon completion of the forecast calculations, the forecast wind speed, direction, ambient temperature, and energy generation data are sent via e-mail or other electronic means to the host and other organizations. The forecasts can also be uploaded to the host FTP server along with appropriate statistics designed to evaluate the accuracy and skill of the forecasts.

3. Application to the Southwest Mesa Facility

Two MM5 forecasts, valid for 48 hours, are generated daily for the periods beginning at 00 UTC (1800 CST) and 12 UTC (0600 CST). As shown in Figure 2, the MM5 model uses four nested modeling grids. The outermost domain (domain D01) consists of 42 x 42 grid points, spaced 45 km apart. It covers a geographical area of 1890 km x 1890 km, including the whole state of Texas and parts of neighboring states and northern Mexico. Figure 6-3 shows the terrain elevations in the outermost domain. The first inner domain (domain D02) consists of 76 x 76 grid points with a 15 km resolution, and the second inner domain (domain D03) consists of 46 x 46 grid points with a 5 km resolution. The innermost domain (domain D04) is centered on the Southwest Mesa plant, and consists of 34 x 34 grid points with a 1.67 km resolution.

Initial conditions at the MM5 grid points are calculated by interpolating the NCEP ETA forecast data. Lateral boundary conditions are derived from the ETA forecasts and updated every six hours throughout the MM5 forecasts. Following the wind forecasts and their adjustment by the adaptive statistical scheme, a site-specific wind power curve supplied by EPRI is used to derive the generated wind energy. The generated energy is also adjusted by the adaptive statistical scheme in the final forecast. The forecast parameters include hourly average wind speed, wind direction, ambient temperature and power output. Table 1 presents an example final forecast is for Southwest Mesa. Final forecasts are uploaded twice a day to the EPRI FTP server. AMI also maintains a password-protected Web site that includes graphical displays of MM5 forecasts (AMI website http://www.amiace.com). To minimize human errors, the above forecasts are completely automated, including all model simulations and evaluation. A Linux PC with dual AMD Athlon microprocessors performs the model simulations.

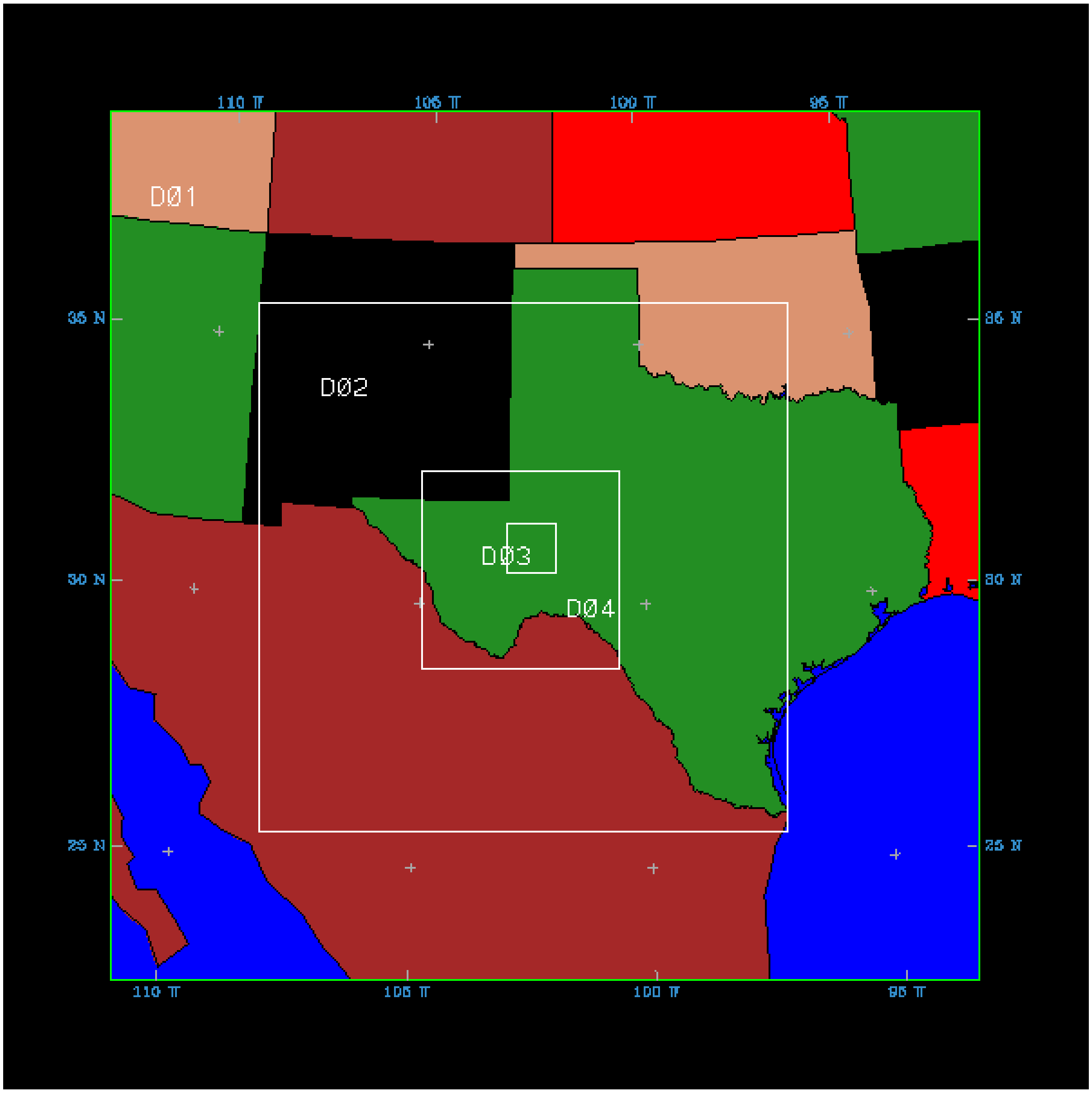


Figure 2 MM5 Modeling Grids for the Southwest Mesa Facility. Innermost grid D04 is centered on Southwest Mesa with a 1.67 km cell spacing

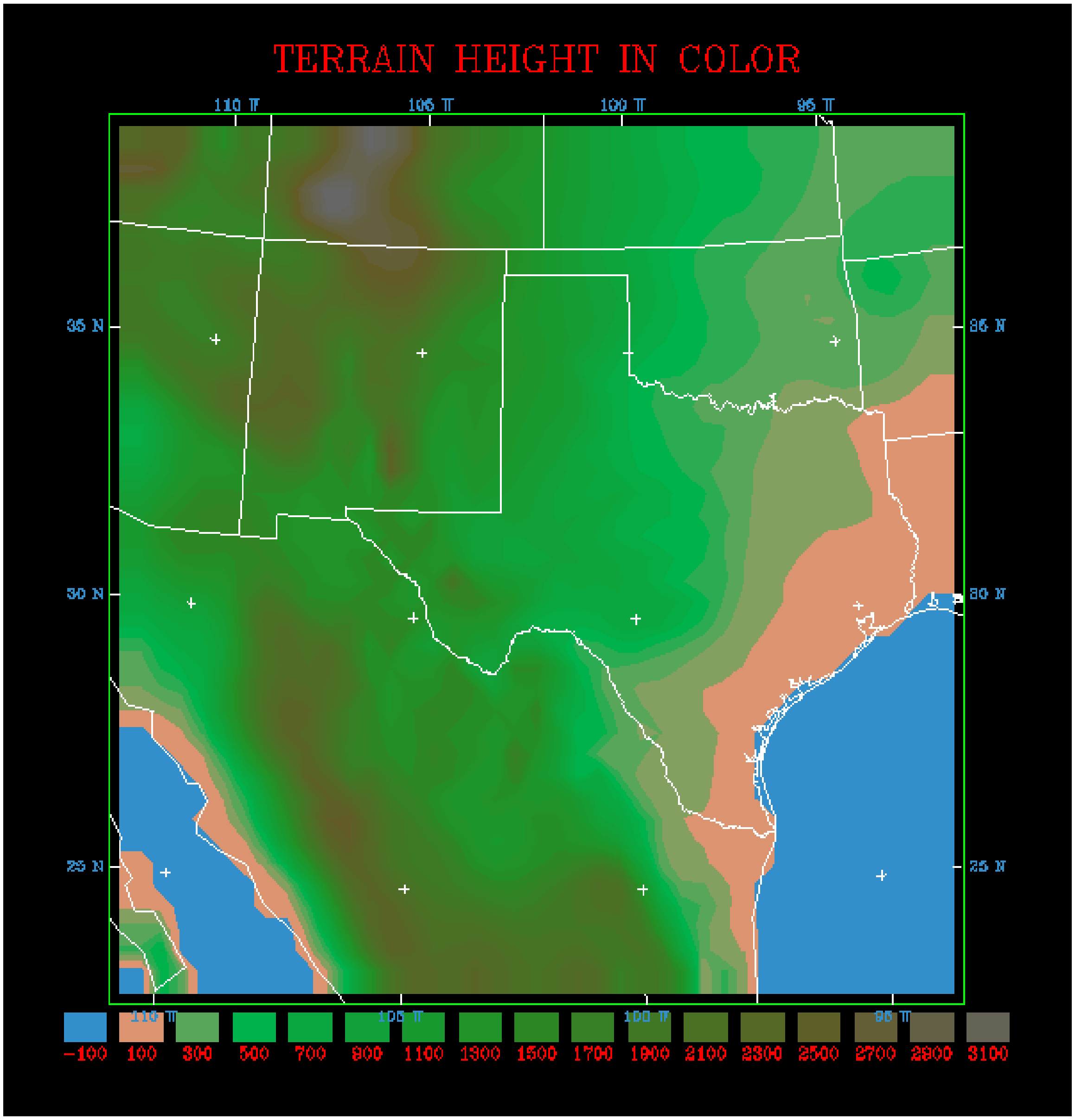


Figure 3 Terrain Elevations (m) Around the Southwest Mesa Facility. Outermost grid D01 has a spatial resolution of 45 km.

Table 1 Example Forecast for Southwest Mesa

Wind Plant	Contractor	Forecast Issued (UTC)	Forecast Issued (CST)	Forecast Hour	Forecast Hour (CST)	Wind Speed (m/sec)	Wind Direction	Ambient Temp. (deg C)	Power (kW)
SWM	AMI	2002070112	2002070106	1	2002070106	6.8	152	20	12064
SWM	AMI	2002070112	2002070106	2	2002070107	8.0	139	19	21811
SWM	AMI	2002070112	2002070106	3	2002070108	9.4	136	19	34596
SWM	AMI	2002070112	2002070106	4	2002070109	8.9	138	19	29386
SWM	AMI	2002070112	2002070106	5	2002070110	7.2	149	20	14074
SWM	AMI	2002070112	2002070106	6	2002070111	5.5	150	21	6399
SWM	AMI	2002070112	2002070106	7	2002070112	4.0	128	24	1557
SWM	AMI	2002070112	2002070106	8	2002070113	3.6	122	26	702
SWM	AMI	2002070112	2002070106	9	2002070114	4.0	121	27	1397
SWM	AMI	2002070112	2002070106	10	2002070115	5.0	113	27	4106
SWM	AMI	2002070112	2002070106	11	2002070116	5.4	120	28	5834
SWM	AMI	2002070112	2002070106	12	2002070117	5.5	122	27	6504
SWM	AMI	2002070112	2002070106	13	2002070118	6.9	121	27	12113
SWM	AMI	2002070112	2002070106	14	2002070119	7.9	133	26	20290
SWM	AMI	2002070112	2002070106	15	2002070120	8.9	139	25	29893
SWM	AMI	2002070112	2002070106	16	2002070121	10.3	133	24	38015
SWM	AMI	2002070112	2002070106	17	2002070122	9.5	135	23	36022
SWM	AMI	2002070112	2002070106	18	2002070123	8.0	147	23	21586
SWM	AMI	2002070112	2002070106	19	2002070200	10.3	138	22	37881
SWM	AMI	2002070112	2002070106	20	2002070201	9.3	145	21	34340
SWM	AMI	2002070112	2002070106	21	2002070202	9.5	146	21	36547
SWM	AMI	2002070112	2002070106	22	2002070203	7.9	142	21	20379
SWM	AMI	2002070112	2002070106	23	2002070204	7.0	143	20	12743
SWM	AMI	2002070112	2002070106	24	2002070205	5.6	146	20	7046
SWM	AMI	2002070112	2002070106	25	2002070206	3.7	152	20	904
SWM	AMI	2002070112	2002070106	26	2002070207	2.4	154	20	0
SWM	AMI	2002070112	2002070106	27	2002070208	2.4	155	20	0
SWM	AMI	2002070112	2002070106	28	2002070209	2.0	144	21	0
SWM	AMI	2002070112	2002070106	29	2002070210	1.4	144	23	0
SWM	AMI	2002070112	2002070106	30	2002070211	2.1	123	24	0
SWM	AMI	2002070112	2002070106	31	2002070212	4.8	141	25	3761

Table 1 Example Forecast for Southwest Mesa (Cont’d)

SWM	AMI	2002070112	2002070106	32	2002070213	5.8	152	25	7712
SWM	AMI	2002070112	2002070106	33	2002070214	4.9	24	23	3574
SWM	AMI	2002070112	2002070106	34	2002070215	4.1	14	22	1528
SWM	AMI	2002070112	2002070106	35	2002070216	7.1	108	24	12344
SWM	AMI	2002070112	2002070106	36	2002070217	5.4	92	25	4650
SWM	AMI	2002070112	2002070106	37	2002070218	1.8	74	23	0
SWM	AMI	2002070112	2002070106	38	2002070219	5.5	6	21	6051
SWM	AMI	2002070112	2002070106	39	2002070220	7.4	38	20	12013
SWM	AMI	2002070112	2002070106	40	2002070221	8.0	67	21	14286
SWM	AMI	2002070112	2002070106	41	2002070222	6.9	66	22	8248
SWM	AMI	2002070112	2002070106	42	2002070223	5.1	77	22	3555
SWM	AMI	2002070112	2002070106	43	2002070300	5.5	118	22	6243
SWM	AMI	2002070112	2002070106	44	2002070301	8.4	140	22	24746
SWM	AMI	2002070112	2002070106	45	2002070302	7.6	144	22	17527
SWM	AMI	2002070112	2002070106	46	2002070303	7.3	142	21	14714
SWM	AMI	2002070112	2002070106	47	2002070304	8.3	138	21	24183
SWM	AMI	2002070112	2002070106	48	2002070305	9.2	146	21	32775

4. Evaluation of Forecast Results

Statistical and graphical measures have been used to evaluate the accuracy of the AMI-generated forecasts over the 12-month testing period, April 1, 2002 through March 31, 2003. Table 2 and Figures 4 through 6 summarize the forecast performance results.

Wind Speed and Energy Forecasts

Figure 4 presents example 48-hour forecasts of hourly wind speed and generation and observed data from the site for forecasts beginning at 1800 hours on July 18, 2002. The charts compare the observed data from the site with each of three forecasts, the meteorological forecast, persistence forecast, and climatology forecast. The *meteorology* forecast is generated by the WEFS model; the *persistence* forecast assumes that the conditions that existed at the beginning of the 48-hour forecast period will continue or persist through the end of the period; and the *climatology* forecast assumes that the wind speed and generation follow the same daily or diurnal climatological cycle indicated by the average of historical data for each month. The observed wind generation data were adjusted to 100% turbine availability basis for comparison to the wind energy forecasts. The forecast wind speed and generation follow the general direction of the observed data but are generally not in exact agreement.

Forecast Performance

The forecast performance is measured by the monthly and annual mean and mean absolute errors between the forecast and observed hourly wind speeds and energy generation. In addition, two skill scores are calculated to indicate the relative performance of the meteorology vs. persistence and climatology forecasts. Each skill score is equal to one minus the mean absolute error of the meteorology forecast divided by that of the persistence or climatology forecast. A skill score close to one indicates a high degree of skill, while a negative score or score close to zero indicates a low degree of skill.

As shown in Table 2, the annual mean absolute errors of the hourly wind speed and generation forecasts are 2.28 m/sec and 12,319 kW, respectively. Based on the mean annual wind speed (7.61 m/sec) and energy generation (25,450 kW), the normalized mean errors are only -0.2% and -5.2%. Annual man absolute errors are respectively 30% and 48%. The skill scores of the wind speed forecasts are 26% and 28% vs. the persistence and climatology forecasts, respectively. Similar skill scores are obtained for the energy generation forecasts, 27% and 28% vs. persistence and climatology. The wind generation forecast error was lowest for the meteorology forecasts during all months, except April when the climatology forecast error was lower.

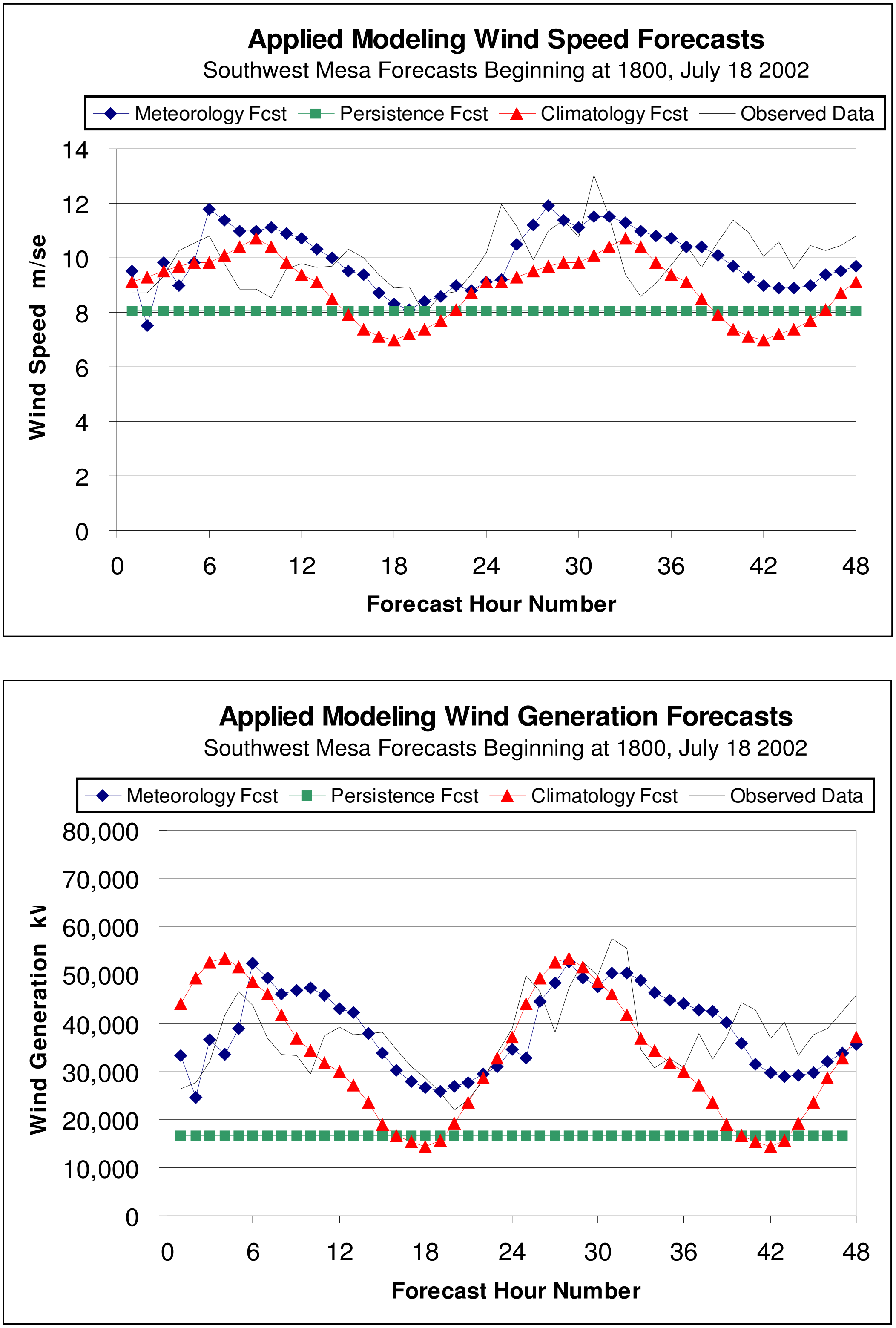


Figure 4 AMI Meteorology, Persistence, and Climatology Forecasts and Observed Hourly Wind Speed and Generation at Southwest Mesa, Beginning at 1800 hours, July 18, 2002

Table 2 Annual Forecast Performance at Southwest Mesa

	Wind Speed m/sec	Generation kW
Forecast Error		
Annual ME (m/sec)	-0.02	-1,322
Annual MAE (m/sec)	2.28	12,319
Normalized Forecast Error		
Annual ME	-0.2%	-5.2%
Annual MAE	30.0%	48.4%
Average Wind Speed or Gen	7.61	25,450
Annual Skill Score		
vs. Persistence	26.1%	28.3%
vs. Climatology	26.8%	28.1%
Wind Forecast Delivery		
Possible Forecasts	730	
Forecasts Delivered	576	
%	78.9%	

Figure 5 presents the normalized annual mean absolute errors of the meteorology, persistence, and climatology forecasts of wind speed and energy generation as functions of the forecast hour between zero and 48 hours. The normalized mean absolute errors of the meteorology forecasts are about 30% and 50% of the mean annual wind speed and energy generation, respectively. The persistence forecast error is lowest during about the first four hours of the forecast period, and the meteorology forecast yields the lowest error beyond about four hours. The climatology forecast generally shows higher error over the entire forecast period and exhibits a cyclic pattern.

Figure 6 presents the normalized monthly mean absolute errors of the meteorology, persistence, and climatology forecasts of wind speed and energy generation for each of the 12 months. The normalized mean absolute error of the wind speed forecasts was in the 17% to 33% range during the windy spring and summer months, April through August, and 26% to 42% during the low-wind fall and winter months, September through March. For the wind energy generation forecasts, the range was much broader, reaching 32% to 56% during the spring and summer, and 46% to 71% during the fall and winter months.

In addition to the AMI wind energy forecast system, the 12-month testing was also conducted for two other systems, from Risoe National Laboratory and TrueWind Solutions, LLC. Figure 7 compares the annual normalized mean absolute errors for all three forecast systems. The AMI system is the most accurate system, with the lowest errors for both wind speed and wind energy forecasts.

5. Conclusions

An accurate and efficient forecasting system that includes advanced meteorological models has been developed by AMI. The system has been applied to a 12-month testing at a 75 Mw wind plant in southwest Texas. Statistical and graphical measures have been used to evaluate the performance of the AMI system. Testing results indicate that the AMI forecasting system has considerable skills in predicting both wind speed and power generation. The system shows large improvement over both persistence and climatological techniques. The AMI forecast system is also the most accurate among three tested systems.

6. References

AMI Environmental Website http://www.amiace.com

EPRI, 2004. *Texas Wind Energy Forecasting System Development and Testing, Phase 2: 12-Month Testing*. EPRI, Palo Alto, CA and U.S. Department of Energy, Washington, D.C. Final Report 1008033, June 2004.

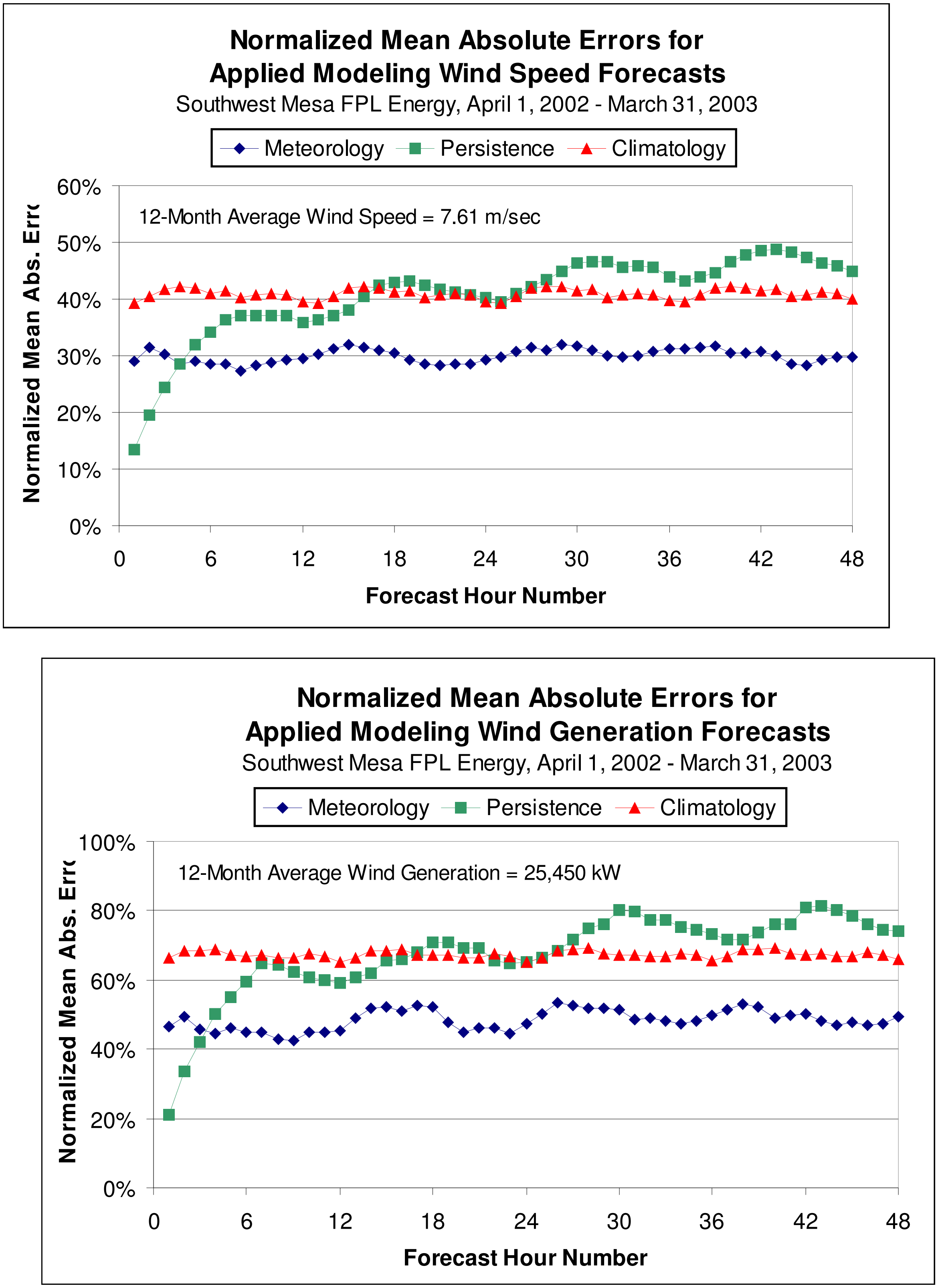
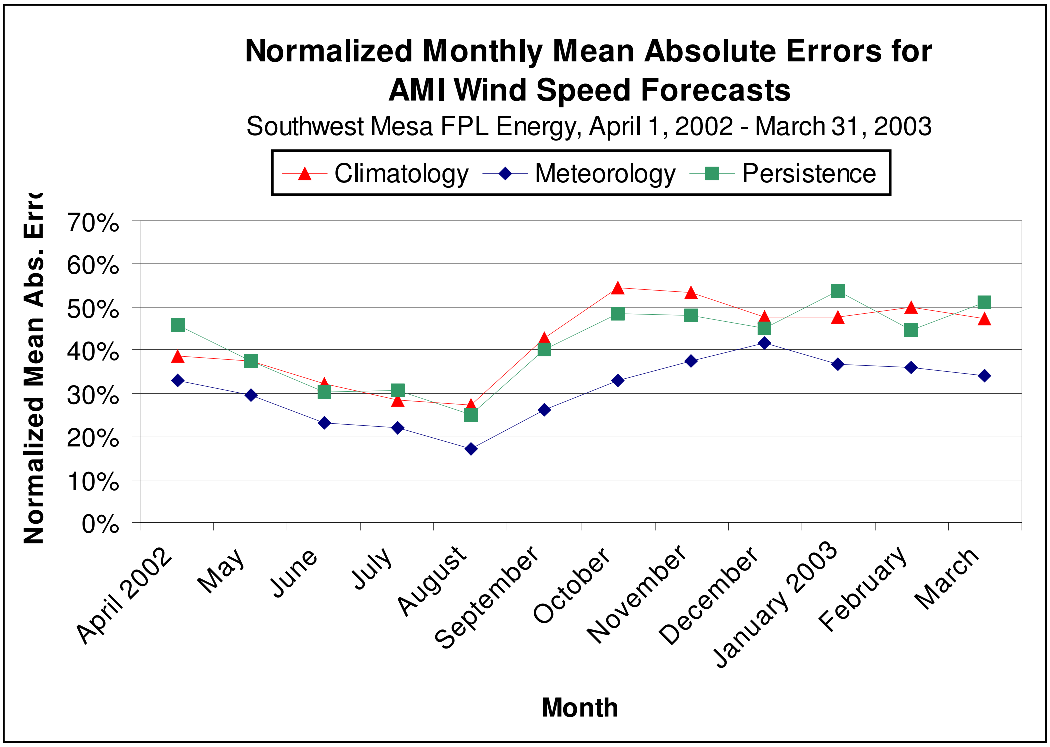


Figure 5 Normalized Annual Mean Absolute Errors for AMI Wind Speed and Generation Forecasts at Southwest Mesa Wind Plant during April 1, 2002 through March 31, 2003



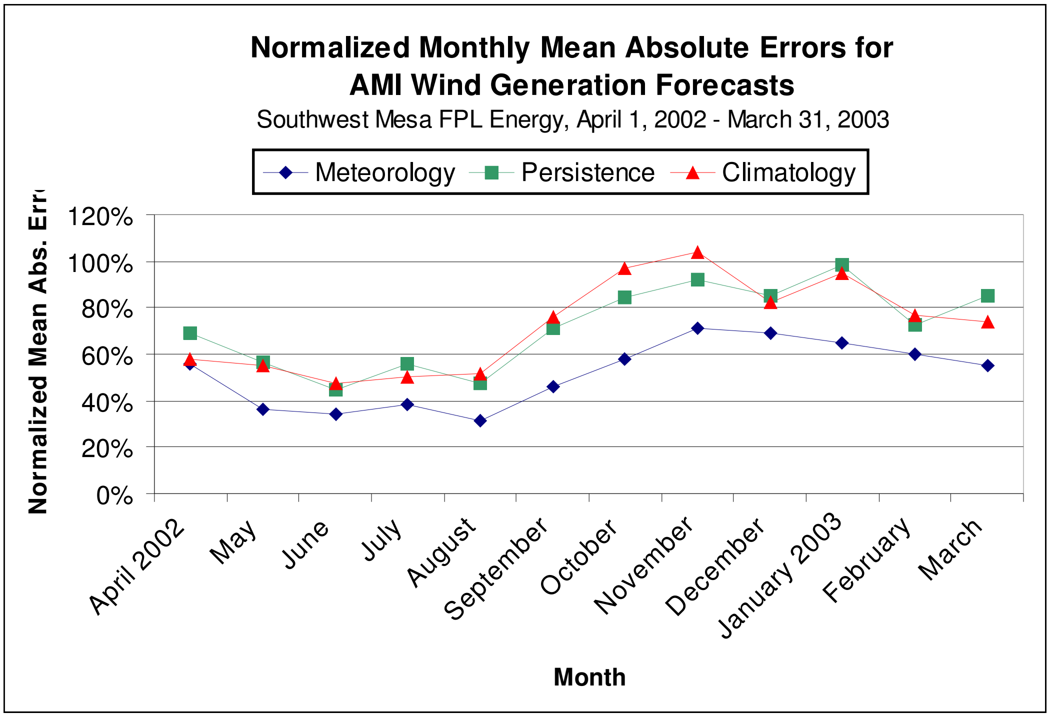


Figure 6 Normalized Monthly Mean Absolute Errors for AMI Wind Speed and Generation Forecasts at Southwest Mesa Wind Plant during April 1, 2002 through March 31, 2003

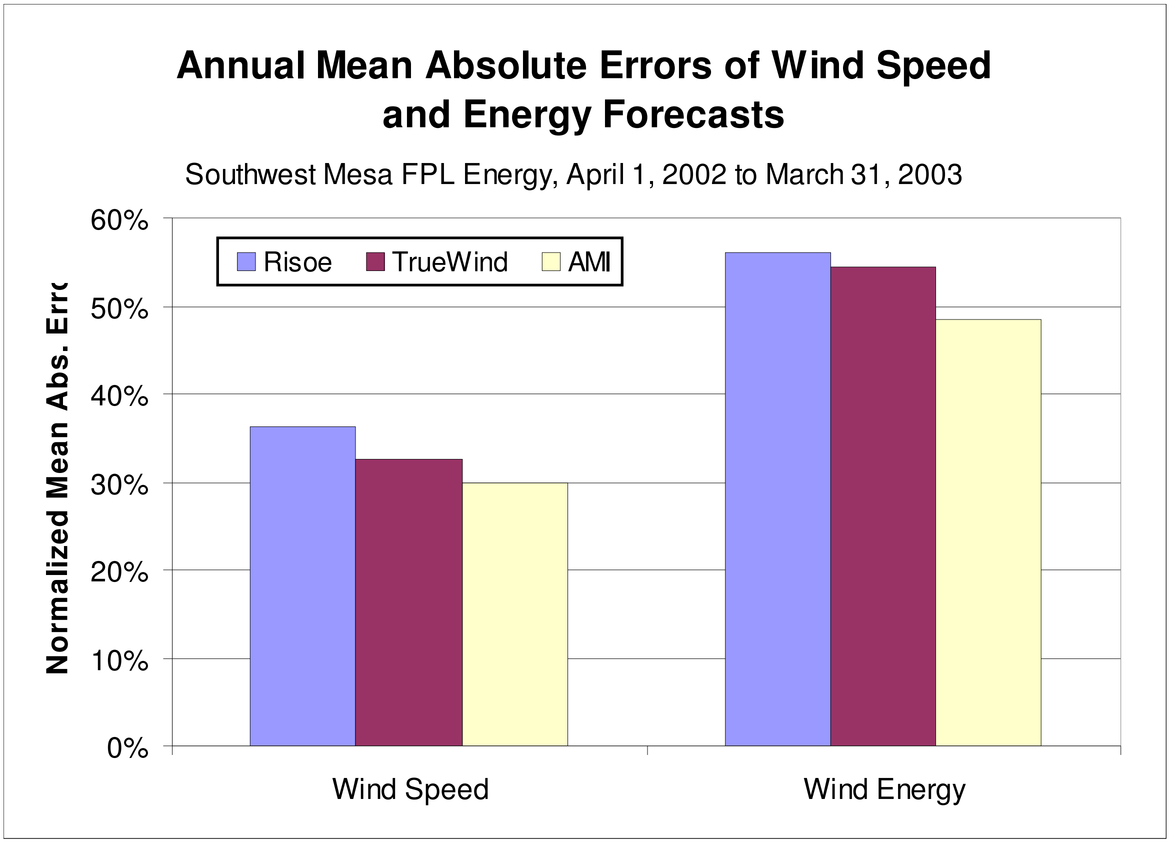


Figure 7 Comparison of Normalized Monthly Mean Absolute Errors for Wind Speed and Generation Forecasts from Risoe, TrueWind and AMI